STATE OF MAINE

DEPARTMENT OF ENVIRONMENTAL PROTECTION

BOARD OF ENVIRONMENTAL PROTECTION

	IN THE MATTER OF
NORDIC AQUAFARMS, INC.	:APPLICATIONS FOR AIR EMISSION,
Belfast and Northport	:SITE LOCATION OF DEVELOPMENT,
Waldo County, Maine	:NATURAL RESOURCES PROTECTION
	:ACT, and MAIN POLLUTANT
	:DISCHARGE ELIMINATION SYSTEM
	:(MEPDES)/WASTE DISCHARGE
A-1146-71-A-N	:LICENSE
L-28319-26-A-N	:
L-28319-TG-B-N	:
L-28319-4E-C-N	:
L-28319-L6-D-N	:
L-28319-TW-E-N	:
W-009200-6F-A-N	:
ME0002771	

Assessment of the Nordic Aquafarms Permit to Satisfy Clean Water Act Requirements

TESTIMONY/EXHIBIT:	NVC/UPSTREAM 7
TESTIMONY OF:	George Aguiar
	James Merkel
DATE:	December 13, 2019

GEORGE AGUIAR

PROFILE

Over 34 years of software development experience concentrating on working with state-of-the-art technologies to solve hard problems. Roles span complete product development life cycle from conception and design to implementation thru deployment and sustaining phases. Fully deployable from project lead to direct heavy lifting with a history of being a key player on teams which successfully met their goals.

Specializing in Rapid Application Development, Object Oriented design and development using WordPress, CiviCRM, JavaScript, PHP, React, VisualStudio.NET building .NET Enterprise and web based Service Oriented Solutions with Silverlight, .NET RIA Services, ADO.NET Entities, ASP.NET, Web Services, ADO.NET, Windows Forms, WPF, WCF, Mobile Internet Toolkit and the Compact Framework in C# and VB.NET with agile approaches to using Microsoft Patterns and Practices.

EXPERIENCE

PRINCIPLE GEORGEAGUIAR.COM – 2011-PRESENT

Specialized version of CiviCrm, a CRM (Customer Relationship Management) system for nonprofits that focuses on Constituents, not Customers. Since 2011, have been providing CiviCrm on WordPress with custom options and training. Maintain websites for over 20 customers and nonprofits. Various long and short term engagements creating and maintaining websites and online web presence. Principle contractor for Promosis.Com: Design, build and maintain PHP websites and back end office tools for online marketing and incentive programs.

PRINCIPLE GLASSMENUS.COM, INC – 2009-2011

Designed and built backend website management tools using Silverlight 3.0, ADO.NET Entities, .NET RIA Services in C# using Visual Studio 8.0 and Blend 3.0 with service pack 1 employing TFS for source code control and project management. Designed and built Customer Relationship Management module which manages customer mailing list and integrates into Microsoft Word 2007 to compose and submit email content with integration into SmarterMail 5.5.

PRINCIPLE ENGINEER TJX COMPANIES – 2007-2009

Enhancements to TJX's customized Buyer Worksheet application; a customized order worksheet written in VB.NET 2005 using Windows Forms and Component One's C1FlexGrid and Excel C1XLBook components. Projects start with analyzing business requirements, writing full UML design documentation and working to construction completion thru quality assurance and deployment all in a SOX compliant and security aware environment. Provided team mentoring delivering classes on Unit Testing, Debugging .Net using Advanced Tools, and Using Team Foundation Version Control.

PRINCIPLE GLASSMENUS.COM – 2005-2007

Headed up development for startup company: OdoClub.com using Flex 2.0, Flash, AJAX, Windows WebForms for Presentation Layer, .NET 3.0, WCF Web Services, Windows Workflow for Business Layer and SQL Server 2005 with Strongly Typed DataSets for the Data Layer. Conceived, designed and implemented a templatized, vertical market website solution using ASP.NET 3.0, C#, WCF, Windows Workflow, Flex 2.0 and AJAX. Solution provides a vertical market website in a box that can easily and economically be used to quickly implement custom websites for a niche market.

SOFTWARE ARCHITECT BCGI – 2003-2005

Primary responsibility for overall architecture for Mobile-Guardian: BCGI's mobile phone access management solution. Duties include setting technical direction, recommending technologies and tools, designing, coding and testing. Analyzed business requirements and transformed marketing requirement documents into high level designs. Produced detailed designs including UML models and proof of concept prototypes. Provided team mentoring, validated code before check in and led technical aspect of interview process. Built and packaged software releases and provided installation and release documentation.

PRINCIPLE ENGINEER STRATUS COMPUTER – 2001-2003

Design and implementation of transition from heterogeneous Oracle 9i based high availability suite of tools to an n-tier .NET architecture based on Microsoft Best Practices and Architecture White Papers ASP.NET Web Forms, Business and Data Layers in C# passing Strongly Typed DataSets, Windows Management Instrumentation, Oracle SQL Mentoring of team members transitioning from ASP3.0/VB6.0 & VC++ 6.0 to .NET development environment including use of VS.NET 2003, Windows Server 2003, IIS 6.0, ASP.NET, ADO.NET and C#

VP PRODUCT ARCHITECTURE DASH.COM, INC. – 1999-2001

Responsible for next generation web site, data warehouse, and agent architecture built on top of IIS 5.0 and SQL Server 2000. Led initial development of IIS/ASP web site and browser based COM pluggin. Responsible for entire high volume web site and agent design, implementation and deployment on IIS web farm and SQL Server cluster. Brought initial concept from prototype to live in 7 months starting solo to build prototype for VC and then development lead. Led team of 17 developers on version 1 as VP of Development and 3 architects for subsequent releases as VP of Architecture.

STATE OF MAINE

COUNTY OF Waldo

PERSONALLY APPEARED, George Aguiar, WHO, UNDERSTANDING THE MEANING OF AN OATH, SWORE THAT THE FORGOING TESTIMONY IS TRUE TO THE BEST OF HIS/HER KNOWLEDGE AND BELIEF, THIS 13th DAY OF DECEMBER 2019.

~~NOTERY~~ PUBLIC ________ Before me,

MY CO~~MMISSION~~ EXPIRES: ________ M. D. F

Miles D. Feider

Attorney at Law

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

George Aguiar (signature) Date: 12/13/19

Printed Name: George Aguiar

Title: Software Engineer

Parties Assisting:

Name: Address: Signature:__________

Name: Address: Signature:__________

CTO ENGINEHOUSE MEDIA, INC – 1998-1999

Design and implementation of a first of a kind DNA-based Ad banner Management work flow product using Exchange/Outlook/IIS/ASP/SQL Server.

PRINCIPLE ENGINEER CENTRA SOFTWARE, INC – 1995-1998

Created Java/Swing client architecture and implemented framework. Designed and implemented Visual J++/Win32 client. Designed and implemented Java browser based client (applets).

SENIOR OPERATING SYSTEMS ENGINEER ALLIANT COMPUTER SYSTEM, INC – 1989-1995

Interactive performance enhancements to multi-processor OS. Device driver, computer resource and system accounting enhancements. Kernel base on UNIX – BSD 4.2.

SENIOR SOFTWARE ENGINEER NEC INFORMATION SYSTEMS INC – 1984-1989

Unix Engineering Workstation lead. PC UNIX (AT&T 5.1) work including internals, drivers, configuration, tuning and system management. Misc. projects: UUCP, Ethernet, NFS, RFS, graphics and X-Windows.

EDUCATION

NORTHEASTERN UNIVERSITY BOSTON, MA – BSEE 1983

SKILLS

Design and hands-on experience with PhpStorm, Microsoft Visual Studio.NET 2005/2008/2010, ASP.NET 1.1, 2.0 3.0, 3.5 & 4.0, Silverlight 3.0, .NET RIA Services, ADO.NET Entities, ADO.NET, Web Services, AJAX, Flex 2.0, Flash 8.0, ActionScript 3.0, WCF, Windows Workflow, Winforms, Mobile Controls, Microsoft Office, .NET Compact Framework, SQL Server 2000 & 2005, Oracle 9i, DHTML, JavaScript, XML, UML, ORM, ERD, Visio, Project, ASP, COM+ 1.5, MTS, MSMQ, C#, DNA, ASP, Visual C ++, Java, Visual Basic 6.0, C++, JSP, EJB, Swing.

James S. (Jim) Merkel: Resume

97 Patterson Hill Rd., Belfast, Maine 04915
(207) 323-1474, email: jimimerkel@gmail.com

Jim is sustainability professional who authored *Radical Simplicity*, a hands-on guide to quantifying and monitoring sustainability. In 1989 he transitioned from the military engineering sector to moving institutions and individuals toward sustainability by: founding organizations, assisting campuses and organizations in measuring ecological footprints, working as Dartmouth College's Sustainability Coordinator, creating city and regional transit and bike lanes and teaching sustainability at universities while experimenting in sustainable living.

Experience:

2014-Current **Filmmaker**, Independent, Belfast, Maine.

2005 – 2007 **Sustainability Coordinator, Dartmouth College**, Hanover, New Hampshire. Worked to integrate environmentally and socially sustainable practices into the College's operations, buildings, culture and strategic plan. Worked to reduce the carbon footprints of the campuses 110 buildings. His work helped Dartmouth College earn the highest grades on the Sustainability Report Card issued by the Sustainable Endowments Institute.

1994 – Present **Founder and director of The Global Living Project (GLP)**
Conducted five multi-week *GLP Summer Institutes* where educators and students lived on an equitable portion of the biosphere. Researched and developed the *100 Year Plan*, a societal approach to global sustainability.

1988 – 1994 **Environment & Community Volunteer Work**, San Luis Obispo, Ca.
Elected to Vice-Chair, Executive Committee Chair, and Conservation Committee Chair of the Santa Lucia Chapter of the Sierra Club. State and federal lobbyist. Drafted legislation. Presented positions on transportation, land-use planning, open-space, peace, water, wilderness, Native American and oil spill issues at over 100 public hearings. Co-founded the Big Mountain Support Group. Delivered humanitarian aid to Navajo families resisting forced government relocation.

1985 - 5/89 **TRW Electronic Products Inc.**, San Luis Obispo, California.
Business Development, Foreign Military Sales, Senior Engineer.

1984 - 1985 **ITT, Vandenberg AFB**, California.
Senior Electronic Engineer. Designed digital, R.F. and computer systems.

1977 - 1984 **Photocircuits**, Aquebogue, New York. Title: Electrical Engineer.

Teaching Experience:

2009-2014 **Unity College, Adjunct Professor**, Unity, Maine. Teaching *Environmental Issues and Insights*, which includes student documentaries.

2009 **Las Cañadas**, Veracruz Mexico. Instructor for weeklong ecological footprinting intensive.

2008 – 2009 **Community College of Vermont**, **Adjunct Professor,** Wilder, Vermont.

2008 – 2009 **Longwood University,** Farmville, Virginia. *Radical Simplicity* selected as reading for *First-year Experience 2008 & 2009*.

2005 **Antioch New England, Adjunct Professor,** Keene, New Hampshire.

2003 **University of British Columbia, Adjunct Professor,** Vancouver, B.C. Instructor for *The Science and Practice of Sustainability*.

Publications:

- *Radical Simplicity* selected for edited book, *Voluntary Simplicity – the poetic alternative to consumer culture*, Stead & Daughters Ltd, New Zealand, 2009.
- Chapter in *Less is more*, New Society Publishers, Canada, 2009.
- Author of *Radical Simplicity – small footprints on a finite earth* (in third printing), New Society Publishers, Canada, 2003. Spanish Translation *Simplicidad Radical*, Fundación Tierra, Spain, 2005

Awards:

2016 Arthur Morgan Award, Yellow Springs, OH.

2008 Living Hero Award, New Hampshire Life Magazine, Concord, NH.

2006 Graduation Speaker, The Putney School, Vermont.

2006 Graduation Speaker, Vermont Law School, Vermont.

2000 Sustainable Living Award, Environmental Youth Alliance, Vancouver, B.C.

1999 The Bill Deneen Award for Outstanding Environmental Leadership, Nipomo, Ca.

1994 Gaia Fellowship, Earthwatch, research low resource use and high life quality in Kerala, India. Researched light living in the Himalayas.

1992 Clean Air Award - American Lung Association, San Luis Obispo, Ca.

1991 Group of the Year Award for the Big Mountain Support Group - Economic Opportunities Commission, San Luis Obispo, Ca.

1991 Citizen of the Year Nomination - Economic Opportunities Commission, San Luis Obispo, Ca.

1990 Beyond War Award for work with the Earth Day Coalition, San Luis Obispo, Ca.

Academic Background:

- State University of New York at Stony Brook, B.S. in Electrical Engineering, May 1984.
- Suffolk County Community College, New York, A.A.S. in Electrical Technology, January 1981.

STATE OF MAINE
COUNTY OF Waldo

PERSONALLY APPEARED, James S. Meakel, WHO, UNDERSTANDING THE MEANING OF AN OATH, SWORE THAT THE FORGOING TESTIMONY IS TRUE TO THE BEST OF HIS/HER KNOWLEDGE AND BELIEF, THIS 5th DAY OF DECEMBER 2019.

M. D. F.

~~NOTERY PUBLIC~~ Miles D. Frieden

MY COMMISSION EXPIRES: Attorney at Law

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

James S Merkel ____________________ Date: 12/13/2019

Printed Name: James S. Merkel

Title: Director: Global Living Project

Parties Assisting:

Name: Address: Signature:__________

Name: Address: Signature:__________

Authors:
James Merkel
George Augiar

Nordic Aquafarms' **Total** Carbon Footprint

Summary

The findings of this study include:

1. That the proposed facility is greenhouse gas (GHG) intensive, and that lower carbon solutions to feeding humanity are readily available. Our calculations have revealed that the applicant's annual GHG emissions represent approximately 5 to 6 percent of the 2030 total state GHG target.

2. If this facility were built and operated an unfair burden would be placed on existing businesses and residents to meet Maine's climate targets and the governor's executive orders.

3. The applicant should be required to amend their plan to:
   a.) demonstrate carbon neutrality utilizing wind and solar power.
   b.) find a Brownfield site that has stable soils to avoid releasing carbon stored in the forest and soil, and to maintain the sequestration of a mature 35 acres of forests and wetlands.
   c.) find a location with access to deep ocean currents, or utilize a completely closed system.

Our findings demonstrate that the construction (embodied CO2) and operations (CO2) of Nordic Aquaculture farms (collectively, "the Project") as proposed by the Applicant's Site Location and Development Permit Application (SLODA) to the Department of Environmental Protection (DEP) on 5/16/2019 (the "Application") adds significantly to statewide greenhouse gas emissions. Our calculation estimates have revealed that the applicant's GHG contribution of between 0.55 and 0.76 MMTCO2e represents 4.6 – 6.4 percent of the 2030 total state GHG target, and between 12.8 and 17.6 percent of the 2050 target. To approve these new large sources of carbon emissions, while making commitments to reduce GHG, violates the intent of PL 237, §576-A. This large-scale aquaculture facility proposed by Nordic Aquafarms (NAF) in Belfast, Maine would also

make it difficult to "achieve carbon neutrality by 2045" as mandated by the Executive Order No. 10FY 19/20, signed by Governor Mills on September 23, 2019.[1]

By conducting three separate life-cycle assessments of Nordic's proposal, along with surveying similar assessments of other recirculating aquaculture systems (RAS), an estimate of both embedded and operational CO_2e (Life-cycle CO_2e = Embodied CO_2 + Operational CO_2) was established. The results support what the literature has determined: land-based aquaculture requires significant energy and feedstock, and produces large amounts of greenhouse gases (GHG).[2] [3]

Introduction

There is no shortage of warnings, reports and political statements concerning GHG emissions, and the irreversible consequences of climate change. The United Nations *Emissions Gap Report Summary* that was issued on November 26, 2019 states the situation clearly: "[The] findings are bleak. Countries collectively failed to stop the growth in global GHG emissions, meaning that deeper and faster cuts are now required."[4]
Business-as-usual has accelerated the crisis which

> "is more severe than anticipated, threatening natural ecosystems and the fate of humanity (IPCC 2019). Especially worrisome are potential irreversible climate tipping points and nature's reinforcing feedbacks (atmospheric, marine, and terrestrial) that could lead to a catastrophic "hothouse Earth," well beyond the control of humans (Steffen et al. 2018). These climate chain reactions could cause significant

1https://www.maine.gov/governor/mills/sites/maine.gov.governor.mills/files/inline-files/Executive%20Order%209-23-2019_0.pdf

[2]Monterey Aquarium Seafood Watch https://www.seafoodwatch.org/-/m/sfw/pdf/standard%20revision%20reference/2015%20standard%20revision/public%20consultation%202/mba_seafoodwatch_criteria%20for%20greenhouse%20gas_msg_final.pdf?la=en

[3]Energy Use in Recirculating Aquaculture Systems https://www.researchgate.net/publication/323891940_Energy_use_in_Recirculating_Aquaculture_Systems_RAS_A_review

[4] UN Environment Programme, Emissions Gap Report 2019 https://www.unenvironment.org/resources/emissions-gap-report-2019

disruptions to ecosystems, society, and economies, potentially making large areas of Earth uninhabitable." [5]

We are, as 11,000 scientists declared on November 5th in BioScience **in a climate emergency**.[6]

Maine

In 2003 Maine enacted PL 237. This law required that the DEP develop and submit a Climate Action Plan (CAP or Plan) for Maine, and mandates the reduction of GHG emissions. Specifically, under §576-A of PL 237 the State's goals for the reduction of emissions for 2020 are 10% below 1990 levels (21.65 MMTCO2e) by January 1, 2020, (19.46 MMTCO2e) which Maine is, according to the 2019 Maine Interagency Climate Adaptation work group (MICA) Update Report, on target to meet. However, §576-A mandates that "by January 2030 the State shall reduce gross annual greenhouse gas emissions to at least 45% below 1990 gross annual greenhouse gas emissions level" putting the 2030 target at 11.91 (MMTCO2e). Furthermore, the law mandates that "by January 1, 2050, the State shall reduce gross annual greenhouse gas emissions to at least 80% below the 1990 GHG emissions level," or to 4.3 (MMTCO2e). By comparison, the applicant's greenhouse gas contribution of between 0.55 and 0.76 MMTCO2e represents 4.6 – 6.4 percent of the 2030 total state GHG target, and between 12.8 and 17.6 percent of the 2045 target.

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[5] Ripple, William J, Wolf, Christopher, Newsome Thomas M., Barnard, Phoebe, and Moomaw, William R. World Scientists' Warning of a Climate Emergency, *BioScience*, biz088, p. 3 https://doi.org/10.1093/biosci/biz088

[6] Ripple, William J, Wolf, Christopher, Newsome Thomas M., Barnard, Phoebe, and Moomaw, William R., World Scientists' Warning of a Climate Emergency, *BioScience*, biz088, https://doi.org/10.1093/biosci/biz088

Authors:
James Merkel
George Augiar

Belfast

As stated in the Belfast's Energy Committee's mission statement, "[t]he committee's objective is to recommend steps to the City Council and city residents that will reduce both greenhouse and air pollution emissions throughout the city." This facility will significantly increase local GHG emissions, while eliminating vital sequestration resources. The facility will also undermine the Belfast Climate Crisis committee's commitment to supporting and enhancing "Ecosystem-based Resilience." Their report states that "solutions [include] conserving and restoring smaller-scale natural ecosystems within the watershed (wetlands, river mouths, beaches, dunes, intertidal and subtidal habitats); designing containment areas; establishing appropriate vegetative cover along shorelines; and mandating low-impact development practices." The Nordic Aquaculture facility is not a "low-impact development practice."

Lifecycle Assessment (LCA) for CO2e

The intention of this research is to establish an estimate of the total carbon (TC) additions to Maine's annual CO2 emissions that can be expected, should the proposed Nordic Aquafarms facility be built in Belfast. Three separate Life-Cycle Assessment (LCA) tools/methodologies were used to establish a framework for accounting for many of the impacts typically ignored when only considering operational flows of resources. Figure 1. illustrates a simplified diagram for a rather complicated analysis. The desired scope for our purposes is to focus on CO2 equivalent emissions related to the entire facility from turning a complex, mature forested site into an industrial facility (concrete, steel, pumps and motors) and then summarizing the larger categories of operational inputs such as feeds, electricity, diesel fuel, and chemicals.

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Nordic Aquafarms' **Total** Carbon Footprint

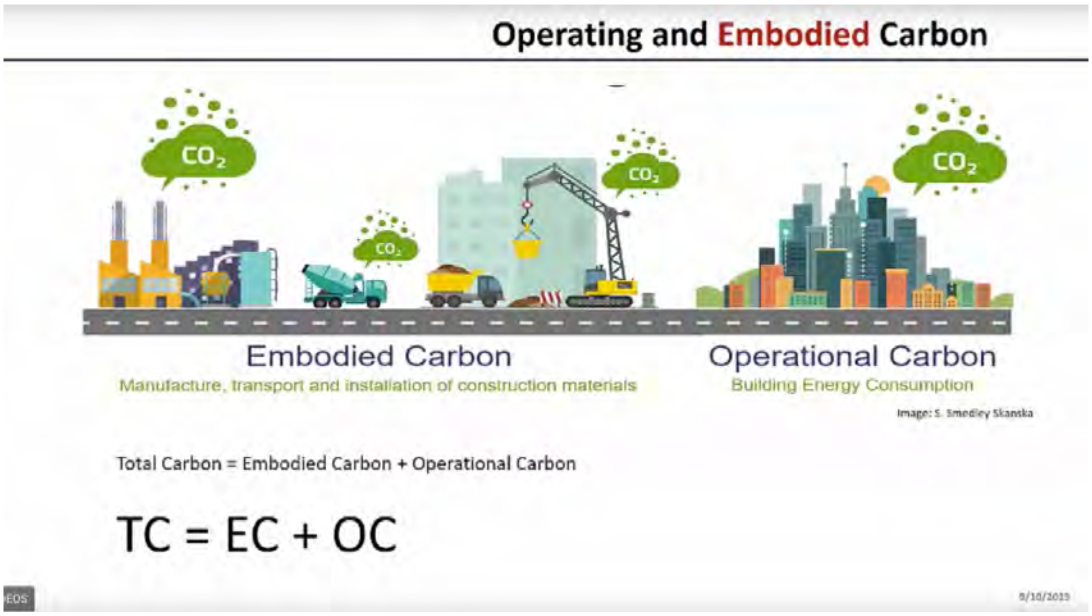

Figure 1

The analysis is an underestimate as many real impacts are difficult to quantify at the design stage, yet it provides a useful estimate for decision-making purposes. In the case of Nordic's proposal, extensive specialized buildings, fuel and chemical tanks, pipelines into the bay, comprise unique and carbon intensive structures, with a broad range of possible scenarios and risks should the project fail prematurely. LCA tools help plan for worst-case outcomes. Maine industries have historically left behind "wicked problems" such as mercury sediments covering miles of the Penobscot River[7], and dioxin pollution in several Maine Rivers.[8] This analysis does not include decommissioning at the end of the useful life of the facility, however, deconstruction at some point, will be carbon intensive.

[7] https://www.maine.gov/dep/spills/holtrachem/index.html

[8] https://www.nrcm.org/programs/waters/cleaning-up-the-androscoggin-river/maines-dioxin-problem/

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Few LCA studies have been conducted on land-based aquaculture. In 2015 Seafood Watch published research on energy use in a variety of aquaculture environments. Their analysis determined land-based recirculating aquaculture systems (LB-RAS) to be the most energy intensive of the studied methods.[9]

Figure 2: Energy use associated with aquaculture feeds (red bars) and farm level activities (blue bars) for a variety of species and production methods in units of megajoules/tonne of seafood, drawn from LCA studies and other information sources. Literature review carried out by Keegan McGrath. These data will be transformed into GHG Intensity per unit of edible protein (KgCO2 equivalent/Kg edible protein) when applied to this criterion.

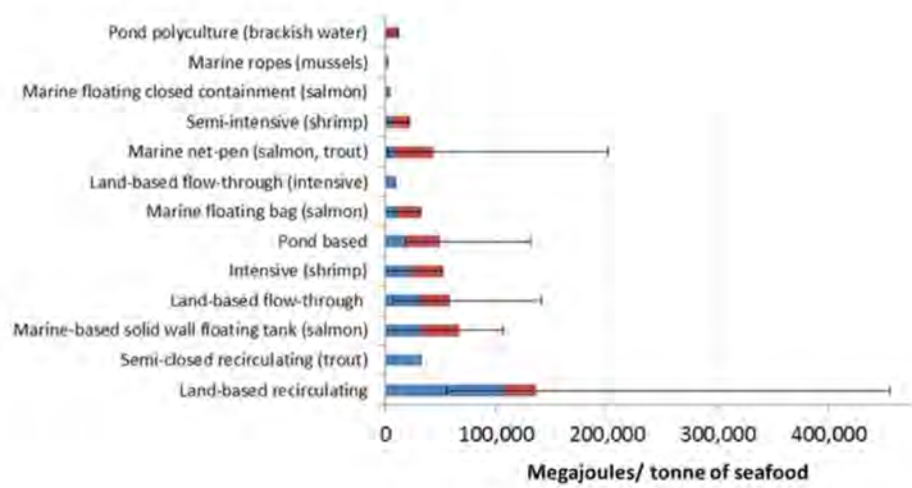

Figure 2: Energy and feed requirements of various aquaculture technologies.

In 2016, a study compared producing Atlantic salmon in open pens in seawater to a hypothetical land-based closed containment recirculating aquaculture system (LBCC-RAS) based upon the Conservation Fund's Freshwater Institute grow out trials of Atlantic salmon.[10] This is the study that the applicant sites to argue that salmon grown in a LBCC-

[9] Monterey Bay Aquarium Seafood Watch https://www.seafoodwatch.org/-/m/sfw/pdf/standard%20revision%20reference/2015%20standard%20revision/public%20consultation%202/mba_seafoodwatch_criteria%20for%20greenhouse%20gas_msg_final.pdf?la=en

RAS system has a lower carbon footprint than shipping open net pen (ONP) salmon by airfreight to Seattle, Washington: 7.4kg CO2e/kg (RAS) vs. 15.2 kg CO2e/kg (airfreight from Norway to Seattle). Electricity to produce 1 tonne of salmon in RAS is cited as 5,460 kWh. However, shipping frozen salmon by container ship from Norway to the US was the lowest footprint option in this study at 3.75kg CO2e/kg.

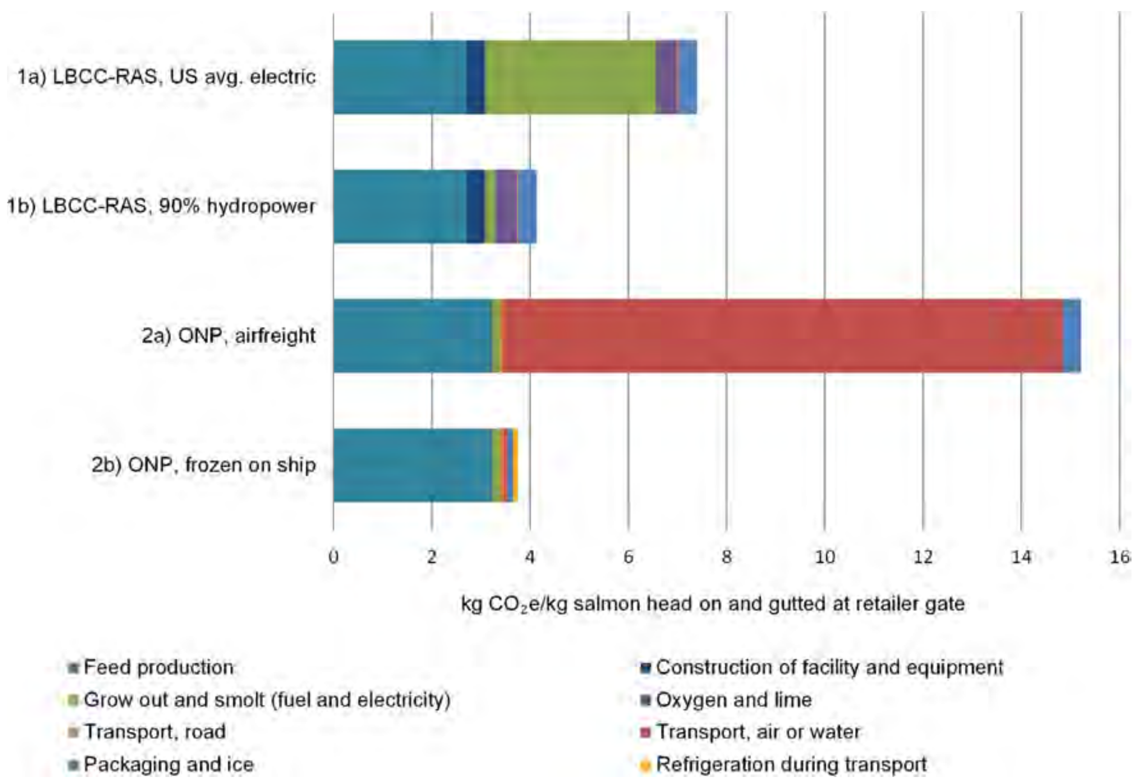

Figure 3: Fish Farm Carbon Footprint Comparisons from 2016 study

This 2016 study had a limited scope, and did not evaluate the carbon footprint of wild caught Maine seafood, or production of plant proteins which have lower carbon

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[10] Yajie Liua, Trond W. Rostena, Kristian Henriksena, Erik Skontorp Hognesa,Steve Summerfeltb, Brian Vincib, Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar):Land-based closed containment system in freshwater and open net pen in seawater, in Aquacultural Engineering 71, (2016) 1-12. https://doi.org/10.1016/j.aquaeng.2016.01.001

footprints than the options this study evaluated. For example, wild caught Demersal fish (eg. Haddock) species have a life-cycle CO2e intensity of *2.4 kg CO2e/kg*. Small Pelagic fish (eg. Sardines) have a lifecycle CO2e of 0.2 kg CO2e/kg.[11] Vegetarian diets including legumes have CO2e in the range of 0.6 kg CO2e.[12]

A more recent LCA paper was published in 2019 which is the first analysis based upon actual data from growing out 29,000 salmon in northern China from 100 g smolts to 4 KG fish.[13] The results of this study were that to grow one tonne of live-weight salmon required 7,509 KWh of electricity and generated 16.7 tonnes of Co2e, 106 kg of SO2 e, 2.4 kg of P e and 108kg of N e (cradle to farm gate). The study cited electricity and feed as the larger components of the overall impact. This more recent study from an actual operation reported roughly double the tonnes of CO2e/tonne of fish compared to the 2016 FreshWater Institute Study (7.4 vs. 16.7).[14] The power per tonne of fish produced was 5,460 kWh in the 2016 study while the more recent China study was 7,509 kWh. Many factors can account for the differences such as power grid composition, fish food sources and makeup, different inventories and assumptions, however, the data are close enough to offer some confidence in their similar methodologies and findings.

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[11] Parker, Robert W.R., Blanchard, Julia, Gardener, Caleb et al., Fuel use and greenhouse gas emissions of world fisheries in Nature Climate Change, VOL 8, APRIL 2018 p. 333–337 http://www.ecomarres.com/downloads/GlobalFuel.pdf

[12] Clune, S. J., Crossin, E., & Verghese, K., Systematic review of greenhouse gas emissions for different fresh food categories. *Journal of Cleaner Production*, *140*(Part 2), 766-783. http://www.research.lancs.ac.uk/portal/en/publications/systematic-review-of-greenhouse-gas-emissions-for-different-fresh-food-categories(153c618e-1b41-4cf4-b23e-7bc635cd2541).html

[13] Song, Xingqiang, Liu, Ying, Brandão, Miguel et al. Life cycle assessment of recirculating aquaculture systems: A case of Atlantic salmon farming in China in *Journal of Industrial Ecology*, Vol 23, Issue 5, Oct 2019, pp. 1077-1086 https://doi.org/10.1111/jiec.12845

[14] Yajie Liua, Trond W. Rostena, Kristian Henriksena, Erik Skontorp Hognesa,Steve Summerfeltb, Brian Vincib, Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar):Land-based closed containment system in freshwater and open net pen in seawater, in Aquacultural Engineering 71, (2016) 1-12. https://doi.org/10.1016/j.aquaeng.2016.01.001

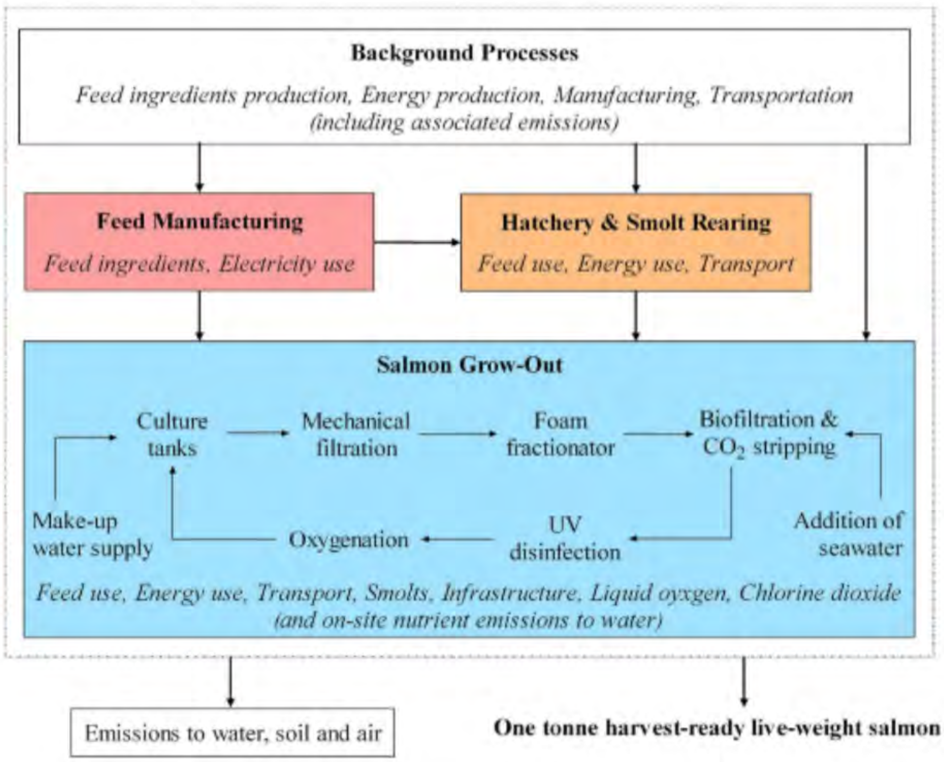

Figure 4: The boundary conditions for the 2019 China example

Figure 4 shows the system boundary and scope for the China example. Life-cycle inventories used SimaPro 8.3 software to capture many of the cradle-to-farm-gate inputs.

To obtain a first order of magnitude estimation for the applicant's proposed Belfast operation, we used the resulting LCA CO2e per metric tonne of fish data from the 2019 China study. At buildout, the proposed Belfast facility anticipates producing 33,000 t/year output. The CO2e from NAF is calculated (16.7 tC/t X 33,000 t/year) to emit 551,100 tCO2e per year from both embodied and operational components. For comparison, an average American car emits 4.6 t/yr, hence the NAF facility can be estimated to be equivalent to adding 119,800 cars to the roads.

Generating specific LCA for the Belfast facility is difficult as the designs change regularly as would be expected for a complex project. We have attempted to be as up to date as possible while focusing on the larger footprint items. For example, earlier plans were for an approximate 18 football fields of roof top solar panels. The panels have been eliminated from the design and 8 diesel generators have been added. The generators use has changed from not just supplying back up power during ice storms, but to shave energy use on a daily basis to reduce the electricity billing rate. Additional changes include, the outflow pipelines being shortened from a mile and a half into Belfast Bay to ⅔'s of a mile. Earlier, 1.5 million gallons/yr. of Methanol was listed and recently was changed to 1 million gallons/yr. of a glycerin product MicroC 2000. Our calculations have kept pace with most reported changes, but are not exhaustive, rather an attempt to capture the larger construction details and design revisions.

In our second LCA analysis we used industry standard spreadsheet calculators looking at as much of the project as possible aiming to include the embodied carbon (EC) specific to this project. Traditionally, only steel and cement are calculated as they are commonly the biggest contributors to a construction projects' EC. Due to the nature of Land-Based RAS (LB-RAS) we attempted to include as many of the significant embodied carbon sources such as the Penobscot Bay pipeline (the design has changed from a trench to buried to above the seabed), the site preparation, backup electrical generation, etc.

Figure 3 is the table from the Conservation Fund's Freshwater Institute grow out trials of Atlantic salmon.[15] To this table, we have added the 2019 China analysis and the first analysis we performed using industry standard spreadsheet (SS1) calculations, an amended estimate of Nordic's annual CO2e emissions based upon amortizing the

[15] Conservation Fund's Freshwater Institute https://doi.org/10.1016/j.aquaeng.2016.01.001

Authors:
James Merkel
George Augiar

construction over a 15 year time frame. We've included the forest and soil carbon release, along with our own lifecycle assessment of the actual site plan released to the public.

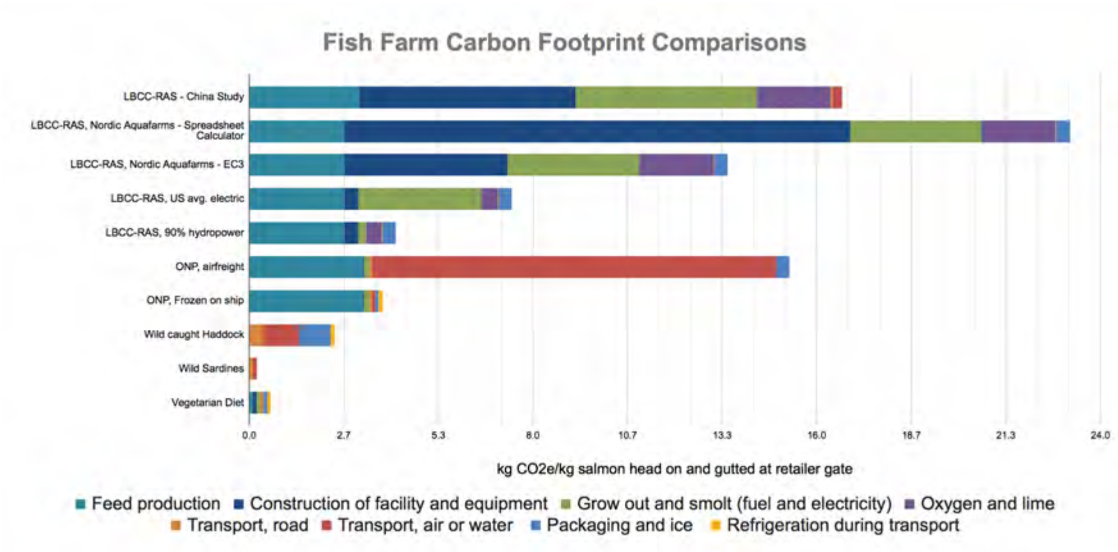

Figure 5: Fish Farm Carbon Footprint Comparisons including our 3 Analyses

In our 3rd analysis, we used the recently released Embodied Carbon for Construction Calculator (EC3). According to the Carbon Leadership Forum, this tool "is a free and easy to use tool that allows benchmarking, assessment and reductions in embodied carbon, focused on the upfront supply chain emissions of construction materials."[16]

This tool is currently in Beta 3 and the database of construction materials is limited to concrete and steel so we only looked at foundations and building envelopes. Unlike our more detailed and time-consuming calculator (SS1), which included tanks, motors, generators, etc, we were limited in Beta 3 to construction materials. By using several LCA tools, we were able to increase the confidence in our results.

[16] Carbon Leadership Forum http://carbonleadershipforum.org/projects/ec3/

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Our results from the spreadsheet calculator, listed in Figure 5 as "BBCC-RAS Nordic Aquafarms - Spreadsheet Calculator" reported carbon intensity of approximately 23 kg CO2e/kg salmon. At buildout, the proposed Belfast facility, producing 33,000 t/year output would emit an estimated 759,000 tCO2e (23 tC/t X 33,000 t/year) from both embodied and operational components. This is equivalent to 165,000 cars to the roads.

Results & Discussion

Life-cycle Assessment – embodied carbon discussion

The life-cycle assessment results of the applicant's proposal support what the literature has determined: land-based aquaculture requires significant energy and feedstock, and produces large amounts of greenhouse gases (GHG).[17] Most significant inputs include: electricity for pumping water and operations; construction embodied energy for buildings, pipes, tanks, wells, pumps, motors, filters, generators; fish foods; forest and wetland elimination, and soil disturbances, are also important contributors.

The embodied carbon results are sensitive to the assumed lifespan of the infrastructure of the project. The China study used 15 years, and conducted a sensitivity analysis to include a 10 and 20-year option. For simplicity, our calculations used 15 years. The lifespan of a new technology is very difficult to predict. Should the facility close in half its expected life (due to falling salmon prices, disease outbreaks, technical issues, or saltwater intrusion on wells) the embodied carbon footprint would double.

It is important to point out that there are many impacts that can and can't be measured using LCA, however, this paper focused upon CO2e emissions from construction and

[17] Monterey Bay Aquarium Seafood Watch https://www.seafoodwatch.org/-/m/sfw/pdf/standard%20revision%20reference/2015%20standard%20revision/public%20consultation%202/mba_seafoodwatch_criteria%20for%20greenhouse%20gas_msg_final.pdf?la=en

operation. RAS facilities of the scale proposed are lacking a history of performance and operating data, which would make for a more accurate LCA. However, the China LCA, which has some actual operational data and a solid methodology, along with a team of researchers, is a useful benchmark.

LCA methods can assist in identifying some of the potential unanticipated impacts of an applicant's project. In this case, a large-scale monoculture discharging into shallow and recovering marine environments create risks that might require regular maintenance, and replacements of filters, pumps and controllers and possibly additional heating and cooling of discharge and intake water that could increase or decrease the estimates in our analysis. Practical difficulties were not included in our analysis, such as construction disputes or design flaws that could drive up embodied and operational emissions. The real-world complexity of both ecosystems and human systems, dictate that these estimates are likely conservative.

It is worth noting that only one of our analysis methods attempted to estimate the total carbon of the eight 2MW generators and diesel engines, the smolt tanks, pumps, and other equipment and machinery, the roadways, parking lots and walkways and the pipeline into the bay. In this analysis, we made the best estimates working from the drawings supplied to Belfast City Planning Office.

Life-cycle Assessment – operational carbon discussion

With electricity and feed among the primary operational footprint drivers of RAS carbon footprint, several limitations in our analysis are noted below:

1) To complete a more accurate LCA would require specific fish feed composition, including the breakdown of amounts of small fish in the feed, chicken and pig slaughterhouse wastes, grains and pulses etc. Feed components derived from fish are regularly shipped from South America. The applicant has not yet decided

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exactly what they will feed their fish. It is also imperative to note that current fish meal is impacting some of the poorest people on the planet, destroying wild food sources for wild fish, and intensifying the impacts of the climate crisis.[18] Many of the small fish used as feed are eaten in other parts of the world and threatened by largescale harvests as feedstocks.

2) The applicant has not been forthcoming with data such as design estimates of annual electricity consumption, so our results have had to make estimates based upon generator sizing checked against the data from other LCA assessments.
3) Maine's electricity grid power source mix might seem favorable given the considerable potentially "renewable" sources utilized. Some sources for CO2 emissions data make assumptions that biomass and hydroelectric are "carbon neutral" and "renewable," however, these terms are inaccurate in accounting for the life-cycle impacts of these energy sources.[19]

Maine's 2017 power-grid used biomass (26%) and hydro-electric (30%). Wood biomass has a higher CO2 per BTU than coal.[20] Hydroelectric dams, while considered to be carbon neutral, are proving to release large amounts of Ch4 and CO2.[21,22]

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[18] Green, Matthew "Plundering Africa: Voracious Fishmeal Factories Intensify the Pressure of Climate Change",*Reuters*October 13, 2018 https://www.reuters.com/investigates/special-report/ocean-shock-sardinella/

[19] Harvey, Chelsea, Heikkinen, Niina, Congress Says "Biomass Is Carbon-Neutral, but Scientists Disagree: Using wood as fuel source could actually increase CO2 emissions", in *Scientific America*E&E News, March 23, 2018 https://www.scientificamerican.com/article/congress-says-biomass-is-carbon-neutral-but-scientists-disagree/

[20] *Carbon Emissions from Burning Biomass for Energy* in Partnerships for Policy Integrity https://www.pfpi.net/wp-content/uploads/2011/04/PFPI-biomass-carbon-accounting-overview_April.pdf

[21] Deemer, Bridget R. Harrison, John A. Li, Siyue et al. *Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis*, in BioScience, Volume 66, Issue 11, 1 November 2016, Pages 949–964, https://doi.org/10.1093/biosci/biw117

[22] Graham-Rowe, Duncan**,** *Hydroelectric Power's Dirty Secret Revealed in New Scientist,* 24 February 2005 https://www.newscientist.com/article/dn7046-hydroelectric-powers-dirty-secret-revealed/#ixzz67klj5iSG

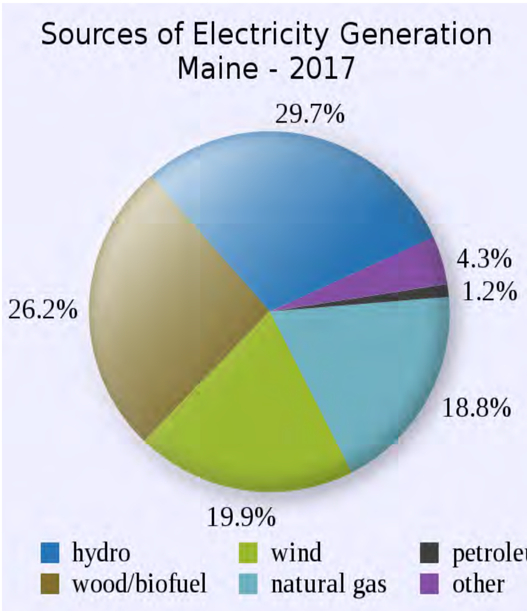

Figure 6

The combustion of wood results in 213 lb CO2/mmbtu (bone dry) while Bituminous coal comes in slightly lower at 205.3 lb CO2/mmbtu.[23] Forests are very effective in sequestering and storing carbon. It is argued that "trees grow back," true, however the lag time for the young forest to sequester carbon at rates that mature forests can is decades long, while the release of carbon from biomass generators is instantaneous. It is the old "slow in, fast out problem."[24] Biomass is only renewable if cut rates and forest practices don't diminish the ecosystem services while harvesting the biomass, (easy to state, difficult to achieve). And while the cutting is taking place, the habitat is under stress, soils and biodiversity are disturbed or eliminated, and forest resilience and long-term health are diminished. All of which can result in additional C02 emissions.

[23] Carbon emissions from burning biomass for energy https://www.pfpi.net/wp-content/uploads/2011/04/PFPI-biomass-carbon-accounting-overview_April.pdf

[24] Moomaw, William R., Masino, Susan A., Faison, Edward K., *Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good* in Frontiers in Forests and Global Change, June 2019, Vol 2, pp 1-27. https://www.frontiersin.org/articles/10.3389/ffgc.2019.00027/full

Hydro-electric dams result in methane and CO2 release, and the elimination of large tracks of forest lands that sequester and store carbon above and below the surface, and provide critical habitat for biodiversity. A 2016 paper, found that GHG emissions from reservoir water surfaces account for 0.8 (0.5–1.2) Pg CO_2 equivalents per year, with the majority of this forcing due to CH_4[25]. It can be viewed as ironic that the very dams that have prevented untold millions of salmon from reproducing are now used to claim low carbon footprints for contained salmon that never see the light of day. The point being raised is that technologies such as large-scale hydroelectric plants solve one problem (cheap electricity) while creating other problems (eg. Ch4 and CO2 release, habitat destruction, loss of fishery).

The applicant plans to install 9 diesel generators, using 900,000 gallons of fuel resulting in 9142 metric tons of CO2e annually. This is equal to adding an additional 1,988 cars to Belfast's roadways. In addition to CO2 emissions, the air quality impacts and noise need to be considered, especially during periods of poor air quality and climate inversions.

Forest, wetlands, and soil removal

The facility requires the elimination of 34 acres of secondary growth mature pine and hardwood trees, and the removal of between 15 and 48 feet of soil totaling an estimated 215,000 cubic yards. It also requires the complete elimination of ten wetlands, nine of which are wetlands of special significance (WOSS). three significant streams will also be eliminated.[26] It is estimated that the forest, and the 17 wetlands of varying sizes, currently

[25] Deemer, Bridget R. Harrison, John A. Li, Siyue et al. *Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis*, in BioScience, Volume 66, Issue 11, 1 November 2016, Pages 949–964, https://doi.org/10.1093/biosci/biw117

[26] While the GHG impact of this is not included in these findings, it is recommended that they be calculated and understood. As stated in the application: https://www.maine.gov/dep/ftp/projects/nordic/applications/NRPA/Attachment%2009%20-%20Site%20Condition/NRPA_A9_SiteConditions_text.pdf

store approximately 13,465 metric tons of carbon above and below ground. Left intact, this forest's current sequestration rate is approximately 42.9 metric tons of carbon each year. Current research is showing that trees increase their carbon sequestration significantly as they age[27,28]. In addition, forests and wetlands have a high value providing multiple ecosystem services, and William R Moomaw's recent work establishes that proforestation, meaning enhancing older forests, is actually the most viable way to achieve CO2 Targets[29].

A large quantity of carbon is stored in forest soils, and is released upon deforestation and disturbance.[30] According to the application "[e]xcavation required to construct the foundations and lower levels of the grow modules will be approximately 15 to 20 feet below the existing grades. The water treatment building includes 2 stories below grade, requiring a cut up to approximately 48 feet below the existing grades to accommodate construction of the lower level and a seawater intake pipeline."[31] Because the soils will have to be removed due to the fact that, "the native silt and clay soils that will be

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"There will be a total of 1,325 linear feet (LF) of impacts to streams within the project area (**Table 9-5**). Streams S3, S5, S6, and S9 will be indirectly impacted by the project. Impacts to stream S9 will be limited to a permanent crossing located between wetlands W8 and W9, along with a temporary crossing during the installation of the force main sewer line. The permanent crossing will be constructed in such a manner to not impair flow during storm events. The upper reaches of streams S3, S5, and S6 will be filled as a result of this project. These filled streams will result in the loss of 1,180 LF of stream bed. Impacts to these streams will typically result in the loss of Groundwater Recharge/Discharge, Floodflow Alteration, and Wildlife Habitats in these locations."

[27] Anderson, Mark G., *Wild Carbon: A Synthesis of Recent Findings* in Wild Works, Volume 1 Northeast Wilderness Trust http://www.newildernesstrust.org/wp-content/uploads/2019/08/WildWorks_V1_WildCarbon-2.pdf

[28] Moomaw, William R., Masino, Susan A., Faison, Edward K., *Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good* in Frontiers in Forests and Global Change, June 2019, Vol 2, pp 1-27. https://www.frontiersin.org/articles/10.3389/ffgc.2019.00027/full

[29] Moomaw, William R., Masino, Susan A. et al. *Intact Forests in the United States*, in Frontiers https://www.frontiersin.org/articles/10.3389/ffgc.2019.00027/full

[30] Dartmouth College. "Clear-cutting destabilizes carbon in forest soils, study finds." ScienceDaily, 15 April 2016. www.sciencedaily.com/releases/2016/04/160415125925.htm

[31] Ransom Project 171.05027.005 Executive Summary Page 1 of 2 Belfast Geotechnical Report\02-03 Report\February 2019 Report\Text Rev.2_final February 27, 2019

excavated are not suitable for reuse as structural fill at the site"[32] a large portion of all the carbon stored in the soils will be emitted into the atmosphere.

Recommendations:

1. **The applicant be required to demonstrate carbon neutrality and not place increased burden for CO2 reductions on Maine's population. Solar and wind generation have become economically viable for the applicant to utilize.**
2. **The applicant should not be permitted to clear a mature forest that currently sequesters carbon or remove soils and wetlands that are currently storing carbon. Rather, they should be required to find a Brownfield site that has stable soils.**
3. **Our LCA studies show that other lower carbon footprint foods are available in Maine.**
4. **The applicant should be required to find a location with access to deep ocean currents, or utilize a completely closed system.**

Conclusion

Our study concludes that proposed facility is CO2e intensive and that lower carbon solutions to feeding humanity are readily available. Our calculations have revealed that the applicant's GHG emissions are between 0.55 and 0.76 MMTCO2e. This represents 4.6 – 6.4 percent of the 2030 total state GHG target, and between 12.8 and 17.6 percent of the 2045 target. To approve these new large sources of carbon emissions, while making commitments to reduce GHG, violates the intent of PL 237, §576-A.

[32] Nordic Aquaculture SLODA Application
https://www.maine.gov/dep/ftp/projects/nordic/applications/SLODA/Section%2011%20-%20Soils/Appendix%2011-B.%20Geotechnical%20Engineering%20Report.pdf

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A final consideration must include the unfair burden of further reductions that existing businesses and residents will have to make to meet Maine's targets and the governor's executive orders if this facility is approved. As stated in the Climate Action Plan for Maine, (CAP) getting to Carbon Neutral by 2045 will not occur under "business-as-usual" scenarios, rather it will require that any future large developments demonstrate carbon neutrality, and preferably be carbon positive.[33] There is a need for the DEP, and the State of Maine, to avoid placing additional burdens on existing enterprises, and to require that new businesses use strategies to achieve carbon neutrality with their proposals.

This facility would use Maine's "commons" including the clean aquatic sea water to dilute effluent, clean ground water, and clean air to receive diesel emissions and capacity on the power grid. The public suffers the loss, while the industry makes profits. Extractive industries should not put the burden of proof on its citizens. With several other RAS facilities proposing to come to Maine (Bucksport, Jonesport, Millinocket…) the CO2 implications are significant.

Maine has made progress towards meeting its climate goals, however, the next set of reductions will be more difficult, as Maine's shifting to fracked natural gas, biomass and hydroelectric each have serious impacts. More solar and wind energy will be helpful. As society grapples with sustainability and climate change, the challenge of new technologies is to solve past problems without creating new problems. The DEP should therefore not approve the NAF project as submitted, for the long list of problems and risks it creates as an untested, new technology. The DEP could require NAF to submit a carbon neutral design utilizing solar and wind power on a brownfield site that connects to

[33] Maine Climate Action Plan, https://www.maine.gov/dep/sustainability/climate/MaineClimateActionPlan2004.pdf

deep ocean currents, or is a closed system. Finally, much better options are available for feeding humanity through local organic vegetable protein, and lower trophic level wild local fish eaten sparingly, a movement known as "Slow Fish"[34] while wild fisheries are restored.

34 https://www.slowfood.com/slowfish/pagine/eng/pagina--id_pg=44.lasso.html

EXHIBIT A7

Executive Order

OFFICE OF
THE GOVERNOR

NO. 10 FY 19/20
DATE September 23, 2019

AN ORDER TO STRENGTHEN MAINE'S ECONOMY AND ACHIEVE CARBON NEUTRALITY BY 2045

WHEREAS, climate change is having negative impacts on Maine and if not addressed will have devastating effects on the state;

WHEREAS, the Gulf of Maine is the second fastest-warming portion of the world's oceans, impacting the state's marine life, environment and commercial fishing;

WHEREAS, the growing seasons in Maine have become unpredictable with erratic frosts, hotter and drier summers, and more severe precipitation events that disrupt agriculture operations;

WHEREAS, the Maine economy is heavily dependent on natural resources including forestry, fisheries, maple sugaring, agriculture and tourism associated with outdoor recreation;

WHEREAS, Maine has abundant forests and working lands that are central to the natural resource-based economy, soil health and quality of life, and their sustainable management can meaningfully improve carbon sequestration;

WHEREAS, clean energy development, energy efficiency, innovation and carbon sequestration through the state's natural resources represent significant opportunities for Maine's economy;

WHEREAS, Maine's universities can produce leading research on climate change, offshore wind, wood-based composites, and biofuels, and Maine's community colleges can provide effective job training for businesses and employees engaged in a growing clean energy economy;

NOW THEREFORE, I, Janet T. Mills, Governor of the State of Maine, pursuant to *Me. Const. Art V, Pt 1, Secs, 1 and 12,* do hereby Order as follows:

I. PREFACE

Maine recently established mandates to reduce greenhouse gas emissions 45 percent below 1990 levels by 2030 and 80 percent by 2050; and a renewable energy mandate of 80 percent renewable energy by 2030 and a goal of 100 percent by 2050. Maine also recently established the Maine Climate Council responsible for Maine's Climate Action Plan to achieve emission reductions and clean energy targets as well as adaptation strategies by December 1, 2020 and to update that plan every four years. Finally, Maine recently joined the United State Climate Alliance, a bipartisan coalition of 25 states committed to addressing climate change.

II. POLICY GOAL

To further the work that is recently underway, Maine shall strive to achieve a carbon neutral economy no later than 2045. The Maine Climate Council shall provide recommendations required to meet these goals in its first report to be issued no later than December 1, 2020, and in every report thereafter.

III. COORDINATING EFFORTS AND INITIATIVES

All policies and programs undertaken to achieve carbon neutrality shall be implemented in a manner that aims to grow the state's economy, protect natural resources, and achieve positive impacts for the people of Maine. The Governor's Office of Policy Innovation and the Future shall coordinate the efforts of the Governor's Energy Office, the Departments of Environmental Protection, Economic and Community Development, Labor, and Agriculture, Conservation and Forestry. The Office shall coordinate the development of policies to advance the sequestration of carbon emissions and grow the clean energy economy in Maine.

IV. REPORTING

The Department of Environmental Protection shall develop a framework for accounting and tracking progress on greenhouse gas reduction, and report on such progress every other year.

V. EFFECTIVE DATE

The effective date of this Order is September 23, 2019.

Janet T. Mills
Governor

Seafood Watch® DRAFT Greenhouse Gas Emissions Criteria for Fisheries and Aquaculture

Multi Stakeholder Group Draft

Contents

Introduction

The Monterey Bay Aquarium is requesting and providing an opportunity to offer feedback on the Seafood Watch Greenhouse Gas (GHG) Emissions Assessment Criteria for Fisheries and Aquaculture during our current revision process. Before beginning this review, please familiarize yourself with all the documents available on our Standard review website.

Providing feedback, comments and suggestion

This PDF document contains the second drafts of the GHG Emissions Criterion for Fisheries and the GHG Emissions Criterion for Aquaculture. A summary of the changes made to the first draft as a result of feedback during the first consultation process is provided at the end of the document, and individual changes are highlighted in the public comment guidance throughout. In their current form, these criteria are companions to the Fisheries and Aquaculture Assessment Criteria and are **unscored** due to data limitations. Seafood Watch will use these criteria to stimulate data collection and may score them in the future. "Guidance for public comment" sections have been inserted and highlighted, and various general and specific questions have been asked throughout. Seafood Watch welcomes feedback and particularly suggestions for improvement on any aspect of the Energy (GHG Emissions) Criteria. Please provide feedback, supported by references wherever possible in any sections of the criteria of relevance to your expertise. Please use the separate GHG Criteria Comment Form, which contains the excerpted "Guidance for public comment" sections from the PDF, to provide your comments.

These criteria were developed in close consultation with Dr. Peter Tyedmers of Dalhousie University, and Seafood Watch is indebted to Dr. Tyedmers for his time and dedication to this effort.

Seafood Watch DRAFT Energy Criteria for Fisheries and Aquaculture

MSG guidance - This section contains the draft guiding principle for the Energy (GHG Emissions) Criteria, which has been edited since the first public consultation to acknowledge the contribution of GHGs to the acceleration of climate change and to acknowledge that GHG emissions from food production are a significant fraction of anthropogenic GHG emissions.

Guiding Principle

The accumulation of greenhouse gases in the earth's atmosphere and water drives ocean acidification, contributes to sea level rise, affects air and sea temperatures, and accelerates climate change. GHG emissions from food production are a significant fraction of anthropogenic GHG emissions[1,2]. Sustainable fisheries and aquaculture operations will have low greenhouse gas emissions compared to land-based protein production methods.

MSG guidance - This section contains an overview of GHGs associated with seafood (and other protein) production methods, the draft rationale and summary for the Energy (GHG Emissions) Criteria for fisheries and aquaculture. This section has been edited since the first public consultation to include the overview of GHG emissions from fisheries and aquaculture. It also contains information about the GHG emissions included in our approach comparing up to the farm gate/dock emissions from seafood to land-based proteins (poultry and beef). In addition, we've clarified that we will be using the median values for comparative protein GHG intensities. Seafood Watch would like to be able to supplement or find replacement values for these comparative GHG intensities which factor soil CO_2 emissions into total GHG emissions, and welcome suggestions for comprehensive, robust values calculated with a uniform methodology for at least poultry and beef.

Overview of Greenhouse Gas Emissions from Fisheries, Aquaculture and Land-based Food Production

The range of GHGs associated with food production are diverse, and not always well described or quantified in life cycle analysis studies about these emissions (Henriksson *et al.* 2012). Here we describe the main GHGs associated with food production up to the farm gate or dock.

The primary GHG emissions associated with wild capture fisheries are from CO_2 emitted via direct fossil fuel combustion. Fossil fuels are used for propulsion, deployment and retrieval of fishing gears, powering cooling systems and other activities (Parker 2015). Other potentially significant GHG emissions from fisheries are associated with refrigerant use (Ziegler *et al.* 2011) and while not GHGs, short-lived, climate-forcing agents, namely black carbon or soot (incompletely oxidized organic carbon), are produced from fuel combustion (McKuin & Campbell In Review).

The GHGs associated with aquaculture production are more varied than those associated with wild capture fisheries and depend on the production method, species farmed and energy input regime (Pelletier et al 2011). These GHGs can include carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Aquaculture CO_2 emissions are associated with farm level energy use and feed production. Feed production CO_2 emissions include both energy use emissions as well as non-energy emissions from soils. These soil CO_2 emissions are associated with land conversion and land use and are not always well described or quantified (Nijdam *et al.* 2012). N_2O emissions are associated with fertilizers used on feed crops (Pelletier & Tyedmers 2010) and from surface waters induced by microbial nitrification and denitrification (Hu *et al*. 2012). CH_4 emissions are associated with feed production and organic material degradation (Nijdam *et al*. 2012). For fed systems, feed production can represent a significant proportion of emissions (Pelletier *et al*. 2011).

[1] An overview of GHG emissions levels associated with food production (including fisheries and aquaculture) are available from the FAO (FAO 2011)

[2] An overview GHG emissions associated with household energy use in the US, including from food are available in Jones *et al.* 2011 and the associated household emission calculator is available at: http://coolclimate.berkeley.edu/calculator

The primary GHG emissions associated with land-based food production systems (including crop and livestock) include CO_2 from energy consumptive activities, CO_2 resulting from land use and land conversion, N_2O from fertilization of arable land and manure management and CH_4 emissions from ruminant livestock (Nijdam *et al.* 2012).

Rationale for and Summary of the Greenhouse Gas Criteria for Fisheries and Aquaculture

Seafood Watch is proposing to incorporate GHG emission intensity into our science-based methodology for assessing the sustainability of both wild caught and farmed seafood products. GHG accumulation in the Earth's atmosphere and water drives ocean acidification, contributes to sea level rise, affects air and sea temperatures and accelerates climate change. The proposed criterion will evaluate greenhouse gas emissions per edible unit of protein from fisheries and aquaculture operations up to the dock or farm gate (i.e. the point of landing), consistent with the scope Seafood Watch assessments.[3,4] Although a reliable index to define sustainable (or unsustainable) emissions of GHGs does not yet exist, as a baseline, we expect sustainable fisheries and aquaculture operations to have relatively low GHG emissions compared to the demonstrably high emission of some land-based protein production methods. Therefore, in order to classify the GHG emission intensity of seafood products, Seafood Watch initially proposes to relate them to those of intensive poultry and beef production up to the farm gate; with products falling below the median value for poultry production considered as low emission sources, those between the median values for poultry and beef as moderate emission sources, and those above the median value for beef as high emission sources. The advantage of this method is that it provides consumers with information concerning relative impacts of food choices, beyond just seafood, enabling them to compare GHG intensity across edible protein sources Currently, Seafood Watch does not have a scalar metric (as we do for the scored criteria) to score the fisheries energy criterion. GHG emission intensity per edible unit of protein for both fishery and aquaculture products will be calculated using species-specific edible protein estimates based on a literature review compiled by Peter Tyedmers (Dalhousie University, Nova Scotia, Canada). The edible protein estimate is based on the percent edible content and the percent protein content of muscle tissue for each species. Seafood Watch has discussed alternative standardization methods, such as excluding the percent protein content of muscle tissue (because invertebrates often have higher values), using wet weights or standardizing by product form, however, we are retaining the edible unit of protein standardization.

We are basing the farm gate median values for poultry (13 kg CO_2/Kg protein) and beef (134 kg CO_2/Kg protein) production on the supplementary information available from Nijdam *et al.* (2012), incorporating, if possible, a quantitative measure of uncertainty associated with these values, such as suggested in Henriksson et al (2015). The values from Nijdam *et al*. (2012) take into account both energy and non-energy GHG emissions, and include N_2O emissions from fertilization of arable land and manure, CH_4 emissions from ruminant production and manure, and CO_2 from fossil fuel energy. While this source acknowledges the importance of CO_2 emissions from soil cultivation, these emissions are not factored in. This likely will underestimate total GHG emissions. Currently, Seafood

[3] Seafood Watch assesses the ecological impacts on marine and freshwater ecosystems of fisheries and aquaculture operations up to the dock or farm gate. Seafood Watch assessments do not consider all ecological impacts (e.g. land use, air pollution), post-harvest impacts such as processing or transportation, or non-ecological impacts such as social issues, human health or animal welfare.

[4] Seafood Watch will direct users of our recommendations to available post-harvest greenhouse gas emissions calculators. Post-harvest emission assessment is outside the scope of the current standards review.

Watch is investigating comparative measures that incorporate soil CO_2 emissions from land use and land conversion to supplement the values from Nijdam *et al.* (2012).

For the wild-capture fisheries criterion, Seafood Watch proposes using Fuel Use Intensity (FUI) to derive GHG emissions intensity for the target fishery plus an FUI derived GHG intensity factor for bait usage when available. For the aquaculture criterion, we propose a measure of direct farm-level GHG emissions use plus an indirect measure of the GHG emissions associated with feed production.. Emissions associated with feed will be evaluated using a tiered approach, using specific ingredient information where available, and will be based on the dominant feed-ingredient categories (aquatic, crop and land animal) when less information is available. An additional grouping for aquatic ingredients may be possible. Values will be sourced from existing data.

Commercial fisheries and fish farms can achieve both environmental and financial benefits from reducing their energy use and non-energy related GHG emissions. We recognize, however, that data collection related to energy use and non- energy GHG emissions are currently limited, so our aim with these criteria are to incentivize the collection and provision of energy use data and non-energy GHG emission data from both fisheries and aquaculture operations to both track and improve the sustainability of seafood products.

In this first iteration, the Seafood Watch Greenhouse Gas Criteria will be unscored additions to the Seafood Watch criteria, and will be used as companion criteria to our sustainable fisheries and aquaculture assessments.

Wild Capture Fisheries Greenhouse Gas Criterion

MSG guidance - This section contains the introduction to the Fisheries Energy (GHG Emissions) Criterion. This section is substantively unchanged from the first consultation draft. Feedback on the methodology is requested in the Methods section.

Introduction

Fuel consumption is the primary driver of GHG emissions up to the point of landing for most wild capture fisheries, and is often the main source of emissions through the entire supply chain (Parker 2014, Parker & Tyedmers 2014). As such, measures of fuel consumption in fisheries provide an effective proxy for assessing the GHG emissions, or carbon footprint, of fishery-derived seafood products. As mentioned earlier, Seafood Watch acknowledges that for some fisheries other GHG emissions and other climate forcing agent emissions may be significant, and will consider these additional emissions as information becomes available.

Fuel consumption varies significantly between fisheries targeting different species, employing different gears, and operating in different locales. Fuel use also varies within fisheries over time: consumption increased in many fisheries throughout the 1990s and early 2000s, but has reversed in recent years as fisheries in Europe and Australia have both demonstrated consistent improvement in fuel consumption coinciding with increased fuel costs since 2004. As a result of this variation in fuel use, while it is difficult to estimate fuel consumption of individual fisheries without measuring it directly, generalizations can be made by analyzing previously reported rates in fisheries with similar characteristics. To this end, Robert Parker (PhD Candidate, Institute for Marine and Antarctic

Studies, University of Tasmania, Australia) and Dr. Peter Tyedmers (Dalhousie University, Nova Scotia, Canada) manage a database of primary and secondary analyses of fuel use in fisheries (FEUD – Fisheries and Energy Use Database). Using this database, the draft Seafood Watch wild capture energy criterion is based on "Fuel Use Intensity "(FUI, as liters of fuel consumed per metric ton of round weight landings, L/MT) converted to Green-House Gas Emission Intensity per edible unit of protein ($KgCO_2$ equivalent/Kg edible protein).

MSG guidance - This section contains the methodology for the Fisheries GHG Emissions Criterion and is substantively unchanged from the first consultation draft, except for the inclusion of example results in Figure 1 and the addition of a section on data collection.

Methods

The sections below describe how GHG emission intensity will be calculated for wild capture fisheries and how data quality will be described.

Part 1: Determining Greenhouse Gas Emission Intensity from Fuel Use Intensity

Fisheries were categorized by species, ISSCAAP (International Standard Statistical Classification of Aquatic Animals and Plants) species class, gear type and FAO area. These codes were used to match each fishery to a subset of records in the FEUD database[5] and each subset was analyzed using R to provide descriptive statistics and a weighted FUI estimate.

The subset of database records used to estimate FUI of each fishery was selected using a ranked set of matching criteria. The best possible match in each case was used. The following ranking of matches were used to choose the subset most appropriate for each fishery's estimate:

1) Records with matching individual species, gear type and FAO area
2) Records with matching individual species and gear type
3) Records with matching species class (ISSCAAP code), gear type and FAO area
4) Records with matching species class (ISSCAAP code) and gear type
5) Records with matching generalized species class (set of ISSCAAP codes), gear type and FAO area
6) Records with matching generalized species class (set of ISSCAAP codes) and gear type

For each fishery, after selecting the most appropriate subset of records, the following information was calculated:

- weighted mean (see below)
- unweighted mean
- standard deviation
- standard error
- median

[5] FEUD currently includes 1,622 data points, covering a wide range of species, gears and regions. The best represented fisheries are those in Europe, those targeting cods and other coastal finfish, and those using bottom trawl gear. Coverage of fisheries from developing countries is limited but increasing. The database focuses on marine fisheries, and includes very few records related to freshwater fishes (except diadromous and catadromous species which are fished primarily in marine environments), marine mammals, or plants.

- minimum value
- maximum value
- number of data points
- number of vessels or observations embedded in data points
- temporal range of data

The weighted mean, intended as the best possible estimate of FUI for each fishery, was calculated and weighted by both number of vessels in each data point and age of the data. To avoid biasing the analyses by large numbers of vessels reported in any one fishery, we used the log of the number of vessels in each data point. For example, the weights of two data points representing 1000 and 10 vessels, respectively, have a ratio of 3:1, rather than 100:1. In addition, data from more recent years were given greater weight (10% difference in weight between subsequent years).

$$w_i = \log 10(v_i + 1) \cdot 0.9^{2014-y_i}$$

$$FUI = \sum_{i=1}^{n} \frac{w_i}{\sum_{i=1}^{n} w_i}$$

w_i = the weight given to data point *i*
v_i = the number of vessels reporting in data point *i*
y_i = the fishing year of data point *i*
n = sample size (number of data points included)

The weighted FUI means (L/t) were converted to GHG emission intensity (KgCO_2 equivalent/Kg edible protein) using a conversion factor of 3.12 kg CO_2 emitted per liter of fuel combusted and species specific percent yield and protein content of fish and invertebrate species. The GHG emission factor is based on an assumed fuel mix of bunker C, intermediate fuel oil, and marine diesel oil, and includes emissions from both burning the fuel and all upstream activities (mining, processing and transporting). This conversion factor was calculated using IPCC 2007 GHG intensity factors and EcoInvent 2.0 life cycle inventory database (Parker *et al*. 2014). The species specific percent yield and protein content of muscle data used to convert landed tonnage to edible protein were derived from Peter Tyedmers unpublished database of published and grey literature values.

Part 2: Quality indicators

The amount of data available pertaining to different species and gears varies dramatically, with some classes of fisheries being researched far more than others. As a result, the “quality” of FUI predictions varies. For example, Atlantic cod (*Gadus morhua*) fisheries have been researched extensively, and so FUI estimates for Atlantic cod are relatively reliable. Meanwhile, some fisheries have not been assessed, and so these estimates are based on other similar fisheries instead. Each FUI estimate generated here was given three quality ratings:

- a ***match quality*** indicator, reflecting the degree to which records in the database matched the species, gear and region criteria for each fishery. The species match is particularly reflected here, as all estimates match the gear type. *Low* = records match the generalized species class (e.g. crustaceans, molluscs); *medium* = records match the species class (e.g. lobsters); *high* = records match the individual species (e.g. Atlantic cod); *very high* = records match the individual species, gear type and region (*e.g.* Atlantic cod caught using longlines in FAO area 27). Table 2 shows a breakdown of assessed fisheries on the basis of the match quality.

Table 2. Criteria used to match Seafood Watch fisheries with FEUD records.

Matching factors	Number of FUI estimates
Individual species, gear type and FAO area	21
Individual species and gear type	15
Species class (ISSCAAP code), gear type and FAO area	64
Species class (ISSCAAP code) and gear type	54
Generalized species class (set of ISSCAAP codes), gear type and FAO area	45
Generalized species class (set of ISSCAAP codes) and gear type	38

- a ***temporal quality*** indicator, reflecting the proportion of data points from years since 2000. *Very low* = all records are from before 2000; *low* = <25% of records are from 2000 on; *medium* = 25-49% of records are from 2000 on; *high* = 50-74% of records are from 2000 on; *very high* = 75% or more of records are from 2000 on.

- a ***subjective quality*** indicator reflects the confidence of the author in each estimate, based on the match criteria, temporal range, variability in the data, sample size, types of sources, and general understanding of typical patterns in FUI.

The subjective quality indicator is a good indication of the relative reliability of each estimate. It takes into account the range of data used, the method of weighting, and the degree to which the estimate reflects previous assessments of FUI in fisheries around the world. There are instances where the subjective quality indicator does not agree with the other quality rankings. For example, some estimates include a large number of older data points, and are therefore given a low temporal quality rating, but because the weighting method used gives more influence to more recent data points, the estimate closely reflects recent findings and is therefore given a high rating.

Data Collection

As part of the assessment process, the analyst will search for and request additional information on Fuel Use for the fishery under assessment to supplement and add to data in the Fuel Use Intensity Database. The analyst will also research the potential for other GHG emissions and non-GHG emissions of substances, like black carbon, which have high global warming potentials.

Communicating GHG intensity values for wild capture fisheries

As stated in the Rationale section, the proposed Seafood Watch GHG Criteria will be unscored additions to our sustainable seafood assessments. GHG intensity values for seafood will be compared to median GHG intensity values for land based protein production: poultry (considered a medium emission protein) and beef (considered a high emission protein). See the Rationale section for more information. Any method of communicating a GHG Intensity value for fisheries based on the FUI estimates generated here should take into account three things:

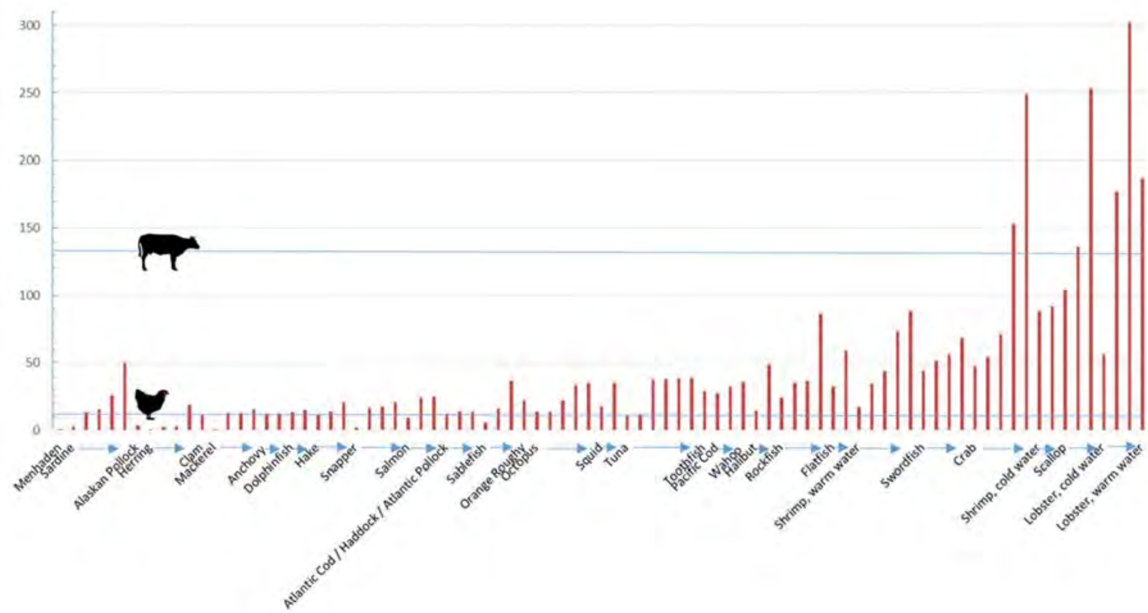
a) the estimates are based on fuel inputs to fisheries only, and, while fuel often accounts for the majority of life cycle carbon emissions, they need to be viewed in the context of the total supply chain. Most importantly, products that are associated with a high amount of product waste and loss during processing, or that are transported via air freight, are likely to have high sources of emissions beyond fuel consumption.

b) the quality of estimates varies, as is reflected in the quality indicators provided. Scoring fisheries with better quality estimates is easier than scoring predicted FUI of fisheries based on similar fisheries. For that reason, it may be justifiable to score only fisheries with a 'high' quality estimate, or to indicate that some scores are based on expected FUI rather than actual reported values.

c) the value should be expressed relative to some base value, reflecting relative performance of similar fisheries and/or alternative fishery products and/or alternative protein sources.

An example of how a subset of fisheries would fall relative to poultry and beef is shown in Figure 1 below.

Figure 1: GHG Intensity Values for a subset of Seafood Watch recommendations, based on work performed by Robert Parker using the FEUD database. Fisheries represented by multiple gear types are shown by multiple red bars. Numerical value of median emission intensity for poultry production and beef production are shown as horizontal lines. Beef and poultry values were derived from Nijdam et al (2012).



Aquaculture Greenhouse Gas Emission Criterion

MSG guidance - This section contains the introduction to the Aquaculture GHG emission Criterion.

Introduction

Feed production and on-site farm energy use are the two major drivers of GHG emissions from aquaculture operations up to the farm gate (Pelletier *et al.* 2011). For fed systems (fed systems comprise 69% of global aquaculture production (FAO 2014)), feed production is often the greater of these two drivers, particularly for net-pen systems where important processes such as water exchange, aeration and temperature regulation are provided naturally by the ecosystem (Pelletier *et al.* 2011). In pond production systems, large variations in the rate of water exchange (i.e. the volume of pumping) and aeration practices mean that farm-level energy use varies greatly between species and regions. Farm-level energy use is often the primary driver of GHG emissions for tank-based recirculating systems which require energy to run all life support and control systems (Parker 2012b) (Samuel-Fitwi *et al.* 2013). In stark contrast, farmed bivalves and aquatic plants (which represent less than 31% of global aquaculture production (FAO 2014)), require few external inputs and have low energy demand (Pelletier *et al.* 2011).

Farm location may also be a significant factor influencing total GHG emissions from aquaculture operations due to differences in the regional mix of energy sources used to generate electricity. Farms that are run primarily on fossil fuel based electricity (such as coal or oil) will have much higher total GHG emissions than those run on renewable energy sources (such as hydropower, wind, geothermal or solar) or on nuclear energy (Parker 2012b).

Additional GHG emissions may result from sources other than farm level energy use and feed production, such as from energy use associated with grow out infrastructure and smolt production and from non-energy emissions of CH_4 and N_2O from ponds (as discussed in the above section "Overview of Greenhouse Gas Emissions from Fisheries, Aquaculture and Land-based Food Production").

Seafood Watch recognizes that energy use varies greatly among different production systems and can be a major impact category for some aquaculture operations. It is noteworthy that improving practices for some of the Aquaculture Assessment Criteria may lead to more energy intensive production systems (e.g. where our recommendations are better for energy-intensive closed recirculation systems than for open systems). Seafood Watch also recognizes (as mentioned in the above section "Overview of Greenhouse Gas Emissions from Fisheries, Aquaculture and Land-based Food Production"), that non-energy emissions associated with aquaculture production may be significant but are not always well described or quantified.

MSG guidance - This section contains the methodology for the Aquaculture GHG Emissions Criterion. This criterion is less well developed than the fisheries criterion, primarily due the greater complexity of assessing the GHG emissions of aquaculture operations and the very limited data available. Changes made to this section since the first public consultation include 1) a tiered approach to evaluating GHG emissions associated with feed based on data availability 2) data from a literature review of farm level energy use and feed energy 3) factoring in non-energy GHG emissions from both feed and farm level activities where this data is available 4) Separation out of sections on data collection and communicating GHG intensity values. Given the paucity of data, Seafood Watch will continue to collect and actively solicit information on GHG emissions associated with feed production and farm level activities. In particular, Seafood Watch will seek out information on the GHG emissions associated with specific feed ingredients.

Methods

Seafood Watch is currently developing the methodology for assessing GHG emissions from aquaculture operations up to the farm gate. This methodology will include an assessment of the cumulative GHG emissions from feed use (primarily feed ingredient production, processing and potentially transport) as well as farm-level emissions from energy use.

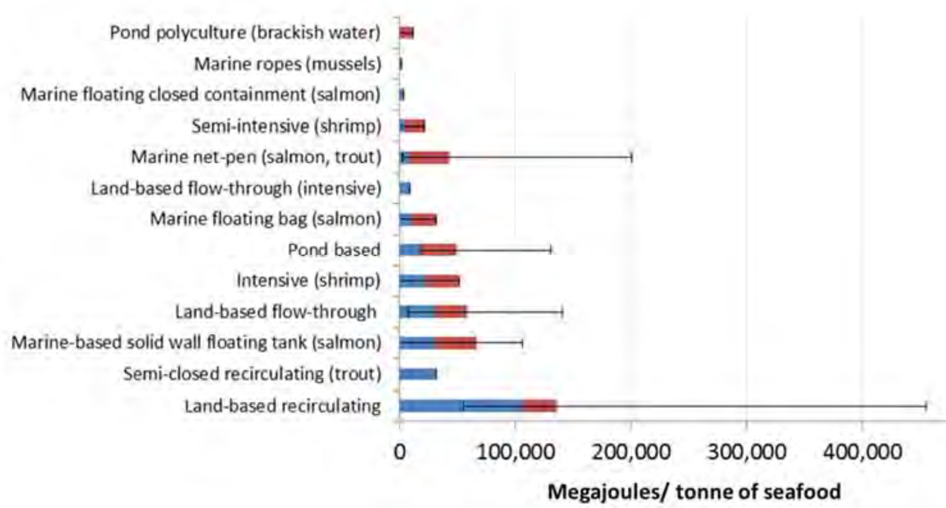
We propose using a tiered approach to evaluating the feed contribution to GHG emissions. Where the specific origins of feed ingredients can be identified, it may be possible to determine the GHG emissions with high accuracy. When the specific ingredients are unknown, we propose basing the feed component on GHG emission estimates of dominant feed ingredient groups; i.e. aquatic (fishmeal and oil), crop and land animal (from Pelletier *et al*. 2009 and from additional sources) along with corresponding estimates of feed types and quantities fed by operations under assessment. We recognize that there may be significant differences in GHG emission values between the feeds in each of these groups, notably within the aquatic feed group (such as between a feed based primarily on fishmeal sourced from bycatch from a regional fishery on the low end of the spectrum and a feed sourced primarily from a distant reduction fishery), and we will break out the feeds in these groups where possible.

For the farm-level component, Seafood Watch proposes quantifying GHG emissions associated with pumping, aeration and other energy consumptive activities. Seafood Watch will draw data from existing studies and data gathered directly from aquaculture operations. As an initial step, Seafood Watch has compiled information from Life Cycle Analysis (LCA) studies and other sources on farm level energy use and energy use associated with feeds (carried out by Keegan McGrath). The results are summarized in Figure 2. When data are not available to finely estimate GHG emissions for each component (feed and farm-level energy), Seafood Watch proposes defaulting to GHG estimates based on the most closely related species type, production type and the energy mix most commonly used in the region under assessment.

As with the Fisheries criterion, all emissions estimates will be standardized to GHG Intensity per edible unit of protein (KgCO_2 equivalent/Kg edible protein).

The total GHG emissions will be obtained by summing the GHG emissions from feed ingredients (Part 1 below) and farm-level energy use (Part 2 below).

Figure 2: Energy use associated with aquaculture feeds (red bars) and farm level activities (blue bars) for a variety of species and production methods in units of megajoules/tonne of seafood, drawn from LCA studies and other information sources. Literature review carried out by Keegan McGrath. These data will be transformed into GHG Intensity per unit of edible protein (KgCO2 equivalent/Kg edible protein) when applied to this criterion.



Part 1: GHG Emissions associated with feed ingredients/ Energy Return on Investments

As mentioned above, Seafood Watch proposes using a tiered approach to quantify the GHG Intensity (KgCO_2 equivalent/Kg edible protein) of feed ingredients. The tiers are based on the level of information available for the species and production system in the region or country under assessment. The first tier will be used when Seafood Watch can determine the specific feed ingredient mix and can determine associated GHG emission intensity values associated with the primary components (ideally taking into account the energy and non-energy emissions associated with the feed). Data on the specific feed ingredient mix will be requested at the start of the assessment process with the goal of using this first tier. Seafood Watch will employ the second tier when we are unable to determine the specific feed ingredient mix, but can determine the percentage of the three dominant ingredient types (aquatic, crop and land animal). When significant differences in GHG emissions can be clarified between feeds used from the dominant ingredient types, we will use a hybrid of the first and second tiers.

Factored into the GHG Intensity calculation for both tiers (and the hybrid tier) is the Economic Feed Conversion Ratio (eFCR), the total amount of feed used to produce a given output of harvested fish biomass, taking into account loss of feed via escapes, death, predation, disease, environmental disasters and other losses. In addition to the GHG Intensity value, Seafood Watch will provide an estimate of confidence in the value (whether this will be a numerical value or a scalar value is being discussed)

GHG Emissions for Feed Ingredient Inputs:

Tier 1
Cumulative GHG emission from feed = Total of ingredient specific GHG emission values* x eFCR

* Depending on the data collected by the analyst, this will be the total of ingredient specific GHG emission values or a total value for a feed formulation. Seafood Watch is currently investigating the derivation method for calculating feed specific or formulation specific GHG values, and input for how best to accomplish this is requested during this second public consultation process.

Tier 2
a) Aquatic ingredient inclusion rate = _____ %
b) Crop ingredient inclusion rate = _____ %
c) Land animal ingredient inclusion rate = _____ %
d) Economic Feed Conversion Ratio (eFCR) = _____

Cumulative GHG emissions from feed (kg CO_2-eq/t) = [(a x 2158) + (b x 1007) + (c x 4138)] x (d)[6]

For all tiers: Total feed cumulative GHG emissions (expressing edible return on investment) = ________ Kg CO_2 equivalents/Kg of edible protein

Kgs of edible protein (above) will be derived from metric tons of harvested fish using two factors:
- the species specific edible percentage and
- the species specific protein percentage of muscle tissue.

These percentages will be drawn from Peter Tyedmers' unpublished database.

Part 2: Farm-Level Energy Use

For this component Seafood Watch proposes to quantify the GHG emissions associated with direct farm-level energy use. The primary energy consumptive farm activities are water pumping and aeration but also might include activities such as temperature regulation, filtration, feed and chemical dispersal and harvesting. We acknowledge that additional energy consumptive activities are associated with aquaculture production, such as from grow out infrastructure and smolt production, but are not included in our assessment. We propose the following assessment methods, depending on data availability. For each of the options, Seafood Watch intends to provide an

[6] Mean values for the feed ingredient groups were derived from Pelletier *et al.* 2009, using the methodology described in Pelletier *et al.* 2010.

estimate of confidence in the value (whether this will be a numerical value or a scalar value is under consideration)

Farm-level data
As the most accurate measure, Seafood Watch aims to obtain farm-level information on total energy use as well as the energy mix (e.g. diesel versus electricity, but also the regional mix of fuels used for electricity generation) specific to the aquaculture operations under assessment in order to estimate farm-level GHG emissions. In addition to farm level energy, Seafood Watch aims to obtain information on non-energy GHG emissions produced at the farm level. Such non-energy emissions include N_20 and CH_4 from ponds (see the discussion in the section above: "Overview of Greenhouse Gas Emissions from Fisheries, Aquaculture and Land-based Food Production"). As with the feed component, GHG emissions will be standardized to the Kgs of edible protein.

Energy use values from scientific and grey Literature
Where farm-level information is not available, Seafood Watch proposes to model GHG emissions based on production method, species and farm-level energy use data and non-energy GHG emissions published in peer reviewed journals and available from grey literature. To estimate GHG emissions, this farm-level energy use data will be synthesized with data on the most common mix of fuels used for electricity generation in the region of assessment. As with the feed component, GHG emissions will be standardized to the Kgs of edible protein.

Relative energy use from water pumping and aeration
When farm-level or literature data are unavailable, Seafood Watch has developed the following tables to classify energy use from water pumping and aeration on a relative scale, which can be translated to relative GHG emission intensity. This method does not factor in non-energy GHG emissions:

Water Pumping
A crude estimated measure of the energy used in pumping water

Use pumping data or descriptions to select score value from the table below.

	Water pumping characteristics[7]	**Score**
Zero	No significant water pumping, e.g. cages, passive fill ponds, gravity fed tanks/ponds/raceways.	5
Low	Static ponds	4
Low-Moderate	Harvest discharge or occasional exchange	3
Moderate	Low daily exchange rate >0 to 3%	2
Moderate-High	Significant daily water exchanges 3-10%	1
High	Large daily water exchanges, recirculation systems >10%	0

Note - low energy use is given a high score

Energy use (pumping) score = ______ (range 0-5)

Record water pumping data here if available:
Pumped volume per metric ton of product _______ m^3 MT^{-1}]
Average pumping head height _______ m
Average pump power _______ KW or HP

[7] As a guide, Low = <1000 m^3/MT, Low-Moderate = 1000 – 5,000 m^3/MT, Moderate = 5,000 – 20,000 m^3/MT, Moderate-High = 20,000-150,000 m^3/MT, High = >150,000 m^3/MT

Aeration

A crude estimated measure of the energy used for aeration

	Aeration characteristics[8] or average duration	Score
Zero	Zero	5
Low	Minimal aeration	4
Low-Moderate	Low power and/or short duration <6h/day	3
Moderate	Moderate power and/or 6-12h/day	2
Moderate-High	Moderate-high power and/or 12-18h/day	1
High	High power and/or >18 hours per day	0

Note low energy use is given a high score

Energy use (aeration) score = _____ (range 1-5)

Record aeration data here if available:
Aeration energy use = ______ kW·h per MT
Average aeration duration per day ______
Aerator power ______ kWh or HP

Overall Farm-level Calculations

Farm Energy Use (FEU) = Pumping + aeration
Farm Energy Use Score (FEU) = ______ (range 0-10)

If the above method is used, Seafood Watch will determine a conversion to GHG emissions in order to combine this measure with the feed GHG measure.

Data Collection

As mentioned in the above methods sections, the analyst will search for and request additional information on 1) farm level GHG emissions (both energy and non-energy GHG emissions), 2) the country/regional energy mix or if off the grid – the energy sources generally used for that production system and 3) information on feed composition and GHG values associated with the ingredients used.

Communicating GHG intensity values for aquaculture operations

As stated in the Rationale section, the proposed Seafood Watch GHG Criteria will be unscored additions to our sustainable seafood assessments. GHG intensity values for seafood will be compared to median GHG intensity values for land based protein production: poultry (considered a medium emission protein) and beef (considered a high emission protein). See the Rationale section for more information. Any method of communicating a GHG Intensity value for aquaculture will need to be transparent about the GHGs included in the derived GHG value as well as those emissions which are likely significant but which are not included in the assessment due to lack of data.

[8] As a guide, low = <500 kW·h per MT, Low-Moderate = 500 – 1,500 kW·h per MT, Moderate = 1,500-3,000 kW·h per MT, Moderate-High = 3,000 – 4,500 kW·h per MT, High = >4,500 kW·h per MT (values are for example only (based on Boyd et al, 2007) and need refining)

Summary of Changes Made Since the First and Second Public Consultation

Several changes were made to the Criteria for Fisheries and Aquaculture as a result of the first consultation process feedback from the Seafood Watch Technical Advisory Committees, feedback solicited during an expert webinar and from collaborative work with Peter Tyedmers, who is both on the Seafood Watch Technical Advisory Committee for Aquaculture and was involved in the expert webinar. No substantive changes were made as a result of the second consultation process. Seafood Watch would like to thank and acknowledge everyone who provided feedback. These revisions are briefly described in bulleted format here:

- Revised the Guiding Principle to acknowledge the contribution of GHGs to the acceleration of climate change and to acknowledge that GHG emissions from food production are a significant fraction of anthropogenic GHG emissions.
- Included an overview of the range of GHG emissions associated with fisheries and aquaculture in the introductory information. The purpose of this is to acknowledge the range of potential GHGs associated with seafood production and provide for the assessment of the full range of emissions as information becomes available.
- Provided additional information about the GHG emissions included in our approach comparing up to the farm gate/dock emissions from seafood to land-based proteins. In addition we've clarified that we will be using the median values for comparative protein GHG intensities.
- Included example results for the Fisheries Criterion
- Created a tiered approach to evaluate GHG emissions associated with feed, based on data availability
- Included data obtained from a literature review of farm level energy use and feed energy
- Factored in non-energy GHG emissions from both feed and farm level activities when these data are available.
- Added separate sections on data collection both the fisheries and aquaculture criteria
- Added separate section on communicating GHG intensity values for aquaculture.

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EXHIBIT C7

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Aquacultural Engineering
Volume 81, May 2018, Pages 57-70

Review

Energy use in Recirculating Aquaculture Systems (RAS): A review

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https://doi.org/10.1016/j.aquaeng.2018.03.003

Highlights

- RAS energy use is a drawback, increasing operational costs and environmental impact.
- RAS design should comprehend water and energy use, waste discharge and productivity.
- Economic and environmental sustainable RAS is achieved quantifying all energy flows.
- Fossil based fuels are less cost-effective and renewable energies of potential use.

Abstract

Recirculating aquaculture systems (RASs) are intensive fish production systems, with reduced use of water and land. However, their high energy requirement is a drawback, which increases both operational costs and the potential impacts created by the use of fossil fuels. Energy use in RAS has been studied indirectly and/or mentioned in several publications. Nevertheless, its importance and impacts have not been studied. In aiming to achieve economic and environmentally sustainable production a compromise has to be found between water use, waste discharge, energy consumption and productivity. The current review discusses published studies about energy use and RAS designs efficiencies. Moreover, with the aim of making an industry baseline study a survey about the energy use in commercial scale RAS was conducted. The design of more efficient and less energy dependent RAS is presented, including optimized unit processes, system integration and equipment selection. The main conclusions are: fossil based fuels are less cost-effective than renewable energies; energy is of little concern for the majority of the industry, and renewable energies are of potential use in RAS.

Keywords

Energy use; Recirculating aquaculture systems; Environment; Optimized-designs; Cost-effectiveness; Sustainability

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UN environment programme

EXHIBIT D-7

Emissions Gap Report 2019

Executive Summary

ISBN: 978-92-807-3766-0
Job number: DEW/2263/NA

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Suggested citation
UNEP (2019). Emissions Gap Report 2019. *Executive summary*. United Nations Environment Programme, Nairobi.

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Emissions Gap Report 2019

Executive summary

Executive summary – Emissions Gap Report 2019

Introduction

This is the tenth edition of the United Nations Environment Programme (UNEP) Emissions Gap Report. It provides the latest assessment of scientific studies on current and estimated future greenhouse gas (GHG) emissions and compares these with the emission levels permissible for the world to progress on a least-cost pathway to achieve the goals of the Paris Agreement. This difference between "where we are likely to be and where we need to be" has become known as the 'emissions gap'.

Reflecting on the ten-year anniversary, a summary report, entitled Lessons from a decade of emissions gap assessments, was published in September for the Secretary-General's Climate Action Summit.

The summary findings are bleak. Countries collectively failed to stop the growth in global GHG emissions, meaning that deeper and faster cuts are now required. However, behind the grim headlines, a more differentiated message emerges from the ten-year summary. A number of encouraging developments have taken place and the political focus on the climate crisis is growing in several countries, with voters and protestors, particularly youth, making it clear that it is their number one issue. In addition, the technologies for rapid and cost-effective emission reductions have improved significantly.

As in previous years, this report explores some of the most promising and applicable options available for countries to bridge the gap, with a focus on how to create transformational change and just transitions. Reflecting on the report's overall conclusions, it is evident that incremental changes will not be enough and there is a need for rapid and transformational action.

The political context in 2019 has been dominated by the United Nations Secretary-General's Global Climate Action Summit, which was held in September and brought together governments, the private sector, civil society, local authorities and international organizations.

The aim of the Summit was to stimulate action and in particular to secure countries' commitment to enhance their nationally determined contributions (NDCs) by 2020 and aim for net zero emissions by 2050.

According to the press release at the end of the Summit, around 70 countries announced their intention to submit enhanced NDCs in 2020, with 65 countries and major subnational economies committing to work towards achieving net zero emissions by 2050. In addition, several private companies, finance institutions and major cities announced concrete steps to reduce emissions and shift investments into low-carbon technologies. A key aim of the Summit was to secure commitment from countries to enhance their NDCs, which was met to some extent, but largely by smaller economies. With most of the G20 members visibly absent, the likely impact on the emissions gap will be limited.

As regards the scientific perspective, the Intergovernmental Panel on Climate Change (IPCC) issued two special reports in 2019: the Climate Change and Land report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems, and the Ocean and Cryosphere in a Changing Climate report. Both reports voice strong concerns about observed and predicted changes resulting from climate change and provide an even stronger scientific foundation that supports the importance of the temperature goals of the Paris Agreement and the need to ensure emissions are on track to achieve these goals.

This Emissions Gap Report has been prepared by an international team of leading scientists, assessing all available information, including that published in the context of the IPCC special reports, as well as in other recent scientific studies. The assessment production process has been transparent and participatory. The assessment methodology and preliminary findings were made available to the governments of the countries specifically mentioned in the report to provide them with the opportunity to comment on the findings.

1. GHG emissions continue to rise, despite scientific warnings and political commitments.

- GHG emissions have risen at a rate of 1.5 per cent per year in the last decade, stabilizing only briefly between 2014 and 2016. Total GHG emissions, including from land-use change, reached a record high of 55.3 $GtCO_2e$ in 2018.

- Fossil CO_2 emissions from energy use and industry, which dominate total GHG emissions, grew 2.0 per cent in 2018, reaching a record 37.5 $GtCO_2$ per year.

- There is no sign of GHG emissions peaking in the next few years; every year of postponed peaking means that deeper and faster cuts will be required. By 2030, emissions would need to be 25 per cent and 55 per cent lower than in 2018 to put the world on the least-cost pathway to limiting global warming to below 2˚C and 1.5°C respectively.

- Figure ES.1 shows a decomposition of the average annual growth rates of economic activity (gross domestic product – GDP), primary energy use, energy use per unit of GDP, CO_2 emissions per unit of energy and GHG emissions from all sources for Organisation for Economic Co-operation and Development (OECD) and non-OECD members.

- Economic growth has been much stronger in non-OECD members, growing at over 4.5 per cent per year in the last decade compared with 2 per cent per year in OECD members. Since OECD and non-OECD members have had similar declines in the amount of energy used per unit of economic activity, stronger economic growth means that primary energy use has increased much faster in non-OECD members (2.8 per cent per year) than in OECD members (0.3 per cent per year).

- OECD members already use less energy per unit of economic activity, which suggests that non-OECD members have the potential to accelerate improvements even as they grow, industrialize and urbanize their economies in order to meet development objectives.

- While the global data provide valuable insight for understanding the continued growth in emissions, it is necessary to examine the trends of major emitters to gain a clearer picture of the underlying trends (figure ES.2). Country rankings change dramatically when comparing total and per capita emissions: for example, it is evident that China now has per capita emissions in the same range as the European Union (EU) and is almost at a similar level to Japan.

- Consumption-based emission estimates, also known as a carbon footprint, that adjust the standard territorial emissions for imports and exports, provide policymakers with a deeper insight into the role of consumption, trade and the interconnectedness of countries. Figure ES.3 shows that the net flow of embodied carbon is from developing to developed countries, even as developed countries reduce their territorial emissions this effect is being partially offset by importing embodied carbon, implying for example that EU per capita emissions are higher than Chinese when consumption-based emissions are included. It should be noted that consumption-based emissions are not used within the context of the United Nations Framework Convention on Climate Change (UNFCCC).

Figure ES.1. Average annual growth rates of key drivers of global CO_2 emissions (left of dotted line) and components of greenhouse gas emissions (right of dotted line) for OECD and non-OECD members

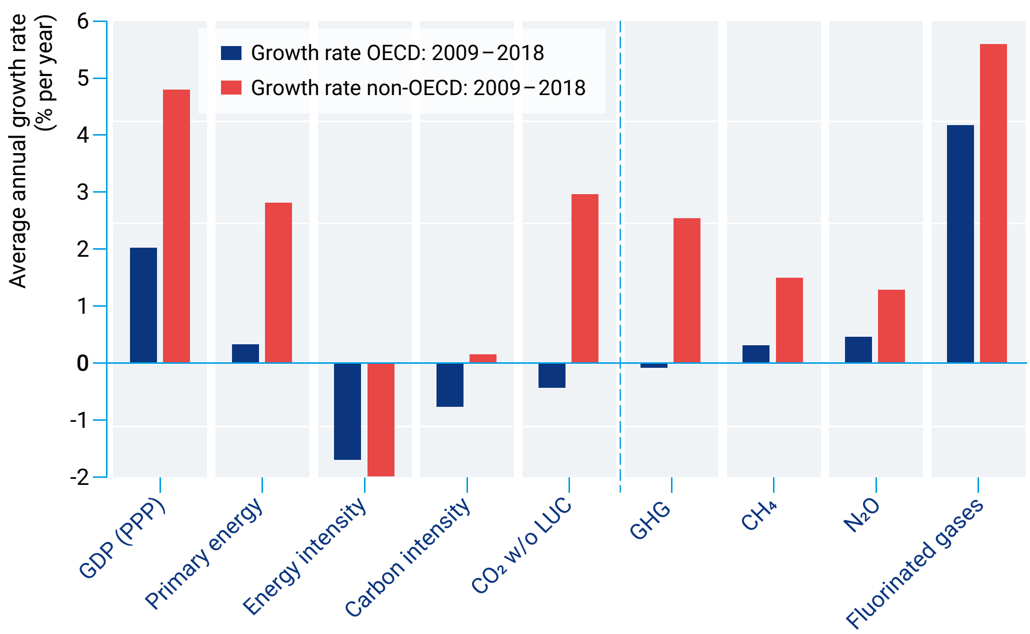
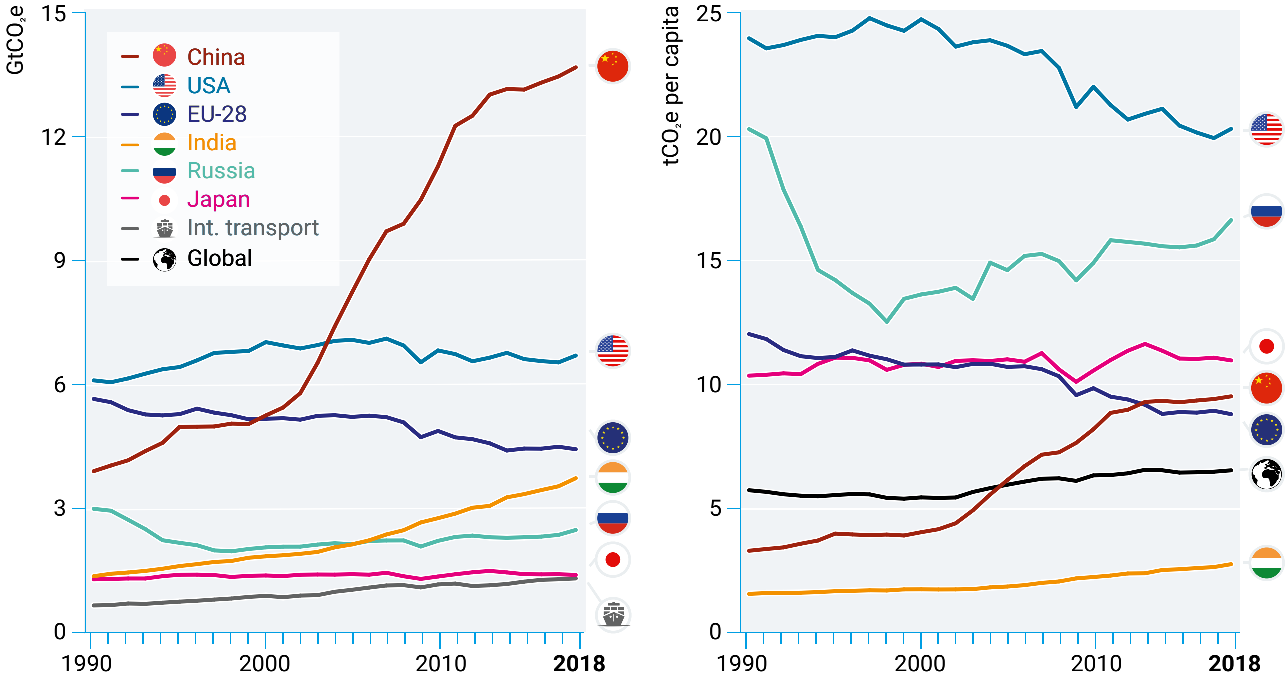


Figure ES.2. Top greenhouse gas emitters, excluding land-use change emissions due to lack of reliable country-level data, on an absolute basis (left) and per capita basis (right)



2. G20 members account for 78 per cent of global GHG emissions. Collectively, they are on track to meet their limited 2020 Cancun Pledges, but seven countries are currently not on track to meet 2030 NDC commitments, and for a further three, it is not possible to say.

- As G20 members account for around 78 per cent of global GHG emissions (including land use), they largely determine global emission trends and the extent to which the 2030 emissions gap will be closed. This report therefore pays close attention to G20 members.

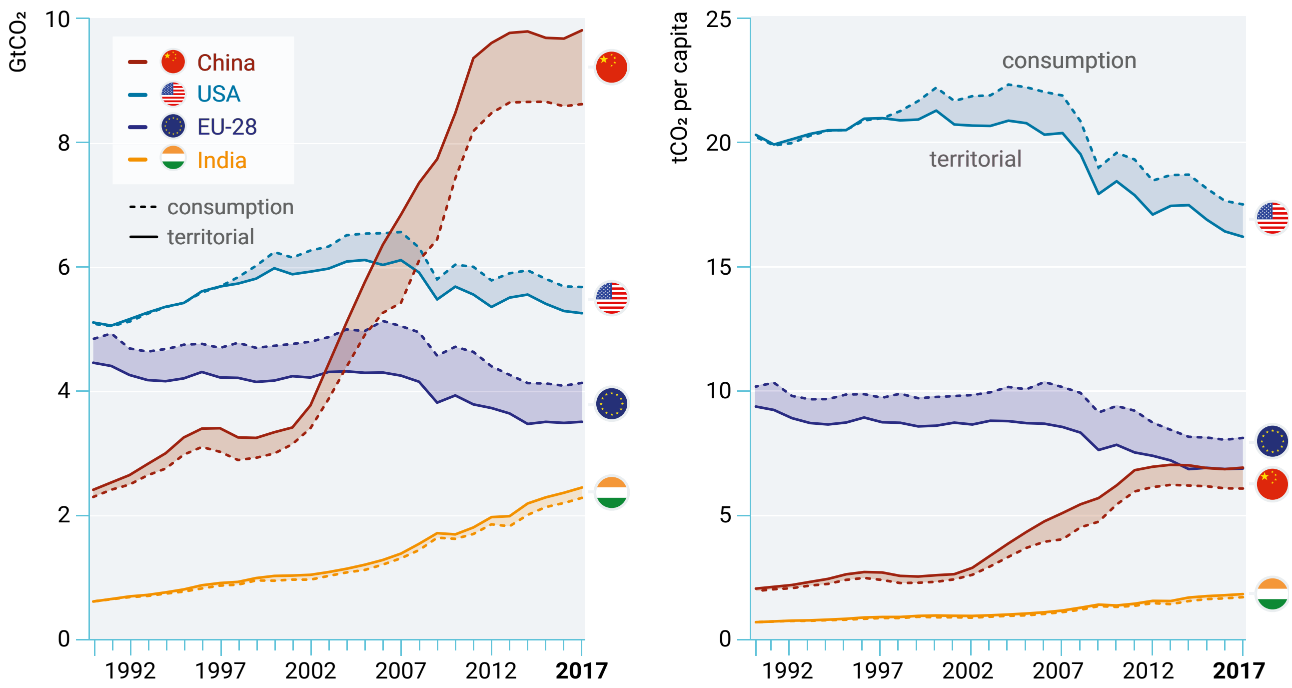
- G20 members with 2020 Cancun Pledges are collectively projected to overachieve these by about 1 $GtCO_2e$ per year. However, several individual G20 members (Canada, Indonesia, Mexico, the Republic of Korea, South Africa, the United States of America) are currently projected to miss their Cancun Pledges or will not achieve them with great certainty. Argentina, Saudi Arabia and Turkey have not made 2020 pledges and pledges from several countries that meet their targets are rather unambitious.

- Australia is carrying forward their overachievement from the Kyoto period to meet their 2020 Cancun Pledge and counts cumulative emissions between 2013 and 2020. With this method, the Australian Government projects that the country will overachieve its 2020 pledge. However, if this 'carry-forward' approach is not taken, Australia will not achieve its 2020 pledge.

- On the progress of G20 economies towards their NDC targets, six members (China, the EU28, India, Mexico, Russia and Turkey) are projected to meet their unconditional NDC targets with current policies. Among them, three countries (India, Russia and Turkey) are projected to be more than 15 per cent lower than their NDC target emission levels. These results suggest that the three countries have room to raise their NDC ambition significantly. The EU28 has introduced climate legislation that achieves at least a 40 per cent reduction in GHG emissions, which the European Commission projects could be overachieved if domestic legislation is fully implemented in member states.

- In contrast, seven G20 members require further action of varying degree to achieve their NDC: Australia, Brazil, Canada, Japan, the Republic of Korea, South Africa and the United States of

Figure ES.3. CO_2 emissions allocated to the point of emissions (territorial) and the point of consumption, for absolute emissions (left) and per capita (right)



America. For Brazil, the emissions projections from three annually updated publications were all revised upward, reflecting the recent trend towards increased deforestation, among others. In Japan, however, current policy projections have been close to achieving its NDC target for the last few years.

- Studies do not agree on whether Argentina, Indonesia and Saudi Arabia are on track to meet their unconditional NDCs. For Argentina, recent domestic analysis that reflects the most recent GHG inventory data up to 2016 projects that the country will achieve its unconditional NDC target, while two international studies project that it will fall short of its target. For Indonesia, this is mainly due to uncertainty concerning the country's land use, land-use change and forestry (LULUCF) emissions. For Saudi Arabia, the limited amount of information on the country's climate policies has not allowed for further assessments beyond the two studies reviewed.

- Some G20 members are continuously strengthening their mitigation policy packages, leading to a downward revision of current policy scenario projections for total emissions over time. One example is the EU, where a noticeable downward shift has been observed in current policy scenario projections for 2030 since the 2015 edition of the Emissions Gap Report.

3. Although the number of countries announcing net zero GHG emission targets for 2050 is increasing, only a few countries have so far formally submitted long-term strategies to the UNFCCC.

- An increasing number of countries have set net zero emission targets domestically and 65 countries and major subnational economies, such as the region of California and major cities worldwide, have committed to net zero emissions by 2050. However, only a few long-term strategies submitted to the UNFCCC have so far committed to a timeline for net zero emissions, none of which are from a G20 member.

- Five G20 members (the EU and four individual members) have committed to long-term zero emission targets, of which three are currently in the process of passing legislation and two have recently passed legislation. The remaining 15 G20 members have not yet committed to zero emission targets.

Table ES.1. Global total GHG emissions by 2030 under different scenarios (median and 10th to 90th percentile range), temperature implications and the resulting emissions gap

Scenario (rounded to the nearest gigaton)	Number of scenarios in set	Global total emissions in 2030 [$GtCO_2e$]	Estimated temperature outcomes			Closest corresponding IPCC SR1.5 scenario class	Emissions Gap in 2030 [$GtCO_2e$]		
			50% probability	66% probability	90% probability		Below 2.0°C	Below 1.8°C	Below 1.5°C in 2100
2005-policies	6	**64** (60–68)							
Current policy	8	**60** (58–64)					**18** (17–23)	**24** (23–29)	**35** (34–39)
Unconditional NDCs	11	**56** (54–60)					**15** (12–18)	**21** (18–24)	**32** (29–35)
Conditional NDCs	12	**54** (51–56)					**12** (9–14)	**18** (15–21)	**29** (26–31)
Below 2.0°C (66% probability)	29	**41** (39–46)	Peak: 1.7-1.8°C In 2100: 1.6-1.7°C	**Peak: 1.9-2.0°C In 2100: 1.8-1.9°C**	Peak: 2.4-2.6°C In 2100: 2.3-2.5°C	Higher-2°C pathways			
Below 1.8°C (66% probability)	43	**35** (31–41)	Peak: 1.6-1.7°C In 2100: 1.3-1.6°C	**Peak: 1.7-1.8°C In 2100: 1.5-1.7°C**	Peak: 2.1-2.3°C In 2100: 1.9-2.2°C	Lower-2°C pathways			
Below 1.5°C in 2100 and peak below 1.7°C (both with 66% probability)	13	**25** (22–31)	Peak: 1.5-1.6°C In 2100: 1.2-1-3°C	**Peak: 1.6-1.7°C In 2100: 1.4-1.5°C**	Peak: 2.0-2.1°C In 2100: 1.8-1.9°C	1.5°C with no or limited overshoot			

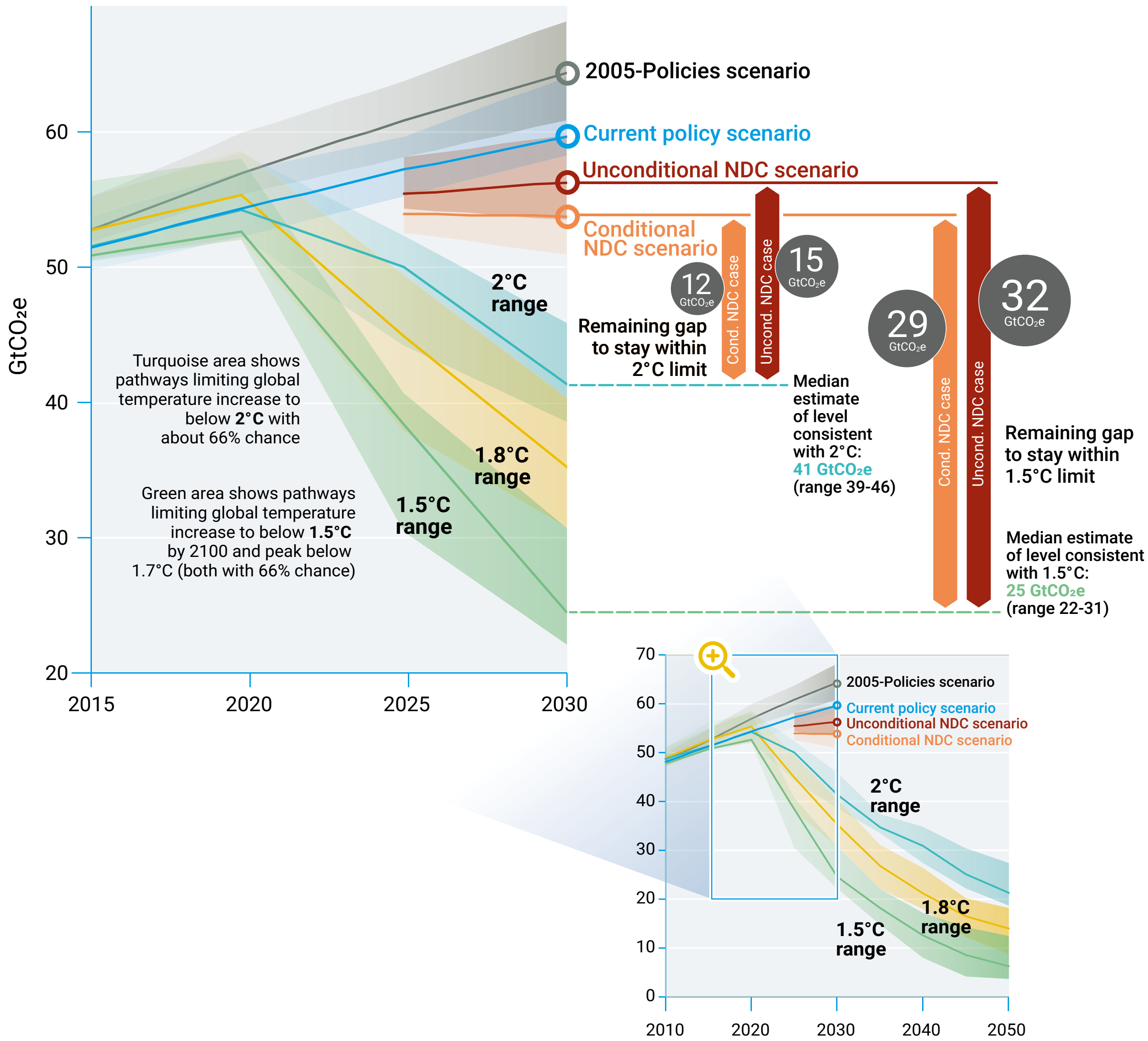
4. The emissions gap is large. In 2030, annual emissions need to be 15 $GtCO_2e$ lower than current unconditional NDCs imply for the 2°C goal, and 32 $GtCO_2e$ lower for the 1.5°C goal.

- Estimates of where GHG emissions should be in 2030 in order to be consistent with a least-cost pathway towards limiting global warming to the specific temperature goals have been calculated from the scenarios that were compiled as part of the mitigation pathway assessment of the IPCC Special Report on Global Warming of 1.5°C report.

- This report presents an assessment of global emissions pathways relative to those consistent with limiting warming to 2°C, 1.8°C and 1.5°C, in order to provide a clear picture of the pathways that will keep warming in the range of 2°C to 1.5°C. The report also includes an overview of the peak and 2100 temperature outcomes associated with different likelihoods. The inclusion of the 1.8°C level allows for a more nuanced interpretation and discussion of the implication of the Paris Agreement's temperature targets for near-term emissions.

- The NDC scenarios of this year's report are based on updated data from the same sources used for the current policies scenario and is provided by 12 modelling groups. Projected NDC levels for some countries, in particular China and India, depend on recent emission trends or GDP growth projections that are easily outdated in older studies. Thus, studies that were published in 2015, before the adoption of the Paris Agreement, have been excluded in this year's update. Excluding such studies has had little impact

Figure ES.4. Global GHG emissions under different scenarios and the emissions gap by 2030



on the projected global emission levels of the NDC scenarios, which are very similar to those presented in the UNEP Emissions Gap Report 2018.

- With only current policies, GHG emissions are estimated to be 60 $GtCO_2e$ in 2030. On a least-cost pathway towards the Paris Agreement goals in 2030, median estimates are 41 $GtCO_2e$ for 2°C, 35 $GtCO_2e$ for 1.8°C, and 25 $GtCO_2e$ for 1.5°C.

- If unconditional and conditional NDCs are fully implemented, global emissions are estimated to reduce by around 4 $GtCO_2e$ and 6 $GtCO_2e$ respectively by 2030, compared with the current policy scenario.

- The emissions gap between estimated total global emissions by 2030 under the NDC scenarios and under pathways limiting warming to below 2°C and 1.5°C is large (see Figure ES.4). Full implementation of the unconditional NDCs is estimated to result in a gap of 15 $GtCO_2e$ (range: 12–18 $GtCO_2e$) by 2030, compared with the 2°C scenario. The emissions gap between implementing the unconditional NDCs and the 1.5°C pathway is about 32 $GtCO_2e$ (range: 29–35 $GtCO_2e$).

- The full implementation of both unconditional and conditional NDCs would reduce this gap by around 2–3 $GtCO_2e$.

- If current unconditional NDCs are fully implemented, there is a 66 per cent chance that warming will be limited to 3.2°C by the end of the century. If conditional NDCs are also effectively implemented, warming will likely reduce by about 0.2°C.

5. Dramatic strengthening of the NDCs is needed in 2020. Countries must increase their NDC ambitions threefold to achieve the well below 2°C goal and more than fivefold to achieve the 1.5°C goal.

- The ratchet mechanism of the Paris Agreement foresees strengthening of NDCs every five years. Parties to the Paris Agreement identified 2020 as a critical next step in this process, inviting countries to communicate or update their NDCs by this time. Given the time lag between policy decisions and associated emission reductions, waiting until 2025 to strengthen NDCs will be too late to close the large 2030 emissions gap.

- The challenge is clear. The recent IPCC special reports clearly describe the dire consequences of inaction and are backed by record temperatures worldwide along with enhanced extreme events.

- Had serious climate action begun in 2010, the cuts required per year to meet the projected emissions levels for 2°C and 1.5°C would only have been 0.7 per cent and 3.3 per cent per year on average. However, since this did not happen, the required cuts in emissions are now 2.7 per cent per year from 2020 for the 2°C goal and 7.6 per cent per year on average for the 1.5°C goal. Evidently, greater cuts will be required the longer that action is delayed.

- Further delaying the reductions needed to meet the goals would imply future emission reductions and removal of CO_2 from the atmosphere at such a magnitude that it would result in a serious deviation from current available pathways. This, together with necessary adaptation actions, risks seriously damaging the global economy and undermining food security and biodiversity.

6. Enhanced action by G20 members will be essential for the global mitigation effort.

- This report has a particular focus on the G20 members, reflecting on their importance for global mitigation efforts. Chapter 4 in particular focuses on progress and opportunities for enhancing mitigation ambition of seven selected G20 members – Argentina, Brazil, China, the EU, India, Japan and the United States of America – which represented around 56 per cent of global GHG emissions in 2017. The chapter, which was pre-released for the Climate Action Summit, presents a detailed assessment of action or inaction in key sectors, demonstrating that even though there are a few frontrunners, the general picture is rather bleak.

- In 2009, the G20 members adopted a decision to gradually phase out fossil-fuel subsidies, though no country has committed to fully phasing these out by a specific year as yet.

- Although many countries, including most G20 members, have committed to net zero deforestation targets in the last few decades, these commitments are often not supported by action on the ground.

- Based on the assessment of mitigation potential in the seven previously mentioned countries, a number of areas have been identified for urgent and impactful action (see table ES.2). The purpose of the recommendations is to show potential, stimulate engagement and facilitate political discussion of what is required to implement the necessary action. Each country will be responsible for designing their own policies and actions.

7. Decarbonizing the global economy will require fundamental structural changes, which should be designed to bring multiple co-benefits for humanity and planetary support systems.

- If the multiple co-benefits associated with closing the emissions gap are fully realized, the required transition will contribute in an essential way to achieving the United Nations 2030 Agenda with its 17 Sustainable Development Goals (SDGs).

- Climate protection and adaptation investments will become a precondition for peace and stability, and will require unprecedented efforts to transform societies, economies, infrastructures and governance institutions. At the same time, deep and rapid decarbonization processes imply fundamental structural changes are needed within economic sectors, firms, labour markets and trade patterns.

- By necessity, this will see profound change in how energy, food and other material-intensive services are demanded and provided by governments, businesses and markets. These systems of provision are entwined with the preferences, actions and demands of people as consumers, citizens and communities. Deep-rooted shifts in values, norms, consumer culture and world views are inescapably part of the great sustainability transformation.

- Legitimacy for decarbonization therefore requires massive social mobilization and investments in social cohesion to avoid exclusion and resistance to change. Just and timely transitions towards sustainability need to be developed, taking into account the interests and rights of people vulnerable to the impacts of climate change, of people and regions where decarbonization requires structural adjustments, and of future generations.

- Fortunately, deep transformation to close the emissions gap between trends based on current

Table ES.2. Selected current opportunities to enhance ambition in seven G20 members in line with ambitious climate actions and targets

Argentina

- Refrain from extracting new, alternative fossil-fuel resources
- Reallocate fossil-fuel subsidies to support distributed renewable electricity-generation
- Shift towards widespread use of public transport in large metropolitan areas
- Redirect subsidies granted to companies for the extraction of alternative fossil fuels to building-sector measures

Brazil

- Commit to the full decarbonization of the energy supply by 2050
- Develop a national strategy for ambitious electric vehicle (EV) uptake aimed at complementing biofuels and at 100-per cent CO_2-free new vehicles
- Promote the 'urban agenda' by increasing the use of public transport and other low-carbon alternatives

China

- Ban all new coal-fired power plants
- Continue governmental support for renewables, taking into account cost reductions, and accelerate development towards a 100 per cent carbon-free electricity system
- Further support the shift towards public modes of transport
- Support the uptake of electric mobility, aiming for 100 per cent CO_2-free new vehicles
- Promote near-zero emission building development and integrate it into Government planning

European Union

- Adopt an EU regulation to refrain from investment in fossil-fuel infrastructure, including new natural gas pipelines
- Define a clear endpoint for the EU emissions trading system (ETS) in the form of a cap that must lead to zero emissions
- Adjust the framework and policies to enable 100 per cent carbon-free electricity supply by between 2040 and 2050
- Step up efforts to phase out coal-fired plants
- Define a strategy for zero-emission industrial processes
- Reform the EU ETS to more effectively reduce emissions in industrial applications
- Ban the sale of internal combustion engine cars and buses and/or set targets to move towards 100 per cent of new car and bus sales being zero-carbon vehicles in the coming decades
- Shift towards increased use of public transport in line with the most ambitious Member States
- Increase the renovation rate for intensive retrofits of existing buildings

India

- Plan the transition from coal-fired power plants
- Develop an economy-wide green industrialization strategy towards zero-emission technologies
- Expand mass public transit systems
- Develop domestic electric vehicle targets working towards 100 per cent new sales of zero-emission cars

Japan

- Develop a strategic energy plan that includes halting the construction of new freely emitting coal-fired power plants, as well as a phase-out schedule of existing plants and a 100 per cent carbon-free electricity supply
- Increase the current level of carbon pricing with high priority given to the energy and building sector
- Develop a plan to phase out the use of fossil fuels through promoting passenger cars that use electricity from renewable energy
- Implement a road map as part of efforts towards net-zero energy buildings and net-zero energy houses

USA

- Introduce regulations on power plants, clean energy standards and carbon pricing to achieve an electricity supply that is 100 per cent carbon-free
- Implement carbon pricing on industrial emissions
- Strengthen vehicle and fuel economy standards to be in line with zero emissions for new cars in 2030
- Implement clean building standards so that all new buildings are 100 per cent electrified by 2030

policies and achieving the Paris Agreement can be designed to bring multiple co-benefits for humanity and planetary support systems. These range, for example, from reducing air pollution, improving human health, establishing sustainable energy systems and industrial production processes, making consumption and services more efficient and sufficient, employing less-intensive agricultural practices and mitigating biodiversity loss to liveable cities.

- This year's report explores six entry points for progressing towards closing the emissions gap through transformational change in the following areas: (a) air pollution, air quality, health; (b) urbanization; (c) governance, education, employment; (d) digitalization; (e) energy- and material-efficient services for raising living standards; and (f) land use, food security, bioenergy. Building on this overview, a more detailed discussion of transitions in the energy sector is presented in chapter 6.

8. Renewables and energy efficiency, in combination with electrification of end uses, are key to a successful energy transition and to driving down energy-related CO_2 emissions.

- The necessary transition of the global energy sector will require significant investments compared with a business-as-usual scenario. Climate policies that are consistent with the 1.5°C goal will require upscaling energy system supply-side investments to between US$1.6 trillion and US$3.8 trillion per year globally on average over the 2020–2050 time frame, depending on how rapid energy efficiency and conservation efforts can be ramped up.

- Given the important role that energy and especially the electricity sector will have to play in any low-carbon transformation, chapter 6 examines five transition options, taking into account their relevance for a wide range of countries, clear co-benefit opportunities and potential to deliver significant emissions reductions. Each of the following transitions correspond to a particular policy rationale or motivation, which is discussed in more detail in the chapter:

    - Expanding Renewable Energy for electrification.
    - Phasing out coal for rapid decarbonization of the energy system.
    - Decarbonizing transport with a focus on electric mobility.
    - Decarbonizing energy-intensive industry.
    - Avoiding future emissions while improving energy access.

- Implementing such major transitions in a number of areas will require increased interdependency between energy and other infrastructure sectors, where changes in one sector can impact another. Similarly, there will be a strong need to connect demand and supply-side policies and include wider synergies and co-benefits, such as job losses and creation, rehabilitation of ecosystem services, avoidance of resettlements and reduced health and environmental costs as a result of reduced emissions. The same applies for decarbonizing transport, where there will be a need for complementarity and coordination of policies, driven by technological, environmental and land-use pressures. Policies will need to be harmonized wherever possible to take advantage of interdependencies and prevent undesirable outcomes such as CO_2 leakage from one sector to another.

- Any transition at this scale is likely to be extremely challenging and will meet a number of economic, political and technical barriers and challenges. However, many drivers of climate action have changed in the last years, with several options for ambitious climate action becoming less costly, more numerous and better understood. First, technological and economic developments present opportunities to decarbonize the economy, especially the energy sector, at a cost that is lower than ever. Second, the synergies between climate action and economic growth and development objectives, including options for addressing distributional impacts, are better understood. Finally, policy momentum across various levels of government, as well as a surge in climate action commitments by non-state actors, are creating opportunities for countries to engage in real transitions.

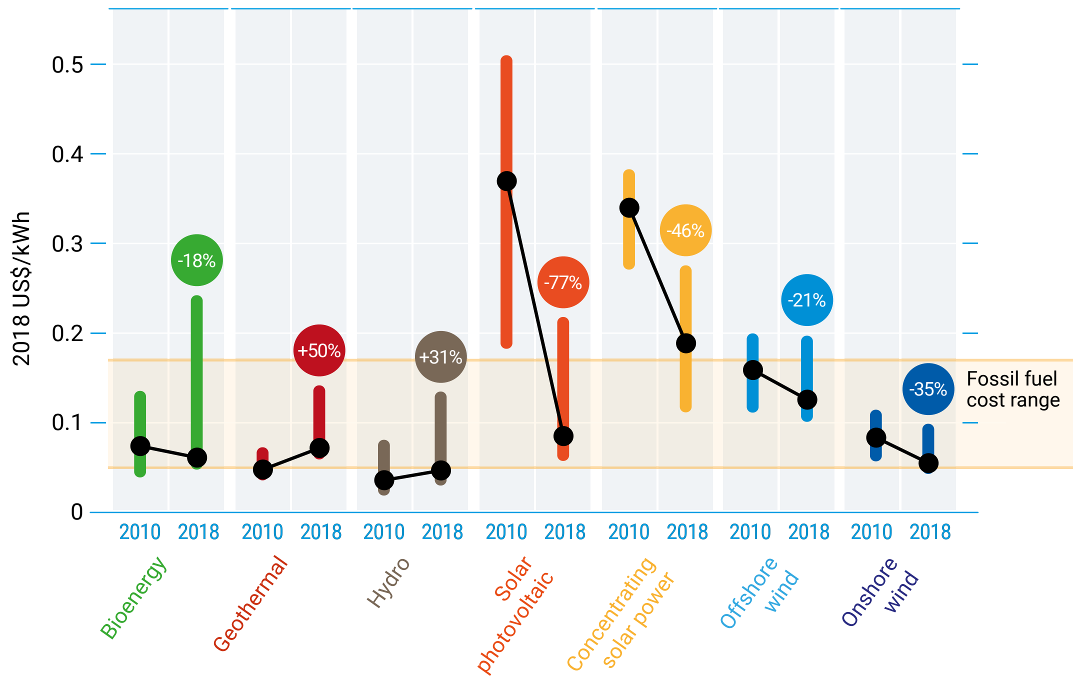
- A key example of technological and economic trends is the cost of renewable energy, which is declining more rapidly than was predicted just a few years ago (see figure ES.5). Renewables are currently the cheapest source of new power generation in most of the world, with the global weighted average purchase or auction price for new utility-scale solar power photovoltaic systems and utility-scale onshore wind turbines projected to compete with the marginal operating cost of existing coal plants by 2020. These trends are increasingly manifesting in a decline in new coal plant construction, including the cancellation of planned plants, as well as the early retirement of existing plants. Moreover, real-life cost declines are outpacing projections.

A short summary of the main aspects of each transition is presented in table ES.3.

Table ES.3. Summary of five energy transition options

Option	Major components	Instruments	Co-benefits	Annual GHG emissions reduction potential of renewables, electrification, energy efficiency and other measures by 2050
Renewable energy electricity expansion	• Plan for large shares of variable renewable energy • Electricity becomes the main energy source by 2050, supplying at least 50 per cent of total final energy consumption (TFEC) • Share of renewable energy in electricity up to 85 per cent by 2050 • Transition	• Flexibility measures to take on larger shares of variable renewable energy • Support for deployment of distributed energy • Innovative measures: cost reflective tariff structures, targeted subsidies, reverse auctions, net metering	• Greater efficiency in end-use energy demand • Health benefits • Energy access and security • Employment	• Power sector: 8.1 $GtCO_2$ • Building sector: 2.1 $GtCO_2$ • District heat and others: 1.9 $GtCO_2$
Coal phase-out	• Plan and implement phase-out of coal • Coal to renewable energy transition • Expand carbon capture usage and storage systems • Improve system-wide efficiency	• Regional support programmes • Tax breaks, subsidies • Carbon pricing • Moratorium policies • De-risking of clean energy investments • Relocation of coal workers (mines and power plants)	• Lower health hazards (air, water, land pollution) • Future skills and job creation	Share of the power emissions reduction from a coal phase-out: 4 $GtCO_2$ (range: 3.6– 4.4 $GtCO_2$), with 1 $GtCO_2$ from the OECD and 3 $GtCO_2$ from the rest of the world
Decarbonize transport	• Reduce energy for transport • Electrify transport • Fuels substitution (bioenergy, hydrogen) • Modal shift	• Pathways for non-motorized transport • Standards for vehicle emissions • Establishing of charging stations • Eliminating of fossil-fuel subsidies • Investments in public transport	• Increased public health from more physical activity, less air pollution • Energy security • Reduced fuel spending • Less congestion	Electrification of transport: 6.1 $GtCO_2$
Decarbonize industry	• Demand reduction (circular economy, modal shifts and logistics) • Electrify heat processes • Improve energy efficiency • Direct use of biomass/ biofuels	• Carbon pricing • Standards and regulations, especially on materials demand reduction	• Energy security • Savings and competitiveness	• Industry: 4.8 $GtCO_2$
Avoid future emissions and energy access	• Link energy access with emission reductions for 3.5 billion energy-poor people	• Fit and auctions • Standards and regulations • Targeted subsidies • Support for entrepreneurs	• Better access • Meet basic needs and SDGs	• N/A

Figure ES.5. Changes in global levelized cost of energy for key renewable energy technologies, 2010-2018



9. Demand-side material efficiency offers substantial GHG mitigation opportunities that are complementary to those obtained through an energy system transformation.

- While demand-side material efficiency widens the spectrum of emission mitigation strategies, it has largely been overlooked in climate policymaking until now and will be important for the cross-sectoral transitions.

- In 2015, the production of materials caused GHG emissions of approximately 11.5 $GtCO_2e$, up from 5 $GtCO_2e$ in 1995. The largest contribution stems from bulk materials production, such as iron and steel, cement, lime and plaster, other minerals mostly used as construction products, as well as plastics and rubber. Two thirds of the materials are used to make capital goods, with buildings and vehicles among the most important. While the production of materials consumed in industrialized countries remained within the range of 2–3 $GtCO_2e$, in the 1995–2015 period, those of developing and emerging economies have largely been behind the growth. In this context, it is important to keep in mind the discussion about the point of production and points of consumption (see figure ES.6).

- Material efficiency and substitution strategies affect not only energy demand and emissions during material production, but also potentially the operational energy use of the material products. Analysis of such strategies therefore requires a systems or life cycle perspective. Several investigations of material efficiency have focused on strategies that have little impact on operations, meaning that trade-offs and synergies have been ignored. Many energy efficiency strategies have implications for the materials used, such as increased insulation demand for buildings or a shift to more energy-intensive materials in the lightweighting of vehicles. While these additional, material-related emissions are well understood from technology studies, they are often not fully captured in the integrated assessment models that produce scenario results, such as those discussed in this report.

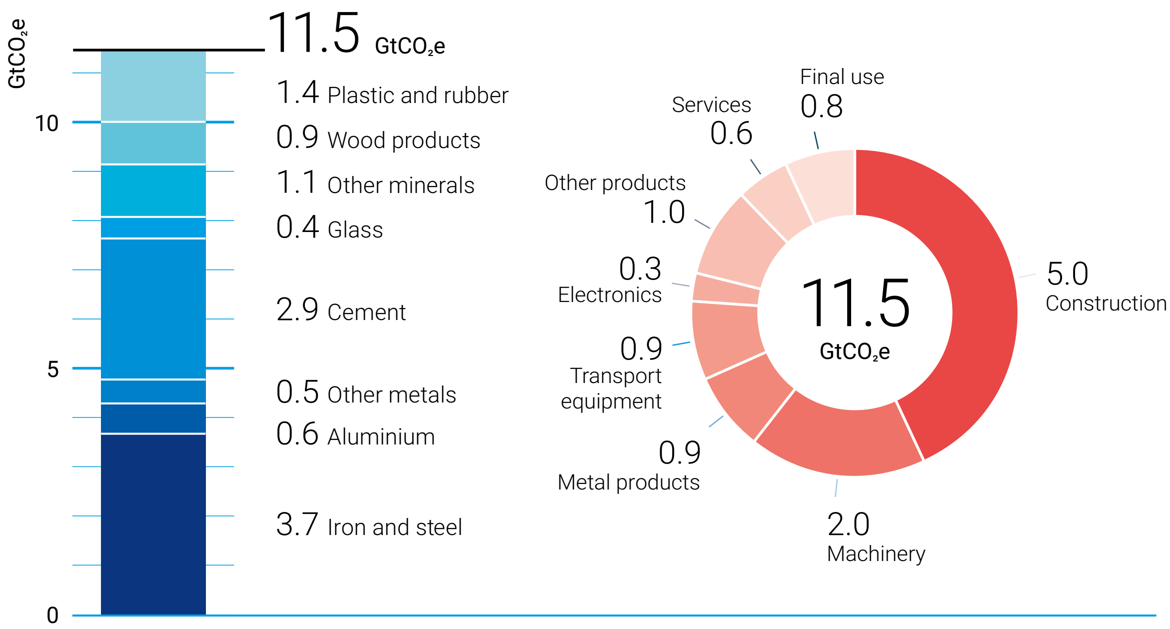
- In chapter 7, the mitigation potential from demand-side material efficiency improvements is discussed in the context of the following categories of action:

  - Product lightweighting and substitution of high-carbon materials with low-carbon materials to reduce material-related GHG emissions associated with product production, as well as operational energy consumption of vehicles.

  - Improvements in the yield of material production and product manufacture.

  - More intensive use, longer life, component reuse, remanufacturing and repair as strategies to obtain more service from material-based products.

Figure ES.6. GHG emissions in $GtCO_2e$ associated with materials production by material (left) and by the first use of materials in subsequent production processes or final consumption (right)



- Enhanced recycling so that secondary materials reduce the need to produce more emission-intensive primary materials.

► These categories are elaborated for housing and cars, showing that increased material efficiency can reduce annual emissions from the construction and operations of buildings and the manufacturing and use of passenger vehicles, thus contributing a couple of gigatons of carbon dioxide equivalent in emission reductions to the global mitigation effort by 2030.

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Issue Section: Viewpoint

World Scientists' Warning of a Climate Emergency FREE

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William R Moomaw Author Notes

BioScience, biz088, https://doi.org/10.1093/biosci/biz088
Published: 05 November 2019

A correction has been published:
BioScience, biz152, https://doi.org/10.1093/biosci/biz152

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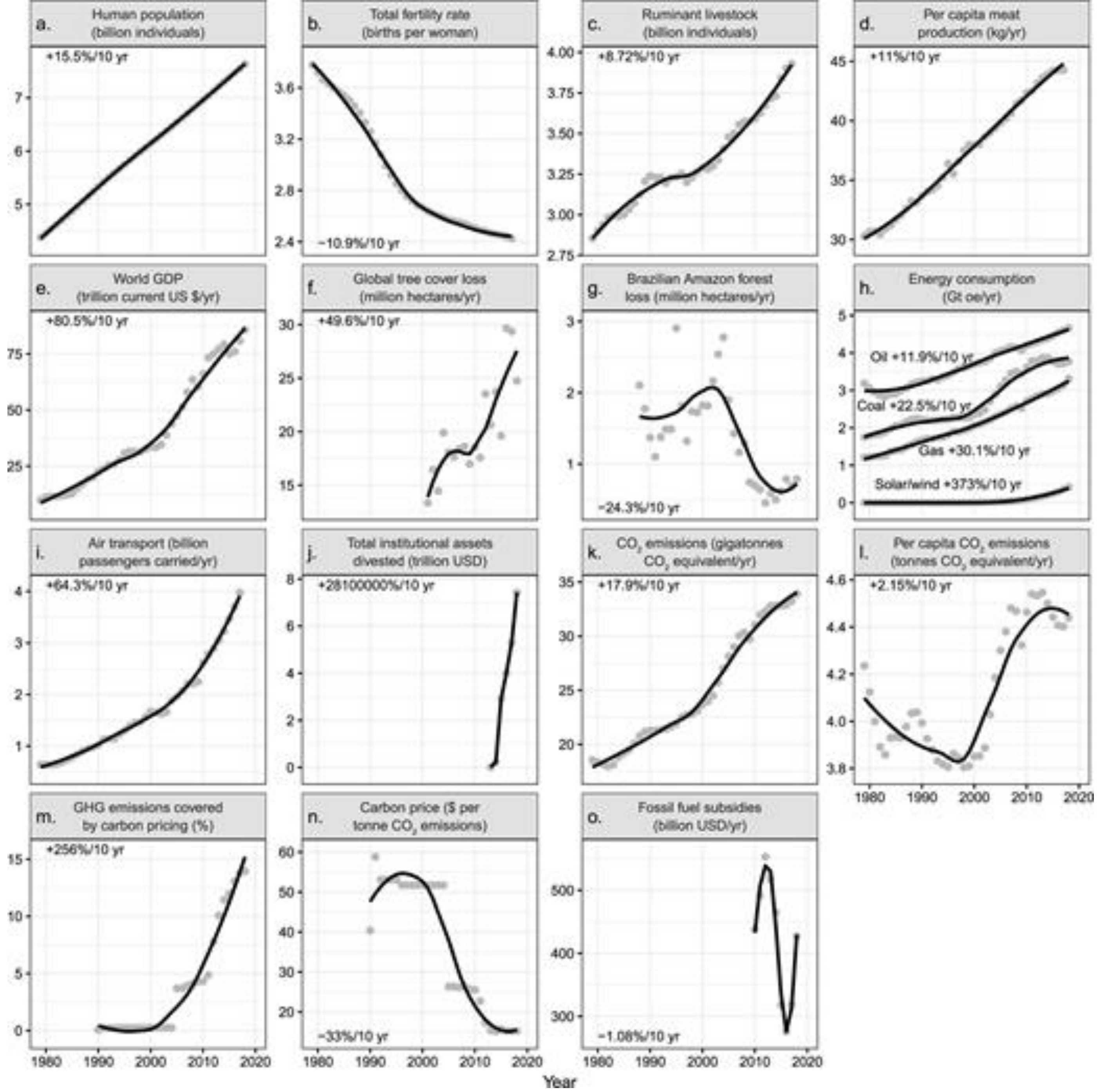
Issue Section: Viewpoint

Scientists have a moral obligation to clearly warn humanity of any catastrophic threat and to "tell it like it is." On the basis of this obligation and the graphical indicators presented below, we declare, with more than 11,000 scientist signatories from around the world, clearly and unequivocally that planet Earth is facing a climate emergency.

Exactly 40 years ago, scientists from 50 nations met at the First World Climate Conference (in Geneva 1979) and agreed that alarming trends for climate change made it urgently necessary to act. Since then, similar alarms have been made through the 1992 Rio Summit, the 1997 Kyoto Protocol, and the 2015 Paris Agreement, as well as scores of other global assemblies and scientists' explicit warnings of insufficient progress (Ripple et al. 2017). Yet greenhouse gas (GHG) emissions are still rapidly rising, with increasingly damaging effects on the Earth's climate. An immense increase of scale in endeavors to conserve our biosphere is needed to avoid untold suffering due to the climate crisis (IPCC 2018).

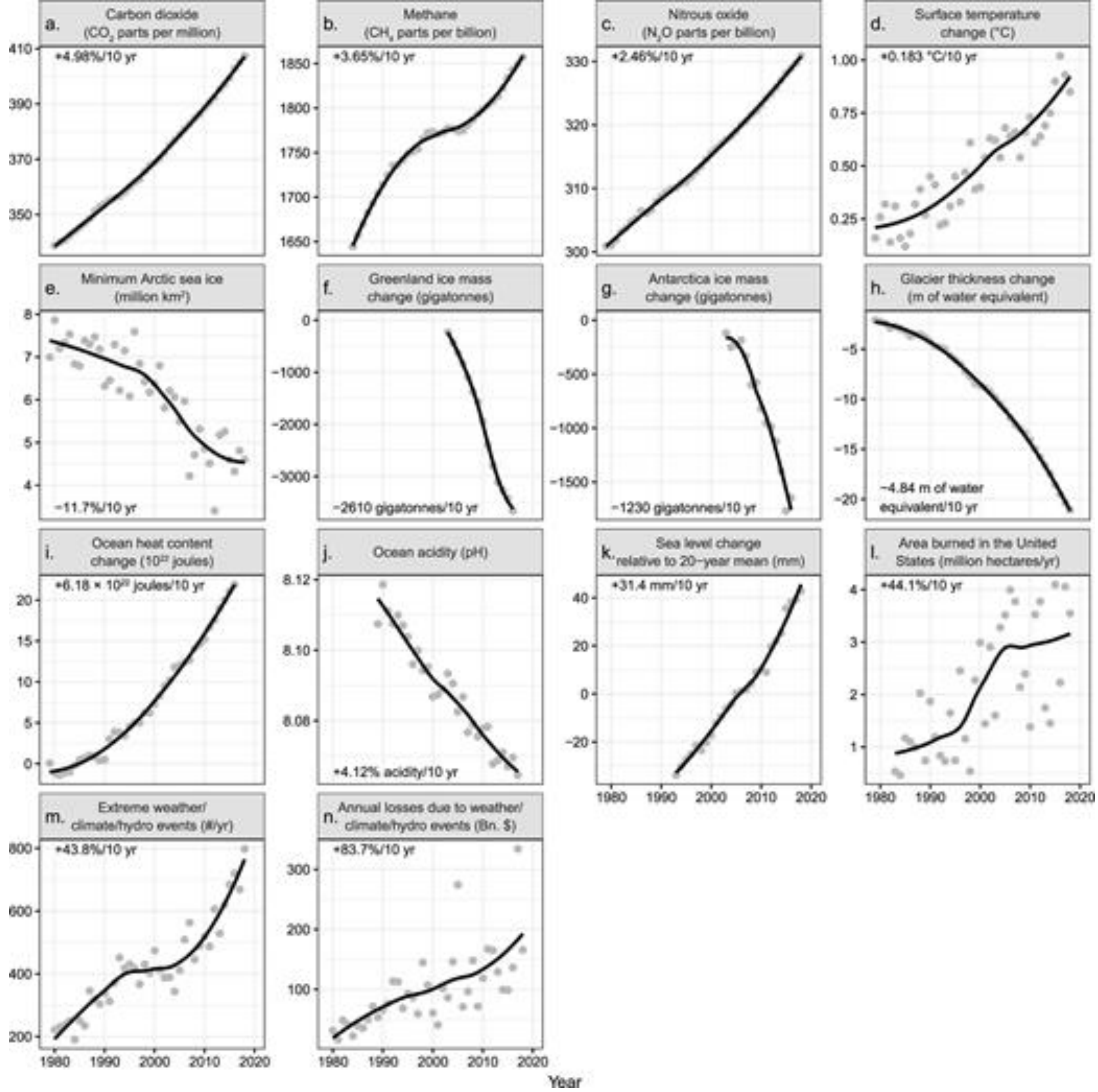
Most public discussions on climate change are based on global surface temperature only, an inadequate measure to capture the breadth of human activities and the real dangers stemming from a warming planet (Briggs et al. 2015). Policymakers and the public now urgently need access to a set of indicators that convey the effects of human activities on GHG emissions and the consequent impacts on climate, our environment, and society. Building on prior work (see supplemental file S2), we present a suite of graphical vital signs of climate change over the last 40 years for human activities that can affect GHG emissions and change the climate (figure 1), as well as actual climatic impacts (figure 2). We use only relevant data sets that are clear, understandable, systematically collected for at least the last 5 years, and updated at least annually.

Figure 1.



Change in global human activities from 1979 to the present. These indicators are linked at least in part to climate change. In panel (f), annual tree cover loss may be for any reason (e.g., wildfire, harvest within tree plantations, or conversion of forests to agricultural land). Forest gain is not involved in the calculation of tree cover loss. In panel (h), hydroelectricity and nuclear energy are shown in figure S2. The rates shown in panels are the percentage changes per decade across the entire range of the time series. The annual data are shown using gray points. The black lines are local regression smooth trend lines. Abbreviation: Gt oe per year, gigatonnes of oil equivalent per year. Sources and additional details about each variable are provided in supplemental file S2, including table S2.

Figure 2.



Climatic response time series from 1979 to the present. The rates shown in the panels are the decadal change rates for the entire ranges of the time series. These rates are in percentage terms, except for the interval variables (d, f, g, h, i, k), where additive changes are reported instead. For ocean acidity (pH), the percentage rate is based on the change in hydrogen ion activity, a_{H+} (where lower pH values represent greater acidity). The annual data are shown using gray points. The black lines are local regression smooth trend lines. Sources and additional details about each variable are provided in supplemental file S2, including table S3.

The climate crisis is closely linked to excessive consumption of the wealthy lifestyle. The most affluent countries are mainly responsible for the historical GHG emissions and generally have the greatest per capita emissions (table S1). In the present article, we show general patterns, mostly at the global scale, because there are many climate efforts that involve individual regions and countries. Our vital signs are designed to be useful to the public, policymakers, the business community, and those working to implement the Paris climate agreement, the

United Nations' Sustainable Development Goals, and the Aichi Biodiversity Targets.

Profoundly troubling signs from human activities include sustained increases in both human and ruminant livestock populations, per capita meat production, world gross domestic product, global tree cover loss, fossil fuel consumption, the number of air passengers carried, carbon dioxide (CO_2) emissions, and per capita CO_2 emissions since 2000 (figure 1, supplemental file S2). Encouraging signs include decreases in global fertility (birth) rates (figure 1b), decelerated forest loss in the Brazilian Amazon (figure 1g), increases in the consumption of solar and wind power (figure 1h), institutional fossil fuel divestment of more than US$7 trillion (figure 1j), and the proportion of GHG emissions covered by carbon pricing (figure 1m). However, the decline in human fertility rates has substantially slowed during the last 20 years (figure 1b), and the pace of forest loss in Brazil's Amazon has now started to increase again (figure 1g). Consumption of solar and wind energy has increased 373% per decade, but in 2018, it was still 28 times smaller than fossil fuel consumption (combined gas, coal, oil; figure 1h). As of 2018, approximately 14.0% of global GHG emissions were covered by carbon pricing (figure 1m), but the global emissions-weighted average price per tonne of carbon dioxide was only around US$15.25 (figure 1n). A much higher carbon fee price is needed (IPCC 2018, section 2.5.2.1). Annual fossil fuel subsidies to energy companies have been fluctuating, and because of a recent spike, they were greater than US$400 billion in 2018 (figure 1o).

Especially disturbing are concurrent trends in the vital signs of climatic impacts (figure 2, supplemental file S2). Three abundant atmospheric GHGs (CO_2, methane, and nitrous oxide) continue to increase (see figure S1 for ominous 2019 spike in CO_2), as does global surface temperature (figure 2a–2d). Globally, ice has been rapidly disappearing, evidenced by declining trends in minimum summer Arctic sea ice, Greenland and Antarctic ice sheets, and glacier thickness worldwide (figure 2e–2h). Ocean heat content, ocean acidity, sea level, area burned in the United States, and extreme weather and associated damage costs have all been trending upward (figure 2i–2n). Climate change is predicted to greatly affect marine, freshwater, and terrestrial life, from plankton and corals to fishes and forests (IPCC 2018, 2019). These issues highlight the urgent need for action.

Despite 40 years of global climate negotiations, with few exceptions, we have generally conducted business as usual and have largely failed to address this predicament (figure 1). The climate crisis has arrived and is accelerating faster than most scientists expected (figure 2, IPCC 2018). It is more severe than anticipated, threatening natural ecosystems and the fate of humanity (IPCC 2019). Especially worrisome are potential irreversible climate tipping points and nature's reinforcing feedbacks (atmospheric, marine, and terrestrial) that could lead to a catastrophic “hothouse Earth,” well beyond the control of humans (Steffen et al. 2018). These climate chain reactions could cause significant disruptions to ecosystems, society, and economies, potentially making large areas of Earth uninhabitable.

To secure a sustainable future, we must change how we live, in ways that improve the vital signs summarized by our graphs. Economic and population growth are among the most important drivers of increases in CO_2 emissions from fossil fuel combustion (Pachauri et al. 2014, Bongaarts and O’Neill 2018); therefore, we need bold and drastic transformations regarding economic and population policies. We suggest six critical and interrelated steps (in no particular order) that governments, businesses, and the rest of humanity can take to lessen the worst effects of climate change. These are important steps but are not the only actions needed or possible (Pachauri et al. 2014, IPCC 2018, 2019).

Energy

The world must quickly implement massive energy efficiency and conservation practices and must replace fossil fuels with low-carbon renewables (figure 1h) and other cleaner sources of energy if safe for people and the environment (figure S2). We should leave remaining stocks of fossil fuels in the ground (see the timelines in IPCC 2018) and should carefully pursue effective negative emissions using technology such as carbon extraction from the source and capture from the air and especially by enhancing natural systems (see “Nature” section). Wealthier countries need to support poorer nations in transitioning away from fossil fuels. We must swiftly eliminate subsidies for fossil fuels (figure 1o) and use effective and fair policies for steadily escalating carbon prices to restrain their use.

Short-lived pollutants

We need to promptly reduce the emissions of short-lived climate pollutants, including methane (figure 2b), black carbon (soot), and hydrofluorocarbons (HFCs). Doing this could slow climate feedback loops and potentially reduce the short-term warming trend by more than 50% over the next few decades while saving millions of lives and increasing crop yields due to reduced air pollution (Shindell et al. 2017). The 2016 Kigali amendment to phase down HFCs is welcomed.

Nature

We must protect and restore Earth's ecosystems. Phytoplankton, coral reefs, forests, savannas, grasslands, wetlands, peatlands, soils, mangroves, and sea grasses contribute greatly to sequestration of atmospheric CO_2. Marine and terrestrial plants, animals, and microorganisms play significant roles in carbon and nutrient cycling and storage. We need to quickly curtail habitat and biodiversity loss (figure 1f–1g), protecting the remaining primary and intact forests, especially those with high carbon stores and other forests with the capacity to rapidly sequester carbon (proforestation), while increasing reforestation and afforestation where appropriate at enormous scales. Although available land may be limiting in places, up to a third of emissions reductions needed by 2030 for the Paris agreement (less than 2°C) could be obtained with these natural climate solutions (Griscom et al. 2017).

Food

Eating mostly plant-based foods while reducing the global consumption of animal products (figure 1c–d), especially ruminant livestock (Ripple et al. 2014), can improve human health and significantly lower GHG emissions (including methane in the “Short-lived pollutants” step). Moreover, this will free up croplands for growing much-needed human plant food instead of livestock feed, while releasing some grazing land to support natural climate solutions (see “Nature” section). Cropping practices such as minimum tillage that increase soil carbon are vitally important. We need to drastically reduce the enormous amount of food waste around the world.

Economy

Excessive extraction of materials and overexploitation of ecosystems, driven by economic growth, must be quickly curtailed to maintain long-term sustainability of the biosphere. We need a carbon-free economy that explicitly addresses human dependence on the biosphere and policies that guide economic decisions accordingly. Our goals need to shift from GDP growth and the pursuit of affluence toward sustaining ecosystems and improving human well-being by prioritizing basic needs and reducing inequality.

Population

Still increasing by roughly 80 million people per year, or more than 200,000 per day (figure 1a–b), the world population must be stabilized—and, ideally, gradually reduced—within a framework that ensures social integrity. There are proven and effective policies that strengthen human rights while lowering fertility rates and lessening the impacts of population growth on GHG emissions and biodiversity loss. These policies make family-planning services available to all people, remove barriers to their access and achieve full gender equity, including primary and secondary education as a global norm for all, especially girls and young women (Bongaarts and O'Neill 2018).

Conclusions

Mitigating and adapting to climate change while honoring the diversity of humans entails major transformations in the ways our global society functions and interacts with natural ecosystems. We are encouraged by a recent surge of concern. Governmental bodies are making climate emergency declarations. Schoolchildren are striking. Ecocide lawsuits are proceeding in the courts. Grassroots citizen movements are demanding change, and many countries, states and provinces, cities, and businesses are responding.

As the Alliance of World Scientists, we stand ready to assist decision-makers in a just transition to a sustainable and equitable future. We urge widespread use of vital signs, which will better allow policymakers, the private sector, and the public to understand the magnitude of this crisis, track progress, and realign priorities for alleviating climate change. The good news is that such transformative change, with social and economic justice for all, promises far greater human well-being than does business as usual. We believe that the prospects will be greatest if decision-makers and all of humanity promptly respond to this warning and declaration of a climate emergency and act to sustain life on planet Earth, our only home.

Contributing reviewers

Franz Baumann, Ferdinando Boero, Doug Boucher, Stephen Briggs, Peter Carter, Rick Cavicchioli, Milton Cole, Eileen Crist, Dominick A. DellaSala, Paul Ehrlich, Iñaki Garcia-De-Cortazar, Daniel Gilfillan, Alison Green, Tom Green, Jillian Gregg, Paul Grogan, John

Guillebaud, John Harte, Nick Houtman, Charles Kennel, Christopher Martius, Frederico Mestre, Jennie Miller, David Pengelley, Chris Rapley, Klaus Rohde, Phil Sollins, Sabrina Speich, David Victor, Henrik Wahren, and Roger Worthington.

Funding

The Worthy Garden Club furnished partial funding for this project.

Project website

To view the Alliance of World Scientists website or to sign this article, go to https://scientistswarning.forestry.oregonstate.edu.

Supplemental material

A list of the signatories appears in supplemental file S1.

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11,258 scientist signatories from 153 countries (list in supplemental file S1)

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Author notes

William J. Ripple and Christopher Wolf contributed equally to the work.

Supplementary data

biz088_Supplemental_file_S1 - pdf file
biz088_Supplemental_file_S2 - pdf file

Chronicling Biology: Building an Oral History

The Community Ecology of Herbivore Regulation in an Agroecosystem: Lessons from Complex Systems

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Mercury contamination in and along the Penobscot River

Map of entire site (documents/site_map_for_webpage_8_8_2016.pdf) (pdf)

Mallinckrodt (Former Holtrachem Site)

The Mallinckrodt facility, formerly known as the HoltraChem Manufacturing Company, sits on 235 acres on the banks of the Penobscot River in Orrington, Maine. The plant operated under several owners from 1967 through 2000. The facility manufactured chlorine, sodium hydroxide (caustic soda), sodium hypochlorite (chlorine bleach), hydrochloric acid and chloropicrin (a pesticide).

(images/2017-8-31.png)

click to enlarge

DEP is currently overseeing cleanup activity at the site to ensure that the requirements of the 2010 BEP Order are met. It is anticipated that the cleanup activities will be complete some time in 2019. For more up to date and detailed information about the site cleanup and expected timelines, visit www.beyondholtrachem.com (http://www.beyondholtrachem.com)

For more information on the history or current status of this site, please contact Chris Swain (mailto:chris.swain@maine.gov) (207) 485-3852

Mallinckrodt data in Google Earth (../../gis/datamaps/brwm_holtrachem/brwm_holtrachem.kmz)

The Penobscot River

In 2000 the Natural Resources Defense Council (NRDC) and the Maine People's Alliance (MPA) filed suit against Holtrachem and Mallinckrodt (Mallinckrodt) in Federal district court alleging that under RCRA 42U.S.C. § 6972(a)(1)(B) Mallinckrodt caused an "imminent and substantial endangerment to health and the environment" as a result of discharging mercury into the Penobscot River. A 2002 judicial opinion and order (http://www.maine.gov/dep/spills/holtrachem/penobriver/orders/GC_07292002_1-00cv069_MePeople_v_Holtrache.pdf) were issued against Mallinckrodt.
Subsequent court orders required the following activities to take place:

- Phase I & II Mercury Study
- Phase III Engineering Study

More detailed information including all court orders, the Phase I and II Mercury Study, and progress on the Phase III Engineering Study are all available at http://www.penobscotmercurystudy.com/ (http://www.penobscotmercurystudy.com/)
Please note: The State of Maine is not a party to this lawsuit or its subsequent court ordered studies. This lawsuit is also separate from the 2010 BEP order currently undergoing implementation (see above).

For further information please contact Susanne Miller (mailto:susanne.miller@maine.gov) , (207) 941-4190

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Maine’s Dioxin Problem

What is Dioxin?

The term “dioxin” describes a group of highly toxic chemicals that are produced by several industrial processes that use or burn products containing chlorine, including incinerators and “kraft” paper mills. Dioxins are among the most potent toxic chemicals known.

What are the effects of dioxins on human health?

There is compelling scientific evidence that dioxins can cause cancer and disrupt hormonal, reproductive, and immune systems in people. The developing fetus and breastfeeding infants are particularly sensitive to the harmful effects of dioxins. Studies suggest that dioxins are also an “endocrine disrupter” – one of a number of toxic chemicals that interfere with our hormone systems by mimicking natural hormones and blocking or disrupting their normal action.

Human Health Hazards Linked to Dioxins

- Cancer
- Birth and Developmental Defects
- Learning Disabilities
- Increased Risk of Diabetes
- Tumor Promotion
- Decreased Fertility
- Reduced Sperm Counts
- Endometriosis
- Suppressed Immune Systems

The U.S. Environmental Protection Agency has found increasing evidence that levels of dioxins in our bodies are at or near the levels at which many, if not all, of these effects may occur. Therefore, the levels at which many, if not all, of these effects may occur. Therefore, any additional dioxins in the environment are a significant concern and must be eliminated wherever possible.

Are certain people at greater risk?

While dioxins are a general public health hazard, they pose even greater dangers to certain groups:

- Developing fetuses and infants
- Developing fetuses and nursing infants have a higher risk because dioxins are passed to them in utero and through their mother's breast milk at the most sensitive stages of their development. Dioxins accumulate to greater amounts in fatty substances, such as breast milk, than in vegetables and fruits.

- Fish consumers
- Certain populations that consume large amounts of fish, such as recreational and avid anglers, subsistence fish consumers and Native Americans are at an increased risk due to their larger consumption

of fish contaminated with dioxins.

Are dioxins a hazard for wildlife?

Yes. Animals on the top of the food chain, such as birds and mammals that eat contaminated fish, face the greatest risks. Last summer, the U.S. Fish and Wildlife Service (USF&W) linked dioxin discharges from the bleach kraft mill in Lincoln with the reproductive failure among Penobscot River bald eagles. Reproduction among eagles nesting within roughly two miles of the Lincoln mill has been as low as 40% below the statewide average. USF&W also examined total dioxin contamination of bald eagle blood and eggs, and found levels in unhatched eggs near the Penobscot River exceeded "safe" levels by up to 85 times.

How does dioxin get into people and wildlife?

Dioxin get into the bodies of people and wildlife primarily through food.

Air
Dioxins generated by burning of certain plastics and other chlorine-containing materials from incinerators and other sources travel through the air and can fall out on our farmland and food crops. Cows and other animals eat the grasses and plants on which the dioxins have fallen, which contaminates their milk and meat.

Water
Dioxins enter the water food chain – aquatic insects, fish, and shellfish – indirectly from "fall-out" from air and directly from the wastewater discharge pollution from certain industries. In Maine, the discharge of dioxins by "bleach kraft" paper mills contaminates fish in papermaking rivers and the tomalley of lobsters in the bays of these rivers to levels that make them unsafe to eat.

Although there are a number of sources of dioxins in our environment, bleach kraft paper mills are the most significant source of dioxin contamination in Maine's waters. Therefore, elimination of dioxin discharges from these mills is not only a priority but also essential to allow people to enjoy the full economic, recreational, and

environmental benefits of our largest waterbodies.

What is the extent of Maine's paper mill dioxin problem?

In 1985, more than 30 years ago, dioxins were first found in fish below Maine's seven "bleach kraft" paper mills that use chlorine compounds to bleach their paper. These seven mills discharge more than 100 million gallons of wastewater a day to the Penobscot, Kennebec, Androscoggin, Presumpscot and St. Croix Rivers. Although the levels of dioxins in mill wastewaters are sometimes undetectable by conventional methods, they are nonetheless enough to contaminate the fish and shellfish because fish act like sponges for dioxins, accumulating them at 25,000-50,000 times the concentrations present in their environment.

Today, women of childbearing age are still warned strictly limit their intake of fish caught from 250 miles of Maine's rivers below paper mills and NO tomalley from lobsters caught along the entire coast. And the general public is advised to severely restrict their consumption of dioxin-contaminated fish and tomalley.

Can Maine's paper mill dioxin problem be solved?
Yes! Papermaking technologies are available and in use today in the United States and worldwide that would eliminate dioxin discharges by using non-chlorine bleaching processes. These processes pave the way to "closed loop" mills that will not discharge any bleaching wastewaters, thereby drastically reducing the discharge of other toxics, turbidity, color, odor, foam, and oxygen-depleting materials. Totally chlorine-free (TCF) papermaking process produces products that are of a brightness and quality comparable to products bleached with chlorine.

Didn't Maine paper mills already commit to eliminate their dioxin discharges?
On April 8, 1996, Governor Angus King announced that the state's seven bleach kraft pulp and paper mills had signed on to the goal of eliminating the discharge of dioxins. Since then, the paper industry has consistently argued that their pledge to "eliminate" dioxins does not mean that their contribution of dioxins to Maine's waters will be zero.

Will conversion to 100% chlorine dioxide (ECF) technologies eliminate the dioxin problem?
No. Maine mills are claiming that a switch from elemental chlorine to chlorine dioxide will "solve" the dioxin problem. However, the chemistry of the ECF process clearly shows that the main bleaching agent, chlorine dioxide, is still capable of producing dioxins. Research by both the pulp industry and the EPA demonstrates that chlorine dioxide bleaching does not ensure total elimination of dioxins. Totally chlorine free bleaching processes will do the job.

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Aquacultural Engineering
Volume 71, March 2016, Pages 1-12

Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (*Salmo salar*): Land-based closed containment system in freshwater and open net pen in seawater

Yajie Liu [a], Trond W. Rosten [a], Kristian Henriksen [a], Erik Skontorp Hognes [a], Steve Summerfelt [b], Brian Vinci [b]

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https://doi.org/10.1016/j.aquaeng.2016.01.001

Highlights

- Cost of production for land-based closed containment water recirculating salmon farming systems is approximately the same as the cost of production for traditional open net pen salmon farming systems at this scale, when excluding interest and depreciation.
- Return on investment for traditional open net pen salmon farming at this scale is twice that of land-based closed containment water recirculating salmon farming, when land-based produced salmon are sold at a price premium.
- Carbon footprint of salmon produced in land-based closed containment water recirculating aquaculture systems delivered to market in the US is less than half of that for salmon produced in traditional open net pen systems in Norway that is

delivered to the US by air freight.

Abstract

Ocean net pen production of Atlantic salmon is approaching 2 million metric tons (MT) annually and has proven to be cost- and energy-efficient. Recently, with technology improvements, freshwater aquaculture of Atlantic salmon from eggs to harvestable size of 4–5 kg in land-based closed containment (LBCC) water recirculating aquaculture systems (RAS) has been demonstrated as a viable production technology. Land-based, closed containment water recirculating aquaculture systems technology offers the ability to fully control the rearing environment and provides flexibility in locating a production facility close to the market and on sites where cost of land and power are competitive. This flexibility offers distinct advantages over Atlantic salmon produced in open net pen systems, which is dependent on access to suitable coastal waters and a relatively long transport distance to supply the US market. Consequently, in this paper we present an analysis of the investment needed, the production cost, the profitability and the carbon footprint of producing 3300 MT of head-on gutted (HOG) Atlantic salmon from eggs to US market (wholesale) using two different production systems—LBCC-RAS technology and open net pen (ONP) technology using enterprise budget analysis and carbon footprint with the LCA method. In our analysis we compare the traditional open net pen production system in Norway and a model freshwater LBCC-RAS facility in the US. The model ONP is small compared to the most ONP systems in Norway, but the LBCC-RAS is large compared to any existing LBCC-RAS for Atlantic salmon. The results need to be interpreted with this in mind. Results of the financial analysis indicate that the total production costs for two systems are relatively similar, with LBCC-RAS only 10% higher than the ONP system on a head-on gutted basis (5.60 US$/kg versus 5.08 US$/kg, respectively). Without interest and depreciation, the two production systems have an almost equal operating cost (4.30 US$/kg for ONP versus 4.37 US$/kg for LBCC-RAS). Capital costs of the two systems are not similar for the same 3300 MT of head-on gutted salmon. The capital cost of the LBCC-RAS model system is approximately 54,000,000 US$ and the capital cost of the ONP system is approximately 30,000,000 US$, a difference of 80%. However, the LBCC-RAS model system selling salmon at a 30% price premium is comparatively as profitable as the ONP model system (profit margin of 18% versus 24%, respectively), even though its 15-year net present value is negative and its return on investment is lower than ONP system (9% versus 18%, respectively). The results of the carbon footprint analysis confirmed that production of feed is the dominating climate aspect for both production methods, but also showed that energy source and transport methods are important. It was shown that fresh salmon produced in LBCC-RAS systems close to a US market that use an average US electricity mix have a much lower carbon footprint than fresh salmon produced in Norway in ONP systems shipped to the same market by airfreight, 7.41 versus 15.22 kg CO_2eq/kg salmon HOG, respectively. When comparing the carbon footprint of production-only, the LBCC-RAS-produced salmon has a carbon footprint that is double that of the ONP-produced salmon, 7.01 versus 3.39 kg CO_2eq/kg salmon live-weight, respectively.

Previous Next

Abbreviations

CO_2, carbon dioxide; CO_2eq, carbon dioxide equivalents; EBIT, earnings before interest and taxes; FCR, feed conversion ratio; HOG, head-on gutted; IRR, internal rate of return; LBCC, land-based closed containment; LCA, life cycle assessment; NPV, net present value; ONP, open net pen; RAS, water recirculating aquaculture system; ROR, required rate of return; S0, 1/2-year old smolt; S1, 1-year old smolt; TGC, thermal growth coefficent; tkm, ton × kilometers; WFE, whole fish equivalent

Keywords

Salmon; Economics; Carbon footprint; Recirculating aquaculture systems; Net pen aquaculture

1. Introduction

Farmed Atlantic salmon (*Salmo salar*) is sold globally in various forms and markets. The US is an important market for farmed Atlantic salmon, estimated to be more than 350,000 MT in 2014 (Marine Harvest ASA, 2014), and has shown steady growth since the late 1980s (USDA ERS, 2015). In 2014 the US market was primarily supplied by salmon produced in Chile (126,820 MT), Canada (47,454 MT) and Norway (26,208 MT) (USDA ERS, 2015). The US production of Atlantic salmon (18,000 MT [2012]) is relatively small in comparison to the amount consumed in the US (NOAA, 2013). Limited access to suitable coastal water areas and rigorous regulations in the US (NOAA, 2013) curtail the opportunity to produce Atlantic salmon in open net pen systems, the industry's preferred and established technology for the on-growing phase of salmon farming in Norway, Canada, and Chile. An alternative technology to open net pen systems for salmon production is land-based, closed containment (LBCC) water recirculating aquaculture systems (RAS) technology (LBCC-RAS). LBCC-RAS technology had been used for production of a limited number of species, like eel, beginning in the 1980s (Heinsbroek and Kamstra, 1990). Developments in LBCC-RAS technology since the 1980s have led to the ability to culture a wide variety of fish species including cold-water salmonids (e.g., Arctic char, rainbow trout, and Atlantic salmon to smolt size) (Summerfelt et al., 2004, Bergheim et al., 2009, Dalsgaard et al., 2013, Kolarevic et al., 2014). Most recently, freshwater aquaculture of Atlantic salmon from eggs to harvestable size of 4–5 kg in a LBCC-RAS facility has been demonstrated as a viable production technology (Summerfelt et al., 2013). Land-based, closed containment water recirculating aquaculture systems technology offers the ability to fully control the rearing environment, exclude parasites and obligate pathogens, and provide flexibility in locating a production facility close to the market and on sites where the cost of land and power are competitive. This control and flexibility offers advantages over Atlantic salmon produced in open net pen systems (ONP), which is negatively impacted by sea lice and dependent on access to suitable coastal waters and a relatively long transport distance to supply the US market. Interest in production of Atlantic salmon using LBCC-RAS technology has led to construction of a number of commercial LBCC-RAS farms (Summerfelt and Christianson, 2014). Although their current supply to the US Atlantic salmon market is just beginning, plans for a number of US-based LBCC-RAS farms for Atlantic salmon have been reported in the trade press. It is therefore of particular interest to compare such different approaches for production of the same seafood to the same market.

The aquaculture production of Atlantic salmon has been estimated to exceed 1,900,000 MT in 2014; global production has increased 428% since 1994 (Marine Harvest ASA, 2014). Open net pen farming in the ocean has been the major technology for the on-growing portion of the production cycle. The technology for ONP farming with large net pen volumes, exceeding 60,000 m^3 in one pen, has proven to be cost- and energy-efficient (Ziegler et al., 2013), leading to commercial success and founding a large global business. However, the growth of the industry has not been without environmental conflicts, especially towards wild Atlantic salmon and Sea Trout (*Salmo Trutta*) where negative impacts on wild populations due to escapees have been suggested (Naylor et al., 2005). Alternative methods for growing salmon in closed containment systems for the whole production cycle have been attempted since the beginning of the 1990s, with no commercial success, either land-based or in floating bags (Liu and Sumaila, 2007). Recently, a new interest for producing Atlantic salmon in closed containment systems has arisen (Summerfelt and Christiansen, 2014). A variety of closed containment systems are being suggested (Rosten et al., 2013), but LBCC-RAS technology seems to have found a particular global interest, with LBCC-RAS farms being planned, built and put into production in Europe, North America, China, and Norway (Summerfelt and Christianson, 2014).

Norwegian-farmed Atlantic salmon is sold as fresh, frozen, filleted, smoked and cured product. Fresh whole salmon is the primary product and accounts for approximately three quarters of the total value of exports (Statistics Norway, 2015). Fresh salmon has the highest export price. Denmark, France and Japan are the biggest export countries, making up of one-third of total Norwegian salmon exports (Statistics Norway, 2015). Norwegian salmon made up approximately 8% of the US salmon market in 2014 (USDA ERS, 2015).

The production cost of Atlantic salmon farming in Norway has been charted annually since 1986. From 2008–2012 the production cost has varied between 21.04 and 22.98 NOK per kilo WFE (Directorate of Fisheries, 2014). It has recently increased due to the high cost of sea lice treatment (Liu and Bjelland, 2014). The relatively low investment cost for open net pen production sites compared to the investment cost for proposed LBCC-RAS farms has historically favored open net pen production. Norway has the lowest production cost per kilo of salmon compared to Canada, Great Britain and Chile due to economies of scale (Marine Harvest ASA, 2014).

The economic viability of intensive LBCC-RAS has been evaluated (Muir, 1981, Gempesaw et al., 1993, Losordo and Westerman, 1994, De Ionno et al., 2006, Timmons and Ebeling, 2010), though these studies have largely focused on specific system designs for a single level of output, and have not identified the capital and operating cost savings which may exist as water treatment processes are optimized and as technologies are scaled appropriately. De Ionno et al. (2006) reported that increasing LBCC-RAS facility capacity, increasing sale price, and decreasing facility capital cost were the most important factors affecting economic viability. These savings can be significant and can contribute to the success or failure of an aquaculture business employing this type of technology.

Environmental assessments of ONP salmon production and distribution have identified feed production as a dominating climate aspect of salmon aquaculture production, closely followed by transportation of the salmon to retailer (Ziegler et al., 2013). A shift into more closed systems includes changes such as: replacing ocean current energy with electricity; more alternative materials in the production facilities; controlling interactions with the surrounding environment; collecting and utilizing nutrients in the biosolids produced by the fish; and placing the production close to the market or independent of oceans. There are several potential environmental tradeoffs in this shift. Feed efficiency is especially important, but also the balance between an increase in energy use in the growout phase versus a reduction in transport distance.

This paper aims to investigate whether domestic US production of Atlantic salmon in a LBCC-RAS farm is competitive when compared to a similarly sized ONP system overseas, using investor relevant keys like return of investment, production cost, market price, and carbon footprint. In this paper we present an analysis of the investment needed, the production cost, the profitability and carbon footprint of Atlantic salmon farming from eggs to US market (wholesale) using two different production systems—LBCC-RAS technology and ONP technology using enterprise budget analysis and calculating the carbon footprint with the LCA method. In our analysis we compare the traditional ONP production system in Norway and a model freshwater LBCC-RAS facility in the US. We model the necessary product prices to obtain profitability with LBCC-RAS, and compare the profitability to a similarly-scaled ONP system and provide a sensitivity analysis for the most important impact factors. In addition, we incorporate a comparison of the carbon footprint of the two systems using an overview of the consumed materials, feed, energy, transport and energy source.

2. Materials and methods

The feasibility of two commercial-scale farming systems for Atlantic salmon, a LBCC-RAS farm in the US and an ONP farm in Norway, is evaluated through a concept-level design and capital and operational cost analysis for 3300 MT head-on gutted (HOG) production systems. The economic performance is evaluated in detail using an enterprise budget analysis, while the environmental performance is evaluated in detail using attributional life cycle analysis. The ONP system evaluated here was scaled down from the more common large-sized facilities in Norway to fit to the comparable LBCC-RAS system.

2.1. Open net pen system model

Technical design of the ONP model farm is based upon a biological production plan (i.e., bioplan), data and operational practices obtained from Norwegian salmon farmers. Data and specifications of components are gathered from aquaculture industry suppliers in Norway. The ONP model farm includes concept-level design of floating rings, nets, mooring systems, boats, feed barge systems, camera systems, feed distribution systems and remote power systems. The bioplan, which predicted fish growth and size from smolt to harvestable size, results in two active growout sites, using limitations for fish density of 25 kg/m^3 and maximum allowable biomass of 200,000 fish per unit.

The bioplan for the 3300 MT ONP model farm is based upon average ambient sea temperatures from mid-Norway, stocking with two smolt cohorts per year. The ONP system is assumed to stock a cohort of S1 smolts, average size 100 g, on April 1 and a cohort of S0 smolts, average size 75 g, on August 1. Fish growth and associated feed demand are determined by using specific growth rates (SGR) and feed conversion ratios (FCR) given in feed supplier feeding tables for various fish sizes. Fish growth estimates are reduced by 12% to compensate for handling and treatment of the fish during the production cycle. The overall FCR was set to 1.27 to obtain the average FCR from the last 10 years in Norway (Directorate of Fisheries, 2014). Mortalities for smolt to harvest are set to obtain 16% per generation mortality to comply with a dataset available from mid-Norway (Mattilsynet, 2011).

2.2. Land-based closed containment recirculating aquaculture system model

Technical design of the LBCC-RAS model farm is based on data developed by The Conservation Fund's Freshwater Institute growout trials of Atlantic salmon, some of which has been reported (Summerfelt et al., 2013). This includes concept-level water recirculation system designs for each fish grouping developed in the bioplan. Each water recirculation system design includes multiple recirculation modules to allow for staging and movement of fish throughout the facility. Concept designs for incubation, fry, smolt, pre-growout, and growout rearing areas, as well as a final purging system, are completed using steady-state mass balance analyses. Design water quality criteria used in the mass balance analyses are based on The Conservation Fund's Freshwater Institute growout trials. Thermal growth coefficients (TGC) are used to predict fish growth for the bioplan for the 3300 MT LBCC-RAS model farm. Thermal growth coefficient values are based on data collected in growout trial data from The Conservation Fund's Freshwater Institute. Additionally FCR, mortality, head-on gutted yield, and other performance indicators, which are used to develop a biological plan are taken from past growout trials (Summerfelt et al., 2013). The FCR (kg/kg) and TGC (1000 $g^{1/3}$/ °C days) are set to vary according to these growout trial data at different life stages; FCR: Fry, 0.75; smolt, 0.90; pre-growout, 1.0; growout 1.1; and TGC: Fry, 1.25; smolt, 1.40; pre-growout, 2.00; growout, 2.30. The overall average FCR based on the individual values is 1.09. A maximum biomass density of 80 kg/m^3 is used for the biological plan of the LBCC-RAS model farm.

The steady-state feed requirement for the LBCC-RAS model farm is 11,815 kg/day. Water supply required for the entire 3300 MT LBCC-RAS model farm is based on allowing no more than 75 mg/L nitrate-nitrogen at maximum loading in each recirculation system, assuming no passive denitrification within the systems. The amount of water supply needed to maintain this nitrate-nitrogen level in the recirculation systems is calculated to be 7.7 m^3/min, including 1.1 m^3/min for finishing/purging the harvested salmon before slaughter. The resulting water required per feed fed is 803 L/kg feed for the systems that have feeding fish, i.e., all RAS except the purge system. The power requirement for the model farm is 2458 kW, comprised primarily of power required for the water recirculation pumps (2079 kW); the total power required per unit of live weight salmon produced is 5.4 kWh/kg (4.6 kWh/kg for pumping only).

Concept-level design characteristics for each rearing area in both production systems are summarized in Table 1; the inputs required for the two systems are summarized in Table 2; illustrative renderings are shown in Fig. 1. The technical design for each model farm allowed the progression of capital and operating costs for comparison of the two production systems. Cost data used in the development of the concept-level estimates provided here is a combination of industry standard published cost data (Directorate of Fisheries, 2014, Marine Harvest ASA, 2014, RS Means, 2010) and project specific vendor quotations obtained in 2010–2011.

Table 1. Concept-level design characteristics for each rearing system in a 3,300 MT HOG Atlantic salmon land-based closed containment farm (LBCC-RAS) and a 3300 MT HOG open net pen farm (ONP).

Fish Rearing Area	Modules	Units per module	Unit diameter by depth (m × m)	Total Rearing Volume (m^3)	Module Flow Rate (m^3/min)	Total Flow Rate (m^3/min)	Total Makeup Flow Rate (m^3/min)	Maximum Module Feed Rate (kg/day)
LBCC-RAS—fry	1	18	2 by 1.0	57	1.5	1.5	0.08	22.9
LBCC-RAS—smolt	2	4	9 by 2.0	1,018	11.4	22.7	0.19	248.0
LBCC-RAS—pre-growout	3	4	10 by 3.0	2,827	22	66	0.57	549.5
LBCC-RAS—growout	8	5	16 by 4.25	34,180	95	757	5.75	2063.5
LBCC-RAS—final purging	1	2	16 by 4.25	1,709	38	38	1.1	–

ONP—System[a]	2	6	157 by 40	587,000	–[b]	–[b]	–[b]	–

a

The ONP system is a growout system from smolts to harvestable size. Smolts and harvest/packing of the salmon are modeled to be provided by subcontractors.

b

The water exchange in the ONP system is dependent upon water current and conditions of the nets (mesh size and fouling).

Table 2. Input factors and assumptions used in the financial analysis of two production models (LBCC-RAS system and ONP system) for a 3300 MT HOG Atlantic salmon farm.

Input factors	ONP system	LBCC-RAS system
Feed (US$/kg)	1.48	1.50
Farm labor (# person)	6	10
Farm labor (US$/person/year)	125,000	45,000
Processing labor (# person)	–	6
Processing labor (US$/person/year)	0.38/kg[a]	37,500
Livestock (US$/smolt or US$/egg) smolt)	1.53	0.30
Electric (US$/kWh)	0.17	0.05
Oxygen (US$/kg)	–	0.20
Wellboat cost (US$/kg[a])	0.92	–
Bicarbonate (US$/kg)	–	0.35
Management (US$/year)	–	500,000
Other operating cost	0.43 US$/kg fish	–
Insurance (US$/kg[a])	0.02	0.02[b]
Tax level	28%	28%

Equity ratio	30%	40%
Interest loans	3.0%	6.0%

a

Whole fish weight.

b

First year is 0.04 US$/kg.

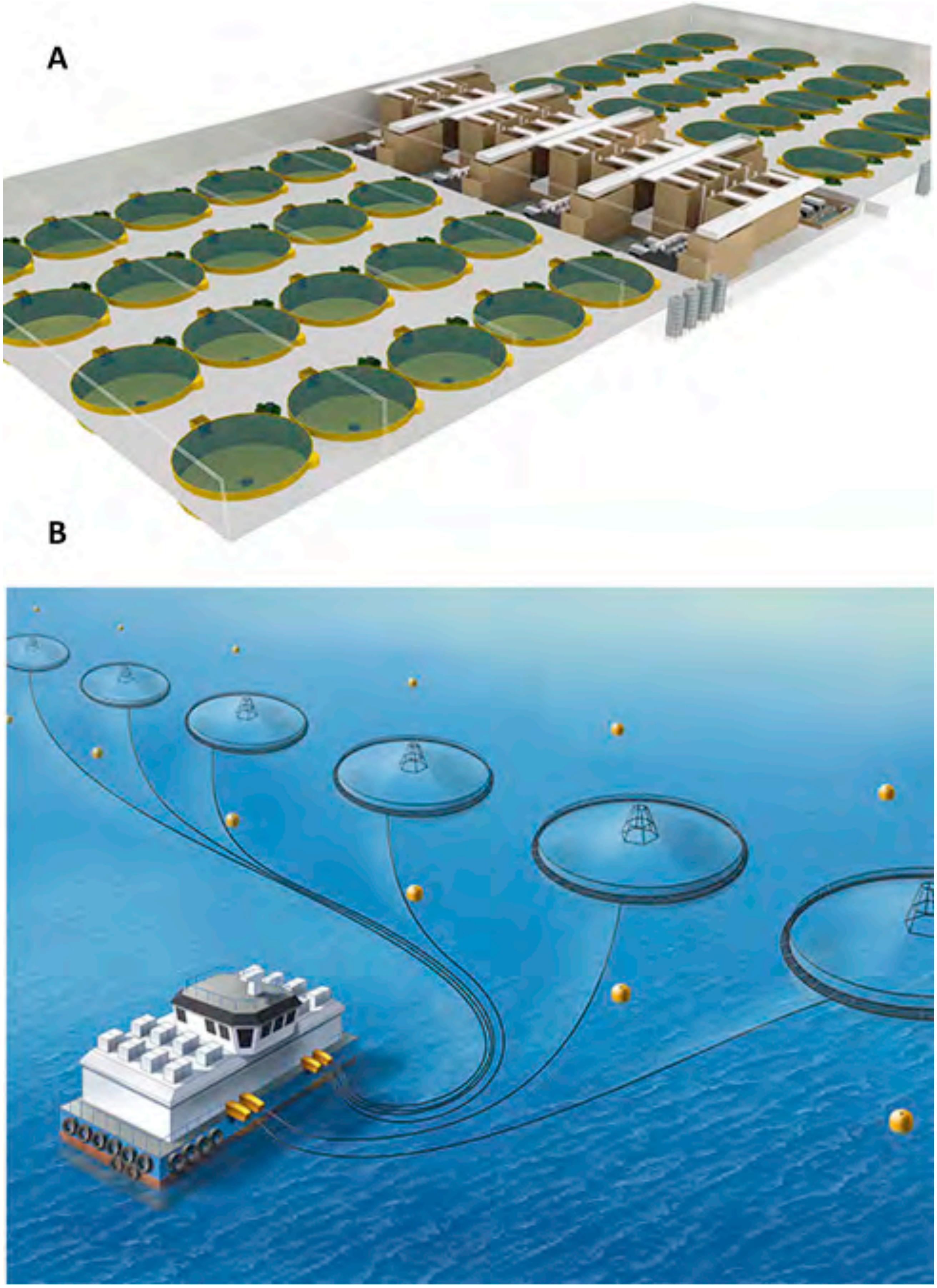

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Fig. 1. Concept-level renderings of the growout rearing area in a 3300 MT HOG Atlantic salmon LBCC-RAS farm (A) and ONP farm (B).

2.3. Economics

Salmon aquaculture is a commercial operation whose purpose to be profitable. The prerequisite for a business to be sustainable is to be profitable in both the short- and long-term and over the investment horizon. The financial performance of these two aquaculture production systems is investigated using an enterprise budget analysis; this allows an assessment of the feasibility and profitability of the two systems. Enterprise budgets, also called production budgets, provide a framework within which all the components of costs and revenues associated with the production of farm products are itemized. The budget is constructed on a production basis, and the assessment is built upon a cash flow analysis. The profitability is calculated based on financial statements such as income statement and balance sheets.

There are a number of well-developed analytical techniques for analyzing profitability (Liu and Sumaila, 2007, Kumar and Engle, 2011). Net present value (NPV) is a commonly used parameter to provide an objective decision of an investment and project. Net present value takes into account the time value of money, and is the difference between the present value of total costs and total revenue over an operational horizon. Positive NPV indicates that an investment is worthwhile. In addition to NPV, other indicators are also used as assessment criteria; these include gross margin, return on investment (ROI), internal rate of return (IRR), payback period, and break-even production and price. Gross margin is expressed as revenue minus variable costs; net income or profit is revenue minus all costs. Return on investment is the rate of return on the initial capital investment and is estimated by profit before taxes divided by the capital investment. Internal rate of return is the discount rate at which net present value of profit is set equal to zero. Breakeven production/price represents the expected production level and market price at which total sale revenue covers total production costs. Breakeven analysis can inform the conditions necessary for the business to become profitable or to remain in business.

2.3.1. Enterprise budget

The enterprise budget is estimated based on a total production of 4000 MT wet weight, which is equivalent to 3300 MT of head-on gutted weight. Head-on gutted yield is estimated to be 88% after a 5% loss of weight during final purging for both the ONP and the LBCC-RAS production systems. The estimates of total investment cost and operating cost of each cost item are based on the production system design models and their associated bioplans. The costs include two parts: capital cost and operating cost.

2.3.2. Capital cost—ONP model

Capital costs incur at the beginning of the operation, and most of these costs are one-time costs. The capital cost for the 3300 MT ONP model farm is based on information gathered from the Norwegian aquaculture industry, and is thereby considered representative for an ONP farm constructed and operated according to Norwegian laws and regulations (Norway, 2008). The ONP model farm includes 3 licenses and 12 pens, and their associated physical components consisting of floating rings, nets, mooring systems, boats, feed barge systems, camera systems, feed distribution systems and remote power systems. The cost of each item is estimated based on current market price suppliers' command. Compared to estimates reported by Marine Harvest (Marine Harvest ASA, 2014), the capital cost for the ONP model farm is considered representative for a two site ONP farm. We assume that the lifespan of nets and feeding system is 5 years, floating rings is 8 years, camera and power systems is 10 years, and the remainder of the equipment is 20 years. These lifespans are used for calculation of depreciation and replacement cost.

The cost for an ONP farming license in Norway is included in the capital cost estimate for the ONP model farm. The current cost of ONP farming licenses is much higher when compared to license costs of the 1990s (Färe et al., 2005); cost for a license in the current open market is approximately 55 million Norwegian kroners, which is equivalent to 8 million US dollars[1] (Aardal, 2014). The total capital cost of the ONP model farm including licenses at current prices is estimated to be 29.7 million US dollars for a total production of 3300 MT head-on gutted salmon (Table 3).

Table 3. Capital expenses for a 3,300 MT HOG LBCC-RAS and ONP Atlantic salmon farm.

ONP system cost components	Cost (US$)
Licences	23,571,429
Floating rings	1,834,286
Nets	857,143
Moorings	342,857
Boats	1,285,714
Feed barges	1,371,429
Camera systems	214,286
Feed distributors	34,114

Power systems	188,571
Total	29,699,829

LBCC-RAS system cost components	**Cost (US$)**
RAS Systems	26,640,557
Effluent treatment	3,487,500
Water supply	675,000
Processing	2,112,030
Building	9,426,413
Engineering	5,080,980
Construction management	1,058,538
Bond	254,049
Contingency (10%)	4,848,102
Total	53,583,169

2.3.3. Capital cost—LBCC-RAS model

The capital cost of the LBCC-RAS model farm includes all RAS systems, water supply, effluent treatment systems, buildings, engineering services, construction management services, a primary processing facility and general contractor bonding requirements. These components are itemized based on material, equipment, labor and subcontractor services, upon which the costs are estimated. Ten percent contingency is applied to capture uncertainty associated with this level of cost estimation. We assume that the lifespan of materials and equipment is 10 years and the lifespan for buildings and tanks is 20 years. These lifespans are used for calculation of depreciation and replacement cost. The cost of bonding is included as insurance may be required by owners that builders must have for large projects and is typically passed back to the owner. There are currently no comparable license costs for a LBCC-RAS farm in the US. The total capital cost including contingency of the LBCC-RAS model farm is estimated to be 53.6 million US dollars for a total production of 3300 MT head-on gutted salmon (Table 3).

2.3.4. Operating cost—ONP model

The operating cost for the ONP model farm is estimated based on data collected by the

Norwegian Directorate of Fisheries (2014) and also Marine Harvest ASA (2014), and are the average costs of the last five years, 2009–2013. Since there are uncertainties associated with these items and the overall cost has increased gradually in the last several years, we applied a 2% increase for the first five year's estimates, and a 3% increase for the remaining year's estimate to account for uncertainties for each cost item. In other words, it is assumed that each cost item will increase 2% for the first five years and 3% for the rest. The operating costs are the average estimates over 15 years. The breakdown of costs is presented in Table 4.

Table 4. Operating expenses for a 3,300 MT HOG LBCC-RAS and ONP Atlantic salmon farm.

Cost item	ONP system		LBCC-RAS system	
	Cost (US$)	Cost (NOK)	Cost (US$)	Cost (NOK)
Feed	2.05	14.34	1.90	13.33
Smolt	0.47	3.30	–	–
Egg	–	–	0.12	0.86
Labor	0.31	2.15	0.52	3.65
Well boat	0.18	1.23	–	–
Health	0.03	0.18	–	–
Electricity	–	–	0.33	2.32
Oxygen	–	–	0.15	1.07
Water treatment	–	–	0.09	0.62
Insurance	0.02	0.16	0.18	1.27
Primary processing	0.43	3.03	0.12	0.83
Transportation	0.25	1.58	–	–
Sales & marketing	0.09	0.60	–	–
Maintenance	0.14	0.99	0.47	3.26
Interest	0.60	4.21	0.65	4.52
Depreciations	0.18	1.28	0.58	4.09

Others	0.33	2.32	0.49	3.45
Total	5.08	35.37	5.60	39.27

2.3.5. Operating cost—LBCC-RAS model

The operating cost for the LBCC-RAS model farm is estimated based on the bioplan designed for an annual production of 3300 MT after primary processing. Cost items include feed, oxygen, bicarbonate, electricity, eggs, labor, stock insurance, interest and depreciation. Feed amount and thus cost, is calculated based on the feed required for growth multiplied by feed conversion ratio at different life stages. The amounts, and thus costs, of oxygen and bicarbonate are dependent on the feed required. Oxygen required is estimated to be 0.60 kg oxygen per kg feed, which includes an oxygen transfer efficiency of 75%. Bicarbonate required is estimated to be 0.20 kg bicarbonate per kg feed, which includes a base chemical availability of 75%. The cost of the electricity is determined by the RAS design, which identified all pumps and motors required for operation. The number, and thus cost, of eggs required is estimated by the assumed mortality rates at different life stages. Labor costs for the LBCC-RAS model farm include management (biological and maintenance), fish culture technicians, laboratory technicians, maintenance mechanics, and primary processing staff. It is assumed that insurance cost for the first year of operation is 4% of standing biomass, and then that declines to 2% of standing biomass in the following years. The ratio between interest and cash for capital cost and first year operating cost was 60/40, and an interest rate of 6% was used. Depreciation of each item was estimated using a straight line approach, meaning depreciation cost was charged evenly throughout the useful life of each capital item. Maintenance cost was estimated to be 10% of the total variable cost. To capture unknown costs, a contingency cost is also included which was assumed to be 10% of the total cost. The increase with 2% for the first 5 years and 3% for the rest are also applied for each cost item due to unforeseen future changes, same as the ONP system.

2.3.6. Sales and income

It takes approximately one year for salmon to grow to market size, therefore, there is no harvest for Year 1 and a proportionally smaller harvest for Year 2. In Year 3 and onwards, a constant harvest of 3300 MT is assumed for the ONP and LBCC-RAS systems. The price used here is the export market price of fresh gutted salmon in the US market, which is approximately 5.97 US$/kg or 41.8 NOK/kg averaged weekly price for the year 2014 (Statistics Norway, 2015). It is also assumed that the price for salmon in the future would increase in a similar way as the cost items, i.e., increased by 2% for the first five years and 3% for the rest. However, preliminary sales of Atlantic salmon produced by a LBCC-RAS farm have commanded a significant price premium (Guy Dean, Albion Fisheries (Vancouver, BC), personal communication, September 4, 2014), here a 30% price premium is assumed which is approximately 7.76 US$/kg. The total sales revenue is calculated based on export price and annual harvest.

2.4. Carbon footprint

The carbon footprint is the sum of potential climate impacts that a product causes from a defined part of its life cycle. The carbon footprint was calculated using life cycle assessment (LCA) methodology that is a tool for environmental assessment (ISO, 2006a, ISO, 2006b). It assesses the inputs of energy and material to the system and from that calculates potential environmental impacts caused by the resource use and outputs to nature in the form of emissions, waste and products. This LCA includes both direct emissions from the feed and salmon production and indirect emissions caused by production and distribution of the commodities and infrastructure that underpin the salmon life cycle.

The potential climate impact, the global warming potential, is calculated by characterizing all emission and impacts into CO_2 equivalents (CO_2eq) according to their radiative properties based on IPCC guidelines (IPCC, 2007).

The goal of the carbon footprint was to compare the potential climate impacts from different ways of providing a retailer in Seattle, WA (US) with Atlantic salmon:

1a) Salmon from a LBCC-RAS system in the US running on electricity generated from a source that uses a typical mix of coal, gas, nuclear, wind and hydropower. Salmon is assumed to be transported fresh to the retailer 250 km by truck.

1b) Salmon from a LBCC-RAS System in the US running on electricity generated from a source that uses 90% hydropower and 10% coal. Salmon is assumed to be transported fresh to the retailer 250 km by truck.

2a) Salmon from a Norwegian ONP system. Salmon is assumed to be transported fresh, first with truck in Norway to Oslo, 520 km, and then with airfreight to Seattle, 7328 km.

2b) Salmon from a Norwegian ONP system. Salmon is assumed to be transported frozen, first with truck in Norway to Oslo, 520 km, and then with ship from Ålesund, Norway, to Seattle through the Panama Canal, 16,473 km.

The functional unit for the assessment, the basis for comparison, was 1 kg of gutted salmon with head on, at the retailer gate. For each case, the assessment included the complete production system, from production of feed ingredients, smolt production and construction of facilities, equipment and transports.

It was assumed that the salmon was gutted close to the production facility and that all byproducts, such as guts, skin and trimmings were utilized mainly for feed production. Mass allocation was applied meaning that the carbon footprint up to slaughter was allocated between the head-on-and-gutted salmon and the byproducts based on their mass. Thus, per unit of mass live salmon and head on and gutted salmon have the same carbon footprint. Important cut offs, processes that are not included in the assessment include: slaughtering process, treatment of the biosolids from the LBCC-RAS system, and transport infrastructure.

2.4.1. Carbon footprint data

Table 5 presents important activity data for the carbon footprint of the two systems. Data for the LBCC-RAS system was derived from the concept-level design. Data for the Norwegian ONP system is gathered from industry actors and industry statistics (Winther et al., 2009, Hognes et al., 2011, Hognes et al., 2014). Data on the climate impacts from capital and operational inputs were modeled with data from the LCA inventory database Ecoinvent v3.1 (2013). Since many of the operations performed at the ONP farm are performed by sub-contractors, and the extent of the activities, e.g., cleaning and priming of nets, are dependent of exact location, these data are based on the assumption of a representative production model.

Table 5. Inventory data for carbon footprint for two production models (LBCC-RAS system and ONP system) for a 3300 MT HOG Atlantic salmon farm. All numbers are per ton of salmon produced or transported.

	Unit	LBCC-RAS System	ONP system
Feed, economic FCR	ton	1.09	1.27
Concrete	kg	82.5	–
Steel, reinforcing	kg	14.40	0.63
Steel, chromium 18/8 steel	kg	–	0.70
Glass fiber	kg	8.93	–
Nylon	kg	–	1.01
Polypropylene	kg	–	1.79

Polyethylene	kg	–	0.28
Fuel	l	–	10.50
Electricity	kWh	5460	–
Oxygen (liquid)	kg	656	–
Lime (calcium carbonate)	kg	219	–
EPS for transport packaging	kg	25	25
Ice	kg	300	300

Both the LBCC-RAS and ONP systems are modeled using the same feed. Based on LCAs of the average Norwegian salmon feed in 2012, the feed is associated with a carbon footprint of 2.5 kg CO_2eq/kg feed at the feed factory gate. This is a feed with the following composition: 12% marine oil; 19% marine protein; 19% oil from crops; 39% protein from crops; 8% starch from crops and 3% micro ingredients (minerals, vitamins, pigments and other). This carbon footprint reflects a feed where 50% of the soy in the feed is equal to the average Brazilian soy, as modeled by the Agrifootprint database (Centre for Design and Society of the RMIT University, 2014), and the remaining coming from old farms where climate impacts from land use change is not included (Hognes et al., 2014).

Electricity for the LBCC-RAS system in case 1b is modeled as being generated from 90% hydropower and 10% coal power with data from Ecoinvent v3.1 (2013). This case is included as an illustrative case for what is possible if this type of electricity is available. Electricity loss of 3.5% was included for the transmission of the power and transformation from high to medium voltage. This associated the electricity with a carbon footprint of 0.04 kg CO_2eq/kWh. For comparison, the Ecoinvent v3.1 database also provides a dataset that describes the electricity available in the regional entity of the North American Electric Reliability Corporation (NERC), that gives a carbon footprint of 0.64 kg CO_2eq/kWh. This was the electricity data used for the LBCC-RAS system in case 1a.

Road transport was modeled with a truck carrying 20 tons of fish, consuming 3.7 L of diesel per 10 km and has a carbon footprint of 0.09 kg CO_2eq/tkm; this also includes fuel used for the refrigeration system and emission of refrigerants (Winther et al., 2009). The fuel consumption reflects a modern truck. For the ONP system in case 2a, airfreight was modeled using data for a Boeing 747–400 from the Agrifootprint database, with an emission factor of 1.18 kg CO_2eq/tkm (Centre for Design and Society of the RMIT University, 2014). This plane is assumed to use 100% of its load capacity (3600 tons) and the emissions include landing and takeoff for a flight of approximately 10,000 km. For the ONP system in case 2b, ship transport was modeled with data for a ship of 120,000 tons (dry weight) utilizing 80% of its capacity, with an emission factor of 0.004 kg CO_2eq/tkm. Emissions from preparing for the return of the ship and re-loading is included in this data. Fuel for running refrigeration systems and emissions of refrigerants were also included with an emission factor of 0.1 kg CO_2eq/h (Winther et al., 2009).

3. Results

3.1. Financial analysis

3.1.1. Capital cost

Tables 3 reports the capital cost of ONP and LBCC-RAS systems. In the ONP system, the largest cost is license fees, which are almost 80% of the total capital cost, while the physical structure cost only accounts for 20%. For LBCC-RAS, the largest cost is the RAS system which is half of the total cost; 18% of the LBCC-RAS capital cost is for building structures. The capital cost of LBCC-RAS is 80% higher than that of the ONP system given the same production capacity. It is important to note that the replacement costs of some cost items are not included in this table, but incorporated into the cash flow analysis.

3.1.2. Operating cost

The operating cost breakdowns for the two systems are presented in Table 4 and Fig. 2. The total operating costs for the two systems are relatively similar, with LBCC-RAS only 10% higher than the ONP system. Without interest and depreciation, the two production systems have an almost equal operating cost, 4.30 US$/kg for ONP and 4.37 US$/kg for LBCC-RAS. Feed is the single biggest cost item accounting for 41% and 34% of the total operating cost for the ONP and the LBCC-RAS systems, respectively. It is worthwhile to note that these operating costs are subject to change with site selection due to differences in power costs, feed shipping costs and other factors. For example, operating costs presented here do not include the cost of heating or cooling that may or may not be required based on the geographic location of the LBCC-RAS facility.

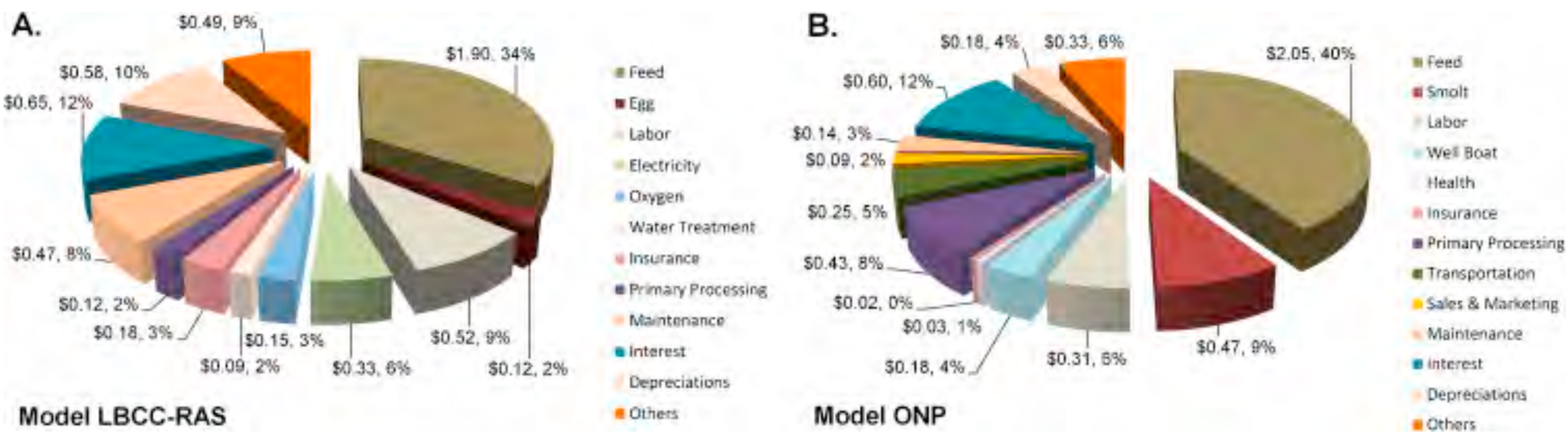

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Fig. 2. Estimated production costs (US$/kg HOG) according to the investments, product price estimates and the biological production plans for a model 3300 MT HOG Atlantic salmon LBCC-RAS farm (A) and ONP farm (B).

3.1.3. Financial indicators

The financial analysis is conducted for a period of 15 years; the discount rate is set to seven percent. The summary of the financial analysis is presented in Table 6. Overall, the ONP model system is financially better than the LBCC-RAS model system, even when the LBCC-RAS is selling product with a price premium. All three cases generate positive operating margins, indicating that from a production operating perspective, all are financially viable. The LBCC-RAS system selling salmon at a price premium is comparatively as profitable as the ONP system, even though its NPV is negative (–20,340,000 US$) and its return on investment (9.01%) is lower than the ONP system's ROI (17.77%). However, when selling salmon at the same price as the ONP system, the LBCC-RAS system is barely financially profitable and not an attractive investment. To be comparable with an ONP system, the LBCC-RAS system must command higher market price to breakeven or be profitable.

Table 6. Economic indicators for a 3,300 MT HOG LBCC-RAS and ONP Atlantic salmon farm. Also presented are indicators for the LBCC-RAS farm selling salmon with a 30% price premium.

Economic indicator	ONP system	LBCC-RAS system	LBCC-RAS system premium price

Operating (gross) margin	38.39%	17.56%	40.64%
Profit margin	23.62%	(–)	18.18%
NPV (million US$)	3.54	–120.20	–20.34
IRR before EBIT	15.96%	(–)	13.28%
IRR	7.94%	(–)	2.67%
ROI	17.77%	(–)	9.01%
Break-even production (MT)	1251	3307	2387
Pay-back period (year)	5.63	(–)	11.10
Break-even price (US$)	5.33	(–)	6.44

The IRR can be considered as the true expected yield from an investment. The IRR before EBIT for the LBCC-RAS with price premium is calculated to be 13.28%. The real IRR for the LBCC-RAS with price premium is 2.67%. The discount rate of 7% used here is below the IRR before EBIT and thus the LBCC-RAS would be an investment that results in a positive NPV. However, the discount rate of 7% used here is also above real IRR, and that investment in LBCC-RAS results in a negative NPV. Investors must make investment decisions based on her expectation(s) on return, whether using the IRR of 13.28% or 2.67%.

3.1.4. Sensitivity analysis

The financial results are very sensitive to some factors. For instance, prices have substantial influence on the results, and are subject to short- and long-term fluctuations due to dynamics in supply and demand. Feed is the largest cost item, so any changes in feed price and feed utilization have large impacts on the economic performance of the operations. Recent figures have suggested the cost of feed has increased gradually. The assumption for feed conversion ratio during growout is one of the most critical values in the estimation because it drives the largest component of the cost of production—feed cost during growout. Performance data from repeated Freshwater Institute trials indicate a feed conversion ratio less than 1.1 during the final growout phase (Summerfelt et al., 2013); utilizing lower FCR values during final growout instead of 1.1 would reduce the cost of production, by potentially up to 6%. Feed is also the major factor influencing the carbon footprint. Other factors such as mortality rates, power cost and mortality also have impacts on financial performance.

3.2. Carbon footprint results

If the alternative is intercontinental export of fresh salmon by air, then a modern and efficient LBCC-RAS system close to the market can be a more climate friendly alternative, even when running on electric power that mainly originates from fossil fuels (7.4 versus 15.2 kg CO_2eq per kg HOG salmon at retailer gate in Seattle). If the LBCC-RAS system is running on 90% hydropower the carbon footprint of the LBCC-RAS salmon is further reduced to 4.1 kg CO_2eq per kg HOG salmon at the retailer gate. The most climate friendly alternative of all is to ship frozen salmon from Norway with a modern container ship, 3.8 kg CO_2eq per kg HOG salmon at the retailer gate. A frozen product is not directly comparable with a fresh, but with modern freezing technologies, the quality of frozen products is not necessarily inferior to fresh.

At the producer gate, before transport to the retailer in Seattle, the production systems have climate impacts per unit produced of 3.4 versus 3.7 and 7.0 kg CO_2eq/kg salmon live-weight for the ONP and the LBCC-RAS using hydropower or average fossil fuel based electricity, respectively (Table 7 and Fig. 3).

Table 7. Estimated carbon footprint with component contributions at the producer gate and the retailer gate for the following scenarios: (1a) Salmon from a LBCC-RAS system in the US running on a typical electricity mix; (1b) Salmon from a LBCC-RAS system in the US running on electricity generated predominantly from hydropower; (2a) Salmon from a Norwegian ONP system transported by airfreight to Seattle; (2b) Salmon from a Norwegian ONP system transported by ship to Seattle.

	1a)	1b)	2a)	2b)
Feed production	2.69	2.69	3.21	3.21
Construction of facility and equipment	0.39	0.39	0.02	0.02
Grow out and smolt (fuel and electricity)	3.48	0.21	0.16	0.16
Oxygen and lime	0.44	0.44	–	–
At producer gate (live weight)	7.01	3.73	3.39	3.39
Transport, road	0.03	0.03	0.06	0.062
Transport, air or water	–	–	11.40	0.09
Packaging and ice	0.37	0.37	0.37	0.11
Refrigeration during transport	0.00	0.00	0.00	0.10

At retailer gate (HOG)	7.41	4.14	15.22	3.75

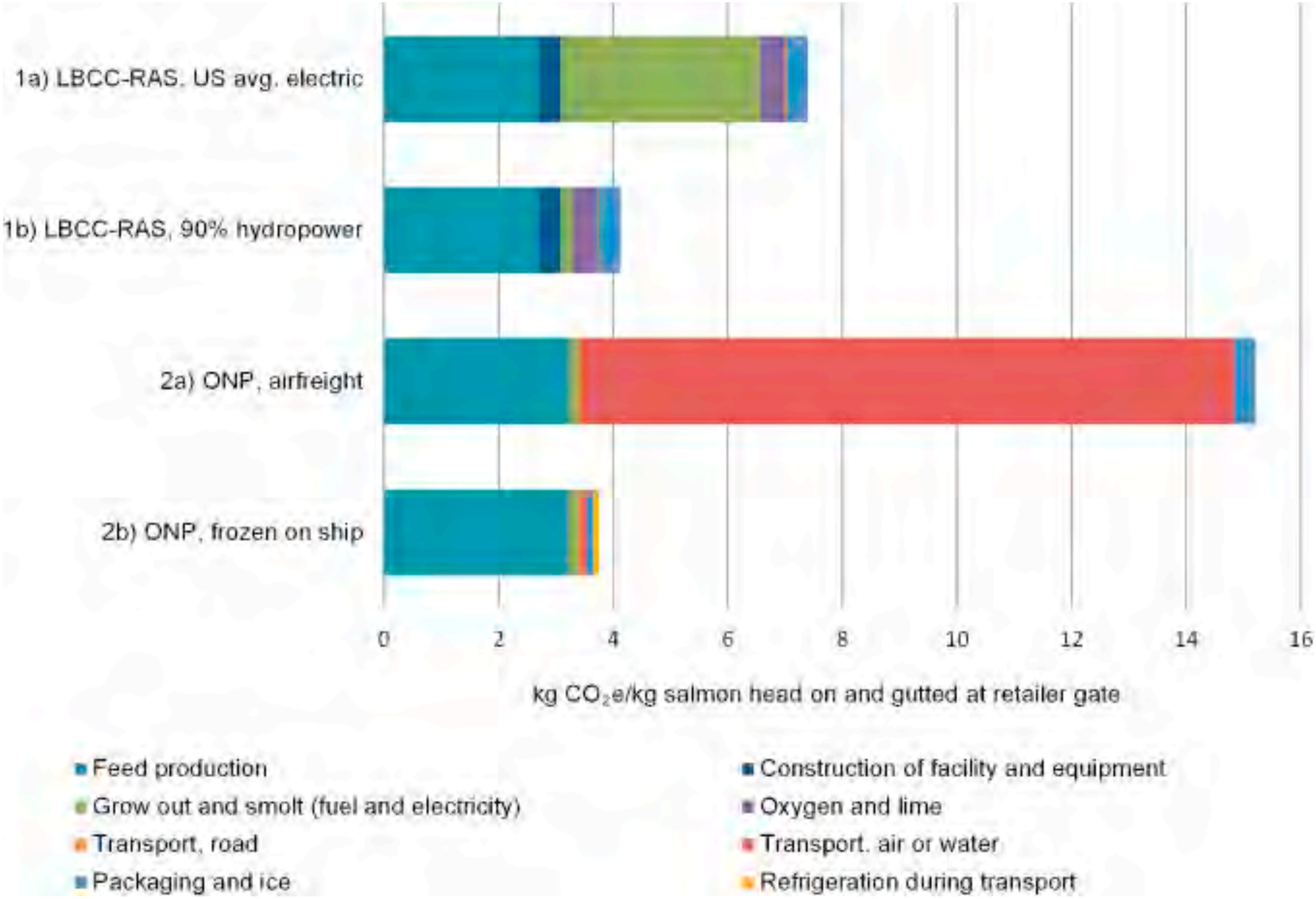

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Fig. 3. Estimated carbon footprint with component contributions at the producer gate and the retailer gate for the following scenarios: (1a) Salmon from a LBCC-RAS system in the US running on a typical electricity mix; (1b) Salmon from a LBCC-RAS system in the US running on electricity generated predominantly from hydropower; (2a) Salmon from a Norwegian ONP system transported by airfreight to Seattle; (2b) Salmon from a Norwegian ONP system transported by ship to Seattle.

The more general findings confirmed what previous LCAs have found that fish feed is the dominant climate aspect for the selected salmon products, but that energy used in growout and emissions from transports are also important. Production and maintenance of equipment and production facilities are not important climate aspects compared to feed production, transport and water treatment.

4. Discussion

Given current technology development and possible increases in market price for salmon and production input factors, the ONP system still remains the most profitable, even at this relatively small scale. To achieve comparative financial performance, the LBCC-RAS system requires a price premium, at least 25% higher than current market prices. This is mainly due to considerably higher capital cost for the LBCC-RAS system. However, the difference in operating costs between both systems is relatively small. If the feed conversion ratio can be further improved from 1.1 to 1.0 for LBCC-RAS systems, the gap will be even smaller since feed is the most important cost item. However, improvements in feed conversion ratio are also likely to happen in ONP systems, so the difference in the future for optimized systems is hard to predict. It is important to note that ONP systems are just for the growout phase in Norway, and that salmon now spend more of their lifecycle in LBCC-RAS smolt production facilities (Dalsgaard et al., 2013). Additionally, other costs such as managing sea lice and loss due to disease could further increase the operating cost of ONP systems significantly (Liu and Bjelland, 2014). The largest limiting factor for using LBCC-RAS system appears to be the capital cost. Thus, there are economic incentives for advancing technological innovations of LBCC-RAS systems that can reduce capital cost to become more competitive with ONP systems.

LBCC-RAS systems are not a new technology, and have been used for the last twenty years for growing out both freshwater species, such as eel and catfish, and marine species like trout and sea bass (Martins et al., 2010, Badiola et al., 2012). There is increasing interest in applying LBCC-RAS for the salmon smolt stage in Nordic countries and Europe (Dalsgaard et al., 2013). However, due to low returns on investment and and a history of failures when the technology was not well advanced, LBCC-RAS have not been used widely.

Economic incentives have been proven to be more effective than traditional command and control policy (Bailly and Willmann, 2001, Liu et al., 2013). Market-based economic instruments such as taxes, subsidies, fees/charges and eco-labeling can create incentives for the industry to foster cost-effective technology innovation and adaptation such as LBCC-RAS systems or other closed containment systems (Rosten et al., 2013). However, such incentive-based approaches have to be executed with the vectors of market and social forces such as environmental policy and consumers. Eco-labeling farmed products would be a market-driving power to change consumers' purchasing behavior. Concerned consumers are likely willing to pay more for the products which are produced in an environmental sustainable way. Subsidies and taxes can be used to stimulate cost-effective technology innovation and adaptation, e.g., rewarding improved environmental performance from capturing and controlling waste streams in closed-containment systems or eliminating sea lice infestation.

While environmental policies may also have a role, in Norway, "green" concessions for salmon farming require the aquaculture industry to employ technological and operational innovations and solutions to reduce the incidence of salmon lice and escapes. These technologies require upfront investment which can be significant, but over the long run, such technological innovation would increase social license to operate through improved environmental performance and reduced conflict with other resource users, perceived market payoffs through reduced costs to obtain and maintain a license to operate, and monitor and mitigate negative impacts, e.g., costs of recapturing escapes. Captured nutrient laden waste streams associated with LBCC-RAS may also result in ancillary revenue streams, e.g., aquaponics.

The carbon footprint analysis showed that, with respect to climate impact, producing close to the market is preferable by a good margin, especially when the LBCC-RAS system utilized electricity generated from 90% hydropower and the alternative is to export fish fresh, fast and a long distance. Even if salmon is LBCC-RAS produced with electricity based on fossil fuels, intercontinental export of fresh fish on airplanes is not a preferable option. However, environmental considerations involving high inputs of electricity should be followed up with a discussion of what is the environmentally optimum way of using available electricity. Electricity is of the highest energy quality available, and many industrial and infrastructure processes do not have an alternative to electricity. Export of frozen salmon was the best option of all, but cannot be directly compared with fresh salmon. Still, this result points to a future option, with product development, improvement of logistic chain management, to maintain quality through the transport, and market acceptance, frozen intercontinental export has the potential to compete with local LBCC-RAS products. Another important assumption regarding transport is that most intercontinental export of fresh Norwegian salmon is done with flights that also carry passengers. Thus a more precise comparison should include details and insight into how it is reasonable to allocate the fuel used and corresponding emissions between goods and passengers. In addition to this, the LCA data that is available on flight transport is highly variable. This indicates that more precision on the exact age/technology and size of the aircrafts being used should be included.

The carbon footprint contained several cut-offs and assumptions that limits the conclusions that can be drawn, e.g., the same data on feed was used for salmon production in the US and Norway. There are likely to be differences in the carbon footprint of the feeds that would actually be used. A potentially important cut off is that treatment of the biosolids was not included. Biosolids could be seen as both waste and a resource, but either way handling it will involve the use of both energy and transports together with emissions from the biosolids itself. Still, this aspect was left out because it would be difficult to compare to the ONP system, where there is no biosolids capture and waste feed and feces is discharged directly in the ocean.

Most often, the concentrated effluent of LBCC-RAS systems now in operation in North America and Europe are treated in order to meet stringent wastewater discharge permits. Thus a flow-through system will have a higher eutrophication potential. However, if the concentrated effluent of a LBCC-RAS is not treated there is no such advantage to be obtained. Rosten et al. (2013) suggests a classification system for closed containment systems from 1 to 4, where category 4 is the most closed system towards the external environment applying treatment of both inlet and outlet of a LBCC-RAS system. Acidification and toxic potentials are strongly connected to energy consumption and thus similar to climate impacts with regards to where and why they occur.

Aquaculture technologies have been compared with LCA previously; our assessment was compared with a selection of peer reviewed literature (Table 8). This selection of literature points to the same main conclusions: feed production is a dominating factor for carbon footprint in salmon aquaculture, and for LBCC-RAS, the use of energy for water treatment can be equally important and equipment and infrastructure is of minor importance. The importance of energy used for water treatment depends on how this energy is produced. The literature also shows that important parameters for the LCA, such as the FCR and energy used for water treatment varies considerably. This study has not gone into the details to explain these differences, but important reasons are probably that the studies rely on different assumptions, experimental data and site specific properties. These differences make it difficult to compare the final carbon footprint among studies. In addition to differences in the aquaculture systems that are compared, it is also not possible to be sure that the data on feed that are used are comparable. Finally, there are also methodical differences, e.g., Ayer and Tyedmers (2009) used allocation based on the energy content in the different outputs rather than their mass and Samuel-Fitwi et al. (2013) used system expansion.

Table 8. Data from published studies on LCAs of LBCC-RAS for rearing salmonids.

System analyzed and method	Electricity consumption (kWh/kg)	Feed efficiency	Carbon footprint of product (kg CO_2eq/kg)	Reference
Salmon production with marine net-pen, marine floating bag, land-based saltwater flow	Net-pen: 1.49	Net-pen: 1.30	Net-pen: 2.07	Ayer and Tyedmers

through and a land-based freshwater RAS. Assessment from feed and smolt production to farm gate	Land, flow through: 13.4 Land, recirculating: 22.6 Electricity mix 80% fossil fuels	Land, flow through: 1.17 Land, recirculating: 1.45	Bag: 1.90 Land, flow through: 2.77 Land, recirculating: 28.20	(2009)
Trout production with a flow through system and a hypothetical recirculating system. From feed production to fish ready for slaughter	Flow through low pumping: 2.36 Recirculation: 10.7 86.6% nuclear energy	Flow through: 1.10 Recirculation: 0.80	Flow through: 2.02 Recirculation: 1.60–2.04	d'Orbcast el et al. (2009)
Rainbow trout production in flow through systems (extensive and intensive) and recirculating system. From feed production to fish ready for slaughter	Intensive flow through: 2.55 Recirculating: 19.6 Electricity based on fossil fuels	Flow through: 0.91–1.2 Recirculating: 0.86	Flow through extensive: 2.24 Flow through intensive: 3.56 Recirculating: 13.60	Samuel-Fitwi et al. (2013)
Rainbow trout production with flow-through, recirculating and semi-closed system. From feed production to fish ready for slaughter	Flow-through: 0.65 Recirculating:	Flow through: 1.15 Recirculating:	Flow through: 1.16 Recirculating:	Dekamin et al. (2015)

	8.1 Semi-closed: 7.6	1.47 Semi-closed: 1.57	6.10 Semi-closed: 6.38	
Salmon production with in a floating tank, flow-through, solid-walled aquaculture system. From feed production to fish ready for slaughter	Actual production cycle: 7.3 Intended production cycle: 4.6	Hatchery: 1.5 Grow out actual: 1.46 Grow out intended 1.37	Actual: 3.87 Intended: 3.03	McGrath et al. (2015)

The conclusion with regards to the hypothesis that a LBCC-RAS produced salmon will have a higher carbon footprint than one from an ONP system is solely dependent on what carbon dioxide emission the electricity production is attributed with and the method and form that the product is transported to market with. If the electricity for the LBCC-RAS is considered to be primarily hydropower then the carbon footprint for the two systems at the producer gate are relatively close (3.39 and 3.73 kg CO_2eq/kg salmon live-weight). If the electricity for the LBCC-RAS is considered to be the average US mix dominated by fossil fuels, then the LBCC-RAS has a higher carbon footprint at the producer gate (7.01 versus 3.39 kg CO_2eq/kg salmon live-weight). The carbon footprint demonstrates the importance of the emissions associated with electricity generation for LBCC-RAS systems.

In a market where electric power is a commodity in short supply, and where power markets are connected through economy and/or the grid, it is challenging to argue that power is supplied from one specific source. On top of this, renewable energy, such as hydropower, is often sold to clients that pay extra for a certificate to claim that their electricity is produced from renewable sources. For this system to work, as well as for carbon footprint, it would require a mechanism that ensures that the sum of certificates that are sold do not exceed the renewable power that is actually available and that everybody who does not buy certificates uses a carbon footprint of their electricity that does not include the renewables that are sold with certificates. This is what is then called the residue mix. As far as these authors know, no such system exists today and it is recognized to be “good practice” to use the average production mix in the grid where the electricity use takes place. The grid here being what is physically and/or economically connected.

Extending the carbon footprint to include transport to market for the most likely production systems, fresh salmon produced in LBCC-RAS systems close to a US market that use an average US electricity mix and fresh salmon produced in Norway in ONP systems shipped to the same market by airfreight, yields the result that LBCC-RAS has a much smaller carbon footprint, 7.41 versus 15.22 CO_2eq/kg salmon HOG, respectively. In this case the carbon footprint associated with transport is the dominant factor for ONP-produced salmon, accounting for more carbon footprint than the entire production on a kg salmon HOG basis (Fig. 3).

5. Conclusions

In this paper, we compare the economic and environmental performance of the Norwegian open net pen system in the sea and the US land-based, closed containment water recirculating aquaculture system for the same production capacity targeting the same US market. The scale used for the open net pen system is smaller than the average operation scale in Norway, so both systems could be scaled up to higher production capacity. This will result in reduction in cost due to scale of economy. However, the main findings are drawn:

- Capital cost for land-based closed containment water recirculating salmon farming systems is significantly greater than capital cost for traditional open net pen salmon farming systems, but increasing net pen site license costs in Norway are bringing the capital costs closer.

- Production cost for land-based closed containment water recirculating salmon farming systems is approximately the same as production cost for traditional open net pen salmon farming systems at this scale, when excluding interest and depreciation.

- Return on investment for traditional open net pen salmon farming at this scale is twice that of land-based closed containment water recirculating salmon farming, when land-based produced salmon are sold at a price premium.

- Internal rate of return for earnings before interest and tax for traditional open net pen salmon farming at this scale is only slightly greater than that of land-based closed containment water recirculating salmon farming, when land-based produced salmon are sold at a price premium.

- The carbon footprint of salmon produced in land-based closed containment water recirculating aquaculture systems that are using a typical US electricity mix based on fossil fuels is twice that of salmon produced in traditional open net pen systems, when delivery to the market is not included.

- The carbon footprint of salmon produced in land-based closed containment water recirculating aquaculture systems delivered to market in the US is less than half of that for salmon produced in traditional open net pen systems in Norway that is delivered to the US by air freight.

Acknowledgements

The authors thank the Agriculture Research Service of the United States Department of Agriculture (Agreement No. 59-1930-1-130) and the Norwegian Research Council for funding this work.

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[1] 1 US dollar = 7 Norwegian kroners.

nature climate change

ARTICLES
https://doi.org/10.1038/s41558-018-0117-x

EXHIBIT I-7

Fuel use and greenhouse gas emissions of world fisheries

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Food production is responsible for a quarter of anthropogenic greenhouse gas (GHG) emissions globally. Marine fisheries are typically excluded from global assessments of GHGs or are generalized based on a limited number of case studies. Here we quantify fuel inputs and GHG emissions for the global fishing fleet from 1990–2011 and compare emissions from fisheries to those from agriculture and livestock production. We estimate that fisheries consumed 40 billion litres of fuel in 2011 and generated a total of 179 million tonnes of CO_2-equivalent GHGs (4% of global food production). Emissions from the global fishing industry grew by 28% between 1990 and 2011, with little coinciding increase in production (average emissions per tonne landed grew by 21%). Growth in emissions was driven primarily by increased harvests from fuel-intensive crustacean fisheries. The environmental benefit of low-carbon fisheries could be further realized if a greater proportion of landings were directed to human consumption rather than industrial uses.

Production, distribution and consumption of food contribute unequivocally to global climate change, accounting for a quarter of anthropogenic greenhouse gas (GHG) emissions[1,2]. Production of animal protein in particular is a substantial and growing driver of global warming, accounting for approximately half of all food production-related emissions[2–6]. As income and affluence in developing countries increase and diets approach the meat-rich consumption of the developed world, emissions associated with food production are likely to grow at least up until the middle of this century[7–9]. Together, these trends could see an increase in diet-related emissions of over 30% by 2050[9]. Dietary choices, particularly as they relate to animal protein, have pronounced effects on the per capita emissions of food consumption[9–11].

The Paris Agreement adopted by the 2015 United Nations Climate Change Conference, COP21, aims to keep global warming under 2 °C and optimally under 1.5 °C, requiring urgent reduction of GHG emissions from all sectors[12,13]. The proposed efforts of individual countries to limit emissions, in the form of Nationally Determined Contributions, range substantially and intended methods to achieve these proposed reductions include food-production and related industries to varying extents. Given the part that food production, and animal protein production in particular, plays in global emissions, tracking and reducing emissions from these systems will be an important component of national and international initiatives to limit climate change while still meeting the diverse food needs of a growing population. Identifying those countries in which particular food sectors contribute most heavily to overall emissions and present the clearest opportunities for improvement, will assist in domestic efforts to curb emissions. To this end, there is an emerging interest and need to quantify and characterize the drivers of emissions from all important sectors of the global food industry[14,15].

Production by fisheries is a critically important source of nutrition and income around the world, yet it is underrepresented in measurements of GHG emissions from food production. These assessments typically either exclude fisheries entirely[16] or generalize the contribution of fisheries based on small amounts of data[9,17,18], thereby failing to include the vast variation in emissions between fisheries targeting different species and operating different gears in different environments[19]. Fisheries are typically energy-intensive operations that produce the majority of their emissions directly from burning fossil fuels, and exhibit a marked variation both across and within fleets in the amount of fuel that is required[14,19,20]. The extent to which global fisheries rely on fossil fuel inputs was previously assessed[21]; in that study it was estimated that the total fleet consumption was 50 billion litres in 2000[21]. The future of fishery systems and fish production will be heavily influenced by climate change[22], while volatile energy prices and related regulations and policies will affect fishermen, fishing communities and nations whose livelihoods and food security depend on the ocean[23,24].

Here, we synthesize fuel use data from a Fisheries Energy Use Database (FEUD), adapted to account for non-fuel GHG emissions, with a database of global marine fishery landings to estimate annual GHG emissions from the global fishing fleet over two decades. We provide a global breakdown of wild-capture fishery emissions per country, and compare each nation's fishing emissions against those from agriculture and livestock production. We demonstrate that fisheries can contribute substantially to the national emissions of those countries that rely most heavily upon fishing as a source of food and income, and show that overall emissions from the industry have increased while landings have remained relatively constant. Finally, we show that, while some sectors of the industry are associated with high rates of emissions, many fisheries, particularly those targeting small pelagic species, can provide low-carbon sources of animal protein compared to land-based alternatives.

Results

Emissions of national and global fishing fleets. We estimate that the world's fishing fleets in 2011 burned 40 billion litres of fuel and emitted 179 million tonnes of CO_2-equivalent (CO_2-eq)

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GHGs to the atmosphere, or 2.2 kg CO_2-eq per kg of landed fish and invertebrates.

The national fishing fleets with the largest overall GHG emissions were based in China, Indonesia, Vietnam, the United States and Japan (Fig. 1). These five countries accounted for 37% of landings and 49% of total emissions in 2011, together producing 81 million tonnes CO_2-eq. The substantial contribution to fishery emissions from Asia reflects the extent of fishing and the scale of fleets based in the region. Fishing fleets based in China alone emitted 50 million tonnes CO_2-eq, approximately one quarter of total global emissions from fisheries, more than the combined impact of all fisheries in Europe and the Americas (Table 1). Countries that disproportionately targeted crustaceans, including Saudi Arabia and Australia, had the most carbon-intensive fleets. The west coast of South America, on the other hand, exhibited the least carbon-intensive production, accounting for 15% of global fishery production in 2011 and just 3% of fishery-sourced emissions, owing to the relatively high percentage of landings from the relatively low-fuel input Peruvian anchovy fishery.

The drivers behind national patterns in emissions are evident when looking at individual countries with diverse fleets. The United States, for example, had the fourth highest total emissions by fisheries in 2011, but, in terms of intensity per unit of landings, had a relatively low-carbon fleet (Fig. 1). The largest fisheries in terms of landings in the United States include two very low-input small-pelagic fisheries targeting Gulf menhaden (*Brevoortia patronus*) and Atlantic menhaden (*Brevoortia tyrannus*), as well as the Alaska pollock (*Gadus chalcogrammus*) trawl fisheries, which consume relatively little fuel compared to similar whitefish fisheries[20,25]. Fisheries for these three species made up over 40% of the total 5.2 million tonnes that were harvested by US fleets in 2011. By contrast, Australian fisheries harvest substantially lower volumes than those of many other countries but disproportionately target high-value crustacean species, including rock lobsters and prawns. The fuel use intensity (FUI) of these fisheries is several orders of magnitude greater than that of many small-pelagic fisheries. As a result, while contributing only 0.5% of overall global emissions, Australian fleets were amongst the most carbon-intensive in 2011, with an average emissions intensity (5.2 kg CO_2-eq per kg) that was several times the average of the US fleet (1.6 kg CO_2-eq per kg).

Emissions by fishing sector. Contribution to overall fishing emissions varies markedly between sectors when national and global fleets are disaggregated by species class (Table 1). Fisheries for pelagic species that are typically under 30 cm in length, which accounted for a fifth of reported landings over the entire period, contributed only 2% of global fishery emissions. Crustacean fisheries, on the other hand, accounted for only 6% of landings but over 22% of emissions. Fisheries for lobster and shrimp harvest relatively low volumes per trip compared to those targeting finfish and, particularly in the case of trawl fisheries that target crustaceans, consume substantial quantities of fuel in the process.

Upwards of a third of reported global marine fishery landings are used for non-food purposes, although the proportion of landings for these purposes has decreased over time[26–28]. Most landings for non-food purposes are directed to meal and oil production for supplying aquaculture and livestock feeds. These reduction fisheries are located primarily in Chile, Peru, Thailand, Europe, China and the USA[29,30]. Non-food fisheries were responsible for 15% of the global emissions by the fishing industry in 2011, with an average emission intensity of approximately 1.1 kg CO_2-eq per landed kg of fish. Reduction fisheries for meal and oil produced only 4% of 2011 fishing emissions, averaging 0.4 kg CO_2-eq per kg landed.

The non-motorized fishing sector was estimated to account for six million tonnes of landed fish and invertebrates in 2011. The vast majority of these landings were in Africa and Asia, based on estimated percentages of non-motorized fishing vessels by country in these regions[31]. Non-motorized vessels are still associated with some

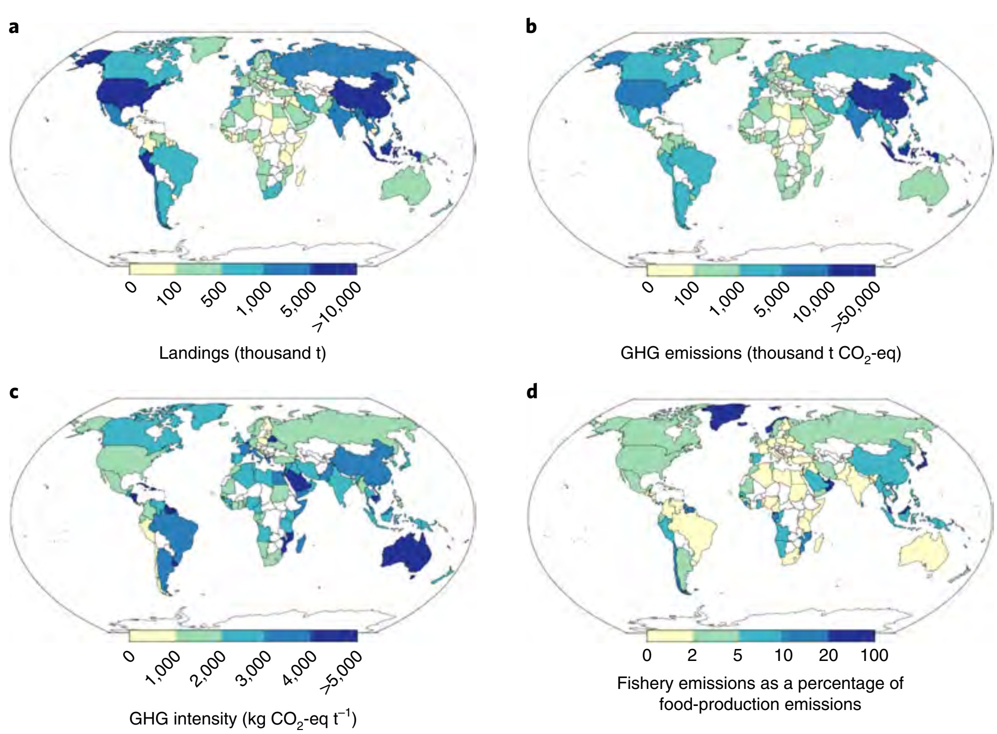

Fig. 1 | Production and GHG emissions by fisheries for each country. a, Landings by national fishing fleets in 2011 in millions of tonnes. **b** Aggregate GHG emissions by national fishing fleets, up to the point of landing in thousands of tonnes CO_2-eq. **c**, Emission intensity of fishery landings in kg CO_2-eq per tonne. **d**, GHG emissions from fisheries as a percentage of emissions from agricultural production.

Table 1 | Fishery GHG emissions by sector in 2011

Industry sector	Landings (million tonnes)	Fuel use intensity ($l\ t^{-1}$)	Emissions intensity (kg CO_2-eq per kg)	Total emissions (million t CO_2-eq)
Global fisheries	81	489	2.2	179
By vessel type				
Motorized	74	532	2.3	174
Non-motorized	6	0	0.7	5
By product type				
Human consumption	57	592	2.7	152
Non-food products	24	246	1.1	27
Meal and oil	18	82	0.4	7
By species group				
Pelagic fish <30 cm	17	42	0.2	3
Pelagic fish >30 cm	21	430	1.9	41
Demersal molluscs	3	523	2.4	7
Demersal fish	31	539	2.4	75
Cephalopods	4	613	2.8	10
Crustaceans	5	1,739	7.9	43
By region				
Latin America	16	235	1.0	16
North America	6	380	1.7	10
Europe	12	390	1.7	20
Africa	5	385	1.8	9
Asia (excluding China)	28	554	2.5	71
Oceania	1	636	2.8	3
China	13	809	3.7	50

non-fuel emissions, but contribute less than 2% to overall atmospheric emissions from the sector as a whole. A potential source of concern for fishery management in developing countries is the expected increase in reliance on fossil fuels as fleets shift from traditional methods to energy-intensive industrialized operations[32]. Fuel use in these regions already accounts for a relatively larger portion of fishing costs[33] and increased costs could potentially threaten the capacity of subsistence and small-scale operators to fish.

Trends in emissions from 1990 to 2011. Total landings from the world's fishing fleets remained relatively unchanged over the period from 1990 to 2011 (Fig. 2). Fluctuations throughout the period were driven primarily by varying harvests of small pelagic species, particularly from the Peruvian anchovy fisheries off the coast of Peru and Chile (see for example, the drop in landings corresponding to the El Niño event in 1998).

Emissions from world fisheries increased by 28% from 1990 levels over the two decades analysed, contributing 39 million tonnes CO_2-eq more GHGs to the atmosphere in 2011 than in 1990 (Fig. 2). Average emissions intensity per tonne of landings increased by 21% over the same period. Much of the overall increase in emissions over this time period can be attributed to catch composition. In particular, landings from high-input crustacean fisheries increased by 60%. GHG emissions from global fishing fleets increased with increasing catch rates of crustaceans ($P<0.001$) and demersal and reef fish ($P=0.001$) (multiple regression, $r^2=0.96$). Trends in some species groupings were also influenced by increasing fuel inputs to fisheries through the 1990s and early 2000s observed in European waters[34,35], the North Atlantic[36] and around Australia[37], although these trends have reversed in some sectors in recent years. Trends in emissions were significantly correlated to FUI for large pelagic fishes ($r^2=0.71$, $P<0.001$), demersal fishes ($r^2=0.67$, $P<0.001$), and crustaceans ($r^2=0.33$, $P=0.005$), suggesting that changing FUI estimates, rather than variable landings alone, contributed to the variation in emissions in these sectors.

Comparison to agriculture and livestock. Global emissions from agriculture and livestock production in the FAOSTAT database, excluding those associated with burning savannah and cropland, amounted to 5 billion tonnes CO_2-eq in 2011[17]. Emissions from fisheries, at 179 million tonnes, account for approximately 4% of combined fishery, agriculture and livestock emissions. In approximately half of the world's countries, including almost all industrialized nations, fisheries account for less than 5% of domestic food production emissions (Fig. 2). However, in some coastal and island countries, including Kiribati, the Marshall Islands and the Maldives, where agriculture is limited and most domestically produced protein comes from the ocean, fisheries account for almost all food-production emissions. Among industrialized countries and regions, fishing fleets from Iceland (80%), Greenland (72%), Taiwan (50%), Norway (38%), Japan (21%) and Denmark (12%) contribute substantially to domestic food production-related emissions, reflecting the relative role that fisheries have in the economies, diets and cultures in these countries.

Compared to other sources of animal protein, products derived from marine fisheries and destined for human consumption produce relatively low GHG emissions (Fig. 3). Over half of fishery-derived products for consumption were estimated to produce fewer GHGs than the low end of emission ranges for pork, beef and lamb. Average fisheries had a carbon footprint similar to the range reported for poultry production. Previous estimates have suggested that fisheries are emission-intensive sources of protein[9], but were seemingly skewed by over-reliance on case studies of highly fuel-intensive fisheries. The comparisons made here and shown in Fig. 3 present only those fisheries that fish for human consumption; if fish landed for non-food uses were also directed to consumption, their products would be associated with lower emissions than every other major source of animal protein. This, of course, would require increased market demand for products of anchovies and sardines, and would necessitate the substitution of non-fishery feed inputs to aquaculture systems as farm-based fish production continues to grow—potentially increasing emissions from that industry as a result[38].

Reducing emissions from fisheries. Strategies to improve the short- and long-term performance of the industry should include behavioural, technological and managerial efforts. The relative effect of these efforts has been assessed for different fisheries with mixed results. Identifying those factors that influence fuel use most, and that can therefore yield potential for improvement, is difficult: both the direction and magnitude of relationships between fuel use and variables such as vessel size and engine horsepower vary from fishery to fishery[35,39,40]. Behavioural changes, such as reducing vessel speed while steaming and using more selective fishing times and locations, are often suggested as short-term adaptations to increased fuel prices that are easily implemented by fishermen[23]. Indeed, the skill and experience of skippers can help to explain variation in efficiency within fleets[41,42].

Fishery management efforts aimed at reducing overcapacity and rebuilding stocks may have a particular benefit in reducing fuel use and emissions. Fuel use reductions were observed, for example, after government vessel buy-backs in Australia's Northern Prawn Fishery[37,43], as well as following capacity reduction in Taiwanese fishing fleets in 2005[44]. The reduction in fuel use in European fisheries has been attributed at least partially to increased stock biomass

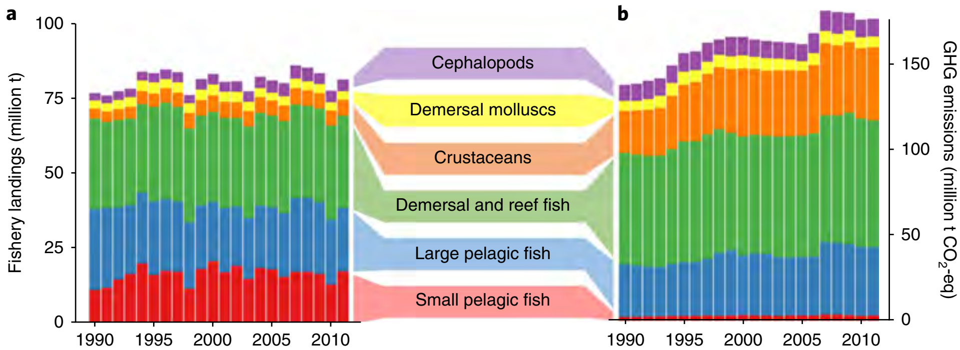

Fig. 2 | Global marine fishery landings and GHG emissions for 1990–2011 categorized by species groups. a, Global marine fishery landings. **b**, Global GHG emissions from marine fisheries.

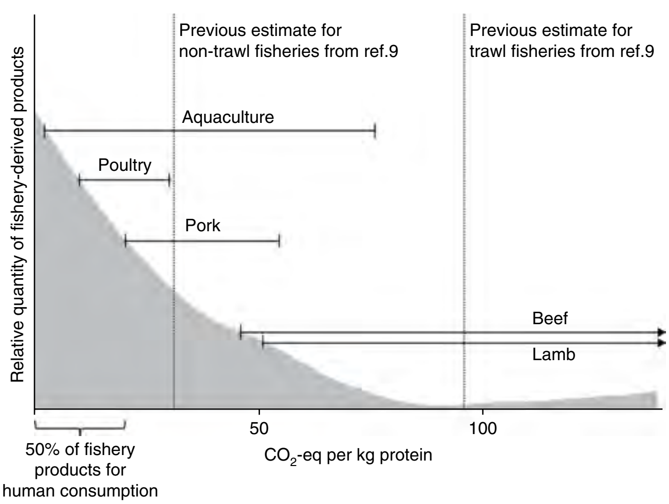

Fig. 3 | Carbon footprint of fishery-derived products for human consumption in 2011 compared to other sources of animal protein. Truncated for display purposes to include 98% of landings. Vertical partitions indicate previous generalized estimates for trawl and non-trawl fisheries[9], showing the percentage of global fisheries below (59%), within (32%) and above (9%) those estimates[9]. Ranges for livestock systems have been previously published[15]: aquaculture, 4–75 kg CO_2 per kg protein; poultry, 10–30 kg CO_2 per kg protein; pork, 20–55 kg CO_2 per kg protein; beef, 45–640 kg CO_2 per kg protein; lamb, 51–750 kg CO_2 kg protein[15].

in recent years[35,39,45]. Even when management measures are not constructed around the rebuilding of stocks or reduction of fleet capacity, substantial changes in FUI can occur[46]. Overall, the potential for management efforts to reduce fuel consumption varies substantially between fisheries with estimates ranging from 20 to 80% in a report by the Organization for Economic Cooperation and Development[45].

Although the results were presented here per fishing country, the management of fisheries, consumption of the fish and the policies that relate to the fisheries, energy and climate change transcend borders and jurisdictions. Many European fisheries, for example, are managed through the European Union rather than by individual states, and so decisions influencing fishing efficiency would be made at an international level. Furthermore, the life cycle of fishery products extends well beyond the point of landing. Emissions from seafood up to the point of consumption are influenced by a number of factors, not least of which is the role of international trade and transport. Over two-fifths of the world's seafood products are traded between countries, and large flows of products originating in the exclusive economic zones of developing countries are imported to markets in the European Union, United States and Japan[26,47]. As a result, fishery-derived products may travel thousands of kilometres from their origin to their point of processing and ultimately to the market, in some cases passing through multiple national borders in the process[28,48]. This transport is a key source of emissions for some products when flown fresh or live by air freight, whereas ship-based transport of frozen or otherwise preserved products does not contribute as much to overall seafood emissions[49]. The extent of seafood trade, the demand for species from distant origins and the desire for fresh products may make transport particularly important for fishery-derived products compared to meat products.

Findings here will help to inform global and regional GHG emissions models as well as food and climate policies both nationally and internationally, helping to illuminate the role that fisheries have in the environmental cost of global food-production systems. As more data are gathered, particularly from small-scale fisheries and from fisheries in developing nations, as well as non-fuel and post-harvest sources of emissions, the patterns provided here will become better informed and more dynamic in highlighting the contribution of diverse seafood production systems to climate change.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41558-018-0117-x.

Received: 1 September 2016; Accepted: 22 February 2018;
Published online: 2 April 2018

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Acknowledgements

Research funding was provided by the Australian Seafood Cooperative Research Centre (Project 100596). R.W.R.P. acknowledges support from the Natural Sciences and Engineering Research Council of Canada (PDF-487958-2016). R.A.W. acknowledges support from the Australian Research Council (Discovery project DP140101377).

Author contributions

R.W.R.P. co-manages FEUD, conducted analyses and wrote the manuscript. J.L.B., C.G. and B.S.G. assisted with projected development and manuscript preparation. K.H. assisted with data analysis and manuscript preparation. P.H.T. developed and co-manages FEUD and assisted with manuscript preparation. R.A.W. provided global fishery landing data and assisted with data analysis and manuscript preparation.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Estimates of fishing effort were sourced from a global database based on estimates of total vessel engine size and number of fishing days in a year, assembled from FAO, the European Union, regional tuna-management bodies and other sources[50,51]. The number of fishing vessels, gross registered tonnage and gear type were sourced from the FAO Fishing Fleet database. The EUROPA Fishing Fleet Register online database provided detailed data about vessel characteristics for country members of the European Union. These data sources were augmented by data from regional tuna associations and various online sources to provide in depth information about fleet sizes and characteristics, and also, importantly, by information about the number of days that this fishing capacity was used each year.

For gear types that could be operated by non-motorized vessels, estimates of non-motorized landings were made based on the reported number of non-motorized vessels in each country's fleet according to the FAO[31]. Because of limited data, non-motorized landing rates for many countries were estimated from neighbouring countries and/or countries with similar socio-economic and fishing conditions.

Fuel consumption rates were extracted from FEUD[19], which contains over 1,600 records of FUI (in litres per round weight tonne of landings), vessel characteristics and fishing operations at various scales (individual vessels, national fleets and global sectors). Records of fisheries operating before 1985 were excluded from analysis, as were any records for which target species group or gear type could not be determined.

Each record from the global landings database was matched to a subset of FEUD records based on a hierarchy of match criteria. All records were matched to gear type, which has a marked influence on fuel consumption rates[15,19]. In cases for which species-specific FUI estimates were not available, matches were based on a set of 30 target groups of species sharing similar characteristics and habitats (for example, pelagic species of <30 cm). First attempts to match records identified FEUD records that matched the target species, gear and fishing country of the landings record. In lieu of successful matches, second attempts matched target species and gear, regardless of fishing country. Third attempts matched target species group, gear and fishing country. Fourth attempts matched target species group and gear, regardless of fishing country. If no fuel use records matched the combination of species target group and gear for a given fishery, an average FUI value across all records was applied.

To generate fuel use estimates for each fishery, all FEUD records matching the above criteria were weighted based on three variables: the number of vessels reporting data, the number of FUI estimates originating from the same data source, and the difference in years between the fishing record and the fuel record. Records reporting data from multiple vessels were attributed a weight equal to the log of the number of vessels plus one, considering that a direct weighting would have given undue influence to records with a large number of reported vessels. If multiple records were derived from the same source material, log weighting was also applied, such that the total relative influence of a data source was equal to the log of the number of data points provided plus one. Finally, record weights were decreased by 10% for each year of difference between the fishing year of interest and the fishing year in the FEUD record. Fuel consumption estimates were thus generated following equation (1)

$$F_{f,y} = \sum \left(F_r \frac{w_r}{\sum (w_r)} \right) \tag{1}$$

where $F_{f,y}$ is the FUI estimate generated for fishery f in year y, F_r is the FUI of record r matching fishery f, w_r is the weighting factor applied to record r using the weighting method in equation (2)

$$w_r = \log(v_r + 1) \frac{\log(s_r + 1)}{s_r} 0.9^{|y_f - y_r|} \tag{2}$$

where v_r is the number of vessels reporting data in record r, s_r is the number of data points coming from the same source as record r, y_f is the year of fishing in fishery f and y_r is the year of fishing of record r.

Average fuel density was assumed to be 0.9 kg l^{-1} with an average carbon content of 860 g kg^{-1}. Total direct emissions from burning fuel were calculated to be 2.8 kg CO_2-eq per litre of fuel based on chemical content of marine fuels and using IPCC 2013 characterization factors[1,52]. Upstream emissions associated with mining, refining and distributing diesel fuel were extracted from the ecoinvent 3.0 life cycle inventory database[53]. Average rates of upstream emissions of 0.5 kg CO_2-eq per litre were applied across all fisheries, although actual upstream emissions vary according to production method, processing location and transport distance.

The combined rate of emissions was 3.3 kg CO_2-eq GHG per litre of fuel combusted.

Life cycle assessments (LCAs) of fisheries over the past decade have estimated non-fuel related inputs to account for between 10 and 40% of total emissions up to the point of landing[54–57]. This includes emissions from vessel construction and maintenance, gear manufacture, loss of refrigerants and other activities. Refrigerant loss in particular has been identified as a key source of emissions in some fisheries[12,13]. Fishery LCAs have primarily reported data for large, industrial fleets in developed countries, and relatively little data are available on rates of emissions from artisanal or small-scale fisheries or for those in developing countries, although data availability for the latter is increasing[55,58,59]. Non-fuel-related emissions vary between fisheries, but the limited coverage of studies providing data for different fisheries to date did not allow for the incorporation of that variation in the analysis presented here. Instead, an average of 25% was assumed across the industry. No additional emissions were attributed to the use of bait, a key source of GHG emissions in some fisheries, such as those for American lobster (*Homarus americanus*),[60] in order to avoid double-counting, assuming that bait was sourced either from the fishing vessels themselves or from other fisheries already accounted for. Non-fuel-related emissions for non-motorized vessels were considered to be equivalent to the non-fuel-related emissions of their motorized counterparts, in order to account for emissions associated with vessels, gear and other inputs to those fisheries. Total fuel and non-fuel emission intensity of each fishing record were then calculated using equation (3)

$$G_{f,y} = \frac{3.3 F_{f,y} t_m + 1.1 F_{f,y} (t_m + t_n)}{(t_m + t_n)} \tag{3}$$

where $G_{f,y}$ is the total emissions from fishery f in year y, t_m is the tonnage landed by motorized vessels, t_n is the tonnage landed by non-motorized vessels.

National fishery GHG emissions were compared against agriculture and livestock emissions at a country level using data reported in the FAOSTAT Emissions Database[17]. All emissions associated with direct food production from agricultural and livestock production were included. Major sources of emissions included enteric fermentation (34% in 2011), application and management of manure (23%), on-farm energy use (13%) and use of synthetic fertilizers (11%). Emissions associated with the burning of savannah and shrubland (4%) were excluded as their primary function was not considered to be directly related to food production, and because their inclusion would have greatly expanded agricultural emissions in some countries in which burning is required for multiple reasons, such as fire prevention and forest regeneration. Important to note is that emissions associated with land use change are not included in the FAO dataset, so values here do not consider, for example, emissions that result from deforestation of land for soy or palm oil production.

For further investigation of the role of different sectors, species were grouped into six categories and then trends in catch, modelled GHG intensity and contribution to overall GHGs from the industry were assessed. Linear models within each category identified the extent to which overall emissions were influenced by changes in modelled FUI, rather than variation in the harvest alone. Multiple regression of global aggregate emissions relative to landings from each species category identified the effect of global catch composition on the overall emission estimate. Fishery landings by non-food sectors (for example, fishmeal, nutraceuticals and so on) were separated from fishery landings intended for human consumption, assuming 75% of non-food landings originated from fisheries targeting pelagic species under 60 cm in length. Reduction fisheries for meal and oil, in particular, were assumed to be sourced from fisheries targeting pelagic species under 60 cm in length, with the majority of products coming from small pelagic species such as Peruvian anchovy (*Engraulis ringens*), South American pilchard (*Sardinops sagax*), Gulf menhaden (*Brevoortia patronus*) and Atlantic herring (*Clupea harengus*). Country of origin for reduction fisheries was based on global fishmeal production data from the US Department of Agriculture[29] and production in Europe was further disaggregated based on the relative rate of small-pelagic harvests in European countries.

Comparisons of fishery emissions to livestock production systems were made on the basis of kg CO_2-eq emissions per kg of edible protein, including only those fisheries whose products were destined for human consumption in 2011. Landed weight of fish was translated to values per kg protein based on species-specific edible yields and protein content of flesh, with average values of 40 and 20%, respectively. An additional 0.5 kg CO_2-eq per kg of landed fish was added across all fisheries to account for post-landing emissions, including inputs to processing, packaging and transportation[15]. The resulting distribution of fishery-derived products by GHG emissions intensity was compared to the range of emissions from livestock LCAs[15], as well as values previously calculated for global trawl and non-trawl fisheries[9].

Data availability. The data that support the findings of this study are available from the corresponding author upon request. The global fisheries catch database used in this study is available from ref. [51].

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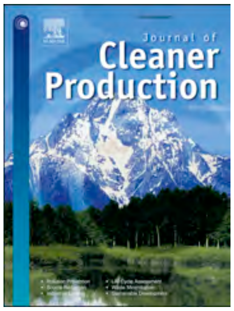
EXHIBIT J-7

Accepted Manuscript



Systematic review of greenhouse gas emissions for different fresh food categories

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PII: S0959-6526(16)30358-4

DOI: 10.1016/j.jclepro.2016.04.082

Reference: JCLP 7106

To appear in: *Journal of Cleaner Production*

Received Date: 7 July 2015

Revised Date: 23 February 2016

Accepted Date: 19 April 2016

Please cite this article as: Clune S, Crossin E, Verghese K, Systematic review of greenhouse gas emissions for different fresh food categories, *Journal of Cleaner Production* (2016), doi: 10.1016/j.jclepro.2016.04.082.

Systematic review of greenhouse gas emissions for different fresh food categories

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Journal of Cleaner Production

Type: review document

Word count: 10,328 excluding appendix and reference list.

Key words: streamlined LCA, food, sustainable diets, systematic review

Abstract

This paper presents the results of a systematic literature review of greenhouse gas emissions for different food categories from life cycle assessment (LCA) studies, to enable streamline calculations that could inform dietary choice. The motivation for completing the paper was the inadequate synthesis of food greenhouse gas emissions available in the public domain. The paper reviewed 369 published studies that provided 1,718 global warming potential (GWP) values for 168 varieties of fresh produce. A meta-analysis of the LCA studies was completed for the following categories: fresh vegetables (root vegetables, brassica, leaves and stems); fresh fruits, (pepo, hesperidium, true berries, pomes, aggregates fruits and drupes); staples (grains, legumes, nuts, seeds and rice); dairy (almond/coconut milk, soy milk, dairy milk, butter and cheese); non-ruminant livestock (chicken, fish, pork); and ruminant livestock (lamb and beef). The meta-analysis indicates a clear greenhouse gas hierarchy emerging across the food categories, with grains, fruit and vegetables having the lowest impact and meat from ruminants having the highest impact. The meta-analysis presents the median, mean, standard deviation, upper and lower quartile, minimum and maximum results for each food category. The resultant data enables streamline calculations of the global warming potential of human diets, and is illustrated by a short case study of an Australian family's weekly shop. The database is provided in the Appendix as a resource for practitioners. The paper concludes with recommendations for future LCA studies to focus upon with respect to content and approach.

1 Introduction

The consumption of food contributes to a significant proportion of a person's overall greenhouse gas impact (Dey et al., 2007), with agricultural production accounting for 19%–29% of global anthropogenic greenhouse gas emissions (Vermeulen et al., 2012). Consumers are also displaying 'a moderately high level of concern' for the sustainability with respect to food production (Grunert et al., 2014, p.187). Life cycle assessments (LCAs) of food ingredients and products provide the primary means to understand a food's environmental impact, discussed in this paper with specific respect to a food's Global Warming Potential (GWP)[1]. While a substantial number of food LCA studies have been completed, comparing food impacts to enable decision making with confidence is difficult at present for four reasons.

First, it is often cited that LCA results should not be compared (Desjardins et al., 2012; Foster et al., 2006; McAuliffe et al., 2016; Röös et al., 2013) due to variation in methodology choices, functional units, as well as temporal and regional differences[2]. Second, no single comprehensive review was identified that adequately covers the breadth of fresh foods available to consumers and caterers. As Helle et al. (2013, p.12643) state 'data availability and quality remain primary obstacles in diet-level environmental impact assessment', while Pulkkinen et al. (2015) calls for the creation of a database that communicates data quality, uncertainty and variability to reliably differentiate between the GWP of food types. Previous studies have compiled LCA data to compare different foods (e.g. Audsley et al., 2009; Berners-Lee et al., 2012; Bradbear and Friel, 2011; de Vries and de Boer, 2010; Foster et al., 2006; Nijdam et al., 2012; Sonesson et al., 2010; Roy et al., 2009). While these are useful attempts, the identified studies are inadequate in the coverage of fresh foods available. Environmental Product Declarations (EPDs) attempt to inform consumers of the environmental impacts (carbon, water and ecological footprint) of specific foods, however they also fall short in breadth of items covered at present. The most comprehensive attempt at carbon footprint labelling was performed by Tesco (2012), however failed to label key categories such as fresh fish, pork, lamb or beef before finishing in 2012 due to the scale of the labelling scheme and a lack of participation from other retailers (Head et al., 2013). Third, studies that do compare results may often present singular figures. Peters et al. (2010) and Röös et al. (2011) argue that a range of impacts should be reported from LCA's to better represent the variety of environmental impacts, as opposed to a singular figure. Finally, there is a lack of synthesised open access LCA data in the public domain available to consumers to inform decision-making.

Therefore this paper presents a systematic literature review and meta-analysis of food LCA studies in the last 15 years to assess the GWP of fresh food. This paper aims to utilise existing GWP values from a variety of LCA studies to generate a database that enables the streamline accounting for individual meals, diets, catering organizations, or nations. The collation and characterisation of data on the GWP values for different food categories is the focus of this paper. The meta-analysis identifies areas where there is strong agreement in the GWP values, a short case study on the use of the GWP data to assess diets is provided in the discussion section, prior to recommendations being provided on how future food LCA studies could be undertaken to enable more direct comparisons.

1. GWP values (represented as *kg* CO_2*-eq/kg* produce) was selected as an environmental indicator due to the global significance of climate change, and as a consistent metric reported in LCA studies. For example, Renouf and Fujita-Fimas (2013) identified that 92% of Australian food LCA's reported Greenhouse gas emissions. The Life Cycle Impact Assessment guidance flagship project of UNEP/SETAC suggest that the sensitivity of LCA results should be explored to metrics other than GWP, such as fine particulate matter emissions, land and water use, and biodiversity loss (Frischknecht et al., 2016). Using one indicator in GWP only is a limitation of the paper, expanding to include additional indicators is an area for further research.
2. These methodological differences are discussed later in the paper in section 4.1.

2 Method

2.1 Systematic review strategy

The systematic review was completed following the PRISMA Statement protocol to minimize the risk of bias, and increase scientific validity (Moher et al., 2009). The systematic literature search for food LCA studies was completed in February 2015 across three types of literature: peer reviewed scholarly journal papers; conference proceedings; and, EPDs (see Fig. 1). Searches for peer reviewed journals were completed in Sciencedirect using the key words 'LCA + food + CO2'. Conferences proceedings were reviewed from the international conference 'Life Cycle Assessment in the Agri-Food Sector' from 2010-2014. The EPD search was completed in Google using the key words 'environmental product declaration', carbon footprint and carbon label.

The initial studies reviewed identified additional studies for review by two mechanisms; first, scanning the document text and reference list for additional studies, and second, using the cited in function from Google scholar to identify relevant articles for review. Grey literature in the form of industry and government reports were identified through these two mechanisms. The inclusion of grey literature to avoid bias and ensure the systematic review is as thorough as possible is viewed as best practice (Blackhall, 2007). A limited number of targeted food searches were completed to identify foods that were absent. This was completed for almonds, cashews, peanuts, kangaroo, goat, turkey, ostrich, emu, rabbit, and quinoa.

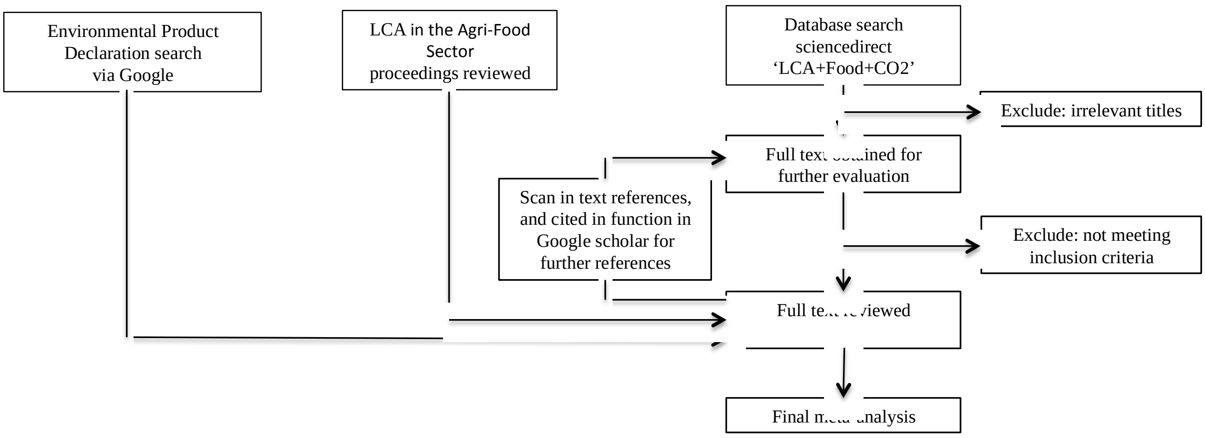

Figure 1 Systematic literature review process

Studies were included in the meta-analysis if they disclosed the LCA results in terms of CO_{2}-*eq*/mass unit for raw produce, and disclosed the system boundary, functional unit and location of production. Studies were excluded if results were only presented in alternative functional units such as eco-points, percentages, *kg* CO_{2}-*eq*/ha., live weight gain/year or *kg* CO_{2}-*eq*/protein. Studies were also excluded if they included cooking, air-freight or canning without disclosing the percentage that these activities accounted for as they significantly alter the results. For example fruit and vegetables studies that cited international airfreight added 9.5 to 10 *kg* CO_{2}-*eq/kg* to Milà i Canals et al.'s (2008) study of vegetables and 11 to 12.5 *kg* CO_{2}-*eq/kg* from Hofers (2009). Avoiding air freighted produce has been raised in previous studies and is not a focus of the paper (e.g Jungbluth et al., 2000).

2.2 Synthesizing results for comparison

GWP values from the reviewed studies were collated into a database under the following broad category headings: fresh fruits, vegetables and staples; dairy; non-ruminant livestock and ruminant livestock. In addition, data relating to the LCA method were collated including:

- Year of study
- Geographic location of study.
- Original system boundary
- LCA approach utilised (process based or economic input-output or hybrid LCA)
- Unique descriptors (e.g. species, feed type, farming methods etc.)

Each GWP value recorded was converted into a common functional unit and system boundary in kg $CO_{2\text{-}eq}$ /kg bone free meat (BFM) or produce, at the regional distribution centre (RDC).

2.2.1 Conversion of functional units to bone free meat

In LCA, the functional unit is the unit by which all environmental results are reported. The functional unit is typically based on the primary function that a product or service provides. Defining the functional unit for food can be challenging and as such, the functional units can vary between food studies. Functional units reviewed in this study for meat products included:

- Head of animals per year
- Kilogram Live Weight (LW)
- Kilogram Hot Standard Carcass Weight (HSCW)
- Kilogram Carcass Weight (CW)
- Kilogram edible meat from carcass or kg bone free meat (BFM)
- Kilogram of prime retail cut or chicken breast

To enable comparison, the GWP values for meat studies were converted to a common functional unit in kg $CO_{2\text{-}eq}$ /kg BFM. A significant variation in results can occur depending on the functional unit, particularly for meats. For example, only 43% of a live weight (LW) pig is edible meat (Sonesson et al., 2010). Table 1 illustrates the conversion ratios identified in the literature that were utilised to enable the conversions.

Table 1 Conversion of alternate functional units to bone free meat (BFM)

	Beef	Sheep	Pork	Chicken	Fish
Ratio Hot Standard Carcass Weight: Carcass Weight	1:0.98[a]	1:0.98[a]	NA	NA	NA
Ratio Live Weight: Bone Free Meat	1:0.485[b]	1:0.43[c]	1:0.43[d]	1:0.54[d]	1:0.625[e]
Ratio Carcass Weight: Bone Free Meat	1:0.695[f]	1:0.66[c]	1:0.59[d]	1:0.77[d]	

Sources:
a) Average from Pazdiora et al. (2013)
b) Extrapolated from Desjardins et al. (2012)
c) Average from Wilson and Edwards (2008), Liu and Ockerman (2001), and Young and Gregory (2001)
d) From Sonesson et al. (2010)
e) From Food and Agriculture Organization, Fisheries and Aquaculture Department (FAO 2013)
f) From U.S Department of Agriculture (USDA1992)

2.2.2 Accounting for variation in system boundaries

The system boundary used in the food LCA studies also varied, such as:

- Farm to farm gate

- Farm to slaughterhouse
- Farm to regional distribution centre (RDC)
- Farm to point of sale (retail)
- Farm to cooked in home
- Farm to human consumption and excretion

To enable comparison, the GWP values were converted to the system boundary of the Regional Distribution Centre. The system boundaries were recorded in the database. The packaging and transport median figures from Table 2 were added to studies where the system boundary finished at the farm gate.

Table 2 Post farm gate emissions identified from a sample of studies

Life cycle stage post-farm gate	Number of GWP values	Median *kg CO_2-eq/kg*	Mean *kg CO_2-eq/kg*	Stdev	Min *kg CO_2-eq/kg*	Max *kg CO_2-eq/kg*
Processing meats [a, b, c, d]	5	0.59	0.66	0.14	0.54	0.87
Processing vegetables [d, e, f,]	15	0.06	0.07	0.04	0.01	0.13
Packaging [a, c, d,]	8	0.05	0.06	0.06	0.01	0.21
Transport to RDC [a, b, c, d, e, f,]	21	0.09	0.13	0.19	0.02	0.95
Retail [a, b, d, e,]	20	0.04	0.10	0.25	0.01	1.14

Sources:
a) Eady et al. (2011)
b) Ledgard et al. (2010)
c) Bengtsson and Seddo (2013)
d) Svanes (2008)
e) Yoshikawa et al. (2008)
f) Lantmännen (2010)

The LCA studies typically analysed farm inputs from chemicals and fertilisers; fuel and energy inputs from irrigation and machinery for cultivation, harvesting and processing; and transport and refrigeration to the regional distribution centre. Outputs included emissions released from fertilised soils, plants and animals in fields (see Fig. 2). Nurseries for horticulture, while important are presented outside the simplified system boundary, as Cerutti et al.'s (2014) review stated only 3/19 studies included this stage. Most food LCA's also exclude infrastructure and capital goods (Mungkung and Gheewala, 2007; Roma et al., 2015). Infrastructure and capital goods are also excluded within PAS 2050 (BSI, 2011) and Gabi's LCA software model for Agriculture (Deimling and Rehl, 2016), and presented outside the simplified system boundary.

Human consumption, including how consumers travel to shops, store food, cook, dispose of food and packaging, and excrete were outside the scope of the study, and were excluded from entries entered into the database[3]. Fruits and vegetables that were grown in a greenhouse were analysed in a separate greenhouse category.

[3] The authors acknowledge that consumption, and end-of-life management of food and packaging will alter results. Of particular note is the 30% of purchased food that is not eaten, with a potential causal relationship to packaging design (see for example Wikström et al. 2014). This remains outside the scope of the study.

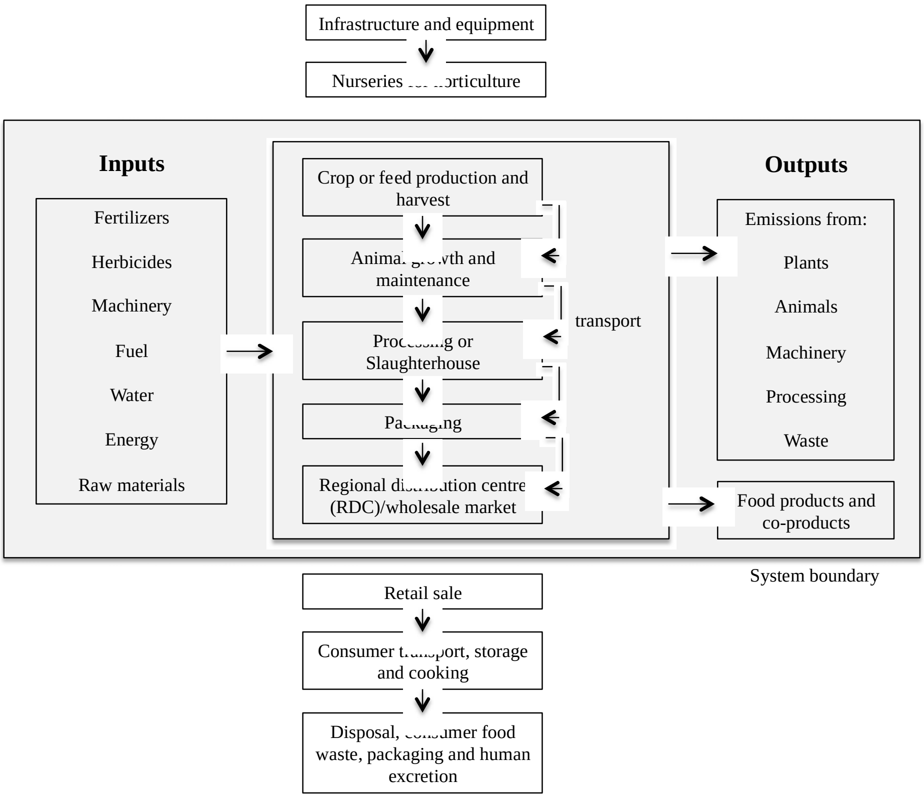

Figure 2 Simplified system boundary

2.3 Meta-analysis of data

The database (see Appendix) was analysed across each food category in Microsoft Excel to calculate statistics, including:

- Number of studies
- Number of GWP scenarios (one study may present multiple comparative results, all results were entered)
- Median, mean, standard deviation, upper and lower quartiles, minimum and maximum

Key statistics were represented schematically using box-whisker plots to assist in understanding the spread and interpretation of the data points. Further analysis was completed on food categories that had multiple data entries to check for correlation between GWP values and geographic locations, farming methods or species.

3 Results of systematic literature review on Food GWP values

3.1 Located literature

The meta-analysis cites 369 published LCA studies that provided 1,718 GWP values for fresh produce from the year 2000 to 2015. 192 journal papers, 80 conference papers, 64 reports (for industry and government), 29 web-based EPDs, and four theses were utilised in total. The majority of GWP values (58%) were from the last five years (see Fig. 3). It is of note that most studies produced multiple GWP values, for example the studies may compare different food types, growing regions, methodological choices or production methods.

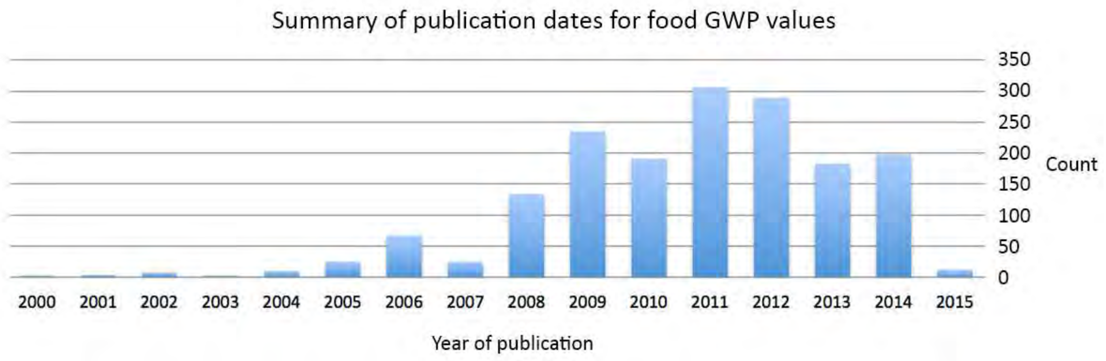

Figure 3 Summary of publication dates for food GWP values

Searching via Sciencedirect produced 3,355 results, the first 1,000 titles were scanned for relevance, of which 113 LCA studies were downloaded for review, 47 being directly used for analysis. Eight studies were used to mine citations. The initial 47 studies identified an additional 64 references to review, which in turn provided further references.

Conference papers from the proceeding from the 'Life Cycle Assessment in the Agri-Food Sector' conferences in 2014 (n = 33), 2012 (n = 20), and 2010 (n = 13) were reviewed. Ruini et al.'s (2014) conference paper 'LCA applied to sustainable diets' and accompanying database was significant in identifying a substantial number of conference and journal articles for review.

EPD studies (n = 29) were primarily identified through the 'international EPD system' webpage (EPD international, 2015) that provided 21 studies. Industry reports (grey literature, n = 64) were identified through in text citations in journal and conferences papers.

The identified literature was predominately European centric (see Fig. 4 and Table 3), with the British Isles (n = 245), and Europe (n = 930) accounting for 68% of the utilised GWP values (n = 1,175), followed by North America (n = 167) and Oceania (n = 143). Asia (n = 77), South America (74) and Africa (n = 23) were less represented. Within Europe, Spain (n = 187) France (n = 173), Sweden (n = 153) and the Netherlands (n = 139) were dominant.

Table 3 Location of food GWP values collated in the database

Region	**Number of recorded GWP values**
Europe	930
British Isles	245
Oceania (Australia and New Zealand)	143
North America	167
Asia	77
South America	74
World	39
Africa	23
Middle East	2
Other (no location specified for 'imported' products)	18
Total	**1718**

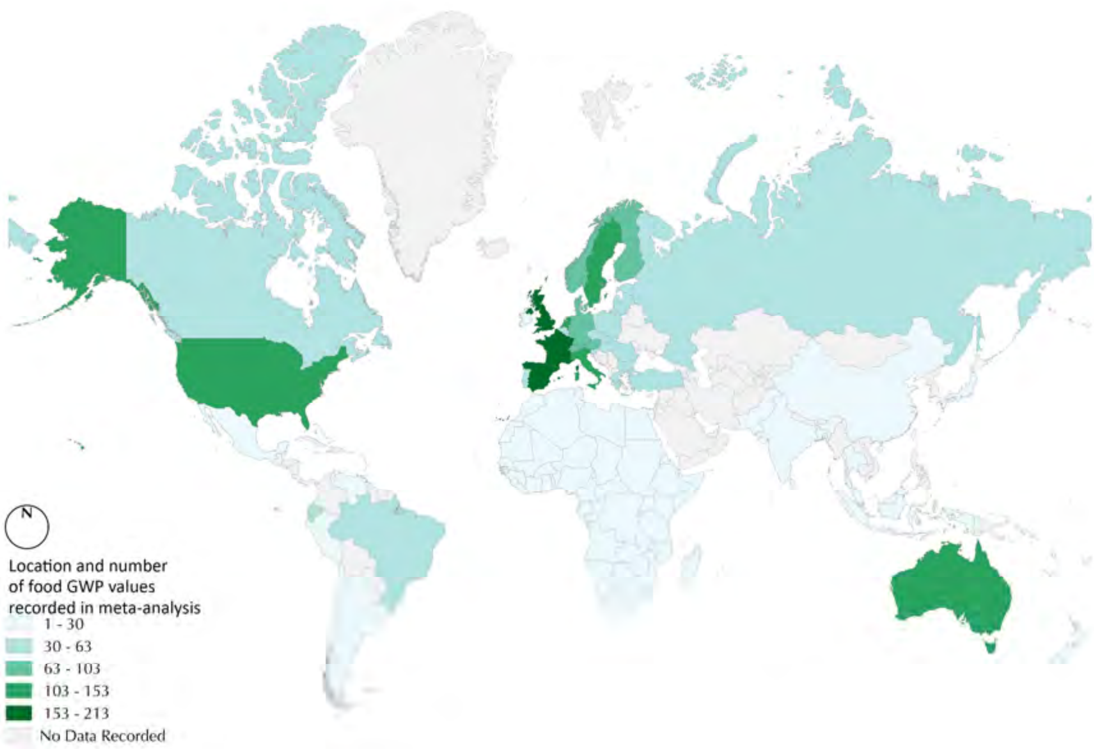

Figure 4 Location and number of food GWP values recorded from reviewed LCA studies

3.2 Overview of results between food categories

The summary of results for the GWP values recorded are presented in Fig. 5 and Table 4, they present a large variation in results between food categories. At the broadest level the lowest median GWP values were for field-grown vegetables (0.37 *kg CO_{2}-eq/kg*), field-grown fruit (0.42 *kg CO_{2}-eq/kg*), cereals (except rice) and pulses (0.50-0.51 *kg CO_{2}-eq/kg*). Slightly higher values for tree nuts were found (1.20 *kg CO_{2}-eq/kg*). Rice had the highest impact of the plant based field grown crops (2.55 *kg CO_{2}-eq/kg*), slightly higher than fruit and vegetables from heated greenhouses (2.13 *kg CO_{2}-eq/kg*).

Non-Ruminant livestock had medium GWP values in fish (3.49 *kg kg CO_{2}-eq/kg BFM*), chicken (3.65 *kg CO_{2}-eq/kg BFM*) and pork (5.77 *kg CO_{2}-eq/kg BFM*). Dairy products (cheese) and butter also shared a medium GWP values.

Ruminant livestock in lamb (25.58 *kg CO_{2}-eq/kg BFM*) and beef (26.61 *kg CO_{2}-eq/kg BFM*) had the highest median GWP values.

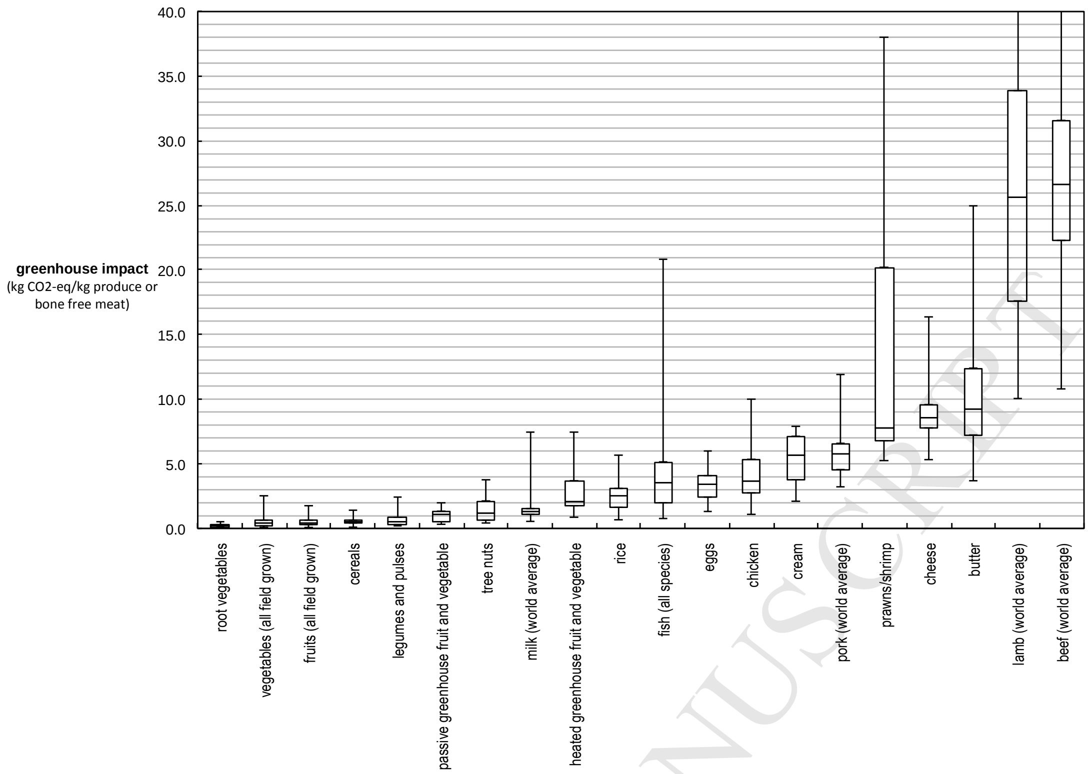

Figure 5 Summary of GWP values (*kg CO_2.eq/kg* produce or bone free meat) across broad food categories

Table 4 Summary of GWP values (*kg CO_2.eq/kg* produce or bone free meat) across broad food categories

Name	**Median**	**Mean**	**Stdev**	**Deviation from mean**	**Min**	**Max**	**Q1**	**Q3**	**No. of LCA studies**	**No. of GWP values**
Vegetables (all field grown vegetable)	0.37	0.47	0.39	83%	0.04	2.54	0.19	0.60	33	140
Fruits (all field grown fruit)	0.42	0.50	0.32	64%	0.08	1.78	0.28	0.63	77	250
Cereals	0.50	0.53	0.22	42%	0.11	1.38	0.38	0.63	31	90
Legumes and Pulses	0.51	0.66	0.45	67%	0.15	2.46	0.36	0.83	16	51
Passive greenhouse fruit and vegetable	1.10	1.02	0.49	48%	0.32	1.94	0.54	1.35	5	15
Tree nuts combined	1.20	1.42	0.93	66%	0.43	3.77	0.61	2.13	7	21
Milk world average	1.29	1.39	0.58	41%	0.54	7.50	1.14	1.50	77	262
Heated greenhouse fruit and vegetable	2.13	2.81	1.61	57%	0.84	7.4	1.74	3.7	18	53
Rice	2.55	2.66	1.29	48%	0.66	5.69	1.64	3.08	12	27
Eggs	3.46	3.39	1.21	36%	1.30	6.00	2.45	4.05	19	38
Fish: all species combined	3.49	4.41	3.62	82%	0.78	20.86	1.99	5.16	47	148
Chicken	3.65	4.12	1.72	42%	1.06	9.98	2.77	5.31	29	95
Cream	5.64	5.32	1.62	31%	2.10	7.92	3.82	7.14	3	4
Pork: world average	5.77	5.85	1.63	28%	3.20	11.86	4.50	6.59	38	130
Prawns/shrimp	7.80	14.85	12.37	83%	5.25	38.00	6.76	20.20	7	11
Cheese	8.55	8.86	2.07	23%	5.33	16.35	7.79	9.58	22	38
Butter	9.25	11.52	7.37	64%	3.70	25.00	7.28	12.41	4	8
Lamb: world average	25.58	27.91	11.93	43%	10.05	56.70	17.61	33.85	22	56
Beef: world average	26.61	28.73	12.47	43%	10.74	109. 5	22.26	31.57	49	165

Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and references

This initial broad overview identifies a clear hierarchy within the GWP values. The above categories are presented in detail in the sub-sections below to identify further trends in the data. Details of the GWP values for individual foods from lowest to highest median values are presented in Table 5.

Table 5 Individual GWP values (*kg CO_{2}-eq/kg* produce or bone free meat) from low to high

Name	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Onion	0.17	0.18	0.11	60%	0.06	0.37	0.10	0.21	7	9
Celery	0.18								1	1
Potatoes	0.18	0.20	0.08	41%	0.08	0.36	0.16	0.26	16	25
Carrots	0.20	0.22	0.15	65%	0.04	0.50	0.11	0.31	10	13
Zucchini/button squash	0.21	0.42	0.50	121%	0.09	1.17	0.16	0.46	3	4
Cucumber/gherkins	0.23	0.33	0.32	96%	0.13	1.30	0.19	0.31	7	15
Beetroot	0.24	0.23	0.11	50%	0.11	1.61	0.18	0.29	2	3
Pumpkins	0.25	0.33	0.25	74%	0.15	0.73	0.16	0.37	4	8
Rockmelon/cantelope	0.25								1	1
Beans: plake	0.26	0.30	0.12	38%	0.22	0.43	0.24	0.35	1	3
Lemons and limes	0.26	0.30	0.06	19%	0.18	0.45	0.22	0.35	2	3
Mushrooms	0.27	0.27	0.29	110%	0.06	0.48	0.16	0.37	3	2
Guavas	0.28								1	1
Apples	0.29	0.36	0.19	53%	0.18	0.89	0.21	0.47	21	33
Swedes/rutabage	0.29								1	1
Pears	0.31	0.33	0.13	41%	0.19	0.63	0.27	0.33	4	8
Quinces	0.31	0.31	0.01	5%	0.30	0.32	0.31	0.32	2	2
Beans: green	0.31	0.51	0.47	93%	0.24	1.55	0.26	0.46	4	7
Watermelons	0.32	0.32	0.09	29%	0.25	0.38	0.28	0.35	2	2
Dates	0.32								1	1
Orange	0.33	0.35	0.12	34%	0.18	0.59	0.25	0.45	9	20
Kiwi fruit	0.36	0.47	0.26	55%	0.15	0.88	0.29	0.68	5	9
Cauliflowers and broccoli	0.36	0.35	0.06	17%	0.28	0.42	0.32	0.39	4	4
Grapes	0.37	0.41	0.25	60%	0.15	0.88	0.31	0.41	5	6
Oats	0.38	0.44	0.12	26%	0.38	0.67	0.38	0.45	4	6
Rye	0.38	0.41	0.07	17%	0.36	0.49	0.37	0.44	2	3
Peas	0.38	0.60	0.77	128%	0.15	2.46	0.21	0.50	6	8
Cherries	0.39	0.48	0.40	83%	0.26	0.88	0.31	0.56	2	4
Beans: gigante/butter	0.39	0.36	0.09	25%	0.26	0.43	0.32	0.41	1	3
Almond/coconut milk	0.42	0.42	0.03	8%	0.39	0.44	0.39	0.44	1	4
Peaches and Nectarines	0.43	0.54	0.24	44%	0.38	0.81	0.41	0.62	3	3
Figs	0.43								1	1
Barley	0.43	0.49	0.24	49%	0.11	0.98	0.34	0.60	7	13
Apricot	0.43								1	1
Chestnuts	0.43								1	1
Beans	0.43	0.62	0.45	73%	0.22	1.55	0.26	0.72	11	22
Mandarin	0.45								1	1
Tomatoes	0.45	0.46	0.18	39%	0.08	1.00	0.35	0.55	19	56
Maize/corn	0.47	0.63	0.38	60%	0.40	1.38	0.42	0.61	6	6
Fennel	0.48								1	1
Artichokes	0.48								1	1
Cowpeas	0.49	0.48	0.13	28%	0.33	0.61	0.40	0.57	1	4
Soybean	0.49	0.58	0.04	6%	0.38	0.96	0.44	0.62	2	4
Pineapples	0.50	0.72	0.53	74%	0.40	1.78	0.45	0.64	5	6
Melons	0.51	0.88	0.01	2%	0.30	1.74	0.32	1.55	4	5
Grapefruit and pomelo	0.51								2	1
Tangerines/mandarins	0.51								1	1
Tomatoes: passive greenhouse	0.51	0.67	0.34	51%	0.32	1.28	0.44	0.86	5	8
Wheat	0.52	0.51	0.17	33%	0.18	1.10	0.40	0.60	20	51
Spinach	0.54	0.54	0.51	95%	0.18	0.91	0.36	0.73	2	2
Garlic	0.57								1	1
Strawberries	0.58	0.65	0.36	55%	0.20	1.50	0.37	0.84	15	21
Broccoli	0.60	0.70	0.34	48%	0.37	1.73	0.49	0.70	6	17
Olives	0.63	0.56	0.22	38%	0.22	0.85	0.52	0.66	4	8
Capsicums/peppers	0.66	0.60	0.27	44%	0.23	0.87	0.55	0.71	3	4
Beans: pinto USA dried	0.73								1	1

Soy-milk	0.75	0.88	0.27	31%	0.66	1.40	0.70	0.98	2	8
Beans: french and runner	0.75	0.85	0.37	44%	0.52	1.37	0.63	0.97	1	4
Chick peas	0.77	0.67	0.19	29%	0.45	0.80	0.61	0.79	2	3
Asparagus	0.83	0.92	0.49	53%	0.18	2.54	0.60	1.05	5	28
Peanuts	0.83	0.87	0.11	13%	0.80	1.10	0.81	0.87	3	6
Raspberries	0.84								2	1
Currants and gooseberries	0.84								1	1
Sesame seed	0.88								1	1
Ginger	0.88								1	1
Cranberries/blueberries	0.92	0.92	0.07	8%	0.86	0.97	0.89	0.94	2	2
Hazelnuts	0.97	0.97	0.76	78%	0.43	1.50	0.70	1.23	2	2
Ground nuts	0.99	0.99	0.48	49%	0.65	1.33	0.82	1.16	2	2
Lentils	1.03	1.03	0.04	4%	1.00	1.06	1.02	1.05	2	2
Pilchard	1.10	1.10	0.45	41%	0.78	1.41	0.94	1.26	2	2
Peppers: passive and heated greenhouse	1.10	1.08	0.17	16%	0.90	1.25	1.00	1.17	2	3
Quinoa	1.15	1.15	0.07	6%	1.10	1.20	1.13	1.18	2	2
Herring	1.16	1.17	0.17	15%	0.98	1.39	1.09	1.25	3	4
Milk: world average	1.29	1.39	0.58	41%	0.54	7.50	1.14	1.50	77	262
Avocados	1.30								2	1
Yoghurt	1.31	1.43	0.25	18%	1.17	2.00	1.28	1.48	7	11
Eggplants (aubergines)	1.35	1.35	0.07	5%	1.30	1.40	1.33	1.38	1	2
Sunflower seed	1.41								1	1
Cashew nut	1.44	1.55	0.85	55%	1.06	2.27	1.29	1.70	3	4
Melons: passive greenhouse	1.43	1.37	0.11	8%	1.24	1.43	1.33	1.43	1	3
Walnuts	1.51	1.62	1.13	70%	0.50	2.94	1.32	2.54	3	4
Pistachios	1.53	1.53	0.91	60%	0.88	2.17	1.20	1.85	1	2
Almonds	1.54	1.74	1.25	72%	0.51	3.77	0.76	2.33	4	6
Pollock	1.60	1.65	0.47	29%	1.20	2.14	1.40	1.87	2	3
Strawberries: heated greenhouse	1.64	2.56	2.32	91%	0.84	5.20	1.24	3.42	3	3
Carp	1.76	1.80	0.11	6%	1.73	1.93	1.74	1.84	1	3
Zucchini: passive greenhouse	1.77	1.77	0.24	13%	1.60	1.94	1.69	1.86	1	2
Mackerel	1.80	2.00	1.08	54%	0.94	4.50	1.30	2.40	9	21
Rape and mustard seed	2.09								1	1
Cucumbers and gherkins: heated greenhouse	2.10	2.23	0.71	17%	1.68	3.79	1.89	2.12	5	7
Tuna	2.15	2.60	1.45	56%	1.39	6.32	1.75	2.68	4	10
Tomatoes: heated greenhouse	2.20	2.69	1.36	51%	0.92	6.12	1.86	3.65	13	33
Rice	2.55	2.66	1.29	48%	0.66	5.69	1.64	3.08	12	27
Whiting	2.66	2.66	1.59	60%	1.54	3.79	2.10	3.22	2	2
Duck	3.09	3.09	1.44	47%	2.07	4.10	2.58	3.59	2	2
Sea bass	3.27	3.55	1.63	46%	1.91	5.76	2.68	4.14	2	4
Haddock	3.41	3.37	0.08	3%	2.80	3.84	3.03	3.75	2	4
Eggs	3.46	3.39	1.21	36%	1.30	6.00	2.45	4.05	19	38
Salmon	3.47	3.76	1.47	39%	2.04	8.33	2.88	4.13	9	21
Fish: all species	3.49	4.41	3.62	82%	0.78	20.86	1.99	5.16	47	148
Cod	3.51	3.49	1.31	37%	1.58	5.38	2.25	4.50	10	16
Buffalo milk	3.57	3.75	0.86	23%	2.87	5.20	3.14	4.18	1	7
Chicken	3.65	4.12	1.72	42%	1.06	9.98	2.77	5.31	29	95
Lettuce: heated greenhouse	3.70	3.15	1.64	52%	1.30	4.73	1.50	4.51	3	5
Eel	3.88								1	1
Kangaroo	4.10								1	1
Trout	4.20	3.73	1.13	30%	1.37	5.95	3.11	4.33	9	20
Rabbit	4.70	4.70	1.24	26%	3.82	5.58	4.26	5.14	2	2
Cream	5.64	5.32	1.62	31%	2.10	7.92	3.82	7.14	3	4
Pork: world average	5.77	5.85	1.63	28%	3.20	11.86	4.50	6.59	38	130
Ling common	6.45	6.45	4.69	73%	3.13	9.77	4.79	8.11	2	2
Pomfret	6.63	6.63	4.44	67%	3.49	9.77	5.06	8.20	2	2
Rock fish	6.94								1	1
Octopus/squid/cuttlefish	7.13	8.07	2.40	30%	6.39	11.61	6.78	8.42	3	4
Prawns/shrimp	7.80	14.85	12.37	83%	5.25	38.00	6.76	20.20	7	11
Turkey	7.17	6.04	0.66	11%	3.34	8.49	3.82	7.83	3	7
Diamond fish	8.33	8.33	3.27	39%	6.02	10.65	7.17	9.49	2	2
Rhombus	8.41								1	1

Cheese	8.55	8.86	2.07	23%	5.33	16.35	7.79	9.58	22	38
Butter	9.25	11.52	7.37	64%	3.70	25.00	7.28	12.41	4	8
Mussels	9.51	7.54	4.93	65%	1.92	13.90	2.54	9.84	3	5
Hake	9.77	8.98	3.93	44%	2.14	14.15	7.07	11.32	5	7
Porbeagle	11.44								1	1
Shark mako	11.50	11.50	0.09	1%	11.44	11.56	11.47	11.53	2	2
Anglerfish	12.29	12.29	2.63	21%	10.43	14.15	11.36	13.22	2	2
Swordfish	12.84	12.84	1.98	15%	11.44	14.24	12.14	13.54	2	2
Megrim	14.15								1	1
Turbot	14.51	14.51	6.91	48%	9.63	19.40	12.07	16.96	2	2
Sole	20.86								1	1
Lamb: world average	25.58	27.91	11.93	43%	10.05	56.70	17.61	33.85	22	56
Beef: world average	26.61	28.73	12.47	43%	10.74	109.3	22.26	31.57	49	165
Lobster	27.80	21.74	11.7	56%	7.62	28.30	17.71	28.05	3	2
Buffalo	60.43	62.59	20.35	33%	28.78	100.7	43.88	79.14	1	4
Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and references. All fruit and vegetables field grown unless stated, passive greenhouse has no auxiliary heating										

3.3 Fresh Fruit, Vegetables and Staples

The meta-analysis for the fruit and vegetable category is drawn from 122 LCA studies that generated 633 GWP values. Typical processes for the fresh vegetable category include farm inputs from chemicals and fertilisers, fuel and energy inputs from irrigation and machinery for cultivation, harvesting and processing, and transport and refrigeration to the regional distribution centre. Outputs included nitrogen released from fertilised soils and emissions released from plants and fields. Maraseni et al. (2010) for example identified on-farm emissions related on average to: energy used for irrigation (54%), Nitrogen emissions from soils after N-fertiliser (17%), energy use for post-harvest storage (11%), fertiliser input (10%) and machinery and fuel use (8%). The size of the farm (Milà i Canals et al., 2008), species requirement for fertiliser use (i.e. beans) or processing (i.e. asparagus) assist to explain the variations between and within the fruit and vegetable category.

The analysis attempts to identify the values for individual foods (Table 5) as well as trends across the data. The fresh fruits and vegetables results were analysed further in four broad categories: vegetables, fruits, staples and greenhouse fruit and vegetables. These four categories were broken down further into botanical classifications in an attempt to identify key trends within the data, presented below in Table 6 and Fig. 6.

Table 6 Fruit, vegetable and staples GWP values (*kg CO_2-eq/kg* produce)

Group	Classification	Foods included	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values[a]
Vegetables field grown	Brassica	Cabbages, other brassicas	0.23	0.32	0.30	94%	0.12	0.64	0.22	0.38	4	5
	Bulbs, roots and tubers	Onions, garlic, beetroot, swedes and carrots	0.18	0.21	0.12	55%	0.04	0.57	0.14	0.29	21	53
	Leaves	Varieties of lettuce	0.37	0.38	0.14	38%	0.13	0.62	0.27	0.46		26
	Vegetables	Vegetables (all field grown vegetable)	0.37	0.47	0.39	83%	0.04	2.54	0.19	0.60	33	140
	Stem shoots	Asparagus	0.83	0.92	0.49	53%	0.18	2.54	0.60	1.05	5	28
	Brassica	Broccoli and cabbage	0.50	0.57	0.33	58%	0.12	1.73	0.38	0.69	1	26
Fruits field grown	Pome	Apples, pears and quinces	0.29	0.34	0.18	52%	0.18	0.89	0.22	0.38	22	40
	Pepo	Fruit of the gourd family including cucumber, gherkins, zucchini, papaya and melons etc	0.30	0.34	0.29	85%	0.08	1.30	0.18	0.32	13	32
	Hesperidium	Fruits of the citrus family including oranges, mandarins, lemons and limes	0.33	0.35	0.12	34%	0.22	0.59	0.25	0.46	10	28
	Fruit	Fruits (all field grown fruit)	0.42	0.50	0.32	64%	0.08	1.78	0.28	0.63	77	250

	Drupe	Stones fruits including cherries, dates, plumbs, apricots, peach, olives, and coconuts.	0.45	0.57	0.36	63%	0.22	1.78	0.32	0.67	1	19
	Multiple fruit	Pineapples and figs	0.45	0.68	0.50	73%	0.40	1.78	0.44	0.61	5	7
	True berry	Tomatoes, grapes, avocado, peppers, kiwi fruits, guava etc.	0.45	0.52	0.26	50%	0.08	1.40	0.35	0.66	24	83
	Aggregate fruit	Strawberries and raspberries	0.60	0.66	0.35	53%	0.20	1.50	0.38	0.84	15	22
	Musa	Bananas	0.72	0.79	0.30	38%	0.42	1.37	0.48	1.04	10	17
Staples	Cereal	Barley, maize, oats, rye, corn and wheat	0.50	0.53	0.22	42%	0.11	1.38	0.38	0.63	31	90
	Legume	Peas, beans, peanuts, ground nuts, and lentils	0.51	0.66	0.45	67%	0.15	2.46	0.36	0.83	16	51
	Tree nuts	Chestnuts, almonds, hazelnuts, palm nuts-kernels, pistachios, cashew nuts and walnuts	1.20	1.42	0.93	66%	0.43	3.77	0.61	2.13	7	21
	Seeds	Rapeseed (canola), mustard seed, sesame seed and sunflower seed	1.41	1.46	3.70	61%	0.88	2.09	1.15	1.75	1	3
	Cereal	Rice	2.55	2.66	1.29	48%	0.66	5.69	1.64	3.08	12	27
Greenhouse Fruit and vegetables[c]	No auxiliary heating (passive)	Melons, peppers, tomatoes and zucchini	1.10	1.02	0.49	48%	0.32	1.94	0.54	1.35	5	15
	Natural gas heated greenhouse	Lettuce, strawberries and tomatoes	2.07	2.58	1.35	52%	1.16	5.90	1.72	2.88	8	25
	Fuel/oil heated greenhouse	Cucumbers, lettuce, peppers and tomatoes	2.82	2.77	1.17	42%	0.90	4.51	2.01	3.65	3	8
	LPG heated greenhouse	Tomatoes	3.40	2.59	0.42	16%	3.10	3.70	3.25	3.55	2	2
	Average from all heated greenhouse[b]	Cucumber, melons, lettuce, peppers, strawberries, raspberries, tomatoes and zucchini	2.13	2.81	1.61	57%	0.84	7.4	1.74	3.7	18	53

Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and full references.

a) The number of LCA studies and GWP values column from table 5 does not correlate to tables 6, 7 and 8, as one LCA study may provide multiple GWP values for multiple food categories, or provide a singular GWP value for multiple food types e.g. ‘apples and pears’ (counted as separate GWP values under apples, and pears in table 5, and once only as Pome in table 6).

b) The ‘average from all heated greenhouse’ includes LCA values for heating generated by natural gas, oil, LPG, coal, electricity, and CHP, as well as 14 GWP values that came from studies with an unspecified heating source.

c) Fruit and vegetables grown in different greenhouses in the above table is indicative only of reviewed studies, and not what may be grown in different green house types.

The broad level GWP values within the fruits and vegetables see root vegetables with the lowest median value in 0.18 *kg CO_{2}-eq/kg*, field-grown vegetables (0.37 *kg CO_{2}-eq/kg*), field-grown fruit (0.42 *kg CO_{2}-eq/kg*), cereals (except rice) (0.50 *kg CO_{2}-eq/kg*) and pulses (0.51 *kg CO_{2}-eq/kg*). Slightly higher values were found for tree nuts (1.20 *kg CO_{2}-eq/kg*) and seeds (1.41 *kg CO_{2}-eq/kg*). Rice had the highest impact of the plant based filed grown crops (2.55 *kg CO_{2}-eq/kg*). The meta-analysis presents further granularity within the results with minor variations between the botanical classifications, however the majority fall within a narrow band of median figures from 0.29-0.60 *kg CO_{2}-eq/kg* for pome, pepo, leaves, brassica, hesperidium, drupes, multiple fruits, grains, legumes, true berries, and aggregate fruits. This band is small in comparison to the variation in results in the livestock groups. Figures for musa (bananas) would likely join this grouping, however most studies noted production in South America, and shipping to a RDC in Europe (e.g. Iriarte et al., 2014; Lescot, 2012). The number of studies utilised for seeds were under represented and draw on one study only by Audsley et al. (2009).

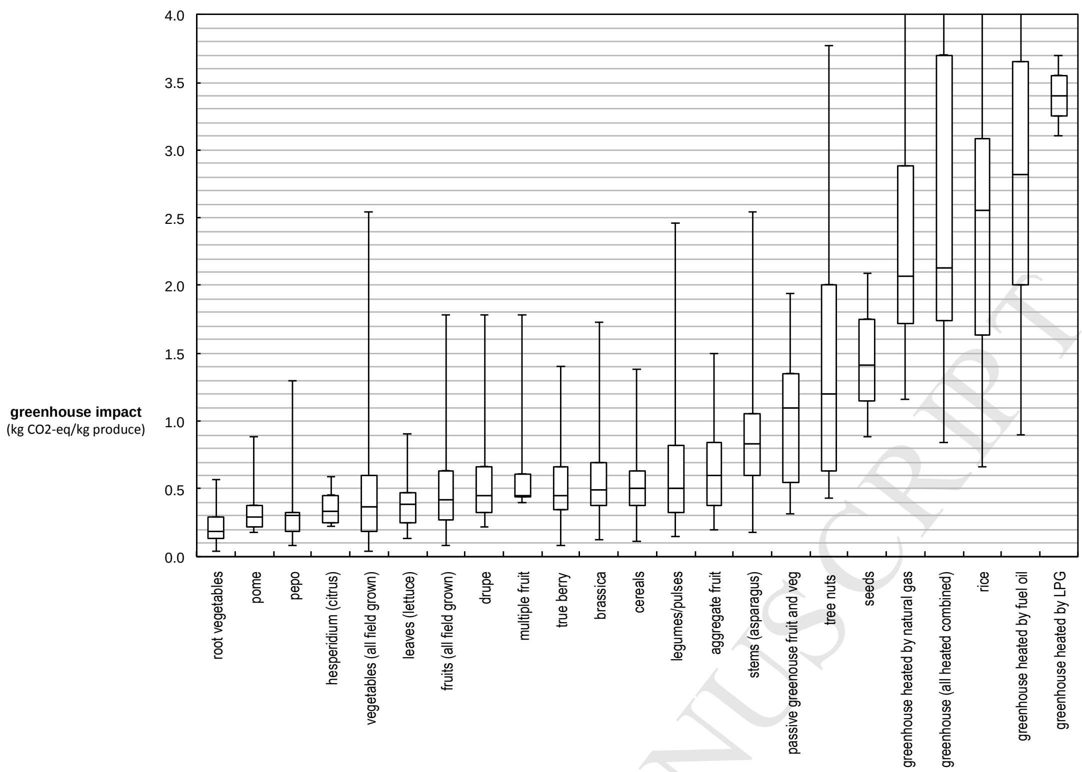

Figure 6 Comparisons of synthesized GWP values across fruit, vegetables and staples classifications

Greenhouse fruit and vegetables from heated greenhouses were notably higher than field-grown equivalents, with a median of 2.13 *kg* $CO_{2\text{-}eq}$*/kg*. Passive greenhouses with no auxillary heating had GWP figures comparable with the upper quartile of some field grown fruit and vegetables (1.10 *kg* $CO_{2\text{-}eq}$*/kg*). The energy source used to heat the greenhouse, local climate and the thermal efficiency of the greenhouse has an impact on the GWP values (e.g. Page et al., 2012; Torrellas et al., 2012), as heating is responsible for the majority of greenhouse gas emissions in heated greenhouses (Boulard et al., 2011).

3.4 Non-ruminant livestock: fish, poultry and pork

The non-ruminant livestock category analysed LCA studies including fish, poultry and pork. 108 LCA studies were reviewed resulting in 446 GWP values. Processes for non-ruminant livestock typically include breeding, feed production, fertiliser use, farm/broiler energy use including heating, as well as transport, processing and refrigeration. Farmed fish share largely these same processes, while wild fish processes largely relate to fuel consumption and emissions from refrigeration during the catch. The results of the non-ruminant livestock category are presented in Table 7 and Figure 7.

Table 7 Non-ruminant livestock: fish, poultry and pork GWP values (*kg* $CO_{2\text{-}eq}$***/kg bone free meat*)**

Classification	Foods included	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Fish	Pilchard	1.10	1.10	0.45	41%	0.78	1.41	0.94	1.26	2	2
	Herring	1.16	1.17	0.17	15%	0.98	1.39	1.09	1.25	3	4
	Pollock	1.60	1.65	0.47	29%	1.20	2.14	1.40	1.87	2	3
	Carp	1.76	1.80	0.11	6%	1.73	1.93	1.74	1.84	1	3
	Mackerel	1.80	2.00	1.08	54%	0.94	4.50	1.30	2.40	9	21
	Tuna	2.15	2.60	1.45	56%	1.39	6.32	1.75	2.68	4	10
	Whiting	2.66	2.66	1.59	60%	1.54	3.79	2.10	3.22	2	2

	Sea bass	3.27	3.55	1.63	46%	1.91	5.76	2.68	4.14	2	4
	Haddock	3.41	3.37	0.08	3%	2.80	3.84	3.03	3.75	2	4
	Salmon	3.47	3.76	1.47	39%	2.04	8.33	2.88	4.13	9	21
	Fish (all species)	3.49	4.41	3.62	82%	0.78	20.86	1.99	5.16	47	148
	Cod	3.51	3.49	1.31	37%	1.58	5.38	2.25	4.50	10	16
	Trout	4.20	3.73	1.13	30%	1.37	5.95	3.11	4.33	9	20
	Diamond fish	8.33	8.33	3.27	39%	6.02	10.65	7.17	9.49	2	2
	Ling common	6.45	6.45	4.69	73%	3.13	9.77	4.79	8.11	2	2
	Pomfret	6.63	6.63	4.44	67%	3.49	9.77	5.06	8.20	2	2
	Octopus, squid, cuttlefish	7.13	8.07	2.40	30%	6.39	11.61	6.78	8.42	3	4
	Hake	9.77	8.98	3.93	44%	2.14	14.15	7.07	11.32	5	7
	Shark mako	11.50	11.50	0.09	1%	11.44	11.56	11.47	11.53	2	2
	Anglerfish	12.29	12.29	2.63	21%	10.43	14.15	11.36	13.22	2	2
	Swordfish	12.84	12.84	1.98	15%	11.44	14.24	12.14	13.54	2	2
	Turbot	14.51	14.51	6.91	48%	9.63	19.40	12.07	16.96	2	2
Shellfish	Prawns, shrimp	7.80	14.85	12.37	83%	5.25	38.00	6.76	20.20	7	11
	Mussels	9.51	7.54	4.93	65%	1.92	13.90	2.54	9.84	3	5
	Lobster	27.80	21.74	11.7	56%	7.62	28.30	17.71	28.05	3	2
Poultry	Duck	3.09	3.09	1.44	47%	2.07	4.10	2.58	3.59	2	2
	Eggs	3.46	3.39	1.21	36%	1.30	6.00	2.45	4.05	19	38
	Chicken	3.65	4.12	1.72	42%	1.06	9.98	2.77	5.31	29	95
	Turkey	7.17	6.04	0.66	11%	3.34	8.49	3.82	7.83	3	7
Rabbit	Rabbit	4.70	4.70	1.24	26%	3.82	5.58	4.26	5.14	2	2
Kangaroo	Kangaroo	4.1								1	1
Pork	Pork EU	5.39	5.60	1.51	27%	3.20	10.25	4.31	6.45	24	91
	Pork world average[a]	5.74	5.85	1.63	28%	3.20	11.86	4.50	6.60	38	129
	Pork Nth America	6.00	6.24	1.46	23%	4.30	8.53	4.97	7.58	6	9
	Pork UK	6.11	5.57	1.13	20%	3.50	6.92	4.54	6.34	5	13
	Pork AU	7.65	7.12	1.81	25%	3.90	9.49	5.83	8.46	3	11

Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and full references.

a) Pork world average includes one additional LCA value from Asia, two from South America and two unspecified world figures.

Fish and chicken had similar median GWP values, 3.49 *kg CO_{2}-eq/kg BFM* for all species of fish and 3.65 *kg CO_{2}-eq/kg BFM* for chicken. The world average for pork was slightly higher with 5.77 *kg CO_{2}-eq/kg BFM*. Within this data, a large variation in results were identified and further analysed by segregating individual species of fish, and the geographic location of pork production.

The analysis of fish was further broken down between different species of fish (see figure 5). Within the results of specific species of fish, pilchards, pollock, carp, herring and mackerel presented low GWP values comparable with some plant based categories in tree-nuts and rice. Medium values were identified for salmon, cod and trout, while hake, anglerfish, swordfish and turbot had high GWP values. The higher values are for species caught offshore by trawling and long line fishing fleets that have significantly higher fuel consumption than coastal fishing fleets (Iribarren et al., 2010a; Iribarren et al., 2010b; Vázquez-Rowe et al., 2012; Vázquez-Rowe et al., 2010). Shell-fish in prawn and shrimps displayed very high variations in GWP values, while lobster had the highest median GWP value in the category with a median value of 27.80 *kg CO_{2}-eq/kg BFM*, which is in part due to the high cost of lobster and the economic allocation method used (Iribarren et al., 2010b).

Chicken (3.65 *kg CO_{2}-eq/kg BFM)* and eggs (3.46 *kg CO_{2}-eq/kg eggs)* displayed similar median values. The type of protein used as feed (Pelletier et al., 2013) and farming methods

(Bengtsson and Seddon, 2013; Leinonen et al., 2012) have previously been identified as significant indicators of GWP values for chicken.

With respect to pork, a notable variation in GWP values was evident when geography was considered, with European pork displaying a lower median value (5.50 *kg* $CO_{2\text{-}eq}$*/kg BFM*) than the UK (6.00 *kg* $CO_{2\text{-}eq}$*/kg BFM*), North America (6.11 *kg* $CO_{2\text{-}eq}$*/kg BFM)*, and Australia (7.65 *kg* $CO_{2\text{-}eq}$*/kg BFM)*.

Limited GWP values were identified for duck, turkey, rabbit, and kangaroo. Therefore comparison with other food groups should be viewed tentatively, however the results are consistent with mid range figures for non-ruminant livestock.

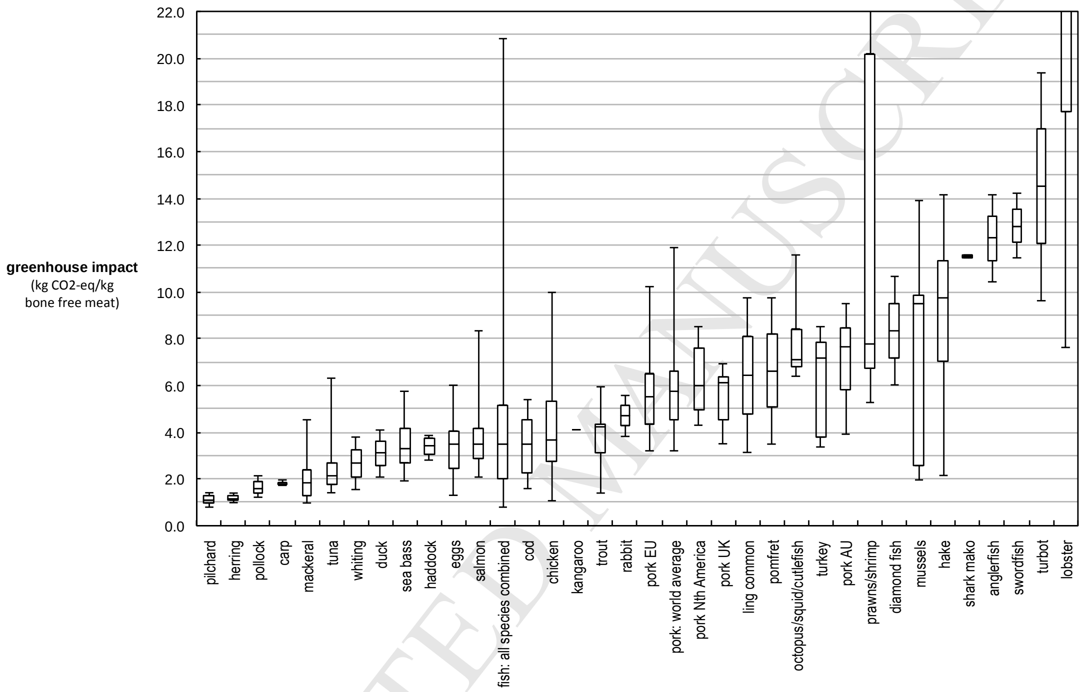

Figure 7 Comparisons of synthesized GWP values (*kg* $CO_{2\text{-}eq}$*/kg* bone free meat) for non-ruminant livestock (fish, poultry and pork)

3.5 Ruminant Livestock: Lamb and Beef

The ruminant livestock category included lamb, beef and buffalo and was compiled from 64 LCA studies resulting in 230 GWP values. The farm processes included inputs associated with breeding, feed production, fertiliser use, farm energy and transport, as well as processing at the slaughter house; the main output was the enteric fermentation process from the livestock. Ruminant livestock are separated from non-ruminants by their multiple guts, whereby the ruminants produce methane as a result of the enteric fermentation process where bacteria converts feed to energy. This process is estimated to account for between 55-92% of the greenhouse profile of cattle (Vergé et al., 2008). The results for the ruminant livestock category are presented in Table 8 and Fig. 8. The geographic location of lamb and beef appear to have an influence on the resultant GWP values (see table 8), as identified by Ledgard et al. (2010).

The median world average for lamb was 25.58 *kg* $CO_{2\text{-}eq}$*/kg* BFM. Australian and New Zealand lamb appeared significantly lower with a median of 17.63 *kg* $CO_{2\text{-}eq}$*/kg* BFM, where as EU lambs median GWP value was substantially higher at 32.70 *kg* $CO_{2\text{-}eq}$*/kg* BFM.

Table 8 Ruminant GWP values (*kg CO_2-eq/kg* BFM)

Classification	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Lamb AU & NZ	17.63	19.01	6.57	35%	10.05	33.49	16.30	21.06	9	19
Lamb UK	24.48	25.84	9.43	36%	11.04	43.17	21.48	30.07	7	12
Lamb world average[a]	25.58	27.91	11.93	43%	10.05	56.70	17.61	33.85	22	56
Lamb EU	32.70	33.84	13.06	39%	14.72	56.70	25.95	41.23	4	16
Beef Australia	22.88	23.06	4.79	21%	14.38	34.53	21.64	25.41	8	24
Beef EU	24.96	26.05	6.78	26%	10.74	42.30	21.69	29.07	25	75
Beef UK	26.57	25.76	6.27	24%	12.37	37.92	21.05	29.22	12	26
Beef world average[b]	26.61	28.73	12.47	43%	10.74	109.35	22.26	31.57	49	165
Beef Nth America	26.82	28.55	6.48	23%	19.60	41.73	23.41	30.53	9	13
Beef Sth America	34.10	38.33	12.48	33%	22.00	69.06	30.03	42.00	14	21
Buffalo	60.43	62.59	20.35	33%	28.78	100.72	43.88	79.14	1	4

Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and full references.

a) The lamb world average includes four additional LCA vales from North America, two from Asia, two from Africa, and one from South America.

b) The beef world average includes four additional LCA values from Asia, and two from Africa.

The world average for beef was 26.61 *kg CO_2-eq/kg* BFM. When geographic locations were compared for beef, South American beef had the highest median greenhouse gas profile with 34.10 *kg CO_2-eq/kg* BFM. Australian beef had the lowest median greenhouse gas profile with 22.88 *kg CO_2-eq/kg* BFM. The higher South American figure could be attributed to the inclusion of land-use change in the system boundary (Cederberg et al., 2011 p. 1773). Buffalo had the highest median greenhouse gas profile of all food analysed with a median of 60.43 *kg CO_2-eq/kg* BFM, identified in one study only. In Australia and the UK, the median value for lamb was less than beef; this trend was reversed in the European studies.

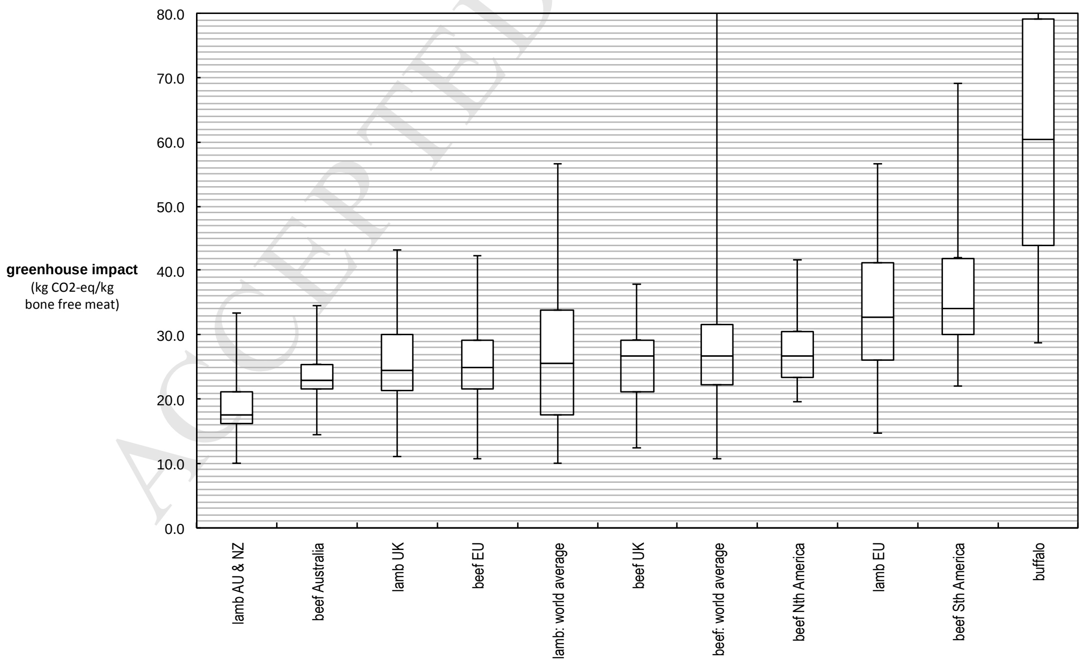

Figure 8 Comparisons of synthesized GWP values for ruminant livestock

3.6 Dairy

The dairy category was developed from reviewing 90 LCA studies that generated 341 GWP values. Milk had the highest number of GWP values (n = 262) identified from all the food categories. Within the dairy category, plant based milk substitutes in almond and soy-milk presented a lower median GWP value (0.42 and 0.75 *kg CO_2-eq/kg*) than dairy milk (1.29 *kg CO_2-eq/kg*). Yoghurt had a similar value to milk, with cream (5.64 *kg CO_2-eq/kg*), cheese (8.55 *kg CO_2-eq/kg*) and butter (9.25 *kg CO_2-eq/kg)* having higher median values (see Table 9 and Fig. 9) due to the high concentration of milk used per kg in their production. As with ruminant livestock, the geographic location had an impact on the GWP value for dairy. This could be expected given dairy is a product of ruminant livestock, mirroring the location-based impacts of beef.

Table 9 Dairy and dairy substitute GWP values (*kg CO_2-eq/kg* or L)

Product	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Almond, coconut milk	0.42	0.42	0.03	8%	0.39	0.44	0.39	0.44	1	4
Soy-milk	0.75	0.88	0.27	31%	0.66	1.40	0.70	0.98	2	8
Milk: AU & NZ	1.14	1.19	0.15	13%	0.94	1.40	1.11	1.32	10	10
Milk: Nth America	1.16	1.34	0.40	30%	0.94	2.06	1.05	1.55	11	19
Milk: British Isles	1.23	1.26	0.23	19%	0.88	1.99	1.12	1.30	16	35
Milk: World average	1.29	1.39	0.58	41%	0.54	7.50	1.14	1.50	77	262
Milk: Europe	1.30	1.32	0.29	22%	0.54	2.39	1.14	1.48	52	175
Milk: Central and Sth America	1.55	1.69	0.61	36%	1.14	3.30	1.41	1.68	5	10
Milk: Asia	2.02	2.53	1.09	43%	1.38	4.60	1.94	2.92	2	7
Milk: Africa	2.50	3.34	1.90	57%	1.02	7.50	1.98	3.70	2	5
Buffalo milk	3.57	3.75	0.86	23%	2.87	5.20	3.14	4.18	1	7
Yoghurt	1.31	1.43	0.25	18%	1.17	2.00	1.28	1.48	7	11
Cheese	8.55	8.86	2.07	23%	5.33	16.35	7.79	9.58	22	38
Cream	5.64	5.32	1.62	31%	2.10	7.92	3.82	7.14	3	4
Butter	9.25	11.52	7.37	64%	3.70	25.00	7.28	12.1	4	8

Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and full references.
a) Milk world average includes one additional LCA value from Belerus, not counted in the EU

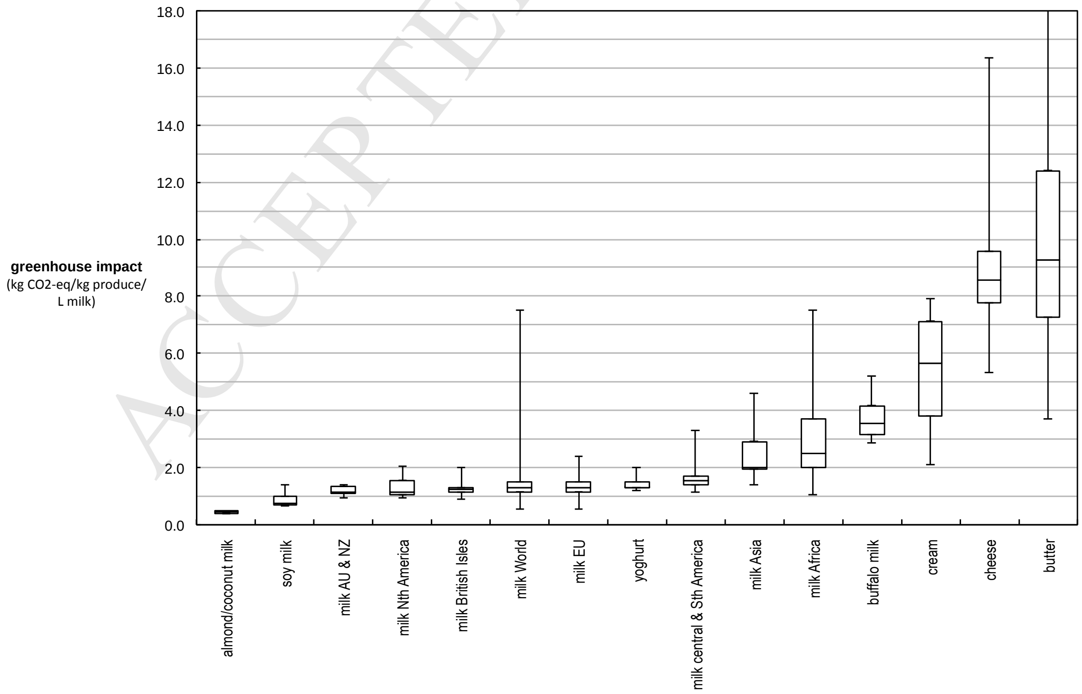

Figure 9 Comparisons of synthesized GWP values for dairy and dairy substitutes

4 Discussion

4.1 Key Trends identified from the meta-analysis

The meta-analysis confirms several existing trends previously identified in the LCA literature including the GWP hierarchy between broad food categories (e.g Head et al., 2013; Niggli et al., 2007)[4]; the hierarchy within plant based foods (Nemecek et al., 2012); and the importance of geographical location for ruminant livestock (e.g. Cederberg et al., 2011; Ledgard et al., 2010). The meta-analysis is also suggestive of new findings including the broad variation in GWP values between species for the fish category; an unequal representation of food types in LCA studies that require further attention (discussed in section 5.1); and the dominance of Europe in LCA publications.

4.2 Attributing the variation between studies and the risk of bias

To assess potential bias within studies, comparisons between methodological choices and publication type were completed for the beef and dairy categories only. Beef and dairy were selected as the category has a substantial number of LCA studies to enable comparison. For the Beef category, results from European LCA studies that used economic-input output (EIO) modelling (top down studies) were compared against studies that used process-based modelling (bottom up studies). In theory, these two approaches should correlate. The review of EIO studies from Lesschen et al. (2011) and others (n = 27 GWP values) when compared to process-based studies (n = 48 GWP values) illustrates that a strong correlation exists between methodological choices (see Figure 9). A very minor variation in median values of 2.6% was identified with respect to beef production and LCA methodological choices (see Fig. 10 and Table 10).

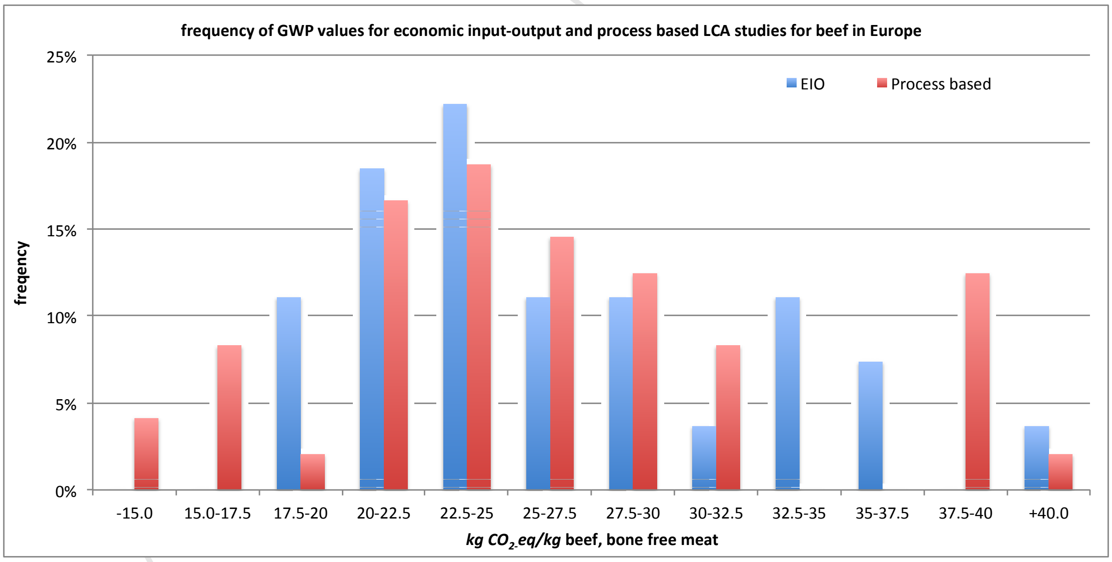

Figure 10 Comparisons of GWP frequencies for economic input-output and process based LCA studies for Beef in Europe

[4] The studies identified arable crops and vegetables to have lower greenhouse gas profiles than dairy, which is lower than poultry and pork, which is lower than beef.

Table 10 Comparisons of GWP values (*kg CO_2-eq/kg*) for economic input-output and process based LCA studies for Beef in Europe

LCA process used	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Beef EU process based LCA studies	24.98	25.76	7.15	28%	10.74	40.00	21.39	28.17	24	48
Beef EU EIO LCA studies	24.30	26.58	6.18	23%	18.30	42.30	21.91	30.45	3	27
Beef EU average combined	24.96	26.05	6.29	24%	10.74	42.30	21.69	29.07	25	75

Several authors have also published papers that compare methodologies between process based, EIO, and hybrid methodologies (e.g. Wiedemann and Yan, 2014), with results generally remaining within a similar quantum.

With respect to publication types, the milk category was the only category where a substantial number of EPDs have been completed to enable comparison between publication types. LCA GWP values were therefore analysed between EPDs (n = 15), conference papers (n = 26), journal papers (n = 174) and grey literature in government and industry reports (n = 22). Minor variation between publication types and GWP values were evident (See Table 11) as results remained within a similar quantum of GWP values.

Table 11 Comparisons of GWP values by publication type with respect to dairy milk (*kg CO_2-eq/L*) for EU, UK, AU, NZ and Nth America

Dairy milk: report type	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Report	1.12	1.13	0.16	14%	0.87	1.47	1.05	1.20	8	22
Conference papers	1.21	1.30	0.23	18%	0.94	1.77	1.14	1.60	14	26
Milk average; EU, UK, AU, NZ and Nth America	1.26	1.30	0.28	21%	0.54	2.39	1.14	1.44	74	237
Journal papers	1.28	1.31	0.30	23%	0.54	2.39	1.14	1.47	44	174
Environmental product declarations	1.38	1.35	0.13	10%	1.10	1.61	1.26	1.41	7	15
GWP values for Africa, Asia, Central and South America excluded from the above analysis as the high values skew the results for the conference category. If included the median for conference papers is 1.40 *kg CO_2-eq/L*, and journal articles 1.30 *kg CO_2-eq/L*										

The variations in GWP values could be attributed on a limited number of occasions to different methodology choices, or publication types. For example Ledgard et al. (2010) present a range of methodological choices and impact on GWP values (see Table 12). This could be open to exploitation if authors wish to select methodologies that could present their work with low GWP values that appear favourable.

Table 12 Effect of modelling assumptions and LCA results, as reported by Ledgard et al. (2010) for New Zealand lamb

Variable	Baseline assumption	Alternate assumption	Variation from baseline result (19 *kg CO_2-eq/kg* BFM)
Oceanic shipping emissions	0.05 *kg CO_2-eq /t*	0.015 *kg CO_2-eq /t*	-4%
Allocation method	Biophysical and economic	Nil	+46%
		Mass based	-34%
Animal methane emissions	Product of energy intake	Constant per animal	-50%
GWP methane	GWP_{100}25	GWP_{100}21	-9%
		GWP_{500}7.6	-39%
		GWP_{20}72	+84%
Carbon uptake and release	As per NZ's inventory for IPCC	Sequestration from soils and trees	Unknown

Despite this, more often the regional differences and variations in processes at each stage of the lifecycle assist in explaining the differences in results. In fact, many comparative studies show a diversity of GWP values from differing production processes, geographic locations or yearly yields. For example, there is Desjardins et al.'s study of beef production (2012), Leinonen et al.'s study for chicken (2012), Winther et al.'s study for fish (2009) and Maraseni et al.'s (2010) and Milà i Canals et al.'s (2008) study of vegetable production. Presenting multiple GWP values is consistent with Peters et al.'s (2010) position that a range of impacts should be reported from LCAs, as opposed to a singular figure. The authors' position when reading the meta-analysis is that the variation in farming methods and conditions has a more significant impact on the presented GWP values than methodological choices or publication type.

4.3 Using the meta-analysis for streamline accounting to inform sustainable diets.

The meta-analysis and accompanying database provides GWP values for a variety of food types that could be used to calculate the GWP of differing diets in a streamlined manner. For example, median figures from an alpha version of the database in this paper were utilised by Verghese et al. (2014) to estimate and compare the GWP values for a variety of weekly shops illustrated in Menzel and D'Alusio's (2005) photographic text Hungry Planet. The study identified 'hotspots' for potential improvements in weekly diets. For example Fig. 11 shows that 54% of an Australian family's food related GWP was due to meat, fish and egg purchases (Verghese et al., 2014).

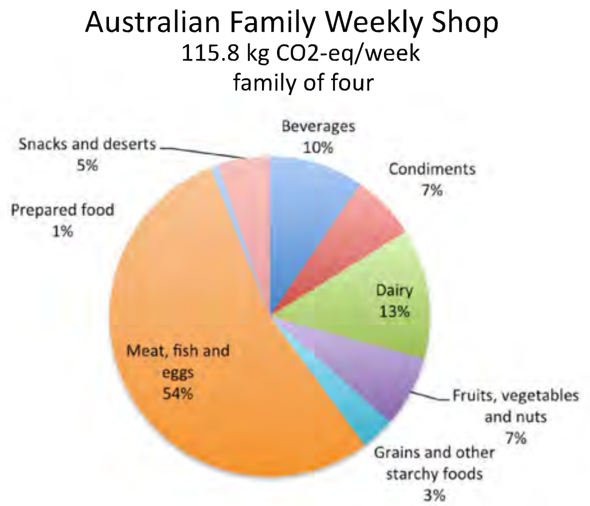

Figure 11 Summary of the GWP for the weekly diet of an Australian family (Verghese et al., 2014).

The meta-analysis and accompanying database from this paper enable numerous alternate scenarios to be created that could reduce the identified 'hotspot' in the 'weekly shop'. Three scenarios were remodelled to illustrate this point, in: a) the original diet[5], b) substituting meats with alternative meats in a 'like for like' manner, and c) creating an alternative plant and fish based diet. Diet c) calculated the protein from food purchased in other sections of Figure 11, and balanced the remaining protein from legumes, nuts and fish to meet the recommended daily intake (RDI) for protein from the National Health and Medical Research Council (2015), replacing all ingredients in Table 13A.

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[5] The meat, fish and dairy section only of the original diet were remodelled using median figures from Table 5 and Table 8. There was limited variation in results for the meat, fish and dairy between the alpha version tested by Verghese (2014) and final figures utilised and presented in Table 5.

Table 13 Streamlined accounting of the GWP of the weekly shop for meat, fish and eggs

A. Meat, fish and eggs: original weekly shop	**Quantity kg**	**Protein/ 100 g**	**Protein g/ week**	**Q1** ***kg CO_2-eq/kg***	**Q1** ***kg CO_2-eq/week***	**Median** ***kg CO_2-eq/kg***	**Median** ***kg CO_2-eq/week***	**Q3** ***kg CO_2-eq/ week***	**Q3** ***kg CO_2-eq/ week***
Beef (AU & NZ)	1.00	20.89	208.90	21.64	21.64	22.88	**22.88**	25.41	25.41
Lamb (AU & NZ)	1.00	18.59	185.85	16.30	16.30	17.63	**17.63**	21.06	21.06
Chicken, whole[a]	1.00	18.56	185.55	2.12	2.12	2.80	**2.80**	4.07	4.07
Chicken breast	1.00	18.56	185.55	2.77	2.77	3.65	**3.65**	5.31	5.31
Eggs	0.38	12.56	47.73	2.45	0.93	3.39	**1.29**	4.05	1.54
Tuna	2.00	23.33	466.60	1.75	3.50	2.95	**5.90**	2.68	5.36
Fish	1.00	15.82	158.15	1.99	1.99	3.49	**3.49**	5.16	5.16
Pork (world average)	0.50	20.60	102.98	4.50	2.25	5.77	**2.89**	6.59	3.30
Ham	0.30	20.60	61.79	4.50	1.35	5.77	**1.73**	6.59	1.98
Salami	0.10	13.50	13.50	2.26	0.23	2.88	**0.29**	3.31	0.33
Total	**8.28**		**1,616.59**		53.08		**62.53**		73.52
a. Whole chicken is calculated using the carcus weight to live weight ration of 1:0.77 provided in Table 1.									
B. Meat, fish and eggs substitute weekly shop 'like for like'[b]	**Quantity kg**	**Protein/ 100 g**	**Protein g/ week**	**Q1** ***kg CO_2-eq/kg***	**Q1** ***kg CO_2-eq/week***	**Median** ***kg CO_2-eq/kg***	**Median** ***kg CO_2-eq/week***	**Q3** ***kg CO_2-eq/ week***	**Q3** ***kg CO_2-eq/ week***
Kangaroo (beef substitute)	1.00	20.85	208.50	4.10	4.10	4.10	**4.10**	4.10	4.10
Rabbit (lamb substitute 50%)	0.50	20.92	104.60	4.26	2.13	4.70	**2.35**	5.14	2.57
Duck (lamb substitute 50%)	0.50	18.28	91.40	2.58	1.29	3.09	**1.55**	3.59	1.80
Chicken, whole	1.00	18.56	185.55	2.12	2.12	2.81	**2.81**	4.07	4.07
Chicken breast	1.00	18.56	185.55	2.77	2.77	3.65	**3.65**	5.31	5.31
Eggs	0.38	12.56	47.73	2.45	0.93	3.39	**1.29**	4.05	1.54
Tuna	2.00	23.33	466.60	1.75	3.50	2.95	**5.90**	2.68	5.36
Pollock (fish substitute)	1.00	15.82	158.15	1.40	1.40	1.60	**1.60**	1.84	1.84
Pork	0.50	20.60	102.98	4.50	2.25	5.77	**2.89**	6.59	3.30
Ham	0.30	20.60	61.79	4.50	1.35	5.77	**1.73**	6.59	1.98
Salami	0.10	13.50	13.50	2.26	0.23	2.89	**0.29**	3.31	0.33
Total	**8.28**		**1,626.34**		**22.07**		**28.14**		**32.19**
b. 'like for like' attempts to substitute meat protein with another meat, e.g. kangaroo is a red meat substitute for beef, rabbit and duck are a meat substitute for lamb.									
C. Alternative weekly shop to meet RDI guidelines for protein	**Quantity kg**	**Protein/ 100 g**	**Protein g/ week**	**Q1** ***kg CO_2-eq/kg***	**Q1** ***kg CO_2-eq/week***	**Median** ***kg CO_2-eq/kg***	**Median** ***kg CO_2-eq/week***	**Q3** ***kg CO_2-eq/ week***	**Q3** ***kg CO_2-eq/ week***
Peanuts	0.50	25.50	127.50	0.81	0.81	0.83	**0.42**	0.87	0.87
Almonds	0.50	21.28	106.40	0.76	0.76	1.54	**0.77**	2.33	2.33
Pinto beans	0.40	21.42	85.68	0.73	0.73	0.73	**0.29**	0.73	0.73
Lentils	0.30	25.38	76.14	1.02	1.02	1.03	**0.31**	1.05	1.05
Pilchards	0.80	24.62	196.96	0.94	0.94	1.10	**0.88**	1.26	1.26
Muesli bars	0.25	4.10	10.23	*	*	*	*	*	*
Peanut butter	0.25	25.50	63.62	*	*	*	*	*	*
Baked beans	1.04	4.70	49.03	*	*	*	*	*	*
Milk	3.89	3.37	131.09	*	*	*	*	*	*
Cheese	0.50	23.65	118.00	*	*	*	*	*	*
Yoghurt	0.50	5.25	26.19	*	*	*	*	*	*
Bread	2.89	9.00	260.10	*	*	*	*	*	*
Breakfast cereal	0.50	8.10	40.42	*	*	*	*	*	*
Pasta	1.00	6.00	60.00	*	*	*	*	*	*
White rice	0.50	6.50	32.43	*	*	*	*	*	*
Total	**13.82**		**1,383.79**		2.14		**2.67**		3.22

* Not applicable, as an overconsumption of proteins exists in the diet of scenarios in Tables 13A and 13B. The necessary proteins could come from other type of food sources already computed in the elements of the baseline scenario (highlighted in grey above) and are different from meat, fish and eggs category in Fig.11. The recommended dietary intake for protein for the family of four was calculated to be 1365 grams per week. 40 g/day for a 9-13 year old boy, 45 g/day for a 14-18 year old women, 46 g/day for a 30-50 year old women and 64 grams per day for a 30-50 year old man (NHMRC, 2015). Protein figures are median values from the USDA National Nutrient Database (2015).

The results from the three scenarios show a large variation in the median GWP per week. Substituting ruminant meat (beef and lamb) for non-ruminant meat (kangaroo, duck and rabbit), and selecting an alternate fish species in pollock (Table 13B) produces an estimate 30% reduction in GWP in relation to the median weekly shop in Fig 11. An alternate diet that attempts to match the recommended weekly protein intake via a plant and fish based diet (Table 13C) produces an estimate 52% reduction in GWP related to the median weekly shop shown in Fig 11[6]. Calculating the diets utilising the lower (Q1) and upper (Q3) quartile values is view by the authors as a proxy measure to calculate data uncertainty, the results provided indicate that there is a significant differences between the three diets (A, B and C) that is far from overlapping, and reliably differentiates between the GWP of the three diets (as desired by Pulkkinen et al., 2015).

The above streamlined results may be less valid than a detailed process based LCA, however this approach can be used to calculate different scenarios and what ifs, helping to better inform consumers of the choices that are available. The compiled database is the foundation for the development of streamlined tools to rapidly calculate the GWP of differing diets. The approach of compiling material $CO_{2\text{-}eq}$ inventories based on LCA data has been utilised to rapidly estimate GWP impacts for packaging (e.g. PIQET design tool), products (e.g. greenfly), and buildings (e.g. Bath Universities ICE database) (Hammond and Jones, 2008; Horne et al., 2009, p.155). As Verghese et al, argue ‘While streamlined LCA tools are compromises, they can be potentially useful and have their own unique role in furthering the use of LCA data in decision making’ (2010, p.108).

5 Recommendations for future LCA practice

5.1 Study under represented food groups

The meta-analysis indicates that the representation of food categories by LCA studies is unequal with respect to particular foods. The literature review identified that limited studies were available for tree nuts in almonds and cashews, and for quinoa, duck, rabbit, turkey, and kangaroo. Better representation of such foods is important as they are positioned in grey literature and popular texts as alternate low GWP protein sources. The lack of published LCA data makes the GWP values on these foods harder to validate, and is critical if attempts are made to inform dietary choice for environmental purposes.

5.2 Methodological choices to assist comparison

The use of common functional units in food LCAs would make it easier to compare reports, avoid misrepresentation and strengthen the validity of comparisons. As Schau and Fet (2008) argue, standardisation of system boundary descriptions and functional units is required. However, as illustrated in our review, different system boundaries and functional units are commonly used. The consistency of reporting in environmental product declarations EPDs that follow PAS2050, GHG protocol or ISO 14067 standards, and the development of product category rules that attempt to make food LCA’s more consistent and therefore comparable is

[6] It is acknowledged that the streamline calculations are for two indicators in protein and GWP only. Changes to diet should be made following nutritional guidelines that include a broader range of metrics. However, the brief calculations above indicate that the modelled diet of the Australian family has a protein intake higher than the recommended daily intake.

welcome[7]. For example the reports available on the 'envirodec' website following the International EPD system based on ISO 14025 and EN 15804 clearly disclose impacts at each stage of the lifecycle to enable comparison (e.g. EPD international, 2015; Stefano, 2013; Villman, 2012).

These two limitations highlight ways that future food GWP comparisons could be strengthened. However, despite the concerns over methodological choices and the limitations of the meta-analysis, the hierarchy identified and median figures collated from a large body of LCA work are valid for use in streamline accounting to enable directional decisions to be made. The collation of data with percentile bands and disclosed standard deviation enables the inclusion of data uncertainty when assessing the greenhouse profiles for food-related diets, as requested by Hallström et al. (2015). The authors agree with Röös et al.'s position that 'when the ranges [of GWP values] are far from overlapping, the exact numbers are less important' (2011, p.329). The meta-analysis of LCAs communicates a clear message and presents generalizable findings that should not be dismissed because of methodological limitations.

6 Conclusion

This paper completed a meta-analysis of data relating to the greenhouse gas emissions for different food categories. While we agree that individual results from LCA studies should not be directly compared with other individual results, the meta-analysis of a large body of LCA work that draws on different methodologies, geographies and farming provides a strong greenhouse gas hierarchy across the food categories. Grains, fruit and vegetables had the lowest impact, with meat from ruminants having the highest impact. This hierarchy is well supported by other comparative literature. The median results could be used with confidence to provide a streamlined estimate of the impact of ingredients for dietary choice or menu planning for individuals and catering companies with a desire to reduce their carbon footprint, primarily by selecting food from differing categories. This is illustrated by a short case study in section 4.3 of an Australian family's weekly shop. The meta-analysis addresses the limitation of previous studies by covering a broader range of food types and GWP values.

Variations in data within each category may be attributable to different LCA approaches, including functional units, methods, geographic location and processes included. The collation of data with percentile bands enables the inclusion of uncertainty when assessing the greenhouse profiles for food-related activities. A key recommendation from the meta-analysis for future LCA practice is to study the underrepresented food types identified in the results and appendix, ideally following protocols (e.g. PAS2050, GHG protocol or ISO 14067) that assist future comparison.

7 Appendix

Please download Appendix.pdf from Data file on page 31

8 References

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[7] Liu et al (2016) paper illustrates in detail the nuanced differences between GHG reporting protocols, and calls for an international standard for carbon labelling. The authors of this paper do not have a position within this debate on which standard is preferable.

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Highlights

- Collates and analyses 369 LCA studies including 168 food types and 1718 GWP values
- Provides generalizable data for the optimisation of low GWP human diets
- Identifies underrepresented food types in need of further study
- Identifies a GWP hierarchy across food categories from low (staples) to high (ruminant livestock)
- Identifies a high variation in fish GWP dependent on species and fishing method

EXHIBIT K-7

DOI: 10.1111/jiec.12845

RESEARCH AND ANALYSIS

WILEY JOURNAL OF INDUSTRIAL ECOLOGY

Life cycle assessment of recirculating aquaculture systems

A case of Atlantic salmon farming in China

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Funding Information
Research Council of Norway through NORDSAT-SNING, grant number 195160, and Eni Norge AS.

Editor Managing Review: Lei Shi

Abstract

Recirculating aquaculture systems (RAS) are an alternative technology to tackle the major environmental challenges associated with conventional cage culture systems. In order to systematically assess the environmental performance of RAS farming, it is important to take the whole life cycle into account so as to avoid ad hoc and suboptimal environmental measures. So far, the application of life cycle assessment (LCA) in aquaculture, especially to indoor RAS, is still in progress. This study reports on an LCA of Atlantic salmon harvested at an indoor RAS farm in northern China. Results showed that 1 tonne live-weight salmon production required 7,509 kWh farm-level electricity and generated 16.7 tonnes of CO_2 equivalent (eq), 106 kg of SO_2 eq, 2.4 kg of P eq, and 108 kg of N eq (cradle-to-farm gate). In particular, farm-level electricity use and feed product were identified as primary contributors to eight of nine impact categories assessed (54–95% in total), except the potential marine eutrophication (MEU) impact (dominated by the grow-out effluents). Among feed ingredients (on a dry-weight basis), chicken meal (5%) and krill meal (8%) dominated six and three, respectively, of the nine impact categories. Suggested environmental improvement measures for this indoor RAS farm included optimization of stocking density, feeding management, grow-out effluent treatment, substitution of feed ingredients, and selection of electricity generation sources. In a generic context, this study can contribute to a better understanding of the life cycle environmental impacts of land-based salmon RAS operations, as well as science-based communication among stakeholders on more eco-friendly farmed salmon.

KEYWORDS

atlantic salmon, feed production, indoor aquaculture, industrial ecology, life cycle assessment (LCA), recirculating aquaculture systems

1 | INTRODUCTION

Development of a sustainable aquaculture industry plays a key role in meeting global food and nutrition security (HLPE 2014). Aquaculture is the world's fastest growing food production sector, which is projected to supply over 60% of fish for direct human consumption by 2030 (World Bank 2013). Among the main groups of species in world trade, salmon and trout became the largest single commodity by value in 2013, and demand is growing steadily, especially for farmed Atlantic salmon (FAO 2016). At present, farmed Atlantic salmon (*Salmo salar*) accounts for around 60% of the world's salmon production (Pawlowski et al., 2016). The current commercial-scale salmon grow-out takes place mostly in cage aquaculture, although salmon smolts have been produced on land (Bergheim, Drengstig, Ulgenes, & Fivelstad, 2009). Despite measures taken to alleviate environmental impacts of the traditional open net-cage salmon farming, significant problems and constraints in relation to parasites (sea lice), diseases, and the escape of fish have proved difficult to overcome (Lekang, Salas-Bringas, & Bostock, 2016).

Recent efforts to tackle the challenges faced by open net-cage aquaculture have been shifted to the development of mitigation measures and alternative farming methods, such as closed-containment systems. In particular, the intensive land-based recirculating aquaculture systems (RAS) technology is regarded as having considerable growth potential (Dalsgaard et al., 2013). According to Ebeling and Timmons (2012), indoor aquaculture is probably the only potential method to ensure a relatively high level of seafood safety. In the case of postsmolt Atlantic salmon farming to marketable size, there are currently only a few land-based RAS in operation, mainly located in Denmark, China, and Canada (Iversen, Andreassen, Hermansen, Larsen, & Terjesen, 2013).

The environmental impacts of the entire seafood value chain have been a high-priority issue for the pursuit of sustainable aquaculture development. In order to assess the environmental impacts of RAS farming in a systems perspective, it is important to take into account the whole fish supply chain, beyond the traditional focus of environmental engineering and risk assessment at farm site. Understanding the life cycle impacts associated with expanding and intensifying aquaculture is also crucial for designing responsible aquaculture systems (Diana et al., 2013). This has, therefore, resulted in a growing interest in employing life cycle thinking-based methodology to assess the overall environmental impacts of seafood production systems.

Life cycle assessment (LCA) is an internationally standardized method for addressing the environmental aspects and potential environmental impacts throughout a product's life cycle (ISO 2006). Although LCA has been widely used in the food industry (Sonesson, Berlin, & Ziegler, 2010), the application of LCA in aquaculture began in the mid-2000s. The first published aquaculture LCA study (Papatryphon, Petit, Kaushik, & van der Werf, 2004) focuses on environmental impact assessment of the entire life cycle of salmonid feeds with different ingredient compositions. In recent years, LCA has proven to be a valuable tool for assessing the potential environmental impacts of aquaculture production systems and informing certification and eco-labeling criteria for the seafood sector (Cao, Diana, & Keoleian, 2013). The application of LCA to seafood supply chains has demonstrated some previously unassessed environmental impacts of fisheries and aquaculture, leading to new insights into the environmental impacts of seafood products, such as those related to greenhouse gases, toxic emissions, eutrophication, and land use (Ziegler et al., 2016).

The application of LCA in salmonid RAS is still in progress. In the past decade, only a number of LCA studies on salmonid aquaculture systems were published, with varying goals and scopes (see Table S1 in the Supporting Information available on the Journal's website). For instance, Ayer and Tyedmers (2009) conducted an LCA of four salmonid culture systems in Canada (i.e., Atlantic salmon farmed in marine open net, marine floating bag and land-based flow-through systems, as well as Arctic char in land-based recirculating system), and they emphasized the need for further assessment of the environmental impacts of material and energy requirements of closed-containment aquaculture. McGrath, Pelletier, and Tyedmers (2015) carried out an LCA of a floating tank, flow-through and solid-walled system for Chinook salmon farming in Canada, and presented the primary contributions from feed provisioning and on-site energy use. Liu et al. (2016) compared an open net-pen system in Norway with a hypothetical land-based RAS in the United States for producing Atlantic salmon, focusing on economic performance and carbon footprint. Due to few published LCA studies on recirculating salmonid fish farming, it becomes difficult to systematically assess the environmental impacts of salmon farmed in RAS, as well as to benchmark the materials and energy requirements of RAS with other salmon farming methods.

So far, there has been no published LCA of indoor salmon RAS farming based on actual operations at the commercial scale. While some salmonid aquaculture LCA publications include the farm-level energy use, few of them give a breakdown of the total electricity use at the most important subprocess level. As emphasized in a recent review of LCA on aquaculture systems by Bohnes and Laurent (2018), one future need of aquaculture LCAs is to construct aquaculture life cycle inventory (LCI) databases with a special need for developing countries.

This paper presented the results of LCI and life cycle impacts of Atlantic salmon (*S. salar*) harvested in a commercial-scale indoor RAS farm in northern China. In a generic context, results of this study can contribute to an improved understanding of the life cycle environmental impacts of salmon produced in land-based RAS and science-based communication among stakeholders on more eco-friendly farmed salmon.

2 | METHODOLOGY AND DATA SOURCES

2.1 | Life cycle assessment

2.1.1 | Goal and scope definition

The goal of the present LCA study was twofold: first, to assess the potential environmental impacts associated with the Atlantic salmon RAS farming system under study (for details of the RAS farm and feed formulations, see Table S2 in the Supporting Information available on the Web), and then to identify environmental hotspots of the whole fish production chain. The functional unit of this study was 1 tonne harvest-ready live-weight Atlantic salmon at the grow-out farm. The system boundaries were from cradle to farm gate, beginning with resource extraction and ending with harvest-ready salmon at the grow-out farm gate (Figure 1).

Both foreground (e.g., feed manufacturing, hatchery and smolt rearing, and salmon grow-out) and background (e.g., energy generation, manufacturing, and feed ingredients production) processes were included. Due to data limitation, three inventory parameters of the hatchery and smolt rearing and feed manufacturing plants were not considered in this study, including infrastructure, on-site wastes and emissions, and transport of raw feed ingredients to the feed manufacturing plant. Among farm-level emissions, only nutrient emissions from the grow-out farm to the receiving water were considered.

This study assessed nine impact categories, including climate change (CC; kg CO_2 eq), terrestrial acidification (TA; kg SO_2 eq), freshwater eutrophication (FEU; kg P eq), MEU (kg N eq), human toxicity (HT; kg 1.4 DB (dichlorobenzene) eq), terrestrial ecotoxicity (TET; kg 1.4 DB eq), freshwater ecotoxicity (FET; kg 1.4 DB eq), marine ecotoxicity (MET; kg 1.4 DB eq), and cumulative energy demand (CED; MJ). As summarized in a review

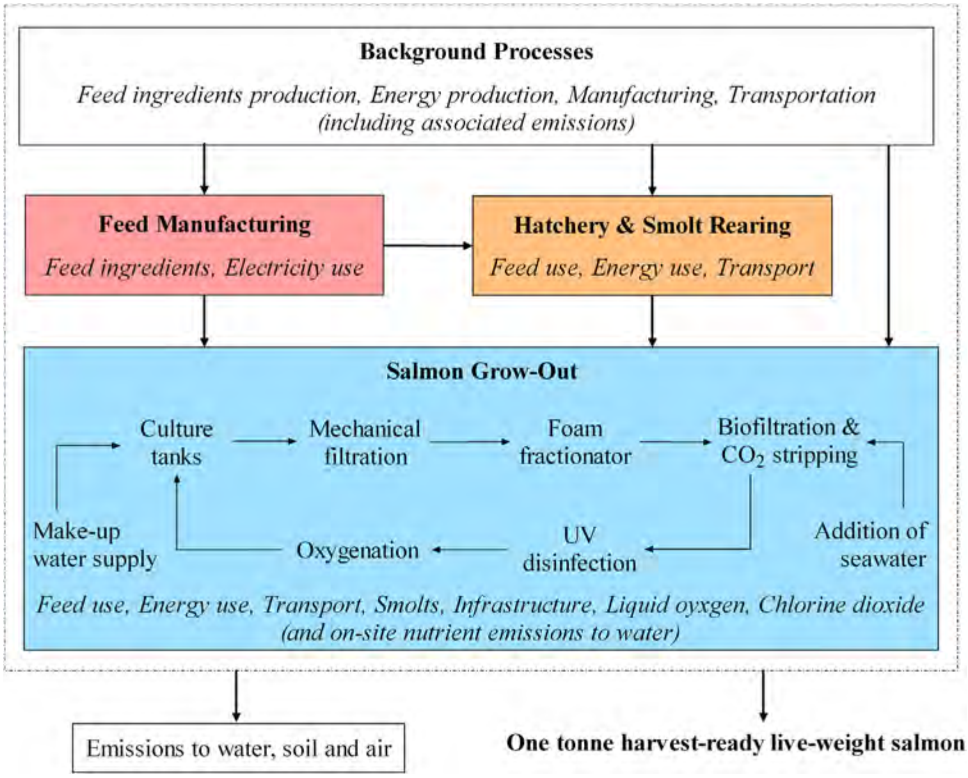

FIGURE 1 System boundaries for the cradle-to-farm gate LCA of the Atlantic salmon RAS farming

of published aquaculture LCA studies (Henriksson, Guinée, Kleijn, & de Snoo, 2012), global warming potential, acidification, and eutrophication are identified as three most frequently addressed impact categories in aquaculture and seafood LCA studies, followed by 12 less adopted impact categories (e.g., energy use, biotic resource use, HT, and ecotoxicity). From an LCA perspective, the “human toxicity” and “terrestrial/marine/freshwater ecotoxicity” indicators reflect the potential impacts of a system on human health and ecosystem, rather than indicating the actual safety levels of products (Notarnicola et al., 2017).

2.1.2 | Life cycle inventory

The LCI phase involves the collection and compilation of all relevant input and output data of a defined system. The foreground (on-farm) material and energy use data came from the production data of the feed manufacturing plant, the hatchery and smolt rearing facility, and the salmon grow-out farm. In specific, the LCI data of the hatchery and smolt rearing and feed manufacturing plants referred to their respective annual average production in 2015. The total and breakdown of electricity use at the hatchery and smolt rearing and salmon grow-out farms were calculated based on the power rating and operational time of all equipment during the period under study. The LCI data of the salmon grow-out farm was based on a full grow-out period (15 months during December 2014–February 2016), with a total production of 145 tonnes of live-weight salmon. During this grow-out period, 12 closed-containment systems (each having four rearing tanks and a total rearing volume of 500 m^3) were operated in parallel.

Background data were taken from extensive LCI databases within SimaPro 8.3 software (see Table S3 in the Supporting Information available on the Web). Since the LCI databases in SimaPro contain only a few ready-to-use processes of feed ingredients, assumptions were made for missing feed ingredient production processes, as listed in Table S4 in the Supporting Information available on the Web.

On-site nutrient emissions from the salmon grow-out farm to water were estimated by means of a nutrient budget modeling approach (Aubin, Papatryphon, Van der Werf, Petit, & Morvan, 2006). In specific, the phosphorous (P) and nitrogen (N) emissions were calculated based on nutrient balance analysis data from the grow-out farm studied. The solid form of P and N in grow-out effluents referred to the respective nutrient in solid fish wastes collected from the mechanical filtration process. The dissolved P and N referred to the respective nutrient in sludge discharged from the biofiltration process. At the time of this study, both the collected solid fish wastes and sludge were discharged into the adjunct sea. Further information on farm-level P and N emissions to receiving water is provided in Table S5 in the Supporting Information available on the Web.

2.1.3 | Life cycle impact assessment

Life cycle impact assessment was performed using two LCIA methods available in the SimaPro v8.3 software, that is, Cumulative Energy Demand v1.09 and ReCiPe v1.13. The CED method aims to quantify the total (“cumulative”) energy demand throughout the cradle-to-farm-gate Atlantic salmon production system. The ReCiPe method is the outcome of alignment between the midpoint-oriented CML 2002 method and the endpoint-oriented Eco-indicator 99 method (Goedkoop et al., 2013). Since the endpoint method (damage-oriented) has a relatively higher uncertainty (Goedkoop et al., 2013), the problem-oriented ReCiPe midpoint (H) v1.13/World ReCiPe method was chosen for the other eight impact indicators assessed in this study. The abbreviation H stands for the ReCiPe hierarchist perspective, referring to the most common policy principles.

2.1.4 | Sensitivity, scenario, and uncertainty analyses

The results of an LCA study can be sensitive to a variety of uncertainty sources, such as LCI data and assumptions made for lacking processes. In order to investigate how the life cycle impacts of the farmed salmon change with alternative LCI parameters, sensitivity analyses were conducted with focus on (a) stocking density (grow-out), (b) economic feed conversion ratio (eFCR), and (c) life expectancy of the grow-out infrastructure. Besides, scenario analyses were made to evaluate the potential implications of (a) substitutes of marine- and poultry-derived ingredients with crop-derived ingredient for feed production and (b) changes of electricity generation sources. In order to check the effects of various uncertainty sources on the modeled LCIA results, Monte Carlo simulation was executed in SimaPro, using 10,000 runs to generate 95% confidence intervals (Goedkoop, Oele, Leijting, Ponsioen, & Meijer, 2016).

3 | RESULTS

3.1 | Life cycle inventory

During the grow-out period, approximately 35,000 Atlantic salmon smolts were transferred to the grow-out farm, with an average mass of 100 g. Correspondingly, 29,000 salmon were harvested with an average mass of 5 kg. This grow-out period had an approximate mortality rate of 13% and a culling rate of 4% (mostly male). The stocking density during the grow-out period was 24.2 kg/m^3 (cf. the farm's design stocking density is 45 kg/m^3). The eFCR of this grow-out period was 1.45 (eFCR = kilogram of feed distributed/kilogram of fish produced, including losses due to uneaten feed and fish mortalities). The calculated eFCR was slightly higher than the farm's empirical eFCR of 1.4, owing to slight overfeeding applied during this grow-out period. The calculated eFCR of the smolt rearing plant was 1.01, close to the plant's average eFCR of 1.0. The water use rate was 1,862 m^3 of seawater per tonne live-weight salmon during the grow-out phase, and 2,000 m^3 of freshwater per tonne smolt produced at the hatchery and smolt rearing facility. A summary of key LCI data is provided in Table S6 in the Supporting Information available on the Web.

The total on-site electricity use of the three foreground systems was 8,420 kWh per tonne live-weight salmon harvested, among which the salmon grow-out farm accounted for 89.2% (7,509 kWh), the hatchery and smolt rearing facility 5.6% (469 kWh), and the feed manufacturing plant 5.2% (442 kWh for feed milling). For the hatchery and smolt rearing facility, the top three electricity users were water circulation pump (2.9%), water-cooling (1.7%), and freshwater supply pump (0.5%). Remarkably, all top four electricity-intensive equipment were in the salmon grow-out farm, including water circulation pump (36.6%), make-up water supply pump (22.1%), UV lamp (16.5%), and biofilter blowers (9.1%). Since no monitoring data were available at the unit operational level, the breakdown of electricity use was calculated by means of the respective technical design data and operational time of the salmon grow-out/hatchery farms and feed milling equipment. Detailed on-site electricity use data appear in Table S7 in the Supporting Information available on the Web.

3.2 | Life cycle impact assessment

The LCIA results of the Atlantic salmon RAS farming system are illustrated in Figure 2 (for details, see Tables S8 and S9 in the Supporting Information available on the Web). The on-site electricity use at the grow-out farm dominated six of the nine impact categories: MET (52%), FET (51%), CC (46%), FEU (42%), CED (40%), and HT (39%). Feed production was the primary contributor to the impacts of TET (95%) and TA (48%). In this study, the feed production process includes both the foreground feed manufacturing (milling) process and all upstream (background) processes for production of feed ingredients. The MEU impact was mostly related to the on-site nutrient emissions of the grow-out farm (87%), followed by feed production (12%). For CED, the top two contributors were grow-out electricity use (40%) and feed production (37%). Liquid oxygen contributed between 5% and 22% to all impact categories, with higher values observed in FEU (22%), HT (16%), MET (14%), and FET (13%). The grow-out infrastructure contributed 6–24% of seven impact categories, but very little to TET (1.4%) and MEU (0.5%). The contribution of transport (salmon feed) seems to be negligible to all impact categories (up to 3%).

Given the importance of salmon feed, contribution analysis of the cradle-to-gate life cycle impacts of feed production was performed (Figure 3; for details, see Tables S10 and S11 in the Supporting Information available on the Web). First, the marine ingredients (fish meal, fish oil, and krill meal) in total were the primary contributor to CC (63%), TA (61%), and CED (57%), largely owing to diesel combusted in fishing vessel. In particular, krill meal contributed most to three impact categories, that is, TA (40%), CC (37%), and CED (33%). Second, the plant-based ingredients in total contributed mainly to TET (50%, among which soybean meal 48% and maize gluten meal 2%), MEU (32%, among which wheat flour 24% and soybean meal 8%), and FET (17%, among which soybean meal 14% and maize gluten meal 3%). Third, electricity use for feed milling contributed mainly to four impact categories: MET (29%), FET (23%), HT (16%), and FEU (16%).

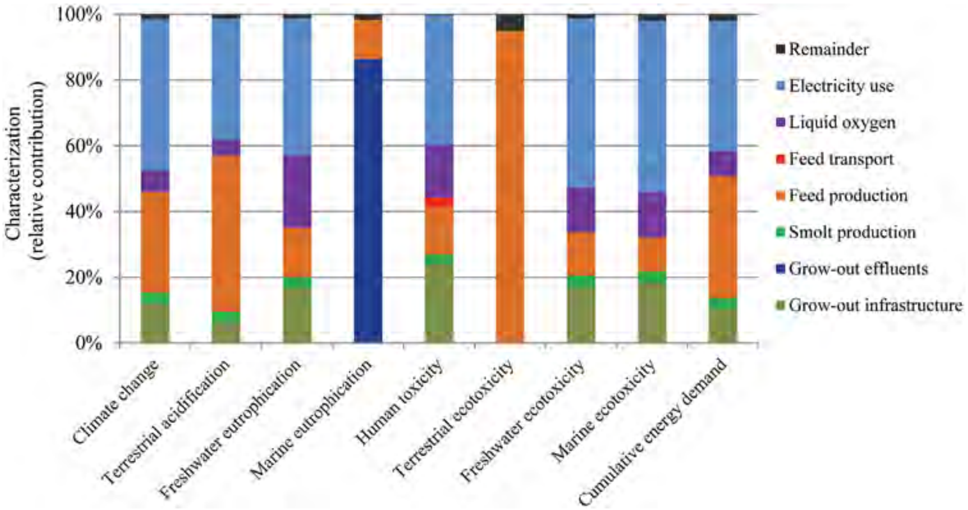

FIGURE 2 Life cycle contribution analysis of 1 tonne salmon harvested at the grow-out farm (cradle-to-farm gate) using the ReCiPe method. The term remainder refers to the sum of processes each less than 2% of the total potential

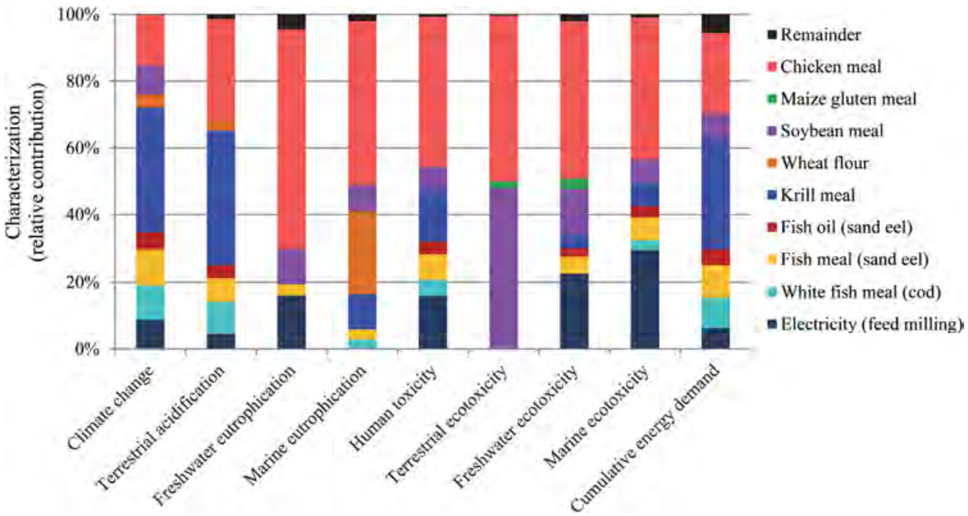

FIGURE 3 Life cycle contribution analysis of 1 tonne salmon feed product using the ReCiPe method (cradle-to-gate, excluding infrastructure and transportation requirements of the feed milling plant). The term remainder refers to the sum of processes each less than 2% of the total potential

Among the feed ingredients used for feed production (Figure 3), chicken meal (only 5% of the salmon feed on a dry-weight basis) dominated six of the nine impact categories assessed, including FEU (66%), TET (50%), MEU (49%), FET (47%), HT (45%), and MET (43%). This was mainly owing to electricity generation and poultry feed production for broiler chicken farms. For the FEU impact (66%), results of specification per process showed that spoil from lignite mining and hard coal mining and for electricity generation accounted for 21% and 16%, respectively, followed by the production of maize grain (10%) and emissions from chicken farms (6%). For the TET impact, results of specification per substance indicated that soil-borne emissions of cypermethrin (as an insecticide) and atrazine (as an herbicide) accounted for 32% and 10%, respectively, out of the total contribution of 50%.

3.3 | Sensitivity, scenario, and uncertainty analyses

Table 1 presents the relative changes of the life cycle impacts per tonne live-weight salmon with alternative LCI parameters and scenarios on feed ingredients and electricity generation sources, compared to the baseline. For a detailed explanation of the selection of sensitivity and scenario analysis parameters and the modeling results, see Section 8 of the Supporting Information available on the Web. The results showed that the life cycle impacts per tonne live-weight salmon were most sensitive to the stocking density of the grow-out farm, followed by changes of electricity generation sources, feed ingredients, eFCR and life expectancy of infrastructure. When increasing the stocking density from 24.2 to 45 kg/m^3, the life cycle impacts per tonne salmon reduced by 20–35% in seven of the nine impact categories (except MEU and TET), while the life cycle impacts

TABLE 1 Sensitivity and scenario analyses for life cycle impacts per tonne live-weight salmon, including the relative change (%) compared to the baseline

LCI parameters	CC (%)	TA (%)	FEU (%)	MEU (%)	HT (%)	TET (%)	FET (%)	MET (%)	CED (%)
Sensitivity analysis									
Stocking density (grow-out)									
S1: 45 kg/m^3	−27.7	−20.7	−30.1	−1.1	−31.5	−1.1	−33.5	−34.5	−24.2
S2: 60 kg/m^3	−27.9	−20.4	−30.7	−1.1	−33.4	−1.3	−34.1	−35.2	−24.4
Economic feed conversion ratio									
S1: eFCR = 1.3	−3.1	−4.9	−1.5	−9.9	−1.5	−9.7	−1.4	−1.1	−3.8
S2: eFCR = 1.1	−7.3	−11.4	−3.6	−23.3	−3.4	−22.8	−3.4	−2.5	−8.9
Life expectancy of infrastructure									
S1: 10-year	+5.9	+3.1	+8.4	+0.2	+11.9	+0.7	+8.4	+9.1	+5.2
S2: 20-year	−3.0	−1.6	−4.2	−0.1	−6.1	−0.4	−4.2	−4.6	−2.6
Scenario analysis									
Feed ingredients									
S1: substitute krill meal (8%) with soybean meal	−9.8	−19.1	+1.0	−1.2	−1.6	+30.8	+0.6	−0.2	−10.4
S2: Substitute chicken meal (5%) with soybean meal	−3.6	−14.4	−9.4	−10.3	−6.1	−28.4	−5.6	−4.2	−7.7
Electricity generation sources									
S1: Replace 20% coal with wind	−14.6	−11.8	−12.0	−0.5	−8.2	−0.1	+9.0	+7.8	−7.1
S2: Replace 20% coal with nuclear	−14.7	−12.0	−13.5	−0.4	−10.1	−0.2	−13.8	−13.9	+0.9

Note. CC, climate change; TA, terrestrial acidification; FEU, freshwater eutrophication; MEU, marine eutrophication; HT, human toxicity; TET, terrestrial ecotoxicity; FET, freshwater ecotoxicity; MET, marine ecotoxicity; CED, cumulative energy demand.

were similar between the stocking density of 45 kg/m^3 and 60 kg/m^3. Regarding the electricity generation scenarios on replacing 20% of coal-based (baseline) with wind- (S1) and nuclear-based (S2) electricity, respectively, the results showed that S1 and S2 had a similar trend in six impact categories, namely, a reduction by 8–15% in CC, TA, FE, and HT while up to 0.5% in MEU and TET.

The effect of uncertainty sources on the respective life cycle impacts per tonne salmon and feed was estimated using Monte Carlo uncertainty analysis in SimaPro v8.3 (see Table S12 in the Supporting Information available on the Web). Regarding the life cycle impacts per tonne live-weight salmon, MEU (CV [coefficient of variation] = 0.9%) had a lowest level of uncertainty and HT (CV = 93%) had a highest level of uncertainty. For the life cycle impacts per tonne salmon feed, a lower level of uncertainty was in CC and TA (CV = 3%), whereas a higher level of uncertainty existed in HT (CV = 42%) and FEU (CV = 35%). It is noted that the results of absolute uncertainties of Monte Carlo analysis in SimaPro currently take into account only the uncertainty in LCI, without considering the uncertainties in the characterization scores themselves (Goedkoop et al., 2016). The results of this Monte Carlo analysis using SimaPro, therefore, can be interpreted as an indicator of the relative uncertainty in each impact category.

4 | DISCUSSION

4.1 | Environmental performance of farmed salmonid fish

In order to better understand the LCI of Atlantic salmon farmed in the indoor RAS farm (hereafter referred to as the Chinese case), a comparison was made with three respective salmonid fish farming literature on (a) Atlantic salmon in a conceptual land-based RAS in the United States and open net-pen system in Norway (Liu et al., 2016), (b) Chinook salmon in a pilot marine floating confined tank in Canada (McGrath et al., 2015), and (c) Atlantic salmon in a land-based, flow-through system and Arctic char in a recirculating system in Canada (Ayer & Tyedmers, 2009) (see Table S13 in the Supporting Information available on the Web).

For simplification purposes, this comparison addressed only six grow-out operational parameters, including stocking density, production losses, farm-level electricity use, liquid oxygen consumption, eFCR, and on-site nutrient emissions. The comparison showed a substantial variance among the LCI data of different salmonid fish farming systems. Take the on-site electricity use as an example. Compared to the concept-level salmon RAS farming in the United States with a maximum stocking density of 80 kg/m^3 and eFCR of 1.09 (Liu et al., 2016), electricity use in the Chinese case (eFCR 1.45) increased by 38% at the baseline stocking density of 24.2 kg/m^3 and decreased by 20% at the design stocking density of 45 kg/m^3. According to the electricity use data reported by Ayer and Tyedmers (2009), the Chinese case (baseline) accounted for 56% of the land-based, flow-through Atlantic salmon farm (stocking density 38 kg/m^3, eFCR 1.17) and 33% of the recirculating Arctic char farm (stocking density 73 kg/m^3, eFCR 1.45) in Canada. Regarding the on-site nutrient emissions to water, the total N and P emissions per tonne salmon of the Chinese case was close to the value reported in the offshore closed-containment case in Canada (McGrath et al., 2015), since the grow-out farm in China currently discharged all collected nutrients to the sea.

The contribution analysis of this cradle-to-farm gate LCA study (Figure 2) confirmed previous results in the literature on the importance of feed production (and on-site energy use in the case of closed-containment systems) to the life cycle impacts of farmed salmon. Based on the average life cycle impacts of open net-pen farmed salmon in Norway, UK, Canada, and Chile, Pelletier et al. (2009) reported that feed accounted for 94% of global warming and acidifying emissions and 93% of cumulative energy use, while farm-level energy use contributed to 4% of cumulative energy use, 3% of global warming, and 3% acidifying emissions. In an LCA of the actual production cycle of Chinook salmon farmed in an offshore closed-containment system, McGrath et al. (2015) concluded that feed production was the primary contributor of global warming (60%) and acidification potential (57%), while the on-site energy use contributed mostly to cumulative energy use (42%). Similarly, this Chinese case study demonstrated that on-site electricity use and feed production dominated eight (ranging 54–95% in total) of the nine impact categories assessed, except the MEU impact.

This study indicated that the contribution of infrastructure needs further investigation in future LCA studies on land-based RAS farming. Previous aquaculture LCA studies either excluded infrastructure or reported it with little contribution to the life cycle impacts of recirculating fish production systems. For instance, Aubin, Papatryphon, van der Werf, and Chatzifotis (2009) presented that infrastructure contributed between 0% and 5% to the overall cradle-to-farm gate life cycle impacts per tonne live-weight turbot in a French recirculating farm. In an LCA of Chinook salmon farmed in an offshore closed-containment system in Canada, by contrast, McGrath et al. (2015) reported relatively higher contributions of infrastructure (mainly a cylindrical tank made of steel and thermoplastics, 20-year life expectancy) to CC (7–12%), acidification potential (5–8%), and CED (6–10%). For comparison, this indoor salmon RAS study (Figure 2) illustrated that the grow-out infrastructure (with a 15-year life expectancy) contributed to HT (24%), MET (18%), FET (17%), FEU (17%), CC (12%), CED (10%), and TA (6%). Limitations of the present study are briefly discussed in Section 10 in the Supporting Information available on the Web.

4.2 | Strategies for improving environmental performance of indoor salmon RAS farming

Environmental hotspots of a life cycle can serve as a basis for developing mitigation measures and strategies toward more eco-friendly salmon production. For the indoor salmon RAS case in this study, feed production, grow-out effluents, and on-site electricity use were identified as main environmental hotspots of the cradle-to-farm gate salmon production system.

Three feed-related issues (grow-out nutrient emissions, eFCR, and feed ingredient production) play a key role in minimizing the life cycle impacts per tonne salmon harvested at the grow-out farm. Toward more sustainable salmon production in RAS, on the one hand, it is crucial to regulating nutrient loading of grow-out effluents discharged to the sea, so as to minimize the potential MEU impact. The collected solid wastes and sludge from the mechanical and biological filtration processes could be used as, for instance, a source of biogas (after anaerobic composting), agriculture fertilizers, and an input in microalgae production (Campo, Ibarra, Gutierrez, & Takle, 2010). On the other hand, a lower eFCR could reduce the life cycle impacts of feed as well as the eutrophication potential of grow-out effluents. The sensitivity analysis results (Table 1) demonstrated that, compared to the baseline eFCR of 1.45, the MEU potential decreased by 10% at the eFCR of 1.3 and by 23% at the eFCR of 1.1. However, appropriate feeding regimes and eFCR in practice depend on a number of interrelated factors, particularly on feed composition, feed digestibility and stability, feeding technology and strategies, fish growth and size, and mortality (Pelletier et al., 2009).

Owing to concerns on overfishing and increasing costs, there have been many efforts to substitute marine protein and fat with plant-based ingredients in production of salmonid feeds (Davidson et al., 2016; Trullàs, Fontanillas, Tres, & Sala, 2015). From an ecological sustainability perspective, it is preferable to produce salmon feed using ingredients with lower environmental impacts, given that eFCR remains similar during the grow-out period. However, environmental trade-offs across impact categories may emerge from substitution of marine ingredients with plant-derived ingredients, as seen from Table S11 in the Supporting Information available on the Web. Compared to the life cycle impacts per tonne soybean meal, this study showed that (a) 1 tonne krill meal was 2–50 times higher in five impact categories (TA, CC, CED, HT, and MEU) and lower by a factor of 0.1–5 in three categories (FET, FEU, and TET), and (b) 1 tonne sand eel-based fishmeal was 2.4 times higher in TA but lower by a factor of 0.01–5 in the other eight categories. It is noted that this streamlined LCA analysis (see Table S11 in the Supporting Information available on the Web) did not consider the differences in the protein and lipid content of alternative feed ingredients, which are important for feed production. In an LCA of aquafeed ingredients, Silva, Valente, Matos, Brandão, and Neto (2018) reported that the production of lipid ingredients required more mass of the ingredient source component.

On-site electricity use was identified as one main environmental hotspot of the studied salmon RAS farming system, owing to the following two reasons. First, the RAS technology is currently energy intensive. Ensuring a continuous water flow is crucial to avoiding system failure for any fish farm depending on a piped water supply (Chadwick, Parsons, & Sayavong, 2010). In this case study, more than half of the total on-site electricity was used by pumps for water circulation (37%) and water supply (22%) during the grow-out period. Compared to the operational stocking density of 24.2 kg/m^3, however, the farm-level electricity use per tonne salmon could decrease by 46% at the design stocking density of 45 kg/m^3 (see Table 13 in the Supporting Information available on the Web). Besides optimization of operational stocking density, a further reduction of the farm-level electricity use per tonne harvested salmon largely depends on the development of energy-efficient pumps and the reduction of unit-level energy consumption. Second, an alternative solution for fish farms would be to generate on-site renewable electricity, such as solar and wind power (if applicable), since a substantial change in country electricity mix may take a long time.

It is interesting to notice that the life cycle impacts per tonne farmed salmon in RAS, to some extent, were sensitive to stocking density of grow-out rearing tanks (Table 1). Since the indoor recirculating systems require relatively high initial capital investments, RAS farming with high stocking densities and yields are expected to offset investment costs (Martins et al., 2010). In a 10-week stress-oriented experiment conducted at the same salmon RAS farm, Liu, Liu, and Wang (2015) reported that the growth rate of 14-month-old post-smolts decreased by 1.6% at medium density (15.1–31.1 kg/m^3, initial to final density) and by 3.8% at high density (30.2–61.3 kg/m^3), compared to low density (7.6–15.7 kg/m^3), while different stocking densities had no influence on the mortality rate. In this regard, an integrated assessment of the salmon RAS production system is needed in future studies to find win–win solutions between operational performance (such as stocking density, water quality, energy use) and fish welfare (condition/quality) in particular.

4.3 | Promoting LCA as a decision support tool for environmental assessment of aquaculture

On the path toward more sustainable aquaculture, life cycle thinking and life cycle approaches should be employed in aquaculture environmental management and decision making. In particular, life cycle thinking aims to extend the traditional focus of environmental engineering on production site to assess the potential environmental impacts of a product throughout the whole value chain.

Although LCA has been regarded as the most mature life cycle based environmental systems analysis method to aid in addressing environmental sustainability challenges (Curran 2015), two aspects deserve further attention for the application of LCA in aquaculture. First, aquaculture LCA studies need to obtain representative, precise, and preferably site-specific data for both foreground and background processes. The currently available LCI databases (such as ecoinvent v3, LCA food DK, and Agri-footprint) have only a few aquaculture-related background processes from different geographic regions. There have been efforts to improve the LCI databases of aquafeed production, such as the reported LCI data of three Peruvian fishmeal plants (Fréon, Durand, Avadí, Huaranca, & Moreyra, 2017). However, there are still very few publications on LCI of feed ingredient production and feed manufacturing processes in China. To reduce uncertainties associated with results of aquaculture LCA studies, it is crucial to have a further update on aquaculture-related LCI database, particularly on fisheries, livestock, and agriculture production, and processing of feed ingredients in highly relevant regions.

Second, aquaculture LCIA results need to be interpreted with caution, especially in the case of comparing the environmental impacts of different fish farming systems. Although LCA has a wide application in land-based products and production processes, a number of aquaculture-specific impacts have not yet been fully considered in LCIA (Samuel-Fitwi, Wuertz, Schroeder, & Schulz, 2012), for example, related to spread of diseases and salmon lice, impacts of trawling on seafloor, effects of escaped salmon on ecosystems, use of medicines and antibiotics, antifouling, and overfishing (Ellingsen & Aanondsen, 2006; Ellingsen, Olaussen, & Utne, 2009). It therefore becomes very hard to make a fair comparison of the life cycle impacts of fish products, for example, between land-based RAS and marine cage aquaculture, even if the same LCIA method employed in an LCA study. In order to better address those aquaculture-specific environmental impacts in LCIA, multidisciplinary cooperation is needed between LCA practitioners, LCA developers, environmental and ecological modelers, and aquaculture experts.

5 | CONCLUSIONS

This paper presents the results of LCI and LCIA per tonne harvest-ready live-weight Atlantic salmon (*S. salar*) in an indoor RAS farm, located in northern China. To our knowledge, this study is the first comprehensive, multi-impact category LCA of Atlantic salmon farmed in indoor RAS at the commercial scale in the world. It provides a broad overview of the ecological challenges of moving offshore salmon fish farming toward land-based production. The LCIA results, based on the ReCiPe midpoint (H) and CED methods, show that (a) feed production was the primary contributor to the impacts of TET (95%) and TA (48%), (b) the on-site nutrient emissions from the grow-out farm contributed most to the MEU impact (87%), and (c) the farm-level electricity use dominated the other six impact categories, ranging between 39% (HT) and 52% (MET). For the life cycle impacts per tonne salmon feed, krill meal (8%) contributed most to TA (40%), CC (37%), and CED (34%), whereas chicken meal (5%) dominated the other six impact categories (43–65%). In particular, the life cycle impacts per tonne live-weight salmon seemed sensitive to stocking density of the grow-out farm. Results of the sensitivity analysis indicated that the life cycle impacts per tonne salmon reduced by 20–35% in seven of the nine impact categories (except MEU and TET) when the stocking density increased from 24.2 kg/m^3 (operational data of the period studied) to 45 kg/m^3 (design data of this grow-out farm).

Results of the present study would be useful for enhancing understanding of the environmental performance of farmed salmon in indoor RAS at the commercial scale, and serve as a basis for developing LCA-based innovations toward more eco-friendly farmed salmon. In the development of strategies and mitigation measures toward more sustainable aquaculture production from an LCA perspective, this study also indicates that it is important (a) to analyze the relative contribution of respective mitigation measures to the overall life cycle impacts of a system for identifying priority strategies, and (b) to check trade-offs between impact categories and among alternative measures for avoiding a shift of environmental problems. Without LCA, environmental improvement measures of a farm may be suboptimal and cause unintended environmental problem shifting.

To promote the application of LCA as an environmental decision support tool in the aquaculture industry, future research should focus on improving the currently underdeveloped aquaculture-related LCI database and addressing aquaculture-specific environmental impacts in life cycle impact assessment.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Dr. Guoxiang Sun for help with collection of production data on the Atlantic salmon RAS farm in China as well as three anonymous reviewers commissioned by the journal for their helpful comments.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Song X, Liu Y, Pettersen JB, et al. Life cycle assessment of recirculating aquaculture systems: A case of Atlantic salmon farming in China. *Journal of Industrial Ecology*. 2019;23:1077–1086. https://doi.org/10.1111/jiec.12845

Ocean Threats

Pollution

Selling Off the Ocean?

Aquaculture

Overfishing

Pirate Fishing

Destructive Fishing Practices and Bycatch

Climate Change

Fishers' Knowledge

Domino Effect: The Jellyfish Example

Aquaculture

Aquaculture is fastest-growing area of food production in the world. Often suggested as the future of the fish industry, in its current state **it is NOT a solution to overfishing.**

While in certain places some forms of aquaculture can provide an important food source, they must be developed in a responsible way. The rapid growth of intensive aquaculture for species with high commercial value intended for export, such as salmon and shrimp, has already caused dreadful environmental damage and the displacement of many local farmers and fishers whose livelihoods have been destroyed.

Some of the main problems with aquaculture:

Ecosystem Destruction

Intensive fish farms release enormous quantities of organic waste (fecal material) and contaminated water into the natural environment around the farm sites. Every day, all the salmon farms in Scotland put together produce as much excrement as the 600,000 inhabitants of Edinburgh. As a result, the surrounding waters see accelerated, chaotic algae growth, which can prove deadly for certain marine animals and indirectly constitute a danger to humans, who end up eating contaminated shellfish. When an ecosystem has become too compromised, the farm is simply moved elsewhere.

Often **coastal ecosystems** are completely destroyed in order to make room for intensive aquaculture.

This is the case with the artificial ponds created to farm tropical shrimp. **Mangroves are chopped down,** leading to the disappearance of all the species that used to shelter among the trees, including fish of commercial value, oysters, birds, and more, and the removal of natural protection against storms and tsunamis. Fresh-water sources are drained to lower the salt level of the farms and coastal communities are forced to move to survive. It has been estimated that around 35% of mangrove forests have disappeared and that some countries have lost 80% of their mangroves. The human activities causing the destruction of this tropical vegetation are aquaculture (52%, of which 28% shrimp and 14% fish), deforestation (26%) and the diversion of fresh-water streams (11%).

Pressure on Wild Species

Contrary to what one might imagine, aquaculture does not reduce pressure on wild fish species. As practiced today, in many cases, it increases it.

- In intensive aquaculture **the high concentration of animals means parasites and diseases spread easily.** Farmed species, selected for their resistance, often survive only thanks to the massive use of antibiotics and vaccines. But in the adjacent natural environment, local wild fish suffer greatly. For instance, recent research has shown that the area around a single typical British Columbia (Canada) salmon farm generated deadly sea lice at a rate of 33,000 times ambient levels, producing lethal infection of young wild salmon up to 70 km away.

- In many fish farms, **enormous quantities of forage fish, fishmeal and fish oil are used to feed the farmed fish.** Aquaculture often involves fattening up carnivorous fish such as many species of salmon and tuna. Clearly the operation makes sense from a commercial point of view, as the farmed fish command much higher prices than the fish used to feed them, even when these forage fish (sardines, mackerel and herring, for example) can also be eaten by humans. But in the end the quantity of fish used for feed is greater than the quantity produced, and the pressure on wild fish stocks remains high.

Given these issues, aquaculture cannot be seen as an alternative to fishing, particularly in developing countries, where very few people can afford products such as smoked salmon.

- **Farmed fish are selected for characteristics that make them unsuited to living in the wild.** A certain number of fish **escape from the ponds** and then place pressure on the natural environment. In some areas the escaped fish are now more numerous than their wild cousins. They help impoverish the genetic heritage and exacerbate the struggle for survival of native species.

- Some aquaculture businesses use genetic engineering techniques on the farmed species (**genetically modified fish**), usually without any external controls. Genetically modified tuna, salmon and tilapia are now being farmed. Research in this sector is growing rapidly in many countries around the world and is aimed primarily at sterilization. speeding up growth rates and improving resistance to cold and disease. It regards fish, shellfish and other marine organisms such as algae.

To date, we do not know what effects these practices will have on human health. The impact on the aquatic environment has, however, been studied. Various organizations working to protect marine ecosystems point out that it is impossible to guarantee that these fish do not escape and say that their sudden presence in natural environments represents a potential disaster.

Another issue is the introduction of exotic species, which are a threat to the local ecosystem and cause a series of unexpected problems for those who decided to introduce them.

Chosen for their reproductive capacity, fast growth and tolerance of poor-quality water, genetically modified fish and exotic species have significant advantages over wild fish. Farm escapees threaten local species by eating juveniles, directly competing for food and shelter and spreading diseases and parasites.

Human Rights Violations

The industrialization of aquaculture is also leading to issues with human rights.

For some years, serious concerns have been raised about the social impact of shrimp farms, which have seen a huge boom following a massive increase in global demand.

According to the Environmental Justice Foundation, the shrimp industry is often guilty of serious abuses, such as land-grabbing and

EXHIBIT M-7

E&E NEWS

ENVIRONMENT

Congress Says Biomass Is Carbon-Neutral, but Scientists Disagree

Using wood as fuel source could actually increase CO_2 emissions

By Chelsea Harvey, Niina Heikkinen, E&E News on March 23, 2018

Credit: Jean-Christophe Verhaegen *Getty Images*

Lawmakers are once again pushing U.S. EPA and other federal agencies to recognize the burning of biomass as a carbon-neutral energy source. But scientists say that could be a bad move for the climate.

A massive fiscal 2018 federal spending bill unveiled by congressional leaders Wednesday night includes a provision urging the heads of EPA, the Energy Department and the Agriculture Department to adopt policies that "reflect the carbon-neutrality of forest bioenergy and recognize biomass as a renewable energy source."

The language has appeared in similar forms in previous spending bills the last few years, due to pressure from lawmakers in forest-heavy states. This latest version follows recent comments by EPA Administrator Scott Pruitt declaring biomass a carbon-neutral energy source. He has billed the change as part of the administration's broader efforts at "energy dominance."

In a letter to New Hampshire Gov. Chris Sununu (R) last month, Pruitt stated the agency's decision was partly in response to concerns articulated by the forest and forest products industry (*Climatewire*, Feb. 14).

But scientists have been expressing concern for years about the emissions produced by burning biomass. Many experts suggest that declaring wood burning a carbon-neutral form of energy is not only inaccurate, but a potential step backward for global climate change mitigation efforts.

RENEWABLE, YES. BUT CARBON NEUTRAL?

William Schlesinger, a biogeochemist and former president of the Cary Institute of Ecosystem Studies, was among the latest to weigh in with commentary published in *Science* yesterday. He said that "recent evidence shows that the use of wood as fuel is likely to result in net CO_2 emissions."

Biomass is technically a "renewable" energy source, in that trees can be replanted after they're harvested. And some lawmakers have argued that because trees store carbon as they grow, replacement forests will gradually remove the carbon dioxide emitted when the previous trees were burned for energy, making the whole process carbon neutral—that is, putting no net emissions into the atmosphere.

But there are some serious flaws in that argument, many scientists suggest. One of the biggest issues is the matter of timing.

Burning biomass for energy releases large amounts of carbon into the atmosphere all at once. But depending on the type of tree, forests may take decades or even a century to draw the same amount of carbon back out of the air.

“We call it ‘slow in,’ as in it takes a long time for the carbon to accumulate in the forest, and ‘fast out’—you’re burning it so it goes into the atmosphere rapidly,” said Beverly Law, an expert in forest science and management from Oregon State University.

One could argue that the process has the potential to be carbon neutral over very long time scales but not in the short term. And that means it’s not a useful strategy when world leaders are working to reduce global carbon emissions immediately.

Even for the process to be considered carbon neutral on long time scales, Schlesinger noted, forest managers would have to be certain that replacement trees were given enough time to store the same amount of carbon that their predecessors contained when they were harvested. Especially if older, more carbon-rich forests are cleared to make room for faster-growing, easier-to-harvest trees, then even more carbon must be stored away to make up the difference.

The language in the spending bill does indicate that forest biomass for energy should only be considered carbon neutral if it “does not cause conversion of forests to non-forest use.”

Schlesinger also pointed out that much of the wood raised and harvested in the United States for energy purposes is actually shipped to the European Union, where biomass is currently treated as a carbon-neutral energy source. Processing the biomass for energy use (converting trees into wood pellets, for instance) and shipping it overseas only adds to the total emissions produced by the industry, he noted.

According to Law, a more climate-friendly approach would be to simply preserve or add to existing forests without harvesting them—a process that would enhance the nation's natural carbon sinks—and focus instead on truly carbon-neutral sources of energy, like wind and solar. Adopting policies that equate biomass with these cleaner energy sources could be "devastating," she said. "It does exactly the opposite of what we need to do: reduce emissions."

It's hardly the first time scientists and environmentalists have raised the alarm. In 2016, dozens of environmental groups submitted a letter to the Senate Appropriations Committee urging members to reject any language in an upcoming appropriations bill that might deem biomass a carbon-neutral energy source. An energy bill also passed by the Senate in 2016 contained similar language, and more than 60 scientists responded with a letter outlining their concerns. Controversy arose over similar language in spending bills announced in 2017, as well.

SCIENTIFIC DISCUSSIONS 'LEFT HANGING'

The House and Senate have until tonight to pass the 2018 spending bill to avoid another government shutdown. In the meantime, EPA appears primed to follow through with some of the forest product industry's recommendations.

Pruitt said in his letter to Sununu last month that EPA was considering "a range of options consistent with a carbon neutral policy for biomass from forests and other lands and sectors" for Clean Air Act permitting programs. Pruitt described the move as a way to increase the "economic potential" of the nation's forests under an "all of the above" energy policy.

“Unquestionably, by providing certainty for the treatment of biomass throughout the agency’s permitting decisions, the use of biomass energy will be bolstered, to the benefit not only to the forest products industry but to the environment as well, while furthering the Administration’s goal of energy dominance,” he wrote.

EPA is also reviewing certification standards for its federal procurement recommendations. Pruitt’s letter noted that current standards excluded products from managed forests such as those certified by the Sustainable Forestry Initiative and the American Tree Farm System.

The agency did not elaborate when asked for more information about how the agency was progressing toward classifying biomass as carbon neutral.

Pruitt’s statements also came as EPA’s Science Advisory Board remains deadlocked after years of debate on the best way to advise regulators on how to account for emissions from burning biomass. Schlesinger, himself a member of the advisory board, noted that the group has not met since August and that discussions about the designation of biomass energy were “kind of left hanging as to what was happening.”

“If he’s made that decision, it was done without the input of the Science Advisory Board,” he added.

Steven Hamburg, chief scientist at the Environmental Defense Fund and an advisory board member, criticized Pruitt's position during an interview last month.

"The science isn't done," he said. "The administration is not in a position to make a science-based determination in absence of scientific assessment, and this is a science question."

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Carbon emissions from burning biomass for energy

Is biomass "Worse than coal"? Yes, if you're interested in reducing carbon dioxide emissions anytime in the next 40 years.

Biomass burning: a major carbon polluter

It's often claimed that biomass is a "low carbon" or "carbon neutral" fuel, meaning that carbon emitted by biomass burning won't contribute to climate change. But in fact, biomass burning power plants emit **150% the CO_2 of coal, and 300 – 400% the CO_2 of natural gas, per unit energy produced.**

These facts are not controversial and are borne out by actual air permit numbers. The air permit for the We Energies biomass facility (link) at the Domtar paper mill in Rothschild, WI, provides an example of how biomass and fossil fuel carbon emissions compare. The mill has proposed to install a new natural gas boiler alongside a new biomass boiler, and presented carbon emission numbers for both. The relevant sections of the permit are shown below.[1] They reveal that the biomass boiler would emit 6 times more carbon (at 3,120 lb/MWh) than the adjacent natural gas turbine (at 510 lb/MWh).

The Domtar plant was required to show its greenhouse gas emissions from biomass by EPA rules. Although the EPA has proposed a three-year deferral of greenhouse gas permitting for "biogenic" emissions under the "tailoring rule" of the Clean Air Act, this waiver will not go into effect until July 2011. Until then, the EPA is requiring facilities with biogenic emissions to report and try to mitigate their greenhouse gas pollution (using Best Available Control Technology, or BACT) if they are also major emitters of other air pollutants. There is no realistic means to reduce CO_2 emissions, however, other than improving plant efficiency.

Burning biomass emits more CO_2 than fossil fuels per megawatt energy generated:

1. Wood inherently emits more carbon per Btu than other fuels
   - Natural gas: 117.8 lb CO_2/mmbtu
   - Bituminous coal: 205.3 lb CO_2/mmbtu
   - Wood: 213 lb CO_2/mmbtu (bone dry)

2. Wood is often wet and dirty, which degrades heating value
   Typical moisture content of wood is 45 – 50%, which means its btu content per pound is about half that of bone dry wood. Before "useful" energy can be derived from burning wood, some of the wood's btu's are required to evaporate all that water.

3. Biomass boilers operate less efficiently than fossil fuel boilers (data from air plant permit reviews and the Energy Information Administration)
   - Utility-scale biomass boiler: 24%
   - Average efficiency US coal fleet: 33%
   - Average gas plant: 43%

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A. Boiler B02 – 350 MMBTU/hour natural gas. This boiler is subject to NSPS (Part 60, Subparts D and Db).

8. Greenhouse Gases
a. Limitations: BACT. (1) Greenhouse gas emissions may not exceed 190 lb CO_2e per 1,000 pounds of steam produced, or 510 lb CO_2e per MWh of steam produced per month, averaged over any consecutive 12-month period. (s. NR 405.08, Wis. Adm. Code and 10-SDD-058)

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B. Boiler B01 – Biomass and natural gas fired boiler with a capacity not to exceed 800 MMBTU/hour. The boiler is subject to NSPS (Part 60, Subparts D and Db).

11. Greenhouse Gases
(a) Limitations: BACT. (1) Greenhouse gas emissions may not exceed 3,120 pounds of CO_2e per MWh of gross output, averaged over any consecutive 12-month period. *Gross output* means the gross useful work performed by the steam generated. When the unit is generating only electricity, the gross useful work performed is the gross electrical output from the turbine/generator set. For cogeneration, the gross useful work performed is the gross electrical output plus 75 percent of the useful thermal output measured relative to ISO conditions that is not used to generate additional electrical output (i.e., steam delivered to an industrial process). . (s. NR 405.08, Wis. Adm. Code)

If burning biomass emits carbon dioxide, how can it be "carbon neutral"?

CO_2 is CO_2, whether it comes from burning coal or burning trees. So why do some people argue that biomass power generation is "carbon neutral"?

There are two main arguments, the "waste" argument and the "resequestration" argument:

The "waste" argument part 1: "It would have decomposed anyway"
Biomass fuel is often portrayed as being derived from "waste" materials, particularly the tree branches and other material left over after commercial timber harvesting ("forestry residues, slash"), as well as sawdust and chips generated at sawmills ("mill residues"). Because these materials are expected to decay eventually, emitting carbon dioxide in the process, it is argued that burning them to generate energy will emit the same amount of carbon as if they were left to decompose.

This claim only works if the time element is ignored, and if there is actually enough waste to power the proposed facilities.

It takes years and even decades for trees tops and branches to decompose on the forest floor, and during that process, a portion of that decomposing carbon is incorporated into new soil carbon. In contrast, burning pumps the carbon stored in this wood into the atmosphere instantaneously. There is a difference of many years, and even decades, between the immediate emissions from burning residues, and the slow evolution of carbon from natural decomposition. So one question is, how can a form of energy that dramatically *accelerates* the release of CO_2 into the atmosphere be considered carbon neutral? The answer is that it can't be, unless critical factors like time are ignored.

Another important question is, how much of these "forestry residues" are really available, compared to the amount of fuel required by a growing biomass industry? We explore that question in detail elsewhere; here, it's sufficient to state that forestry residues are extremely limited, relative to fuel demand, and that many facilities already harvest whole trees for fuel.

Waste argument, part 2: the "Methane Myth"

Some people claim that it's better to collect logging residues for biomass fuel, rather than leaving them in the forest, because allowing these materials to decompose naturally can emit not just carbon dioxide (CO_2), but also methane (CH_4). Because methane has a greater global warming potential than carbon dioxide, proponents of biomass power argue it is better from a greenhouse gas perspective to burn this material, and emit the carbon as carbon dioxide, rather than let it decompose in the forest, where some of it may be emitted as methane.

There are notable problems with this argument.

- Methane is not produced in upland areas where well-aerated logging residues are decomposing. Instead, it is chiefly produced in wet, low-oxygen environments like wetland soils. Forest soils contain bacteria that produce methane, but also bacteria that consume methane, so the net emissions are small. (EPA's information on methane puts different sources into perspective).
- Landfills can be sources of methane, but according to a study on landfilled wood, "the resistance of most forest products to anaerobic decomposition in landfills is significant"… and that only about 3% of land-filled wood is emitted as methane or carbon dioxide.
- Notably,biomass proponents never mention something that *is* very likely to be a source of methane emissions: the football field-sized, 30 – 70 foot tall, wet, steaming, and poorly aerated piles of chipped wood fuel at many biomass plants. (One study found temperatures in a wood chip pile rose to 230F less than two months after pile completion; temperatures above 180F are considered to produce a high probability of spontaneous combustion. Off-gassing from relatively dry wood fuels can produce, in addition to CO_2, carbon monoxide, methane, butane, ethylene, and other toxic gases. The buildup of gases in the holds of ships transporting wood pellets has caused accidents and fatalities. Spontaneous combustion in wood chip piles is not uncommon.)

The "resequestration" argument.

The other main argument used to justify the idea that biomass energy is carbon neutral is that re-growing plants recapture, or "resequester" an amount of carbon equivalent to that released to the atmosphere by burning biomass fuels, and therefore net carbon emissions are zero.

When trees are used for fuel, it is obviously not possible for the system to be "carbon neutral" in a timeframe meaningful to addressing climate change. A 50 megawatt biomass power plant burns more than a ton of wood a minute. It takes seconds to burn a tree, and many decades to grow it back.

But proponents have devised deceptive arguments to obscure this logic. Some claim that as long as forests in a region are are growing more wood than is being cut, then carbon emissions from biomass burning are neutralized by this growth. This argument seems to persuade some people, but it is wrong. It sidesteps that fact that growing forests are taking up carbon *now* – and that cutting and burning them for fuel dramatically increases carbon emissions from energy compared to the fossil fuels you're replacing (see a letter about how the Washington State Department of Natural Resources made this very mistake, **here**; and see the Manomet team's takedown of a similar argument. We explain the Manomet study in more detail below).

A similar argument states that as long as forests are growing and sequestering carbon in one place, this makes up for the carbon that's emitted by harvesting and burning trees in another place. But those trees "somewhere else" were already sequestering carbon - and cutting and burning trees over *here* does nothing to increase carbon sequestration over *there*. Not to mention that the trees that you burn over *here* are no longer sequestering any carbon at all, but instead are floating around in the air as CO_2. It makes as much sense to discount biomass carbon emissions using this logic, as it does to discount fossil fuel emissions “because trees are taking up carbon somewhere”.

Over long enough time periods, forests cut for biomass fuel can ultimately regrow and recapture the carbon released by burning. But the inescapable conclusion of doing carbon accounting correctly is that burning biomass instead of fossil fuels always represents an extra burst in carbon emissions over some multi-year or multi-decadal period, and in some cases more than a century. It can’t be any other way. When you cut a forest for fuel, you’re *increasing* carbon emissions produced per unit energy by switching to wood, and at the same time, *decreasing* the total amount of forest available to take carbon out of the air and sequester it into growing trees (think of the forest as a scaffolding, upon which more carbon is hung each year. A forest cut for biomass doesn’t have the “infrastructure” to accumulate carbon quickly).

Industry data show that the overwhelming majority of biomass burners are now and will continue to be fueled by wood. Net carbon emissions from burning trees are enormous in part because trees are such long-lived organisms, so it takes decades to centuries to re-grow them after they’re burned.

But what about using crops for fuel, or other plants that have a shorter lifecycle than trees? Plants with a yearly lifecycle – like the perennial grass switchgrass – have lower net carbon emissions over time, because net carbon emitted by harvesting and burning can be re-grown in a shorter period. However, it is important to make sure that using energy crops as fuel doesn’t cause an increase in carbon emissions somewhere else. For instance, cutting down forests and planting switchgrass would represent a massive loss of carbon to the atmosphere from harvesting the trees, as well as the decomposition of roots and soil carbon following harvest. This pulse of carbon would outweigh any benefit of replacing fossil fuels with energy crops for a long time.

And, to replace even a small percentage of fossil fuels with switchgrass or a similar energy crop would take a huge amount of land. Supplying a single 50 MW biomass plant with switchgrass would require harvesting around 65,000 acres a year (assuming 7 tons of switchgrass harvested per acre). To replace any significant amount of the approximately 969,440 MW of fossil-fueled capacity in the U.S. (2009 data), would require tens of millions of acres of land that are currently growing food or feed, not to mention the 30 million acres of corn that are currently devoted to ethanol production, with notable impacts on commodity prices worldwide.

Science-based accounting for biomass energy carbon emissions: the Manomet Study

When citizen scientists and activists discovered that two to four utility-scale biomass electricity generating plants were planned in Massachusetts, they organized. Some basic math quickly revealed that the hundreds of thousands of tons of wood required to fuel these plants would far exceed not only the amount of “forestry residues” generated in the state, but also the state’s total annual commercial sawtimber harvest. Clearly, these plants would be big carbon polluters, but as “renewable energy” they would not have to report or count their emissions under state regulations, which treat all renwables as carbon neutral.

Responding to citizen activism, the state issued a request for proposals for a group to study the forest cutting impacts and net carbon emissions from biomass power. The group that was awarded the contract was headed by the Manomet Study for Conservation Sciences, and included representatives from the Biomass Energy Resource Center, the Forest Guild, and others. Several of the group’s members were already on the record claiming that burning biomass was carbon neutral.

Nonetheless, when the final “Biomass Sustainability and Carbon Policy Study” (aka the “Manomet Report”) was issued, the results surprised even the researchers. The study concluded that net carbon emissions from burning biomass in utility-scale facilities emitted more carbon than even coal, and that it would take decades to pay off the “carbon debt” created by harvesting forests for fuel. Small burners (i.e. thermal and combined-heat-and-power facilities) with higher efficiencies were found to have shorter payoff periods for their carbon debt, but even their emissions exceeded those from fossil fuels for several years.

The study assumed that the carbon debt from “logging residues” used for fuel – that is, the wood left over from sawtimber harvesting, which would decompose and emit carbon anyway – was basically paid off within a few years. But because there is relatively little of this material available in Massachusetts, the main fuel supply for biomass facilities would have to be trees that would not otherwise have been cut. And “trees that would not otherwise have been cut” turned out to have a really large carbon footprint when harvested and burned for fuel.

Upon release of the Manomet Study, the State issued a directive that new rules should be drafted to restrict the eligibility of biomass power for renewable energy credits to those facilities that could demonstrate lifecycle emissions no more than 50% those of a natural gas plant, over a 20 year period. New restrictions were also proposed that restricted the amount of wood that could be taken from a logging site and used for fuel. As of March, 2011, the final version of the rules has not been released, but as drafted, the regulations stood as the sole example of a science-based policy on biomass power anywhere in the U.S, or the world.

The Manomet Study approach to carbon accounting, or, “Carbon accounting ain’t for sissies”.

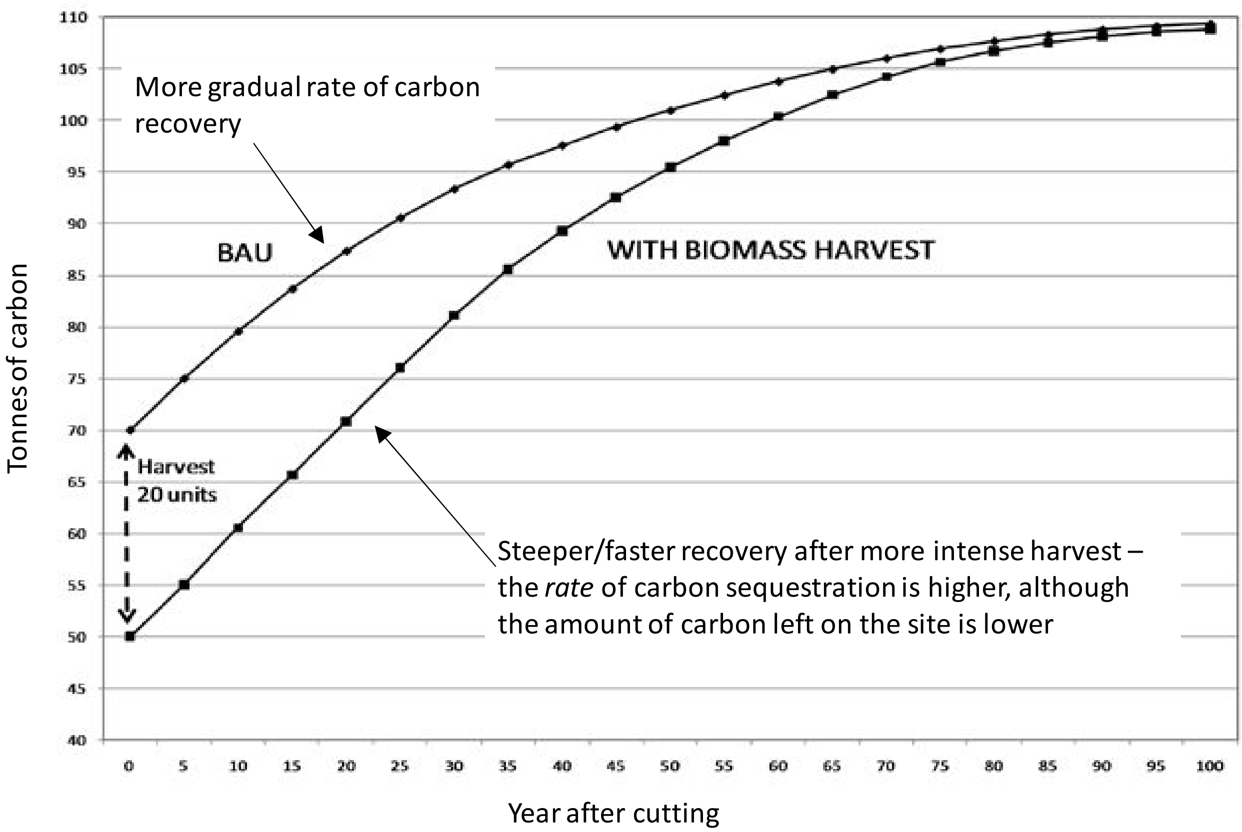
The Manomet team used a computer model of forest growth, the Forest Vegetation Simulator (FVS) to estimate net carbon emissions from biomass power. The FVS uses data collected on forest biomass and growth from the region of interest (in this case, Massachusetts forests) to run the simulations of forest regrowth after harvest.

The strength of the Manomet approach is that it acknowledges that forests *already* represent significant “sinks” for our emissions of carbon dioxide – that is, they convert atmospheric carbon dioxide into wood that takes the carbon out of circulation and thus reduces global warming potential. Forests do this whether the carbon is emitted by burning fossil fuels, or biomass.
The Manomet modeling approach compares carbon release and forest carbon sequestration under two basic scenarios:

1. The “business as usual” (BAU) scenario, where energy is generated from fossil fuels, and forests are cut for commercial timber, but not biomass fuel. Under the BAU scenario, the standing carbon in the forest is reduced down to 70 tonnes/hectare by commercial timber harvesting.

2. Under the “biomass” scenario, forests are still harvested for commercial timber down to 70 tonnes of standing carbon per hectare, but then a further 20 tonnes of forest carbon is harvested for biomass fuel, reducing the standing carbon to 50 tonnes/hectare (these assumptions and scenarios are particular to the model but do not turn out to be very important for the results, because the results largely depend on the magnitude of the *difference* between the two harvest intensities, and not the absolute magnitudes of the harvest intensities themselves).

Manomet’s graphic (from page 98 of the report) shows the regrowth of forest plots cut under the BAU scenario and the biomass scenario. We reproduce it and annotate it below. Notice that the model estimates a higher rate of regrowth (steeper curve) under the heavier harvest of the biomass scenario. This occurs because the model simulates greater penetration of light and greater water and nutrient availability in the more heavily cut forest, which allows the trees remaining on the site and the new trees geminating after harvest to grow faster. The graphic shows how initially, there is a difference of 20 tonnes of carbon between the two scenarios. After a couple of decades of regrowth, the faster rate of carbon sequestration on the more heavily harvested plot starts to narrow the gap between the two curves.



The next step is to add the emissions from energy generation into the model. Manomet estimated the amount of energy that could be generated from the 20 tonnes of biomass per hectare removed in the biomass scenario, then calculated what the carbon emissions would be if the same amount of energy were generated using fossil fuels in the BAU scenario (fossil fuel carbon emissions are a weighted average from power generators in Massachusetts, so are not representative of a 100% coal or a 100% gas scenario, but lie somewhere in-between). For this scenario, Manomet concludes that generating a given amount of energy using biomass would emit 20 tonnes of carbon, and generating the same amount of energy from fossil fuels would emit only 11 tonnes of carbon.

Biomass as fuel emits more carbon per unit energy than using fossil fuels. This creates a "carbon debt", the carbon emitted to the atmosphere that was formerly held in trees or other plants that must be paid back. When trees are harvested and burned as fuel, repaying the debt requires a higher rate of carbon sequestration than in the BAU scenario, where forests were cut for commercial timber but not fuel. If the growth rates were the same, the initial difference of 20 tonnes of carbon following harvest would persist indefinitely.

The growth curves above shows how this carbon debt is repaid. For the carbon held in the biomass scenario to catch up to the BAU scenario requires accelerated growth, and indeed, the FVS model simulates a higher growth rate in the forests cut heavily for both commercial timber and biomass fuel, compared to the forests that are cut just for commercial timber. The higher growth rate allows carbon to accumulate faster in the biomass scenario, eventually closing the gap and catching up to the carbon accumulated in the BAU scenario.

This outcome is heavily dependent on the FVS model assumption of a higher growth rate in the forest cut more heavily for fuel. If this turns out to be not true for any reason – for instance, if cutting forests for biomass actually lets in *too much* sun, overheating and drying the site and interfering with seedling regeneration, then resequestration of the extra carbon emitted by burning biomass may be postponed indefinitely. The model's conclusions will not be sustainted unless the growth rate on the more heavily cut biomass plot eventually exceed the growth rate on the BAU plot.

Further, for these conclusions to hold it is also essential that the forest plot not be cut again, prior to the full resequestration of carbon. To achieve that goal following harvesting for biomass, forests have to be left alone for decades.

For a review of these and other assumptions that likely mean that the Manomet Study painted *too rosy* a picture of the carbon impacts of biomass energy, click here.

Manomet's modeling – a closer look
Getting deeper into the modeling behind the Manomet study requires defining some terms. We try here to present the Manomet approach from a couple of different angles.

First, we look back at the previous graphic, and see that immediately following harvest, there is more standing carbon in the BAU system than the biomass system:

- C_{BAU}: Standing carbon per hectare in the BAU forest, which has been cut for sawtimber = 70 tonnes
- C_{BIO} : Standing carbon in the forest cut for biomass fuel and sawtimber = 50 tonnes

Following harvest, 20 additional tonnes of carbon have been removed as fuel from the biomass system. This is subtracted from the standing carbon (as shown in the term above) and shows up as energy emissions:

- E_{BIO} : Emissions from biomass fuel = -20 tonnes (expressed as a negative number to represent carbon that's been taken out of "solid" form and entered the atmosphere as CO_2.)

In the BAU system, energy was produced by burning fossil fuels instead of biomass, which emitted 11 tonnes of carbon:

- E_F : Emissions from fossil fuels = -11 tonnes

Below are the first 75 years of data that describe the carbon recovery (in tonnes) of single plots harvested under the BAU and biomass scenarios from the graphic above (these values are estimated off Manomet's graphics, so may not match the data used in the model precisely).

year	C_{BAU}	C_{BIO}	$E_F + C_{BAU}$
0	70	50	59
5	75	55	64
10	79.75	60.5	68.75
15	83.75	65.75	72.75
20	87.5	71	76.5
25	90.5	76.25	79.5
30	93.4	81.4	82.4
32	94.25	82.75	83.25
35	95.5	85.5	84.5
40	97.5	89.5	86.5
45	99.4	92.5	88.4
50	101	95.4	90
55	102.5	98	91.5
60	103.75	100.4	92.75
65	105	102.5	94
70	106	104.4	95
75	107	105.5	96

Remembering that in the BAU scenario, energy emissions from fossil fuel combustion were 11 tonnes of carbon, and in the biomass system were 20 tonnes from the material harvested and burned for fuel, we can see that the BAU system as a whole contains 9 tonnes more standing carbon than the biomass system.

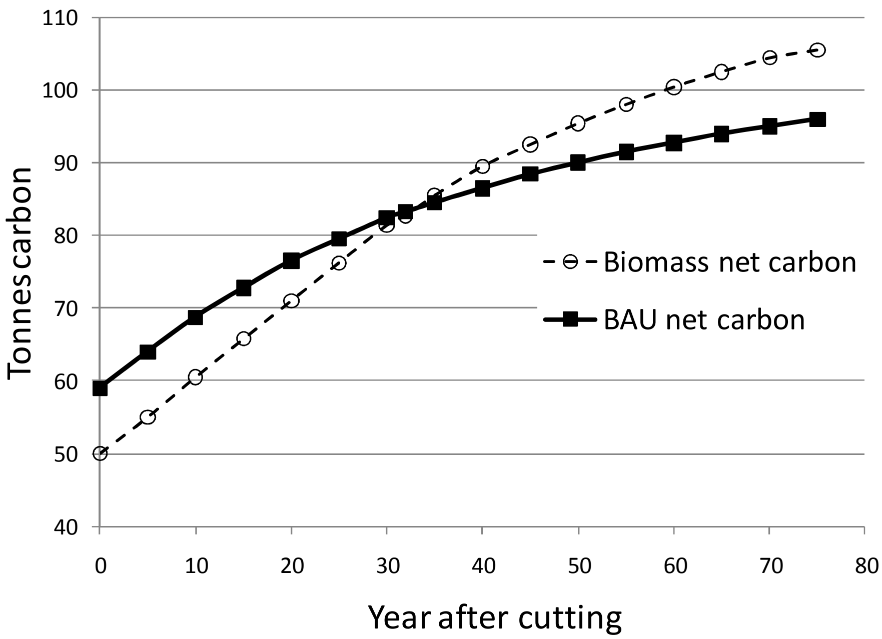
The question thus is, How many years will it take until the gap is closed and $E_F + C_{BAU} = C_{BIO}$?

Five years after harvest:
BAU system: $E_F + C_{BAU} = -11 + 75 = 64$
Biomass system: $C_{BIO} = 55$
So there are still 9 tonnes more carbon held in the BAU system than the biomass system.

At year 25, the growth rate for the biomass scenario is higher than for the BAU scenario, so the gap is narrowing and there is now only 3.25 tonnes more carbon held in the BAU system:
BAU system: $E_F + C_{BAU} = -11 + 90.5 = 79.5$
Biomass system: $C_{BIO} = 76.25$

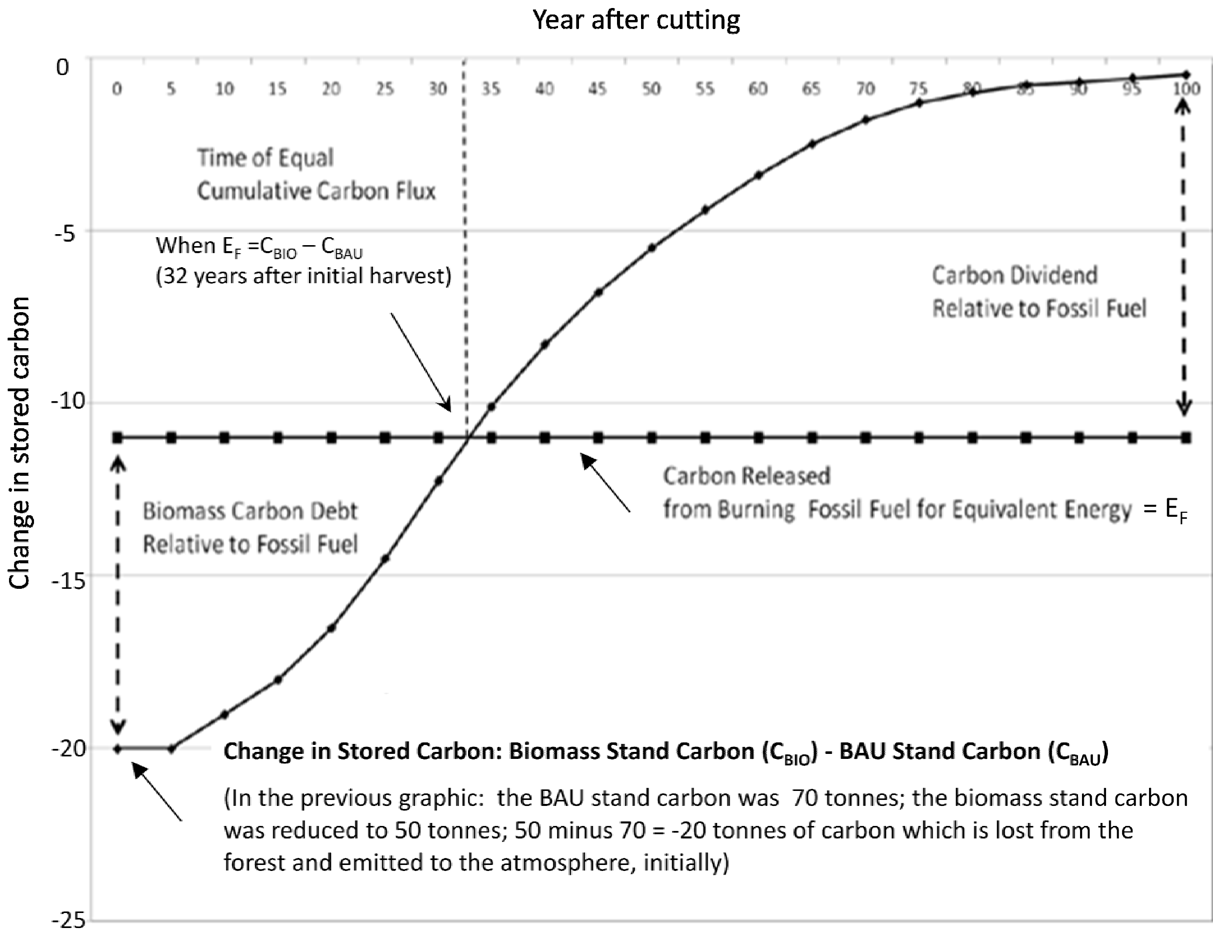
The Manomet model estimates that the gap closes completely at year 32. That is when net carbon held in the two terrestrial systems is equivalent, and net emissions from biomass power equal net carbon emissions from fossil fueled power.

Graphically, Net Carbon looks like this:



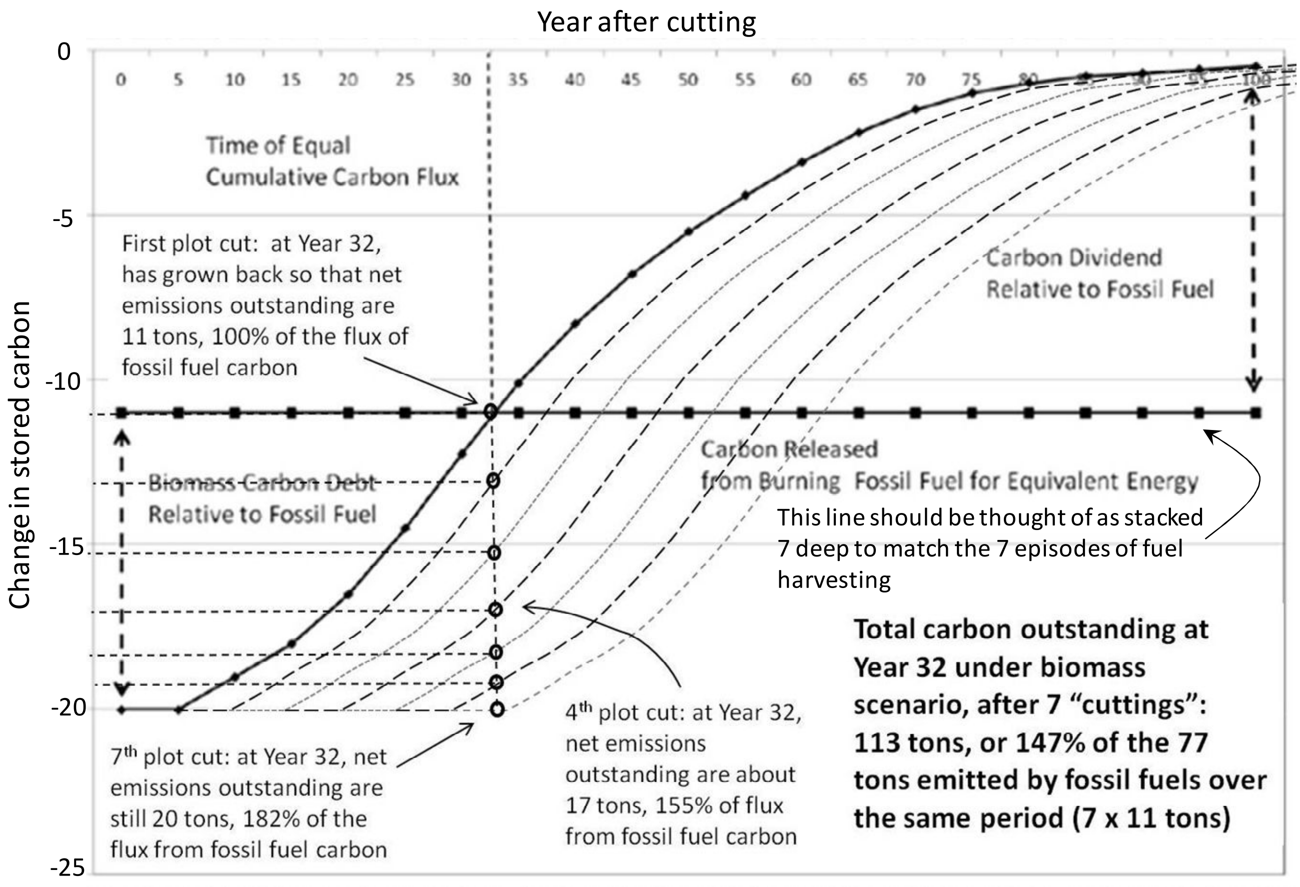
Manomet demonstrates the relationship between the two systems in a way that can be a little difficult to explain. One way to think about it is by rearranging the initial equation. Instead of asking as we did above, At what year does $E_F + C_{BAU} = C_{BIO}$, we rearrange the equation and instead ask, At what year does $E_F = C_{BIO} - C_{BAU}$?

When this is graphed against time, it looks like the following, which appears in the Manomet report on page 98:



The two previous graphics both show that following a single year's worth of fuel harvesting, it takes 32 years to repay the carbon debt and sequester enough carbon so that net emissions from biomass are the *same* as if the energy had been produced from burning fossil fuels. It is especially important to remember that up to this point, we have only been talking about the net carbon emissions through time and the carbon recovery occurring on <u>the plots cut in a single year that have been cut once to yield biomass fuel</u>.

Biomass plants are big investments, and no one builds one to operate for just a single year. To see what a facility's total carbon footprint looks like through time, we replicated the single plot graph to show multiple years of fuel harvesting (as with the former graphics, we have added to and adapted Manomet's charts). The horizontal line describing emissions from fossil fuels should be assumed to be duplicated as well – think of lines stacked on top of each other - since each year's use of biomass for fuel is compared against a year's use of fossil fuels in the BAU scenario.



As in the earlier graphic, net carbon emissions from the initial harvest of biomass achieve 100% parity with fossil fuel emissions at year 32 since the beginning of facility operation. However, at year 32, carbon from the next round of harvesting hasn't achieved 100% parity – it still has a carbon debt of about -13 tonnes. The third round of harvesting has a carbon debt slightly south of -15 tonnes at year 32 since the beginning of operation, and by the fourth round of cutting, the carbon outstanding is -17 tons. Summed over the 7 harvests shown here, the total biomass emissions are still greater than the total fossil fuel emissions, which are 77 tons (11 tons, replicated 7 times).

This is just an example – for visual clarity, the "harvests" have been staggered every five years, instead of occurring every year as they would for a biomass facility in continuous operation – but for this scenario, after 7 rounds of harvests, the net emissions under the biomass scenario are still 147% those in the BAU scenario.

The bottom line: unlike other renewable energy technologies like wind and solar, biomass is a perpetual emitter, meaning that every year's fuel supply requires creating a new "carbon debt".

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[1] The biomass boiler can also burn gas but the emission figures are for biomass, only. Greenhouse gas emissions are expressed as CO_2 equivalents per unit output – i.e., per megawatt-hour – as opposed to being on a per unit heat input basis, as is typical for conventional pollutants. This allows the differences in the boiler efficiencies to be reflected in the final output numbers.

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EDITOR'S CHOICE

Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis FREE

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BioScience, Volume 66, Issue 11, 1 November 2016, Pages 949–964,
https://doi.org/10.1093/biosci/biw117

Published: 05 October 2016

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Collectively, reservoirs created by dams are thought to be an important source of greenhouse gases (GHGs) to the atmosphere. So far, efforts to quantify, model, and manage these emissions have been limited by data availability and inconsistencies in methodological approach. Here, we synthesize reservoir CH_4, CO_2, and N_2O emission data with three main objectives: (1) to generate a global estimate of GHG emissions from reservoirs, (2) to identify the best predictors of these emissions, and (3) to consider the effect of methodology on emission estimates. We estimate that GHG emissions from reservoir water surfaces account for 0.8 (0.5–1.2) Pg CO_2 equivalents per year, with the majority of this forcing due to CH_4. We then discuss the potential for several alternative pathways such as dam degassing and downstream emissions to contribute significantly to overall emissions. Although prior studies have linked reservoir GHG emissions to reservoir age and latitude, we find that factors related to reservoir productivity are better predictors of emission.

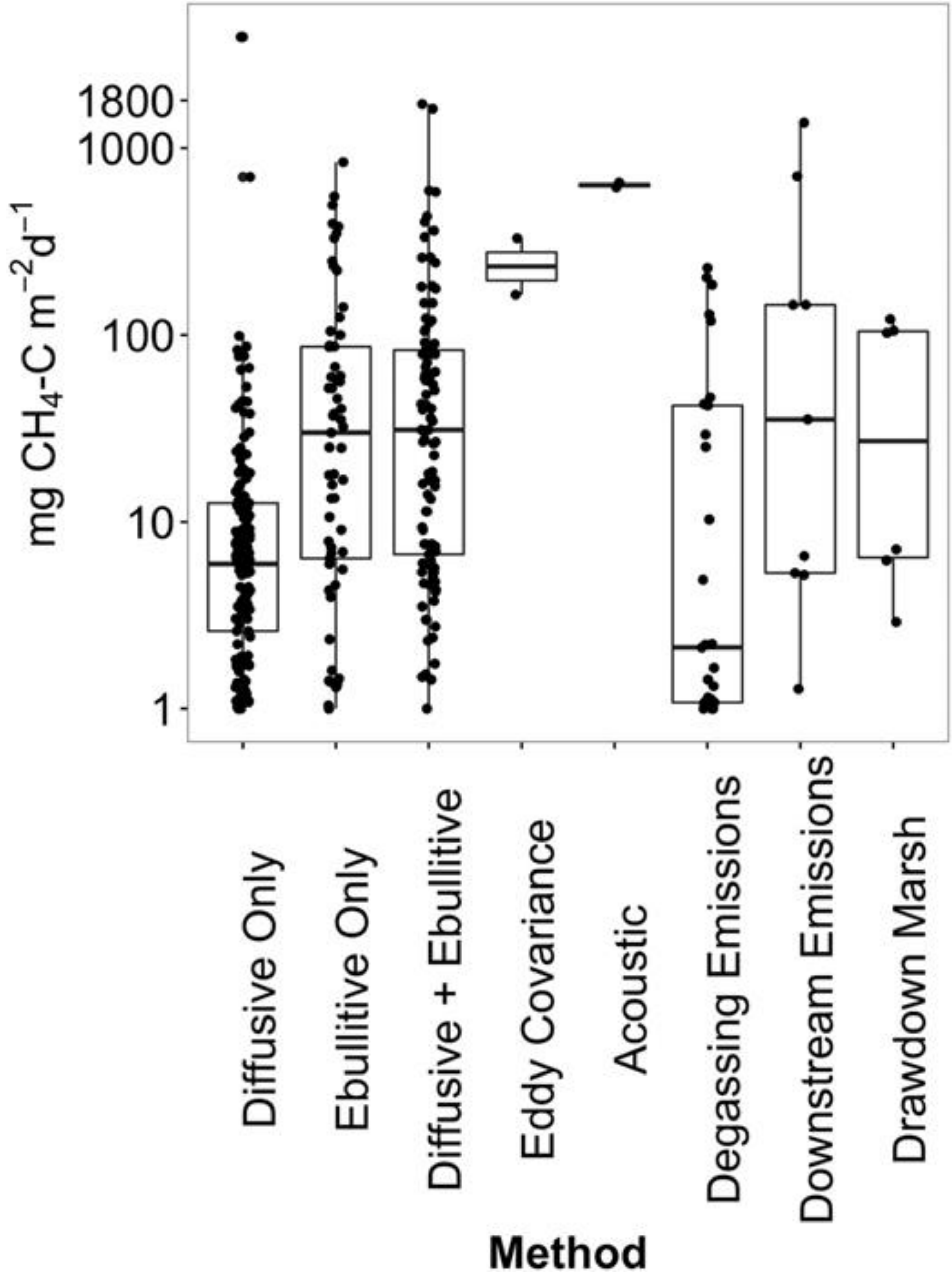
Issue Section: Overview Articles

The construction and operation of over 1 million dams globally (Lehner et al. 2011) has provided a variety of services important to a growing human population (e.g., hydropower, flood control, navigation, and water supply), but has also significantly altered water, nutrient, and ecosystem dynamics and fluxes in river networks. Much attention has been paid to negative impacts of dams on fish and other riverine biota, but the indirect effects on biogeochemical cycling are also important to consider. Although reservoirs are often thought of as "green" or carbon-neutral sources of energy, a growing body of work has documented their role as greenhouse gas (GHG) sources. Artificial reservoirs created by dams are distinct from natural systems in a number of key ways that may enhance GHG emissions from these systems. First, the flooding of large stocks of terrestrial organic matter may fuel microbial decomposition, converting the organic matter stored in above and below ground biomass to carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Second, reservoirs often experience greater fluctuations in water level than natural lakes. Drops in hydrostatic pressure during water level drawdowns can enhance CH_4 bubbling (e.g., ebullition) rates at least over the short term (Maeck et al. 2014). This enhanced ebullition may then decrease the fraction of CH_4 that is oxidized to CO_2, a less potent GHG, by methane oxidizing microbes (Kiene 1991). Finally, the high catchment area–to–surface area ratios and close proximity to human activities (Thornton et al. 1990) characteristic of many reservoirs are likely to increase the delivery of organic matter and nutrients from land to water (relative to natural lakes), potentially fueling additional decomposition.

St. Louis and colleagues (2000) raised the possibility that reservoir GHG emissions contribute significantly to global budgets (table 1). Since that influential review appeared, and in part because of the attention it generated, researchers have quantified GHG fluxes from more than 200 additional reservoirs, and have synthesized regional emissions (Demarty and Bastien

2011, Li et al. 2015) and emissions from particular types of reservoirs (i.e., hydroelectric; Barros et al. 2011, Hertwich 2013) paving the way for a new synthesis of global reservoir GHG emissions. In the sections that follow, we revisit the global magnitude and controls on reservoir GHGs presented by St. Louis and colleagues (2000). This includes (a) explicit incorporation of reservoir CH_4 ebullition measurements, (b) updated global estimates of the magnitude of GHG emissions from reservoir water surfaces including the first global estimates of reservoir N_2O emissions, (c) a discussion of the environmental controls on CO_2, CH_4, and N_2O emissions from reservoir water surfaces, (d) a discussion of the policy implications of these new findings, and (e) recommendations regarding fruitful avenues for future research. Although this synthesis focuses on GHG emissions from reservoir water surfaces, we also describe and discuss several important alternative pathways that can contribute significantly to reservoir GHG budgets (figure 1, supplemental table S1). Given the limited number of studies characterizing these pathways, we do not include them in this global analysis, but stress the need for additional study and eventual incorporation of relevant sources in future global analyses. Finally, we stress that the GHG emissions from reservoir water surfaces synthesized here represent gross fluxes such that CO_2 and CH_4 emissions should be considered alongside estimates of reservoir carbon burial for the purposes of carbon budgeting exercises.

Figure 1.



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Areal CH_4 fluxes associated with reservoir: diffusive-only fluxes (via thin boundary layer and floating chamber with R^2 cutoff values > 0.85, n = 151), ebullitive-only fluxes (via funnels and floating chamber by subtraction, n = 58), diffusive + ebullitive fluxes (via traditional methods n = 89), total CH_4 emission via eddy covariance (n = 2), ebullitive emissions via acoustic measurements (n = 2), degassing emissions (n = 22), downstream emissions (n = 6), and drawdown marsh fluxes (n = 6, 5 from Three Gorges Reservoir). Each dot represents the mean flux from a single published paper. The lines within the boxes indicate median fluxes. The boxes demarcate the twenty-fifth and seventy-fifth percentiles; the whiskers demarcate the 95% confidence intervals.

Table 1.

The global surface area and GHG flux estimates from reservoirs compared with those of other freshwater ecosystems and other anthropogenic activities.

System Type	Surface Area ($x 10^6 km^2$)	Annual teragrams (Tg) C or N (Tg per year)			Areal Rates (milligrams per square meter per day)			Annual CO_2 Equivalents (Tg CO_2 Eq per year)			
		CH_4-C	CO_2-C	N_2O-N	CH_4-C	CO_2-C	N_2O-N	CH_4	CO_2	N_2O	Total
All Reservoirs (This Study)	0.31[a]	13.3	36.8	0.03	120	330	0.30	606.5	134.9	31.7	773.1
All Reservoirs (Other Work)	0.51–1.5[b,c]	15–52.5[b,f]	272.7[b]	–	82–96	498	–	680–2380	1000	–	
Hydroelectric Reservoirs	0.34[e]	3–14[e,f]	48–82[e,f]	–	24–112	386–660	–	136–635	176–301	–	
Lakes	3.7–4.5[c,d,h]	53.7[d]	292[g]	–	40	216	–	2434	1071	–	
Ponds	0.15– 0.86[i]	12[i]	571[i]	–	27[i]	422[i]	–	544	2094	–	
Rivers	0.36–0.65[d,g]	1.1–20.1[d,j]	1800[g]	–	6–98[j]	7954	–	50–911	6600	–	
Wetlands	8.6–26.9[k]	106–198[k]	–	0.97[l]	15–63[k]	–	0.1–0.31	4805–8976		908	
Other Anthropogenic Emissions (2000s)	N.A.	248[m]	9200[m]	6.9[m]	–	–	–	11243	33733	6462	51438

Note: The values presented are mean estimates; the ranges of mean values are reported when there are multiple relevant models. In cases in which the areal rates are not referenced, they were derived from dividing annual teragrams (Tg) of C or N by the global surface-area estimate. The annual CO_2 equivalents were calculated by multiplying the mass-based flux (in units of Tg CH_4, CO_2 or N_2O per year) by the 100-year global warming potential of each gas (1 for CO_2, 34 for CH_4 and 298 for N_2O). [a] (Lehner et al. 2011). [b] (St. Louis et al. 2000). [c] (Downing and Duarte 2009). [d] (Bastviken et al. 2011) . [e] (Barros et al. 2011). [f] (Li and Zhang 2014). [g] (Raymond et al. 2013). [h] (Verpoorter et al. 2014). [i] (Holgerson and Raymond 2016). [j] (Stanley et al. 2016). [k] (Melton et al. 2013). [l] (Tian et al. 2015). [m] (Ciais et al. 2013).

From a GHG-management perspective, it is crucial to understand the relative role of CO_2, CH_4, and N_2O emissions as CH_4 and N_2O are more powerful GHGs than CO_2 (34 and 298 times the global warming potential on a 100-year timescale, respectively; Myhre et al. 2013). To describe the relative contribution of various GHG emissions to global warming, emissions were converted to CO_2 equivalents, a metric that relates the radiative forcing caused by 1 mass unit of trace GHG to that caused by the emission of 1 mass unit of CO_2 over a given time span. Although CH_4 emissions from reservoirs have been implicated as a particularly important source of CO_2 equivalents (Giles 2006), constraining and modeling these fluxes is complicated by the fact that common methodological approaches, which are effective for CO_2 and N_2O emissions, do not capture an important fraction of overall CH_4 flux: bubble-based (ebullitive) CH_4 emissions. Our synthesis confirms that CH_4 emissions are responsible for the majority of the radiative forcing from reservoir water surfaces (approximately 80% over the 100-year timescale and 90% over the arguably more policy-relevant 20-year timescale) and that modeling approaches that ignore ebullitive CH_4 flux may fail to accurately quantify the magnitude of fluxes. We find that more productive, nutrient-rich reservoirs tend to emit more CH_4 than their less productive, nutrient-poor counterparts. Our global estimates support previous assertions (e.g., St. Louis et al. 2000) that GHG fluxes from reservoirs are globally important (approximately 1.3% of anthropogenic CO_2 equivalent emissions over the 100-year timespan), with CH_4 emissions from reservoir water surfaces comparable to those from rice paddies or from biomass burning. Therefore, we suggest the utility of incorporating reservoir CH_4 emissions into Intergovernmental Panel on Climate Change (IPCC) budgets.

Why methods matter

Aquatic GHG fluxes are measured using a variety of techniques (e.g., floating chambers, thin boundary methods, eddy covariance towers, acoustic methods, and funnels; supplemental figure S1) that provide varying degrees of spatial and temporal coverage and accuracy (St. Louis et al. 2000). Many commonly employed techniques for measuring aquatic GHG emissions focus on quantifying the diffusive flux of gases across the air–water interface. For CO_2 and N_2O, which are quite soluble in water (mole fraction solubility of $7.07 \cdot 10^{-4}$ and $5.07 \cdot 10^{-4}$ respectively at 20°C), this is the dominant flux pathway, moving gasses to the atmosphere across the air–water interface. In contrast, CH_4 is relatively insoluble in water (mole fraction solubility of $2.81 \cdot 10^{-5}$ at 20 °C), and is often emitted in the form of bubbles that rise directly from the sediments (Kiene 1991, Bastviken et al. 2004). Several common measurement methods do not capture ebullition (e.g., combining estimates of air–water gas exchange with measurements of dissolved GHG concentrations), whereas others may exclude ebullition events because they interfere with the linear accumulation of CH_4 within a sampling chamber (e.g., floating chambers; supplemental figure S2). A second important challenge for accurate measurements of aquatic CH_4 ebullition is that fluxes are often highly variable in both time and space (Wik et al. 2016). Ebullition is most commonly measured using inverted funnel traps, which float beneath the surface of the water and capture bubbles as they rise through the water column. These funnel traps are typically deployed for relatively short periods of time (minutes to hours) in a relatively small number of locations (generally fewer than 10 sites per reservoir), making it difficult to capture the spatial and temporal variability of fluxes (see the Hot Spots and Hot Moments section below).

Several recent method developments improve the spatial and/or temporal resolution of CH_4 ebullition measurements in lakes and reservoirs. Modified funnel trap designs can support longer-term, temporally resolved data by (a) incorporating an airtight housing equipped with a differential pressure sensor or optical bubble size sensor for automated, high temporal resolution measurements of ebullition fluxes (Varadharajan et al. 2010, Delwiche et al. 2015), and (b) installing an electronic unit to empty the trap once it reaches full capacity so that traps don't fill faster than they can be sampled (cited in Maeck et al. 2014). Acoustic techniques can support higher spatial and temporal resolution ebullition measurements without the cumbersome and invasive field deployments associated with funnel traps. Following calibration of acoustic signal with bubble size (Ostrovsky et al. 2008), an echosounder can be mounted to a boat to estimate ebullition flux at a greater spatial resolution, or mounted to a stationary object for greater temporal resolution. Repeat daily or subdaily echosounder surveys provide a much higher degree of spatiotemporal coverage than that achieved via traditional methods, allowing for more accurate ebullitive flux estimates in survey zones (DelSontro et al. 2015). Still, echosounders are only effective within a certain depth range that depends on transducer frequency, beam angle, and survey boat speed (but generally ranges from 1 to 100 meters), provide no information about bubble CH_4 concentrations without ancillary measurements, and can also be cost prohibitive and challenging to calibrate (Ostrovsky et al. 2008, DelSontro et al. 2015). Eddy covariance techniques, which calculate GHG fluxes on the basis of mean air density and instantaneous deviations in vertical wind speed and gas concentrations, can also overcome some of the difficulty of capturing spatially and temporally variable emissions although they cannot zero in on hot spots for release unless combined with other methods. Currently, the use of eddy covariance systems over lakes and reservoirs is relatively new and poses several challenges. These challenges include (a) high instrument cost, (b) poor sensor performance during wet conditions, and (c) difficulty associated with estimating measurement footprints, especially in small, heterogeneous areas (Fassbinder et al. 2013, Peltola et al. 2013).

Of the studies compiled here, ebullition was measured in only 52% of cases in which reservoir CH_4 emissions were reported (figure 1). In the majority of cases, ebullition was measured with funnels or was lumped with diffusive flux via floating chamber measurements; however, in two studies, researchers estimated methane fluxes via eddy covariance (Eugster et al. 2011, Deshmukh et al. 2014), and in another two studies, researchers estimated ebullitive flux via acoustic methods (DelSontro et al. 2011, 2015). Mean ebullition + diffusion fluxes were over double that of diffusion-only fluxes (103 versus 43 mg CH_4-C per square meter, m^2, per day) and CH_4 fluxes varied significantly on the basis of whether or not ebullition was included (Kruskal Wallis test, $\chi^2 = 52.7$, $p < .001$; figure 1, supplemental table S2). On average ebullition contributed 65% of total diffusive + ebullitive flux ($n = 56$, standard deviation [SD] = 33.5). This is consistent with natural lakes where between 40% and 60% of CH_4 flux generally occurs via ebullition (Bastviken et al. 2004). The relative contribution of CH_4 ebullition to overall CH_4 flux was also highly variable, constituting anywhere from 0% to 99.6% of total CH_4 flux. This highlights how crucial it is to measure both types of CH_4 emission in order to estimate the total flux from reservoir surface waters. Although we did not explicitly address the temporal or spatial resolution of emission data from each system, it is notable that the few published acoustic and eddy covariance-based reservoir CH_4 flux estimates are quite high compared to the median CH_4 flux estimates from less temporally and/or spatially integrated measurement techniques (figure 1). Given the importance of CH_4 ebullition to overall CH_4 fluxes, we only use CH_4 emission estimates that incorporate both ebullition and diffusion in further sections of this article (i.e., to estimate the magnitude and controls on fluxes).

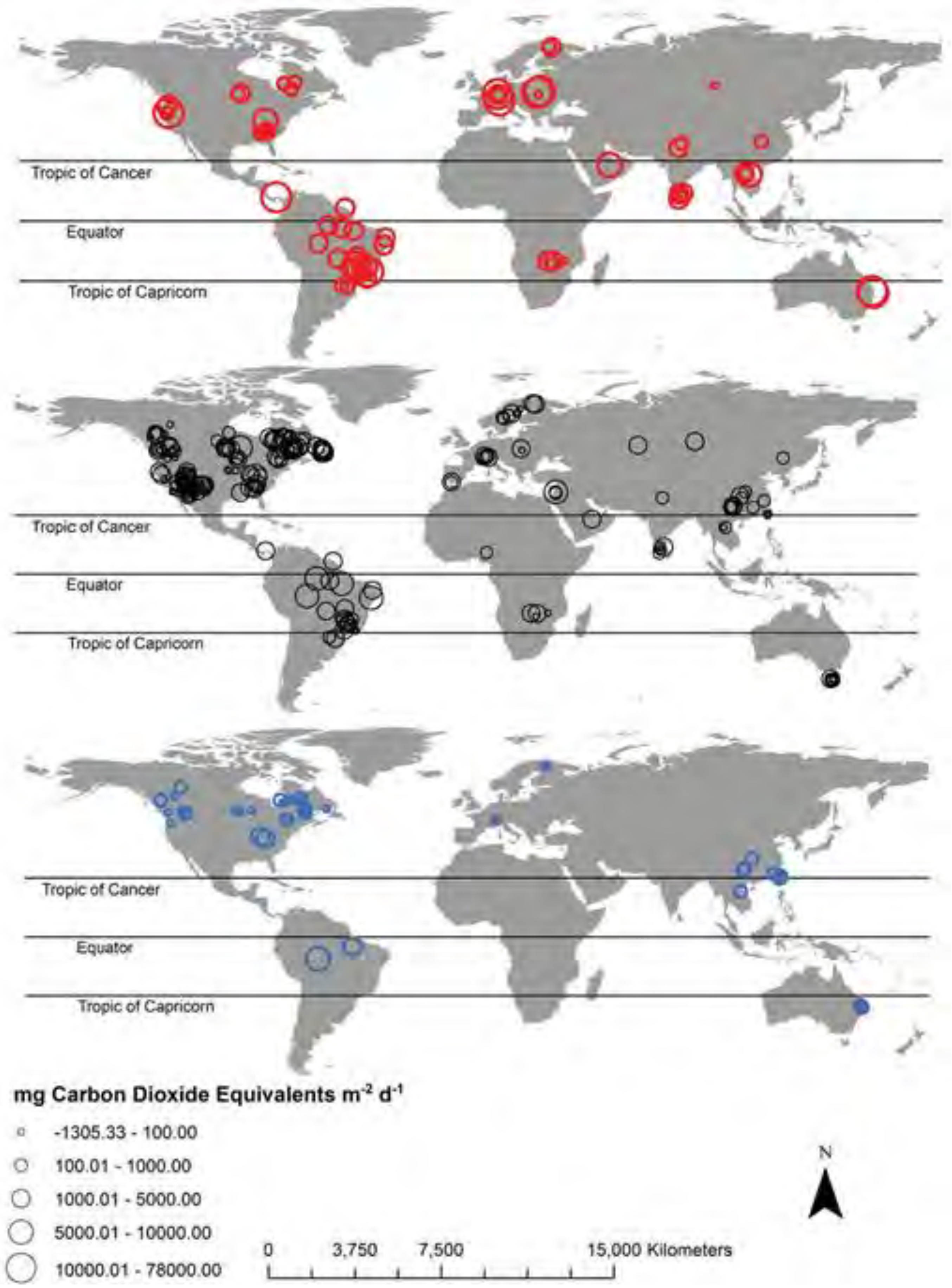
As with CH_4, many studies of CO_2 and N_2O emissions from reservoir water surfaces also suffer from low spatial and temporal resolution (therefore reducing the accuracy of emission estimates). Of the GHG estimates synthesized here, less than 25%, 3%, and 26% of temperate reservoir CH_4, CO_2, and N_2O emission estimates covered 6 months or more of the year. The majority of studies also had fewer than 10 sampling sites and measured fluxes over short periods of time (minutes to hours), often neglecting night sampling in favor of daytime measurements. A more extensive characterization of the spatial and temporal resolution of reservoir GHG sampling was beyond the scope of this analysis, but the role of sampling bias in upscaling efforts is discussed further below (see the section on Hot Spots and Hot Moments).

Patterns in areal fluxes

In total, we assembled areal CH_4, CO_2, and N_2O flux estimates from 161, 229, and 58 systems respectively, although only 75 reservoirs with CH_4 data met the methodological criteria for inclusion in our analyses (figure 2). In contrast to other recent reservoir GHG syntheses (Barros et al. 2011, Demarty and Bastien 2011, Hertwich 2013, Li et al. 2015), we include both hydroelectric and nonhydroelectric systems such as those used for flood control, irrigation, navigation, or recreation. Whereas previous synthesis efforts have lacked measurements from temperate and subtropical systems, our data set addresses this gap by including a number of recent GHG flux estimates from US, European, Australian, and Asian temperate and subtropical reservoirs (figure 2, table 2). This is important given a large number of dams that are either planned or under construction in temperate and subtropical zones (Zarfl et al. 2015). Several alternative flux pathways were not included in the areal flux estimates or the regression analysis, but are reported when available (see supplemental discussion and the

Alternative Flux Pathways section below).

Figure 2.



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Diffusive + ebullitive methane (top), carbon dioxide (middle), and nitrous oxide (bottom) emissions from reservoirs on a CO_2-equivalent basis (100-year horizon). Few reservoirs had measurements for all three gases.

Table 2.

The number of reservoirs with surface water GHG emission estimates by continent, as well as a break down of the number of CO_2, ebullitive + diffusive (E+D) CH_4, diffusive only (D) CH_4, and N_2O emission estimates by continent.

Continent	CO_2	CH_4 (E+D)	CH_4 (D)	N_2O	Total number of reservoirs with any GHG emission estimates
North America	144	23	56	37	158
South America	22	21	1	2	23
Africa	5	4	0	0	5
Europe	18	11	10	7	31
Asia	30	14	6	8	36
Australia	10	2	12	4	14
World	229	75	85	58	267

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Here, we report mean areal (per unit surface area) CH_4 fluxes from reservoir water surfaces that are approximately 25% larger than previous estimates (120.4 mg CH_4-C per m^2 per day, SD = 286.6), CO_2 flux estimates that are approximately 30% smaller than previous estimates (329.7 mg CO_2-C per m^2 per day, SD = 447.7), and the first-ever global mean estimate of reservoir N_2O fluxes (0.30 mg N_2O-N per m^2 per day, SD = 0.9; table 1). The mean areal N_2O emissions reported here are approximately an order of magnitude less than those estimated for US reservoirs (Baron et al. 2013) and are consistent with the areal fluxes reported by Yang and colleagues (2014). 16% of reservoirs were net CO_2 sinks and 15% of reservoirs were net N_2O sinks, whereas all systems were either CH_4 neutral or CH_4 sources (figure 2). The average areal CH_4 emissions that we report from reservoirs are higher than average fluxes from natural lakes, ponds, rivers, or wetlands (table 1). On the basis of the mean areal GHG fluxes in our data set, the majority (79%) of CO_2 equivalents from reservoirs occurred as CH_4, with CO_2

and N_2O responsible for 17% and 4% of the radiative forcing, respectively, over the 100-year timespan.

The higher mean CH_4 emissions reported here are likely due to the exclusion of diffusive-only estimates and a preponderance of high CH_4 flux estimates in the recent literature. Particularly high CH_4 flux estimates have been reported for some temperate reservoirs (Maeck et al. 2013, Beaulieu et al. 2014) and subtropical reservoirs (Grinham et al. 2011, Sturm et al. 2014) that were not included in previous global estimates (St. Louis et al. 2000, Barros et al. 2011, Bastviken et al. 2011), indicating that midlatitude reservoirs can emit as much CH_4 as tropical systems. In fact, we found that CH_4 fluxes from Amazonian reservoirs were statistically indistinguishable from reservoir CH_4 fluxes in other regions (Mann Whitney test, $p = 0.25$; supplemental figure S3). These findings run counter to the common view that low latitude reservoirs (and Amazonian reservoirs in particular) support greater CH_4 emission rates than temperate systems (Barros et al. 2011), but are consistent with the recent influx of higher emission estimates from subtropical and temperate ecosystems mentioned above.

Previous efforts to identify predictors of reservoir GHGs

Reservoir age (Barros et al. 2011, UNESCO–IHA 2012, Hertwich 2013) and latitude (Barros et al. 2011) have been suggested as predictors of CO_2 and CH_4 flux from hydroelectric reservoirs. Elevated GHG emissions from young (less than 10 years) reservoirs are commonly observed (Abril et al. 2005, Bastien et al. 2011, Teodoru et al. 2012) and are thought to be due to rapid decomposition of the most labile terrestrial organic matter, although some reservoirs may continue to have elevated GHG emissions at least 20 years after flooding (Kemenes et al. 2011). Measurements in an oligotrophic system in Canada's boreal zone have shown that heterogeneity in preflood carbon stocks can affect young reservoir CO_2 fluxes, with greater rates of sediment CO_2 production in higher carbon sediments (Brothers et al. 2012). However, the experimental flooding of high, medium, and low carbon boreal forests yielded no discernible relationship between the soil or sediment carbon stock and GHG production over a 3-year time span (Hendzel et al. 2005, Matthews et al. 2005). Reservoir GHG emissions can also be positively correlated with temperature (DelSontro et al. 2010, UNESCO–IHA 2012). Consequently, the negative correlation between latitude and hydroelectric GHG emissions reported in previous work could reflect higher average water temperatures at low latitudes. In addition, lower latitude regions typically experience higher rates of terrestrial net primary production (NPP), a factor that has been positively correlated with GHG emissions from hydroelectric reservoirs (Hertwich 2013). High rates of NPP may promote enhanced leaching of dissolved organic matter (DOM), fueling additional decomposition of terrestrial organic matter within tropical reservoirs.

A growing body of work highlights the role that nutrient status and associated primary productivity may play in determining overall reservoir GHG dynamics. For example, Li and colleagues (2015) reported a negative correlation between both nutrient enrichment and primary production and CO_2 fluxes, and at least one study has argued that increasing primary production can shift lentic ecosystems from CO_2 sources to sinks (Pacheco et al. 2013). This occurs when additional nutrients promote atmospheric carbon sequestration via enhanced photosynthesis leading to accelerated rates of organic carbon sedimentation and burial. At the same time, eutrophication may promote larger CH_4 emissions, both by reducing O_2 concentrations in reservoir bottom waters and by increasing organic matter quantity (as described below). In wetland ecosystems, NPP has been posited as a "master variable" that integrates several important environmental factors influencing CH_4 emission (Whiting and Chanton 1993). Some of these factors are likely to be more important in wetlands than in reservoirs (i.e., rooted plants as conduits for CH_4 exchange), whereas others are applicable across systems (i.e., increased substrate availability associated with elevated rates of carbon fixation). Regionally, positive correlations between chlorophyll *a* concentrations and both dissolved CH_4 concentrations (Indian reservoirs; Narvenkar et al. 2013) and CH_4 fluxes (north temperate lakes; West et al. 2015a) have been found in lakes and reservoirs. Although less is known about the controls on reservoir N_2O flux, strong positive correlations between NO_3^- concentrations and both N_2O concentration and flux have been observed across aquatic ecosystems (Baulch et al. 2011, McCrackin and Elser 2011).

Overall, better predictive tools are needed for identifying environmental controls on reservoir GHGs. Some progress has been made toward accomplishing these tasks through the modeling of hydroelectric CO_2 and CH_4 emissions (Barros et al. 2011, IEA Hydropower 2012, UNESCO–IHA 2012, Hertwich 2013). Still, we are not aware of any modeling efforts that have explicitly incorporated ebullition; instead, existing efforts have used either diffusive-only emissions or a combination of diffusive-only and ebullitive + diffusive emissions. In the section that follows, we explicitly consider ebullition by categorizing CH_4 fluxes on the basis of collection methods and considering the extent to which environmental controls differed on the basis of CH_4 flux pathway (ebullitive versus diffusive). In particular, we explore the hypothesis that nutrient loading and the resulting increase in primary production stimulates GHG emissions from reservoir water surfaces, primarily via enhanced CH_4 production.

Synthesis findings: Productivity predicts the radiative forcing capacity of reservoir GHG emissions

We collated system characteristics likely to covary with, or control, GHG fluxes. These characteristics included morphometric, geographic, and historical properties of study reservoirs (i.e., depth, residence time, volume, surface area, age, and latitude), biologically significant water column solute concentrations (i.e., NO_3^-, total phosphorus, and dissolved organic carbon), and metrics of ecosystem primary productivity (i.e., trophic status and mean or modeled surface water chlorophyll *a* concentrations; see the supplemental materials for a complete list of the tested variables).

Of the factors examined, CH_4 emissions were best predicted by chlorophyll *a* concentrations (positive correlation, $p < 0.001$, $R^2 = 0.50$, $n = 31$); CO_2 emissions were best predicted by reported mean annual precipitation (positive correlation, $p = 0.04$, $R^2 = 0.11$, $n = 33$); and N_2O emissions were most strongly related to reservoir NO_3^- concentrations (positive correlation, $p < 0.001$, $R^2 = 0.49$, $n = 18$, table 3, supplemental figure S6). Although latitude was also a strong predictor of N_2O flux ($p < 0.001$, $R^2 = 0.47$, $n = 55$), latitude and NO_3^- were weak covariates (−0.29 Pearson correlation), and latitude was not a significant predictor of N_2O ($p = 0.10$) in a multiple linear regression model with NO_3 ($p = 0.01$). CH_4 emissions were only weakly related to latitude ($p = 0.05$, $R^2 = 0.04$), and CO_2 emissions were not significantly related to latitude. Whereas CO_2 emissions were weakly related to reservoir age ($p = 0.003$, $R^2 = 0.04$), CH_4 and N_2O fluxes were not (supplemental table S4). The positive, albeit weak, relationship between CO_2 fluxes and mean annual precipitation is consistent with observations in boreal lakes where precipitation has been observed to flush terrestrial carbon into surface waters and enhance CO_2 concentrations and emissions via organic matter degradation (Rantakari and Kortelainen 2005). The relationship between N_2O fluxes and NO_3^- concentrations is consistent with observations from small streams (Baulch et al. 2011) as well as observed positive relationships between concentrations of N_2O and NO_3^- in reservoirs (Beaulieu et al. 2015) and in lakes receiving atmospheric nitrogen deposition (McCrackin and Elser 2011).

Table 3.

The least squared regression statistics for a subset of the best models relating reservoir CO_2, CH_4, and N_2O fluxes to potential predictor variables. All the significant linear regressions ($p < .05$) with $R^2 > 0.1$ are shown. Sign indicates whether the slope of the regression line was positive (+) or negative (–). Note that reservoir CO_2 fluxes are inverse transformed such that a negative regression correlation indicates a positive relationship between the predictor variable and the CO_2 flux. * Indicates modeled predictor. Complete regression statistics can be found in supplemental tables S4 and S5.

Continent	CO_2	CH_4 (E +D)	CH_4 (D)	N_2O	Total number of reservoirs with any GHG emission estimates
North America	144	23	56	37	158
South America	22	21	1	2	23
Africa	5	4	0	0	5
Europe	18	11	10	7	31
Asia	30	14	6	8	36
Australia	10	2	12	4	14
World	**229**	**75**	**85**	**58**	**267**

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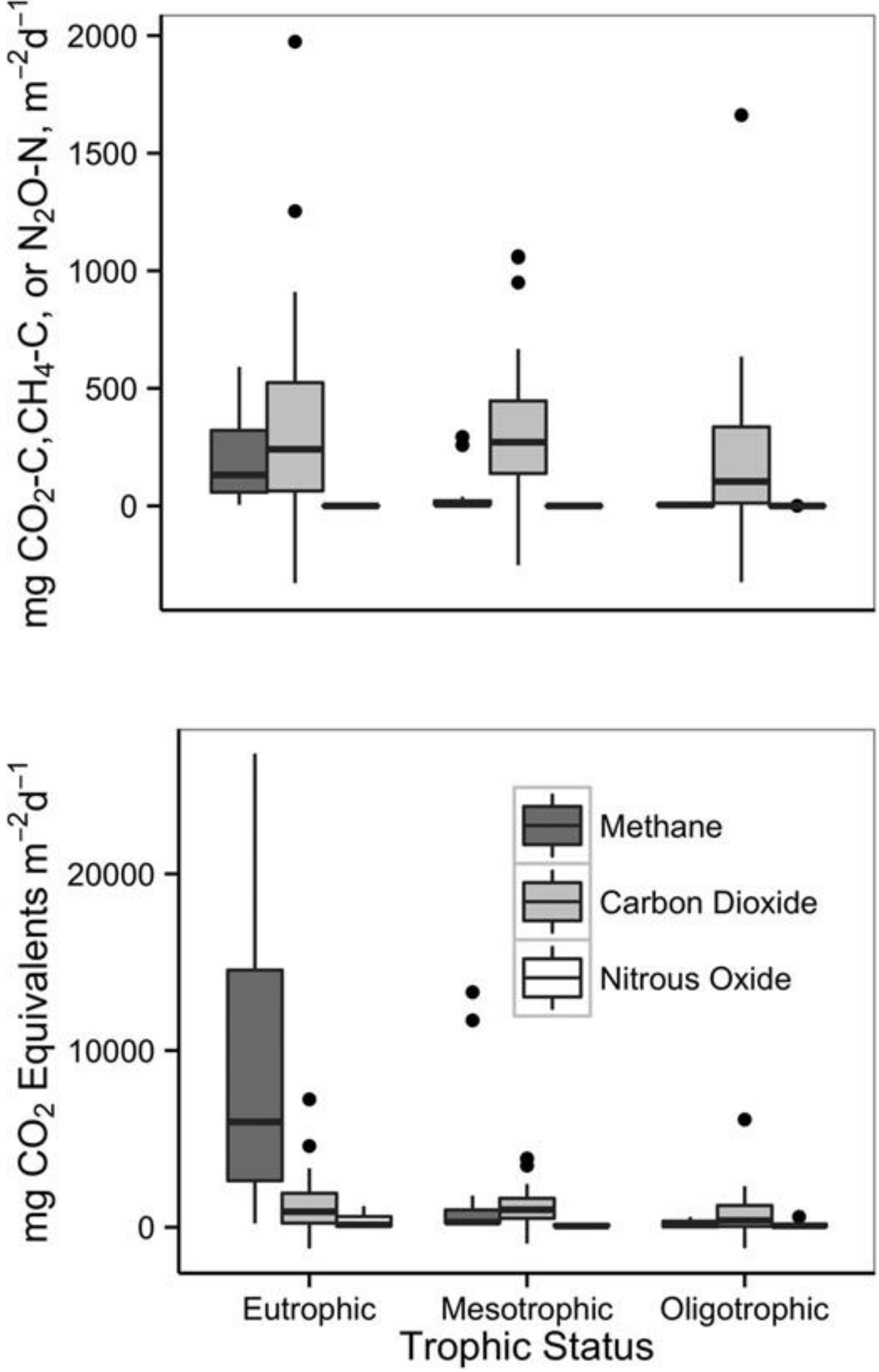
The controls on reservoir CH_4 flux deserve particular attention because our analysis suggests that CH_4 emissions are responsible for 79% of the radiative forcing from reservoirs over the 100 year timespan. Chlorophyll *a* and air temperature were significant predictors of CH_4 emissions from reservoir water surfaces regardless of flux type (i.e., diffusive only, ebullitive only, diffusive + ebullitive; supplemental tables S4 and S5). Mean reservoir depth and chlorophyll *a*, both of which have been reported to control lake and reservoir CH_4 emissions, were weakly correlated in this analysis (Pearson correlation 0.46). Depth was not a significant predictor of CH_4 flux for the whole data set ($p = 0.14$, $R^2 = 0.02$) or for the subset of the data for which chlorophyll *a* concentrations were available ($p = 0.19$, $R^2 = 0.02$), indicating that chlorophyll *a* is a better predictor of system-wide CH_4 emissions than mean depth. Depth has been found to exert an important control on the spatial variability of CH_4 fluxes from lakes, particularly with respect to ebullition (Bastviken et al. 2004, West et al. 2015a). In the marine environment, ebullition-based emissions to the atmosphere are thought to be negligible in waters deeper than 100 meters because of the dissolution of bubbles en route from sediments to the atmosphere (McGinnis et al. 2006), and a recent study of north temperate lakes reported that ebullition rarely occurred at sites deeper than 6 meters (West et al. 2015a). Although both depth and age (discussed above) may be important predictors of carbon emissions in individual reservoir systems, these relationships do not appear to scale up in the global model, which only considers mean values for individual reservoirs (e.g., mean reservoir depth or the mean age of the reservoir when carbon emissions were measured).

The strong positive correlation between reservoir CH_4 flux and chlorophyll *a* is also reflected in the significantly different CH_4 emissions found in systems of different trophic statuses (Kruskal Wallis test, $\chi^2 = 16.8$, $p < .001$). Specifically, eutrophic systems emitted approximately an order of magnitude more CH_4 than oligotrophic ones (figure 3). This pattern has been observed regionally in North American, Swedish, and Canadian lakes (Bastviken et al. 2004, Rasilo et al. 2015, West et al. 2015a) as well as Finnish lakes and reservoirs (Huttunen et al. 2003), and is consistent with recent findings from shallow lake mesocosms where CH_4 emissions were best predicted by factors related to primary production (i.e., nutrient concentrations and primary producer abundance; Davidson et al. 2015). This suggests that the low oxygen and high dissolved organic carbon conditions that often develop in eutrophic systems promote elevated CH_4 production relative to lower nutrient systems. In addition to increasing the quantity of organic carbon and reducing the availability of oxygen, eutrophication may also affect the overall quality of organic matter for fueling CH_4-producing archaea. Algae-derived organic matter has been found to fuel higher rates of CH_4 production than land-based "terrestrial" carbon (West et al. 2012), and may even stimulate the enhanced incorporation of recalcitrant terrestrial carbon into bacterial biomass (i.e., priming effect; Guillemette et al. 2015). Thus, increasingly high fractions of algae-derived organic matter will likely support more methane production.

Figure 3.



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Average reservoir GHG fluxes by trophic status. The top panel shows areal flux rates; the bottom panel shows fluxes converted to CO_2 equivalents. The legend is for both panels. The lines within the boxes indicate median fluxes. The boxes demarcate the twenty-fifth and seventy-fifth percentiles, the whiskers demarcate the 95% confidence intervals, and the dots plot data outside this range. One methane flux from a eutrophic reservoir is removed from the bottom panel (78,000 milligrams CO_2 equivalents per m^2 per day from the Rszezów Reservoir) to improve readability.

Global surface area of reservoirs

Global-scale estimates of reservoir GHG emissions are dependent on estimates of both areal fluxes (discussed above) and global reservoir surface area. There have been a number of recent efforts to improve global reservoir (and lake) surface-area estimates (Downing and Duarte 2009, Lehner et al. 2011, Verpoorter et al. 2014). Although St. Louis and colleagues (2000) estimated global reservoir surface area by multiplying the surface area of reservoirs in the *World Register of Dams* by a factor of four, more recent reservoir surface-area estimates were made assuming that reservoir surface areas follow a pareto distribution (Downing et al. 2006, Lehner et al. 2011). Downing and colleagues (2006) used data from the International Commission on Large Dams together with pareto-based extrapolations to estimate that reservoirs more than 0.01 square kilometers (km^2) cover 258,570 km^2 of the earth's surface. Following this, Lehner and colleagues (2011) used the Global Reservoir and Dam Database (GRAND) together with pareto-based extrapolations to estimate that reservoirs more than 0.00001 km^2 cover 507,102 km^2 of earth's surface. These reservoir surface-area estimates are one-sixth to one-third the value used by St. Louis and colleagues (2000). For our best estimate of global reservoir GHG fluxes, we use 305,723 km^2 of reservoir surface area (table 1). This estimate is based on GRAND and excludes the original surface area of natural lakes that have been modified with water regulation structures (this includes Lakes Victoria, Baikal, and Ontario; Lehner et al. 2011). The 267 reservoirs whose CO_2, CH_4, and/or N_2O emission estimates we synthesize here cover a collective surface area of over 77,287 km^2 (28 reservoirs with unknown surface area), and therefore represent 25% of global reservoir coverage.

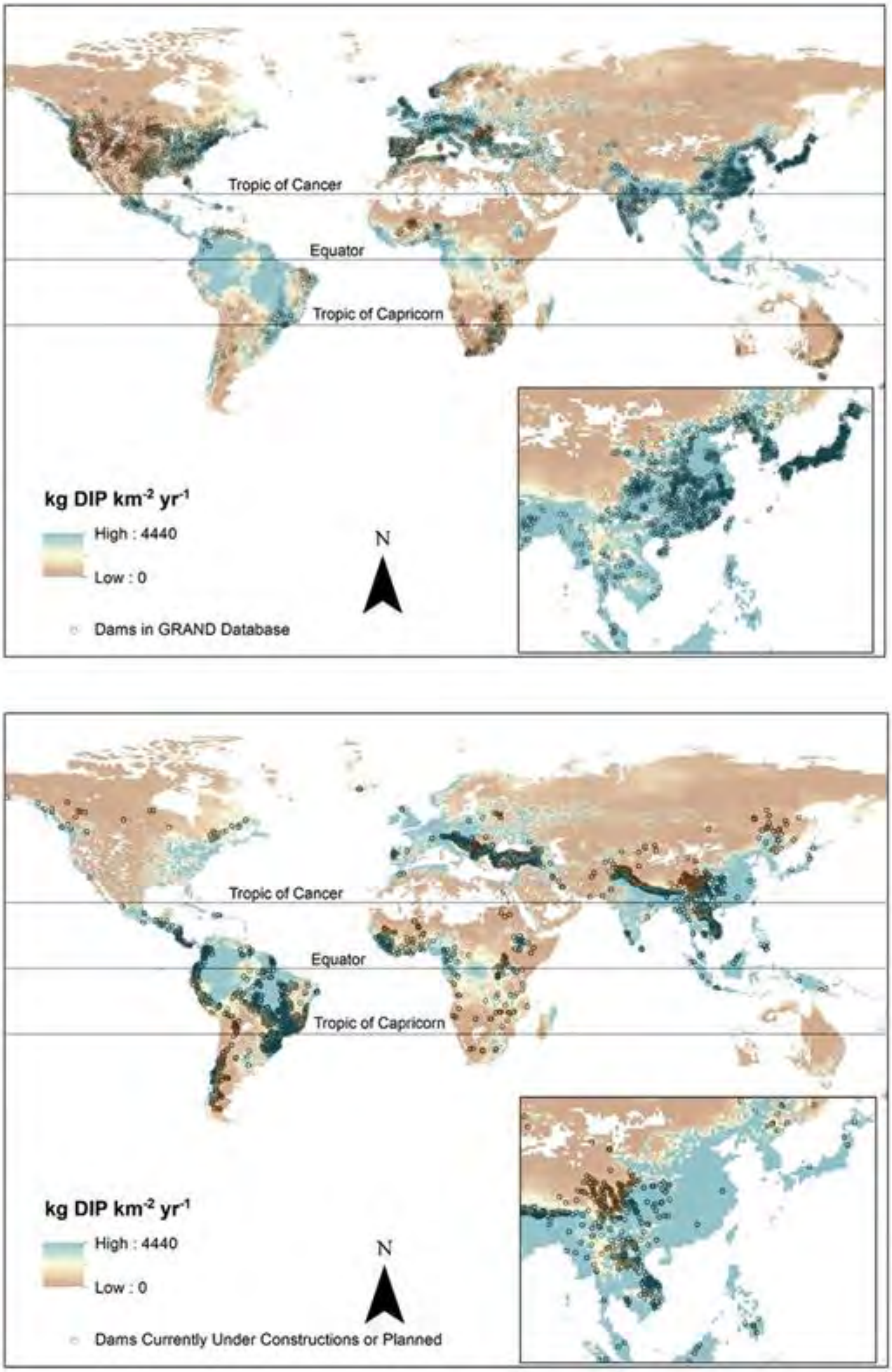
In addition, reservoir surface area is likely to increase substantially in coming decades given the 847 large hydropower projects (more than 100 MW) and 2853 smaller projects (more than 1 MW) that are currently planned or under construction (Zarfl et al. 2015). In this synthesis, reservoirs with more than 1MW installed capacity had a median surface area of 226 km^2. Assuming each of the 847 large hydropower projects that are planned or under construction has an equivalent surface area, this would constitute 225,691 km^2 of additional reservoir surface area, nearly doubling current reservoir surface-area estimates. Although there is a net trend toward dam decommissioning in the United States, most of these removals have been small dams, and the global number of removals is more than offset by recent increases in dam construction (O'Connor et al. 2015).

Global magnitude of reservoir GHG emissions

We report global GHG emissions from reservoir water surfaces on the low end of previously published values (table 1), but stress that these emissions still contribute significantly to global budgets of anthropogenic CO_2 equivalent emissions. CH_4 constituted the majority of CO_2 equivalent emissions from reservoirs, and the per area reservoir CH_4 fluxes reported in this synthesis are higher than per area fluxes for any other aquatic ecosystem (table 1). We estimate that reservoirs emit 13.4 Tg CH_4-C per year (5^{th} and 95^{th} confidence interval: 8.9–22.2 Tg CH_4-C per year), 36.8 Tg CO_2-C per year (5^{th} and 95^{th} confidence interval: 31.8–42.8 Tg CO_2-C per year), and 0.03 Tg N_2O-N per year (5^{th} and 95^{th} confidence interval: 0.02–0.07 Tg N_2O-N per year; table 1). The estimate of global reservoir GHG emissions presented here is calculated on the basis of the product of bootstrapped estimates of mean areal GHG fluxes and best estimates of global reservoir surface area (as was done in a recent estimate of global methane emissions from streams and rivers, Stanley et al. 2016). See the supplemental materials for information about the bootstrapping technique used. Given the dominant controls on GHG emissions from reservoir water surfaces identified in this study and given the current availability of relevant predictor variables at the global scale, we do not see an advantage to segmenting our upscaling efforts at this point in time. Still, identifying regional differences in reservoir GHG emissions remains a needed area of future research (see below section on Uncertainties and Future Research Directions).

Although the global mapping of reservoir trophic status (and associated upscaling of CH_4 emissions) is beyond the scope of this article, recent progress in the mapping of chlorophyll *a* in medium and large-sized lakes and reservoirs shows that about 60% of systems have more than 10 micrograms per liter chlorophyll *a* (Sayers et al. 2015), and would therefore be considered eutrophic by most classification schemes (Cunha et al. 2013). Similarly, a comparison of large reservoir locations (Lehner et al. 2011) with model-predicted dissolved inorganic phosphorus (DIP) yields (Harrison et al. 2010) indicates that most large reservoirs occur in phosphorus enriched regions (figure 4a) that may promote eutrophication of reservoirs. To illustrate, the average DIP yield (per 0.5 degree grid cell) in grid cells with dams is over threefold higher than the global average DIP yield (45 versus 13 kilograms P per km^2 per year). Given this pattern and the high fraction of nutrient enriched, productive reservoirs in our GHG database (of systems where trophic status data were available, 38% and 24% were eutrophic and mesotrophic respectively), it is likely that a large fraction of reservoirs are highly productive and therefore support high CH_4 emission rates. However, overlaying a map of the hydroelectric projects that are currently planned or under construction (Zarfl et al. 2015) on a map of average DIP yield (Harrison et al. 2010) suggests that newer hydroelectric projects will be more evenly distributed between phosphorus enriched and relatively phosphorus poor regions (Figure 4b). Further research is needed to better understand how much P will be *routed through* current and future reservoirs to support large-scale models of reservoir trophic status and associated CH_4 emissions. Specifically, models of riverine DIP yield would need to be downscaled to quantify how much DIP individual reservoirs are intercepting.

Figure 4.



Global NEWS half-degree dissolved inorganic phosphorus (DIP) yield (Harrison et al. 2010) overlaid on existing reservoirs from the GRAND database (Lehner et al. 2011) and hydropower reservoirs currently either under construction or planned (bottom panel; Zarfl et al. 2015). The inset maps show Southeast Asia, a region of rapid dam construction. China is projected to remain the global leader in hydropower dam construction, producing approximately one-fourth of global hydropower (Zarfl et al. 2015).

Emissions from alternative flux pathways

There are several emission pathways that are either nonexistent or of marginal importance in natural lakes, but that may contribute significantly to reservoir GHG budgets. These include: drawdown emissions, downstream emissions, emissions from decomposing wood, and emissions from dam spillways and turbines (e.g., "degassing" emissions). Drawdown emissions occur when fluctuating water levels cause large changes in hydrostatic pressure and create sediments that are periodically inundated with water and then exposed to the atmosphere. Although all aquatic systems experience natural fluctuations in water level, the amplitude and/or frequency of these fluctuations is likely more pronounced in reservoir ecosystems (Zohary and Ostrovsky 2011). Drawdown zones (that are periodically dry and then inundated) may contribute disproportionately to systemwide GHG emissions because of the shifting redox conditions they experience (Lu et al. 2011, Yang M et al. 2014). Drawdown may also be a hot moment for systemwide CH_4 release because reductions in hydrostatic pressure can stimulate ebullition events (Maeck et al. 2014). These events may constitute significant components of annual reservoir-wide CH_4 emission budgets and are the subject of ongoing work, but are not included in the analyses presented here. Degassing emissions from turbines and spillways occur when reservoir water undergoes rapid depressurization and/or aeration resulting in rapid emission of dissolved gasses. GHGs that remain in solution after water passes through a dam either diffuse into the atmosphere or are consumed by microbes (e.g., methane oxidation) downstream of the dam. Downstream emissions refer to GHGs that are produced within the reservoir and emitted from the river channel below a dam. The spatial footprint of these emissions is generally defined as the river reach for which GHG emissions are elevated above background (Kemenes et al. 2007). Finally, the decomposition of standing woody material was found to constitute a large fraction of total GHG emissions in a tropical reservoir (26%–45% of CO_2 equivalents over a 100-year time frame; Abril et al. 2013), but this GHG source remains to be studied in reservoirs from other regions.

Both downstream and degassing emissions are likely highly dependent on reservoir GHG concentrations, dam engineering, spill practices and downstream biogeochemistry. Larger degassing and downstream emissions are expected when the spilled reservoir water is high in

GHGs (Guérin et al. 2006). This generally occurs in systems in which the water is withdrawn from the lower portion of the reservoir (hypolimnetic release), because this water is typically highly pressurized and is also enriched in GHGs relative to surface waters (Kemenes et al. 2007). These emissions may also depend on dam-specific engineering. For example, an aerating weir at Petit Saut reservoir was installed to optimize CH_4 degassing immediately below the dam to avoid problems associated with methane-oxidation-induced hypoxia (Abril et al. 2005). Finally, the environmental controls on methane consumption (e.g., methane oxidation; Abril et al. 2005, Kemenes et al. 2007) and air–water gas exchange rates downstream of a dam may also play an important role in determining the magnitude of downstream emissions.

Measurements of GHG emissions from drawdown zones, downstream river reaches, wood decomposition, as well as spillways and turbines are currently too limited and/or too poorly constrained to meaningfully include in analyses of the controls and magnitude of reservoir GHGs. Still, these pathways may contribute significantly to overall ecosystem fluxes, particularly in the case of CH_4 (figure 1). For a more detailed summary of reservoir GHG fluxes via alternative flux pathways, see the supplemental discussion and table S1.

Uncertainties and future research directions

In developing this synthesis, we identified a number of areas that are beyond the scope of our analysis but that certainly deserve additional attention and research. Although the spatial coverage of GHG flux measurements has improved in recent years, there are still few measurements from many regions, including Africa, Australia, and Russia (table 2, figure 2). With respect to the forms of GHGs measured, there are currently threefold and fourfold more reservoirs with CO_2 emission estimates than for CH_4 (ebullitive + diffusive) and N_2O emissions, respectively (table 2). In addition, there is a crucial need to better constrain GHG emissions from boreal reservoirs, especially the relative role of diffusive versus ebullitive CH_4 emission pathways. The roles of reservoir typology, spatiotemporal variability, and ecosystem productivity in determining GHG emissions all deserve further analysis. In the sections that follow, we highlight some significant research needs that will improve our ability to model and potentially manage reservoir GHG emissions.

Reservoir typology

Currently, there are relatively few GHG flux estimates from nonhydroelectric systems. Although hydroelectric dams are estimated to constitute 30%–62% of global impoundments (Lehner et al. 2011, Varis et al. 2012), 82% of reservoirs with known uses in our GHG database had the capacity to generate hydroelectricity (supplemental figure S7). Although we did not detect any significant difference between the areal emission of CH_4, CO_2, or N_2O from hydroelectric versus nonhydroelectric systems (Mann Whitney test, p = .83, .27, and .87 respectively; figure S3), we also did not consider degassing, downstream, or drawdown zone emissions, all of which are likely to vary on the basis of reservoir typology. Better characterization of reservoir outlet structure (e.g., proportion of surface versus bottom water withdrawals by reservoir type) and associated turbine and downstream GHG emissions would aid our understanding of how different types of reservoirs (hydroelectric, flood control, irrigation etc.) contribute to overall GHG emissions. In addition, small farm impoundments were not included in this data set because of lack of data, but these systems clearly deserve more attention because they are often located in eutrophied areas and are disproportionately active with respect to carbon cycling (Downing et al. 2008). In fact, natural ponds less than 0.001 km^2 are estimated to make up less than 10% of global lake and pond surface area but constitute more than 15% of CO_2 emissions and more than 40% of diffusive CH_4 emissions (Holgerson and Raymond 2016).

Hot spots and hot moments

Lake and reservoir GHG emissions are often highly variable in both space and time. The flux estimates presented in previous sections use available estimates from every reservoir where GHG emissions have been reported (and mean estimates from reservoirs where multiple studies or years of data have been collected), but it is important to note that the spatial and temporal coverage of these emission estimates are highly variable. Reservoir GHG emission estimates are often made at temporal scales ranging from minutes to hours even though lake and reservoir GHG emissions can vary over single day–night cycles (Morales-Pineda et al. 2014, Podgrajsek et al. 2014, 2015), seasonally with changes in productivity and/or river inflow (Knoll et al. 2013, Morales-Pineda et al. 2014, Pacheco et al. 2015), and episodically because of water-level fluctuations (Maeck et al. 2014) or water-column mixing dynamics (Jammet et al. 2015). The spatial coverage of reservoir GHG emission measurements is also often limited; many studies measure emissions at fewer than 5 sites and very few studies have more than 10 sites. Recent spatial analyses of reservoir CH_4 dynamics highlight the disproportionate importance of inlets and other depositional zones toward overall flux (DelSontro et al. 2011, Maeck et al. 2013) as well as from seasonally flooded and downstream zones (see the

Emissions From Alternative Flux Pathways section).

Despite the considerable uncertainty associated with the reservoir-specific GHG emission estimates synthesized here, we argue that these data provide a low-end estimate of global emissions. A recent study quantified the effects of spatial and temporal sampling resolution on diffusive and ebullitive CH_4 emission estimates from 3 shallow boreal lakes and found that low sampling coverage is more likely to lead to underestimates of flux than overestimates (72% chance of flux underestimation when bubble trap sampling is limited to 1–3 days; Wik et al. 2016). The authors estimate that diffusive and ebullitive CH_4 fluxes should be measured from a minimum of 3 and 11 depth stratified sites on at least 11 and 39 days (respectively) to achieve ±20% of the emissions estimated from sampling more intensively (Wik et al. 2016). More work is needed to characterize sampling bias in other types of systems, and to understand how sampling bias scales up. In this analysis, we treated system-specific estimates of GHG flux equally despite a large range in the degree of sampling effort represented by each study.

The development of methods and protocols that effectively capture spatial and temporal variation in GHG fluxes is crucial for improving our ability to compare "apples to apples" between different reservoir systems. Efforts are already being made in this direction (UNESCO–IHA 2010, Bastviken 2015).

Seasonality and ice cover

The seasonality of reservoir GHGs is a major frontier. Future research should aim to quantify both seasonal patterns in emission and the extent to which water-column mixing and other short-term events contribute to annual-scale GHG emissions. Although warmer temperatures have been correlated with higher rates of CH_4 production across a range of ecosystems (Yvon-Durocher et al. 2014), annual-scale reservoir GHG data are currently too limited to make inferences on how seasonal biases may either under or overestimate annual-scale fluxes. Spring (ice melt) and fall (destratification) turnover events can result in pulse emissions wherein gasses that have accumulated under the ice or thermocline are suddenly mixed upward and vented to the atmosphere as a lake circulates. Although turnover data from reservoir systems is extremely sparse (but see Bastien et al. 2011, Demarty et al. 2011, Beaulieu et al. 2014), in lakes, turnover flux may account for an average of 35% (and a range of less than 1% to 70%) of annual CH_4 emissions, with the highest contribution from small systems (Michmerhuizen et al. 1996, Bastviken et al. 2004, Jammet et al. 2015).

Currently, the role of CH_4 oxidation (a microbial process that consumes methane) in mediating atmospheric CH_4 fluxes during lake turnover events is also not well understood. Commonly employed methods for estimating turnover flux use hypolimnion storage (i.e., the gasses that have accumulated under the ice or thermocline) to estimate emissions and assume that there is no significant CH_4 oxidation during turnover (Michmerhuizen et al. 1996). Research in boreal and temperate lakes has found that anywhere between 60 and 94% of the CH_4 stored in the water column can be oxidized during turnover (Rudd and Hamilton 1978, Utsumi et al. 1998) but the environmental controls on turnover-related methane oxidation rates are not well known. Given current uncertainties, our global-scale estimate of reservoir GHG flux does not account for ice cover, but see the supplemental materials for an estimate of the extent to which ice cover could reduce annual-scale emissions (assuming no turnover emissions).

The role of boreal systems

Results from this synthesis suggest that biases in the application of different measurement techniques have led to spurious assignment of age as a significant control on reservoir CH_4 fluxes. In addition, this sampling bias may have overemphasized the significance of latitude as a predictor of CH_4 fluxes. The majority of measurements from old systems and high latitude systems have been diffusive only (supplemental figures S4 and S5), which may underestimate true CH_4 fluxes. It is possible, however, that ebullition is limited in boreal systems. Large-scale monitoring efforts in Canadian hydroelectric reservoirs suggests that CH_4 bubbling constitutes less than 5% of total emissions in many boreal systems (Tremblay pers. comm.). Still, we are aware of only a handful of published studies that report both diffusive and ebullitive emissions from boreal systems, and the fraction of bubbling in these systems covers a broad range (0%–20% in Eastmain reservoir, 18% in Porttipahta reservoir, 61% to 75% in Canadian experimental reservoirs, and 87% in Lokka reservoir [Huttunen et al. 2002, Matthews et al. 2005, Teodoru et al. 2012]). Unfortunately, CH_4 flux measurements from permafrost reservoirs and nonhydroelectric boreal reservoirs are currently lacking. Future study of boreal reservoir GHG fluxes should target these underrepresented systems and incorporate more comprehensive ebullition rate measurements.

The role of reservoir productivity

Recent work has suggested that eutrophication might “reverse” the carbon budget of lakes and reservoirs (i.e., shifting the ecosystem from net heterotrophy to net autotrophy) by converting large amounts of CO_2 to organic matter via elevated primary production (Pacheco et al. 2013). Our analysis does not support this idea. A comparison of CO_2 and CH_4 fluxes from eutrophic reservoirs suggests that eutrophication does little to change the net carbon balance of reservoirs, but greatly increases the atmospheric radiative forcing caused by these systems through the stimulation of CH_4 production (figure 3). This suggests a potential positive feedback loop wherein a warming climate supports larger algal populations, larger algal populations provide more organic matter to support more methane production, and a portion of the methane produced escapes to the atmosphere, where it functions to further warm climate. The relationship between organic matter quality and methane production is an active area of research that may reduce the strength, or possibly even negate, the feedback loop proposed above. A recent laboratory study revealed that algal biomass quality, in terms of lipid content, enhanced rates of methane production (West et al. 2015b). Because algae grown under nutrient rich conditions tend to be relatively lipid poor, the authors posit that this resource quality feedback reduces the strength of the positive feedback between eutrophication and methane production (West et al. 2015b). Developing our understanding of these feedbacks should help inform quantitative modeling efforts.

The larger context

In this study, we have discussed only gross carbon emissions from existing reservoirs, ignoring other stages or factors of a reservoir's carbon cycle that are important to consider. For example, it will be necessary to eventually place gross fluxes in context by comparing them with (a) the GHG balance of the land prior to flooding, (b) the rates of reservoir carbon fixation and storage, (c) the GHGs associated with reservoir creation and decommissioning (e.g., life-cycle-analysis perspective), and (d) the long-term fate of carbon buried in reservoirs that are decommissioned. Few studies have placed reservoir GHG emissions into such a context, but those that have find that reservoirs result in a net carbon footprint that exceeds that of the preflooded landscape and that they are net emitters of CO_2 equivalents (Jacinthe et al. 2012, Teodoru et al. 2012, Faria et al. 2015). A recent analysis of CH_4 fluxes from hydroelectric reservoirs showed that 10% of reservoirs have emission factors (gCO_2e per kilowatt hour) larger than the CO_2 emissions from natural gas combined cycle plants (Hertwich 2013), although the authors did not consider carbon burial offsets. Although dams are responsible for high rates of carbon burial (Clow et al. 2015), it has been argued that at least a portion of this burial would still be occurring farther downstream, perhaps even in coastal waters, in the absence of dams (Mendonça et al. 2012). The role of dams in re-locating sediment carbon pools may be significant in determining total carbon burial (Mendonça et al. 2012) as well as the fraction of carbon that is emitted as CH_4. For example, faster-moving, more oxygenated "lotic" waters typically support more rapid decomposition and CO_2 production but less CH_4 production. Similarly, at the coast, high concentrations of SO_4^{2-} generally prohibit high CH_4 emissions. Accounting for the short and long-term fate of carbon in reservoir sediments is an important next step in global carbon budgeting exercises.

Policy implications

When CH_4, CO_2, and N_2O emissions are combined, our synthesis suggests that reservoir water surfaces contribute 0.8 Pg CO_2 equivalents per year over a 100-year time span (fifth and ninety-fifth confidence interval: 0.5–1.2 Pg CO_2 equivalents per year), or approximately 1.5% of the global anthropogenic CO_2-equivalent emissions from CO_2, CH_4, and N_2O reported by the IPCC (table 1; Ciais et al. 2013) and 1.3% of global anthropogenic CO_2-equivalent emissions from well mixed GHGs overall (Myhre et al. 2013). Therefore, we argue for inclusion of GHG fluxes from reservoir surfaces in future IPCC budgets and other inventories of anthropogenic GHG emissions. The reservoir-based CH_4 emissions reported here (8.9–22.2 Tg CH_4-C per year) are similar in magnitude to estimates of CH_4 emissions from rice paddies and to those from biomass burning (which includes biofuel emissions) by the IPCC (21–30 and 18–29 Tg CH_4-C per year respectively; Ciais et al. 2013). Reservoir CO_2 and N_2O fluxes, however, are lower than other anthropogenic or natural sources as reported by the IPCC (Ciais et al. 2013).

Although global-warming potentials for CO_2-equivalent calculations are often reported for a 100-year time span, the selection of time span is somewhat arbitrary (Myhre et al. 2013). CH_4 is relatively short-lived in the atmosphere (atmospheric lifetime on the order of a decade) relative to CO_2 (atmospheric lifetime on the order of centuries) and therefore has a higher global warming potential over the shorter 20-year time horizon (86 versus 34; Myhre et al. 2013). Policymakers should carefully consider the timescales that are relevant to GHG mitigation efforts, especially given the recent international push to maintain average global temperatures within 1.5–2°C of the pre-industrial mean (Fearnside 2015). Over shorter timescales (decades), and given the exclusion of several important alternative emission pathways (i.e., degassing, downstream and drawdown zone emissions; see section above), reservoirs are almost certainly contributing more than the 0.8 Pg CO_2 equivalents per year calculated here. In fact, when looking over the 20-year time horizon, CO_2 equivalent emissions from reservoir surface waters are estimated at double the flux presented here (1.7 Pg CO_2 equivalents per year, 5^{th} and 95^{th} confidence interval: 1.1 to 2.7 Pg CO_2 equivalents per year). With the current boom in global dam construction (Zarfl et al. 2015), reservoirs will represent an even larger fraction of anthropogenic CO_2 equivalent emissions in the coming years. Therefore, policymakers and water managers that are siting new dams or decommissioning old ones should weigh the multiple services that reservoirs provide against their GHG-related costs in planning to either construct or decommission a dam. A number of papers compare reservoir GHG emissions to those of the natural gas combined cycle (see the Larger Context section above), but many reservoirs do not produce energy at all.

Conclusions

Sixteen years ago, the first global review of reservoir GHG emissions highlighted the potential significance of reservoir surfaces as GHG sources and postulated that factors such as age, water temperature, and organic carbon inputs could regulate fluxes (St. Louis et al. 2000). At that time, there were GHG flux estimates from only 22 reservoir systems and potential controlling factors could not be quantitatively assessed. Here, we discuss a more comprehensive set of reservoir GHG flux estimates than has previously been analyzed, and use that data set to develop new insight into the rates and controls of reservoir GHG fluxes. Specifically, this work highlights the dominant contribution of CH_4 emissions to total reservoir carbon emissions, and the importance of including ebullitive CH_4 emissions in modeling efforts. Furthermore, it appears that reservoir nutrient loading and associated eutrophication leads to increased radiative forcing by reservoirs because of increased CH_4 emissions. The relationship between reservoir eutrophication and GHG emissions presented here provides a crucial first step in identifying potential management opportunities for the reduction of reservoir GHGs. Specifically, watershed nutrient reduction strategies aimed at preventing reservoir eutrophication may also mitigate both CH_4 and N_2O emissions (specifically via reduction of P and NO_3^- loading). In addition, when possible new reservoirs could be strategically sited upstream from anthropogenic nutrient sources. With the need for better global water management and the push for expanded global hydropower capacity, careful siting of new reservoirs, and revising management of existing ones may help balance the positive ecosystem services that reservoirs provide against the GHG emission costs.

This synthesis benefitted from supplemental data graciously provided by Huai Chen, Pierre-Andre Jacinthe, Yang Meng, Yu-Hsuan Wang, and Christiane Zarfl. We also appreciate the helpful input provided by David Bastviken, M. Keith Birchfield, Amy Burgin, Will Forney, Frédéric Guérin, Lesley Knoll, Andreas Maeck, Rebecca Martin, John Melack, Geneviève Metson, Cody Miller, Reed Norton, Dan Reed, Katrin Sturm, Alain Tremblay, and Yan Zhao. Funding was provided by the Hundred Talent Program of the Chinese Academy of Sciences and the National Natural Science Foundation of China (NSFC 31670473) to Li, the European Research Council under the European Union's Seventh Framework Programme (no. FP7/2007-2013) and ERC agreement no. 336642 to Barros, the CNPq/Brazil fellowship 202937/2014-3 to Bezerra-Neto, US Army Corps of Engineers Climate Preparedness and Resilience Programs and National Science Foundation (NSF) DEB Grant no. 135211 to Harrison, and US Environmental Protection Agency STAR Fellowship no. FP917450 and NSF IGERT Fellowship no. 0903714 to Deemer.

Supplemental material

The supplemental material is available online at *Supplementary Data*.

There is also an accompanying supplementary spreadsheet available via Dryad (doi:10.5061/dryad.d2kv0) that contains the complete data set used in this synthesis and accompanying references.

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Supplementary data

Supplementary Data - zip file

BioScience

Online ISSN 1525-3244

Print ISSN 0006-3568

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EXHIBIT P-7

Hydroelectric power's dirty secret revealed

EARTH 24 February 2005

By Duncan Graham-Rowe

Hydropower polluters

Contrary to popular belief, hydroelectric power can seriously damage the climate. Proposed changes to the way countries' climate budgets are calculated aim to take greenhouse gas emissions from hydropower reservoirs into account, but some experts worry that they will not go far enough.

The green image of hydro power as a benign alternative to fossil fuels is false, says Éric Duchemin, a consultant for the Intergovernmental Panel on Climate Change (IPCC). "Everyone thinks hydro is very clean, but this is not the case," he says.

Hydroelectric dams produce significant amounts of carbon dioxide and methane, and in some cases produce more of these greenhouse gases than power plants running on fossil fuels. Carbon emissions vary from dam to dam, says Philip Fearnside from Brazil's National Institute for Research in the Amazon in Manaus. "But we do know that there are enough emissions to worry about."

In a study to be published in *Mitigation and Adaptation Strategies for Global Change*, Fearnside estimates that in 1990 the greenhouse effect of emissions from the Curuá-Una dam in Pará, Brazil, was more than three-and-a-half times what would have been produced by generating the same amount of electricity from oil.

This is because large amounts of carbon tied up in trees and other plants are released when the reservoir is initially flooded and the plants rot. Then after this first pulse of decay, plant matter settling on the reservoir's bottom decomposes without oxygen, resulting in a build-up of dissolved methane. This is released into the atmosphere when water passes through the dam's turbines.

"Drawdown" regions

Seasonal changes in water depth mean there is a continuous supply of decaying material. In the dry season plants colonise the banks of the reservoir only to be engulfed when the water level rises. For shallow-shelving reservoirs these "drawdown" regions can account for several thousand square kilometres.

In effect man-made reservoirs convert carbon dioxide in the atmosphere into methane. This is significant because methane's effect on global warming is 21 times stronger than carbon dioxide's.

Claiming that hydro projects are net producers of greenhouse gases is not new (**New Scientist** print edition, 3 June 2000) but the issue now appears to be climbing up the political agenda. In the next round of IPCC discussions in 2006, the proposed National Greenhouse Gas Inventory Programme, which calculates each country's carbon budget, will include emissions from artificially flooded regions.

But these guidelines will only take account of the first 10 years of a dam's operation and only include surface emissions. Methane production will go unchecked because climate scientists cannot agree on how significant this is; it will also vary between dams. But if Fearnside gets his way these full emissions would be included.

With the proposed IPCC guidelines, tropical countries that rely heavily on hydroelectricity, such as Brazil, could see their national greenhouse emissions inventories increased by as much as 7% (see map). Colder countries are less affected, he says, because cold conditions will be less favourable for producing greenhouse gases.

Despite a decade of research documenting the carbon emissions from man-made reservoirs, hydroelectric power still has an undeserved reputation for mitigating global warming. "I think it is important these emissions are counted," says Fearnside.

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EXHIBIT Q-7

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PERSPECTIVE ARTICLE

Front. For. Glob. Change, 11 June 2019 | https://doi.org/10.3389/ffgc.2019.00027 (https://doi.org/10.3389/ffgc.2019.00027)

Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good

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Climate change and loss of biodiversity are widely recognized as the foremost environmental challenges of our time. Forests annually sequester large quantities of atmospheric carbon dioxide (CO_2), and store carbon above and below ground for long periods of time. Intact forests—largely free from human intervention except primarily for trails and hazard removals—are the most carbon-dense and biodiverse terrestrial ecosystems, with additional benefits to society and the economy. Internationally, focus has been on preventing loss of tropical forests, yet U.S. temperate and boreal forests remove sufficient atmospheric CO_2 to reduce national annual *net* emissions by 11%. U.S. forests have the potential for much more rapid atmospheric CO_2 removal rates and biological carbon sequestration by intact and/or older forests. The recent *1.5 Degree Warming Report* by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits

such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty.

Introduction

Life on Earth as we know it faces unprecedented, intensifying, and urgent imperatives. The two most urgent challenges are (1) mitigating and adapting to climate change (Intergovernmental Panel on Climate Change, 2013, 2014, 2018), and (2) preventing the loss of biodiversity (Wilson, 2016; IPBES, 2019). These are three of the Sustainable Development Goals, Climate, Life on Land and Life under Water (Division for Sustainable Development Goals, 2015), and significant international resources are being expended to address these crises and limit negative impacts on economies, societies and biodiverse natural communities. The recent *1.5 Degree Warming Report* of the Intergovernmental Panel on Climate Change (2018) was dire and direct, stating the need for "rapid, far-reaching and unprecedented changes in all aspects of society." We find that growing additional existing forests as intact ecosystems, termed *proforestation*, is a low-cost approach for immediately increasing atmospheric carbon sequestration to achieve a stable atmospheric carbon dioxide concentration that reduces climate risk. Proforestation also provides long-term benefits for biodiversity, scientific inquiry, climate resilience, and human benefits. This approach could be mobilized across all forest types.

Forests are essential for carbon dioxide removal (CDR), and the CDR rate needs to increase rapidly to remain within the 1.5 or 2.0°C range (Intergovernmental Panel on Climate Change, 2018) specified by the Paris Climate Agreement (2015). Growing existing forests to their biological carbon sequestration potential optimizes CDR while limiting climate change and protecting biodiversity, air, land, and water. Natural forests are by far the most effective (Lewis et al., 2019). Technologies for direct CDR from the atmosphere, and bioenergy with carbon capture and storage (BECCS), are far from being technologically ready or economically viable (Anderson and Peters, 2016). Furthermore, the land area required to supply BECCS power plants with tree plantations is 7.7 million km^2, or approximately the size of Australia (Intergovernmental Panel on Climate Change, 2018). Managed plantations that are harvested periodically store far less carbon because trees are maintained at a young age and size (Harmon et al., 1990; Sterman et al., 2018). Furthermore, plantations are often monocultures, and sequester less carbon more slowly than intact forests with greater tree species diversity and higher rates of biological carbon sequestration (Liu et al., 2018). Recent research in the tropics shows that natural forests hold 40 times more carbon than plantations (Lewis et al., 2019).

Alternative forest-based CDR methods include *afforestation* (planting new forests) and *reforestation* (replacing forests on deforested or recently harvested lands). Afforestation and reforestation can contribute to CDR, but newly planted forests require many decades to a century before they sequester carbon dioxide in substantial quantities. A recent National Academy study titled *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* discusses afforestation and reforestation and finds their contribution to be modest (National Academies of Sciences, 2019). The study also examines changes in conventional forest management, but neglects proforestation as a strategy for increasing carbon sequestration. Furthermore, afforestation to meet climate goals requires an estimated 10 million km^2–an area slightly larger than Canada (Intergovernmental Panel on Climate Change, 2018). The massive land areas required for afforestation and BECCS (noted above) compete with food production, urban space and other uses (Searchinger et al., 2009; Sterman et al., 2018). More importantly, neither of these two practices is as effective quantitatively as proforestation in the next several decades when it is needed most. For example, Law et al. (2018) reported that extending harvest cycles and reducing cutting on public lands had a larger effect than either afforestation or reforestation on increasing carbon stored in forests in the Northwest United States. In other regions such as New England (discussed below), longer harvest cycles and proforestation are likely to be even more effective. Our assessment on the climate and biodiversity value of natural forests and proforestation aligns directly with a recent report that pinpointed "stable forests" – those not already significantly disturbed or at significant risk – as playing an outsized role as a climate solution due to their carbon sequestration and storage capabilities (Funk et al., 2019).

Globally, terrestrial ecosystems currently remove an amount of atmospheric carbon equal to one-third of what humans emit from burning fossil fuels, which is about 9.4 GtC/y (10^9 metric tons carbon per year). Forests are responsible for the largest share of the removal. Land use changes, i.e., conversion of forest to agriculture, urban centers and transportation corridors, emit ~1.3 GtC/y (Le Quéré et al., 2018). However, forests' potential carbon sequestration and additional ecosystem services, such as high biodiversity unique to intact older forests, are also being degraded significantly by current management practices (Foley et al., 2005; Watson et al., 2018). Houghton and Nassikas (2018) estimated that the "current gross carbon sink in forests recovering from harvests and abandoned agriculture to be −4.4 GtC/y, globally." This is approximately the current gap between anthropogenic emissions and biological carbon and ocean sequestration rates by natural systems. If deforestation were halted, and secondary forests were allowed to continue growing, they would sequester −120 GtC between 2016 and 2100 or ~12 years of current global fossil carbon emissions (Houghton and Nassikas, 2018). Northeast secondary forests have the potential to increase biological carbon sequestration between 2.3 and 4.2-fold (Keeton et al., 2011).

Existing proposals for "Natural Climate Solutions" do not consider explicitly the potential of proforestation (Griscom et al., 2017; Fargione et al., 2018). However, based on a growing body of scientific research, we conclude that protecting and stewarding intact diverse forests and practicing proforestation as a purposeful public policy on a large scale is a highly effective strategy for mitigating the dual crises in climate and biodiversity and ultimately serving the "greatest good" in the United States and the rest of the world. Table 1 summarizes some of the key literature supporting this point.

TABLE 1

(https://www.frontiersin.org/files/Articles/449206/ffgc-02-00027-HTML/image_m/ffgc-02-00027-t001.jpg)
Table 1. Comparison of climate and biodiversity benefits of *intact* (either old-growth forest or younger forest managed as Gap 1 or Gap 2, and thus protected from logging and other resource extraction) and traditionally *managed* forests for multiple forest types in the United States.

A Small Fraction of U.S. Forests is Managed to Remain Intact

Today, <20% of the world's forests remain intact (i.e., largely free from logging and other forms of extraction and development). Intact forests are largely tropical forests or boreal forests in Canada and Russia (Watson et al., 2018). In the U.S.—a global pioneer in national parks and wildlife preserves—the percentage of intact forest in the contiguous 48 states is only an estimated 6–7% of total forest area (Oswalt et al., 2014), with a higher proportion in the West and a lower proportion in the East. Setting aside a large portion of U.S. forest in Inventoried Roadless Areas (IRAs) was groundbreaking yet only represents 7% of total forest area in the lower 48 states—and, ironically, management of some IRAs allows timber harvest and road building (Williams, 2000), a scenario happening currently in the Tongass National Forest in Alaska (Koberstein and Applegate, 2018). These scant percentages worldwide and particularly in the U.S. are insufficient to address pressing national and global issues such as rising CO_2 levels, flooding, and biodiversity loss, as well as provide suitable locations for recreation and associated public health benefits (Cordell, 2012; Watson et al., 2018). In heavily populated and heavily forested sub-regions in the Eastern U.S., such as New England, the total area dedicated as intact (i.e., primary management is for trails and hazard removals) is even more scarce, comprising only ~3% of land area. Just 2% of the region is legally protected from logging and other resource extraction (Figure 1). A large portion of forest managed currently as intact or "reserved forest" – and thus functioning as "stable forest" (Funk et al., 2019) – is designated solely by administrative regulations that can be altered at any time.

FIGURE 1

(https://www.frontiersin.org/files/Articles/449206/ffgc-02-00027-HTML/image_m/ffgc-02-00027-g001.jpg)
Figure 1. Distribution of forest cover and intact "wildland" forest across six New England states. At left, map of overall forest cover (green) vs. forest protected legally (red) or managed currently (yellow) as intact in New England. At right, regional and state specific % forest cover (green), % managed as intact Gap 1 (limited intervention other than trails and hazard removals) but not protected legally (yellow), and % legally protected as intact forest (red, designated U.S Geological Survey (USGS) Gap 1 or Gap 2 and primarily federal and state wilderness areas, and certain national parks). Adapted and compiled from National Conservation Easement Database (2014); United States Geological Survey

(2019a,b), and the University of Montana (2019). USGS Gap level 1 or 2 lands receive the highest level of protection from logging and other resource extraction and generally correspond with IUCN protected categories 1a, 1b, and II (https://gapanalysis.usgs.gov/blog/iucn-definitions/ (https://gap-analysis.usgs.gov/blog/iucn-definitions/)).

Intact forests in the U.S. include federal wilderness areas and national parks, some state parks, and some privately-owned holdings and conservation trust lands. Recent studies reveal that intact forests in national parks tend to be older and have larger trees than nearby forests that are not protected from logging (Miller et al., 2016; Table 1). Scaling up protection of intact forests and designating and significantly expanding reserved forest areas are public policy imperatives that are compatible with public access and with the country's use of forest products. Identifying suitable forest as intact (for carbon sequestration, native biodiversity, ecosystem function, etc.) can spawn new jobs and industries in forest monitoring, tourism and recreation, as well as create more viable local economies based on wood reuse and recycling. Public lands with significant biodiversity and proforestation potential also provide wildlife corridors for climate migration and resilience for many species.

Proforestation Increases Biological Carbon Sequestration and Long-Term Storage in U.S. Forests

Net forest carbon reflects the dynamic between gains and losses. Carbon is lost from forests in several ways: damage from natural disturbances including insects and pathogens ("pests"), fire, drought and wind; forest conversion to development or other non-forest land; and forest harvest/management. Together, fires, drought, wind, and pests account for ~12% of the carbon lost in the U.S.; forest conversion accounts for ~3% of carbon loss; and forest harvesting accounts for 85% of the carbon lost from forests each year (Harris et al., 2016). Forests in the Southern US have the highest percentage of carbon lost to timber harvest (92%) whereas the Western US is notably lower (66%) because of the greater contribution of fires to carbon removal. The Northern U.S. is roughly equivalent to the national average at 86% (Harris et al., 2016).

Proforestation produces natural forests as maximal carbon sinks of diverse species (while supporting and accruing additional benefits of intact forests) and can reduce significantly and immediately the amount of forest carbon lost to non-essential management. Because existing trees are already growing, storing carbon, and sequestering more carbon more rapidly than newly planted and young trees (Harmon et al., 1990; Stephenson et al., 2014; Law et al., 2018; Leverett and Moomaw, in preparation), proforestation is a near-term approach to sequestering additional atmospheric carbon: a significant increase in "negative emissions" is urgently needed to meet temperature limitation goals.

The carbon significance of proforestation is demonstrated in multiple ways in larger trees and older forests. For example, a study of 48 undisturbed primary or mature secondary forest plots worldwide found, on average, that the largest 1% of trees [considering all stems ≥1 cm in diameter at breast height (DBH)] accounted for half of above ground living biomass (The largest 1% accounted for ~30% of the biomass in U.S. forests due to larger average size and fewer stems compared to the tropics) (Lutz et al., 2018). Each year a single tree that is 100 cm in diameter adds the equivalent biomass of an entire 10–20 cm diameter tree, further underscoring the role of large trees (Stephenson et al., 2014). Intact forests also may sequester half or more of their carbon as organic soil carbon or in standing and fallen trees that eventually decay and add to soil carbon (Keith et al., 2009). Some older forests continue to sequester additional soil organic carbon (Zhou et al., 2006) and older forests bind soil organic matter more tightly than younger ones (Lacroix et al., 2016).

If current management practices continue, the world's forests will only achieve half of their biological carbon sequestration potential (Erb et al., 2018); intensifying current management practices will only decrease living biomass carbon and increase soil carbon loss. Forests in temperate zones such as in the Eastern U.S. have a particularly high untapped capacity for carbon storage and sequestration because of high growth and low decay rates (Keith et al., 2009) and because of recent recovery from an extensive history of timber harvesting and land conversion for agriculture in the 18th, 19th, and early 20th centuries (Pan et al., 2011; Duveneck and Thompson, 2019). In New England, median forest age is about 75 years of age (United States Forest Service, 2019), which is only about 25–35% of the lifespan of many of the common tree species in these forests (Thompson et al., 2011). Much of Maine's forests have been harvested continuously for 200 years and have a carbon density less than one-third of the forests of Southern Vermont and New Hampshire, Northwestern Connecticut and Western Massachusetts—a region that has not been significantly harvested over the past 75–150 years (National Council for Air Stream Improvement, 2019). Western Massachusetts in particular has a significant portion classifed as Tier 1 matrix forest, defined as "*large contiguous areas whose size and natural condition allow for the maintenance of ecological processes*" (Databasin, 2019). However, forests managed as intact do not need to be large or old in absolute terms to have ecological value: disturbances create gaps and young habitats, and the official policy of the Commonwealth of Massachusetts Department of Environmental Management (now Department of Conservation and Recreation) considers an old-growth forest of at least 2 hectares ecologically significant (Department of Environmntal Management, 1999).

As shown in Table 1, ecosystem services accrue as forests age for centuries. Far from plateauing in terms of carbon sequestration (or added wood) at a relatively young age as was long believed, older forests (e.g., >200 years of age without intervention) contain a variety of habitats, typically continue to sequester additional carbon for many decades or even centuries, and sequester significantly more carbon than younger and managed stands (Luyssaert et al., 2008; Askins, 2014; McGarvey et al., 2015; Keeton, 2018). A recent paper affirmed that letting forests grow is an effective way to sequester carbon—but unlike previous studies it suggested that sequestration is highest in "young" forests (Pugh et al., 2019). This conclusion is problematic for several reasons. One confounding factor is that older forests in the tropics were compared to young forests in temperate and boreal areas; temperate forests in particular have the highest CO_2 removal rates and overall biological carbon sequestration (Keith et al., 2009) but this high rate is not limited to young temperate and boreal forests. The age when sequestration rates decrease is not known, and Pugh et al. defined "young" as up to 140 years. As noted above, Keeton et al. (2011) estimate that secondary forests in the Northeast have the potential to increase their biological carbon sequestration several-fold. More field work is needed across age ranges, species and within biomes, but the inescapable conclusion is that growing forests is beneficial to the climate and maintaining intact forest has additional benefits (Table 1). We conclude that proforestation has the potential to provide rapid, additional carbon sequestration to reduce *net* emissions in the U.S. by much more than the 11% that forests provide currently (United States Environmental Protection Agency, 2019). A recent report on natural climate solutions determined that negative emissions could be increased from 11 to 21% even without including proforestation (Fargione et al., 2018). Quantified estimates of increased forest sequestration and ecosystem services were based on re-establishing forests where possible and lengthening rotation times on private land; they explicitly did not account for proforestation potential on public land.

Although biological carbon storage in managed stands, regardless of the silvicultural prescription, is generally lower than in unmanaged intact forests (Harmon et al., 1990; Ford and Keeton, 2017)—even after the carbon stored in wood products is included in the calculation—stands managed with reduced harvest frequency and increased structural retention sequester more carbon than more intensively managed stands (Nunery and Keeton, 2010; Law et al., 2018). Such an approach for production forests, or "working" forests—balancing resource extraction with biological carbon sequestration —is often termed "managing for net carbon" or "managing for climate change" and an approach that should be promoted alongside dedicating significant areas to intact ecosystems. Oliver et al. (2014) acknowledge a balance between intact and managed forest and suggest that long term storage in "efficient" wood products like wood building materials (with the potential for less carbon emissions compared to steel or concrete, termed the "avoidance pathway") can offer a significant carbon benefit. To achieve this, some questionable assumptions are that 70% of the harvested wood is merchantable and stored in a lasting product, all unmerchantable wood is removed and used, harvesting occurs at optimum intervals (100 years) and carbon sequestration tapers off significantly after 100 years. Forestry models underestimate the carbon content of older, larger trees, and it is increasingly clear that trees can continue to remove atmospheric carbon at increasing rates for many decades beyond 100 years (Robert T. Leverett, pers. comm. Stephenson et al., 2014; Lutz et al., 2018; Leverett et al., under review). Because inefficient logging practices result in substantial instant carbon release to the atmosphere, and only a small fraction of wood becomes a lasting product, increasing market forces and investments toward wood buildings that have relatively short lifetimes could increase forest extraction rates significantly and become unsustainable (Oliver et al., 2014).

Habitat Protection, Biodiversity and Scientific Value of Proforestation

Large trees and intact, older forests are not only effective and cost-effective natural reservoirs of carbon storage, they also provide essential habitat that is often missing from younger, managed forests (Askins, 2014). For example, intact forests in Eastern U.S. national parks have greater tree diversity, live and dead standing basal area, and coarse woody debris, than forests that are managed for timber (Miller et al., 2016, 2018; Table 1). The density of cavities in older trees and the spatial and structural heterogeneity of the forest increases with stand age (Ranius et al., 2009; Larson et al., 2014), and large canopy gaps develop as a result of mortality of large trees, which result in dense patches of regeneration (Askins, 2014). These complex structures and habitat features support a greater diversity of lichens and bryophytes (Lesica et al., 1991), a greater density and diversity of salamanders (Petranka et al., 1993; Herbeck and Larsen, 1999), and a greater diversity and abundance of birds in old, intact forests than in nearby managed forests (Askins, 2014; Zlonis and Niemi, 2014; Table 1). Forest bird guilds also benefit from small intact forests in urban landscapes relative to unprotected matrix forests (Goodwin and Shriver, 2014). Several bird species in the U.S. that are globally threatened—including the wood thrush, cerulean warbler, marbled murrelet, and spotted owl are, in part, dependent on intact, older forests with large trees (International Union for Conservation of Nature, 2019). Two species that are extinct today—Bachman's warbler and Ivory-billed woodpecker—likely suffered from a loss of habitat features associated with old forests (Askins, 2014).

Today, forest managers often justify management to maintain heterogeneity of age structures to enhance wildlife habitat and maintain "forest health" (Alverson et al., 1994). However, early successional forest species (e.g., chestnut-sided warbler and New England cottontail) that are common targets for forest management may be less dependent on forest management than is commonly believed (cf. Zlonis and Niemi, 2014; Buffum et al., 2015). Management also results in undesirable consequences such as soil erosion, introduction of invasive and non-native species (McDonald et al., 2008; Riitters et al., 2018), loss of carbon—including soil carbon (Lacroix et al., 2016), increased densities of forest ungulates such as white-tailed deer (Whitney, 1990)—a species that can limit forest regeneration (Waller, 2014)—and a loss of a sense of wildness (e.g., Thoreau, 1862).

Forest health is a term often defined by a particular set of forestry values (e.g., tree regeneration levels, stocking, tree growth rates, commercial value of specific species) and a goal of eliminating forest pests. Although appropriate in a commercial forestry context, these values should not be conflated with the ability of intact natural forests to continue to function and even thrive indefinitely and provide a diversity of habitats on their own (e.g., Zlonis and Niemi, 2014). Natural forests, regardless of their initial state, naturally develop diverse structures as they age and require from us only the time and space to self-organize (e.g., Larson et al., 2014; Miller et al., 2016).

Intact forests provide irreplaceable scientific value. In addition to a biodiverse habitat an intact forest provides an area governed by natural ecological processes that serve as important scientific controls against which to compare the effects of human activities and management practices (Boyce, 1998). Areas without resource extraction (i.e., timber harvesting, hunting), pest removal, or fire suppression allow for a full range of natural ecological processes (fire, herbivory, natural forest development) to be expressed (Boyce, 1998). Only if we have sufficient natural areas can we hope to understand the effects of human activities on the rest of our forests. Additional research and monitoring projects that compare ecological attributes between intact and managed forests at a range of spatial scales will also help determine how effective protected intact forests can be at conserving a range of biota, and where additional protected areas may need to be established (e.g., Goodwin and Shriver, 2014; Jenkins et al., 2015).

Proforestation and Forest Fires

Given the increase in forest area burned in the United States over the past 30 years (National Interagency Fire Center, 2019), it is important to address the relationship between forest management and forest fires. There is a widely held perception that the severity and size of recent fires are directly related to the fuels that have accumulated in the understory due to a lack of forest management to reduce these fuels (i.e., pulping, masticating, thinning, raking, and prescribed burning; Reinhardt et al., 2008; Bradley et al., 2016). However, some evidence suggests that proforestation should actually *reduce* fire risk and there are at least three important factors to consider: first, fire is an integral part of forest dynamics in the Western U.S.; second, wildfire occurrence, size, and area burned are generally not preventable even with fuel removal treatments (Reinhardt et al., 2008); and third, the area burned is actually far less today than in the first half of the twentieth century when timber harvesting was more intensive and fires were not actively suppressed (Williams, 1989; National Interagency Fire Center, 2019). Interestingly, in the past 30 years, intact forests in the Western U.S. burned at significantly *lower* intensities than did managed forests (Thompson et al., 2007; Bradley et al., 2016; Table 1). Increased potential fuel in intact forests appear to be offset by drier conditions, increased windspeeds, smaller trees, and residual and more combustible fuels inherent in managed areas (Reinhardt et al., 2008; Bradley et al., 2016). Rather than fighting wildfires wherever they occur, the most effective strategy is limiting development in fire-prone areas, creating and defending zones around existing development (the wildland-urban interface), and establishing codes for fire-resistant construction (Cohen, 1999; Reinhardt et al., 2008).

Proforestation and Ecosystem Services: Serving the Greatest Good

In 1905 Gifford Pinchot, Chief of the U.S. Forest Service, summarized his approach to the nation's forests when he wrote "…where conflicting interests must be reconciled, the question will always be decided from the standpoint of the greatest good of the greatest number in the long run." This ethos continues to define the management approach of the U.S. Forest Service from its inception to the present day. Remarkably, however, even in 2018 the five major priorities of the Forest Service do not mention biodiversity, carbon storage, or climate change as major aspects of its work (United States Forest Service, 2018).

Today, the needs of the nation have changed: emerging forest science and the carbon and biodiversity benefits of proforestation demand a focus on growing intact natural public and private forests, including local parks and forest reserves (Jenkins et al., 2015). There is also a growing need across the country, and particularly within reach of highly populated areas, for additional local parks and protected forest reserves that serve and provide the public with solitude, respite, and wild experiences (e.g., Thoreau, 1862). Detailed analysis of over one thousand public comments regarding management of Hoosier National Forest, a public forest near population centers in several states, revealed a strong belief that wilderness contributes to a sense of well-being. Responses with the highest frequency reflected an interest in preservation and protection of forests and wildlife, a recognition of the benefits to human physical and mental health, a sense of ethical responsibility, opposition to damage and destruction, monetary concerns, and a preponderance of sadness, fear and distress over forest loss (Vining and Tyler, 1999).

Quantifiable public health benefits of forests and green spaces continue to emerge, and benefits are highest in populations with chronic and difficult-to-treat conditions like anxiety, depression, pain and post-traumatic stress disorder (Karjalainen et al., 2010; Frumkin et al., 2017; Hansen et al., 2017; Oh et al., 2017). In the United Kingdom "growing forests for health" is the motto of the National Health Service Forest (2019) and there is a recognized need for evidence-based analysis of human health co-benefits alongside nature-based ecosystem services (Frumkin et al., 2017).

Policy Recommendations

To date, the simplicity of the idea of proforestation has perhaps been stymied by inaccurate or non-existent terminology to describe it. Despite a number of non-binding international forest agreements (United Nations Conference on Environment Development, 1992; United Nations Forum on Forests, 2008; Forest Declaration, 2014) and responsibilities by a major UN organization [Food and Agriculture Organization (FAO)], current climate policies lack science-based definitions that distinguish forest condition—including the major differences between young and old forests across a range of ecosystem services. Lewis et al. (2019) further note that broad definitions and confused terminology have an unfortunate result that policymakers and their advisers mislead the public (Lewis et al., 2019). Most discussions concerning forest loss and forest protection are in terms of percentage of land area that has tree canopy cover (Food and Agriculture Organization, 2019). This lack of specificity significantly hampers efforts to evaluate and protect intact forests, to quantify their value, and to dedicate existing forests as intact forests for the future. For example, the UN Framework Convention on Climate Change and the FAO consider and group tree plantations, production forests, and mature intact forests equally under the general term "forest" (Mackey et al., 2015). In addition, "forest conservation" simply means maintaining "forest cover" and does not address age, species richness or distribution—or the degree that a forest ecosystem is intact and functioning (Mackey et al., 2015). The erroneous assumption is that all forests are equivalently beneficial for a range of ecosystem services—a conclusion that is quantitatively inaccurate in terms of biological carbon sequestration and biodiversity as well as many other ecosystem services.

Practicing proforestation should be emphasized on suitable public lands as is now done in U.S. National Parks and Monuments. Private forest land owners might be compensated to practice proforestation, for sequestering carbon and providing associated co-benefits by letting their forests continue to grow. At this time, we lack national policies that quantify and truly maximize benefits across the landscape. At a regional scale, however, some conservation visions do explicitly recognize and promote the multiple values and services associated with forest reserves or wildlands (e.g., Foster et al., 2010) and climate offset programs can be used explicitly to support proforestation. For example, a recent project by the Nature Conservancy protected 2,185 hectares (5,400 acres) in Vermont as wildland and is expected to yield ~$2 M over

10 years for assuring long-term biological carbon storage (Nature Conservancy, 2019). Burnt Mountain is now protected by a “forever wild” easement and part of a 4,452 hectare (11,000 acre) preserve. More public education and similar incentives are needed.

Conclusions

To meet any proposed climate goals of the Paris Climate Agreement (1.5, 2.0° C, targets for reduced emissions) it is essential to simultaneously *reduce greenhouse gas emissions from all sources* including fossil fuels, bioenergy, and land use change, and *increase CDR* by forests, wetlands and soils. Concentrations of these gases are now so high that reducing emissions alone is insufficient to meet these goals. Speculation that untested technologies such as BECCS can achieve the goal while allowing us to continue to emit more carbon has been described as a “moral hazard” (Anderson and Peters, 2016). Furthermore, BECCS is not feasible within the needed timeframe and CDR is urgent. Globally, existing forests only store approximately half of their potential due to past and present management (Erb et al., 2018), and many existing forests are capable of immediate and even more extensive growth for many decades (Lutz et al., 2018). During the timeframe while seedlings planted for afforestation and reforestation are growing (yet will never achieve the carbon density of an intact forest), proforestation is a safe, highly effective, immediate natural solution that does not rely on uncertain discounted future benefits inherent in other options.

Taken together, proforestation is a rapid and essential strategy for achieving climate and biodiversity goals and for serving the greatest good. Stakeholders and policy makers need to recognize that the way to maximize carbon storage and sequestration is to grow intact forest ecosystems where possible. Certainly, all forests have beneficial attributes, and the management focus of some forests is providing wood products that we all use. But until we acknowledge and quantify differences in forest status (Foster et al., 2010), we will be unable to develop policies (and educate landowners, donors, and the public) to support urgent forest-based benefits in the most effective, locally appropriate and cost-effective manner. A differentiation between production forests and natural forest ecosystems would garner public support for a forest industry with higher value products and a renewed focus on reducing natural resource use—and for recycling paper and wood. It could also spur long-overdue local partnerships between farms and forests—responsible regional composting keeps jobs and resources within local communities while improving soil health and increasing soil carbon (Brown and Cotton, 2011). The forest industry as a whole can benefit from proforestation-based jobs that focus on scientific data collection, public education, public health and a full range of ecosystem services.

In sum, proforestation provides the most effective solution to dual global crises—climate change and biodiversity loss. It is the only practical, rapid, economical, and effective means for atmospheric CDR among the multiple options that have been proposed because it removes more atmospheric carbon dioxide in the immediate future and continues to sequester it long-term. Proforestation will increase the diversity of many groups of organisms and provide numerous additional and important ecosystem services (Lutz et al., 2018). While multiple strategies will be needed to address global environmental crises, proforestation is a very low-cost option for increasing carbon sequestration that does not require additional land beyond what is already forested and provides new forest related jobs and opportunities along with a wide array of quantifiable ecosystem services, including human health.

Author Contributions

WM, SM, and EF contributed equally to conceiving, writing and editing this manuscript and all agree to its publication.

Funding

Supported by Charles Bullard Fellowship in Forest Research, Harvard Forest (SM).

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgments

The authors thank the reviewers for improving the manuscript with substantive and thoughtful comments and thank David N. Ruskin, Ph.D. (Trinity College) for feedback and assistance throughout.

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Keywords: biodiversity crisis, Pinchot, afforestation, reforestation, forest ecosystem, biological carbon sequestration, old-growth forest, second-growth forest

Citation: Moomaw WR, Masino SA and Faison EK (2019) Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good. *Front. For. Glob. Change* 2:27. doi: 10.3389/ffgc.2019.00027

Received: 19 January 2019; **Accepted:** 20 May 2019;
Published: 11 June 2019.

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EXHIBIT R-7

WILD CARBON

A synthesis of recent findings

MARK G. ANDERSON, PhD

We find ourselves not at the edge of a precipice, but beyond it. Climate change is altering the world as we know it, no matter how quickly we act to reduce our collective carbon footprint. But the worst impacts are still avoidable with natural climate solutions. Permanently protecting forests and allowing them to grow in landscapes free from direct human manipulation is proving to be one of the most effective and cost efficient methods available to address the climate crisis. While wild nature has a right to exist simply for its intrinsic value, recent science is shedding peer-reviewed light on the exceptional carbon storage capacity of unmanaged land, and its equally important benefits for safeguarding biodiversity. In this short synthesis, ecologist Mark Anderson summarizes recent studies which demonstrate that in our fragmented, fast-developing world, wilderness offers the earth and its community of life the precious gift of time.

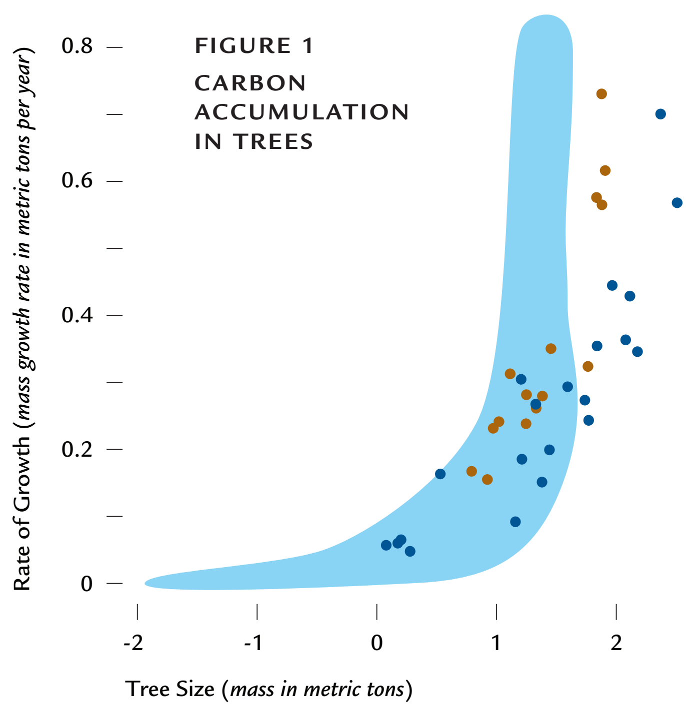
—Jon Leibowitz, Executive Director, Northeast Wilderness Trust

A long-standing debate over the value of old forests in capturing and storing carbon has prompted a surge of synthesis studies published in top science journals during the last decade. Here are five emerging points that are supported by solid evidence.

1) Trees accumulate carbon over their entire lifespan. Plants absorb carbon dioxide from air and transform it into carbon-rich sugars. These are then converted to cellulose to create biomass (trunk, bark, leaf) or transferred below-ground to feed the root-fungal networks. Over the long lifespan of the tree, large amounts of carbon are removed from the air and stored as biomass. Growth efficiency declines as the tree grows but corresponding increases in the tree's total leaf area are enough to overcome this decline and thus the **whole-tree carbon accumulation rate increases with age and size** (Figure 1)**.** A study of 673,046 trees across six countries and 403 species found that that at the extreme, a large old tree may sequester as much carbon in one year as growing an entire medium size tree (Stephenson et al. 2014). At one site, large trees comprised 6 percent of the trees but 33 percent of the annual forest growth. Young trees grow fast, but old trees store a disproportional amount of carbon.

2) Old forests accumulate carbon and contain vast quantities of it. Old-growth forests have traditionally been considered negligible as carbon sinks. Although individual trees experience an increasing rate of carbon sequestration, forest stands experience an "S-curve" of net sequestration rates (e.g. slow, rapid, slow). The expected decline in older stands is due to tree growth being balanced by mortality and decomposition. To test the universality of carbon neutrality in old forests, an international team of scientists reviewed 519 published forest carbon-flux estimates from stands 15 to 800 years old and found that, in fact, net carbon storage was positive for 75 percent of the stands over 180 years old and the chance of finding an old-growth forest that was carbon neutral was less than one in ten (Luyssaert et al. 2014). They concluded that **old-growth forests are usually carbon sinks, steadily accumulating carbon and containing vast quantities of it**. They argued that carbon-accounting rules for forests should give credit for leaving old-growth forest intact. This is important globally, as old forests in the tropics have acted as long-term net biomass/carbon sinks but are now vulnerable to edge effects, logging and thinning, or increased mortality from disturbances (Brienen et al. 2015, Lan Qui et al. 2018).

3) Old forests accumulate carbon in soils. The soil carbon balance of old-growth forests has received little attention, although it was generally accepted that soil organic carbon levels in old forests are in a steady state. In 2017, Guoyi Zhou and colleagues measured the 24-year dynamics of the soil carbon in an old-growth forest at China's Dinghushan Biosphere Reserve. They found that **soils in the top 20-cm soil layer accumulated atmospheric carbon at an unexpectedly high rate**, with soil organic carbon concentration increasing from about 1.4 percent to 2.4 percent



Aboveground mass growth rates for 58 species (shaded area) juxtaposed with two of the most massive tree species on earth: Swamp Gum (*Eucalyptus regnans*—brown dots) and Coast Redwood (*Sequoia sempervirens*—blue dots). Mass growth rate equals the total mass accumulated each year after accounting for respiration. The mass of a tree is primarily carbon, so the figure shows that annual carbon accumulation increases with the size of the tree. (Adapted from Stephenson et al. 2014.)

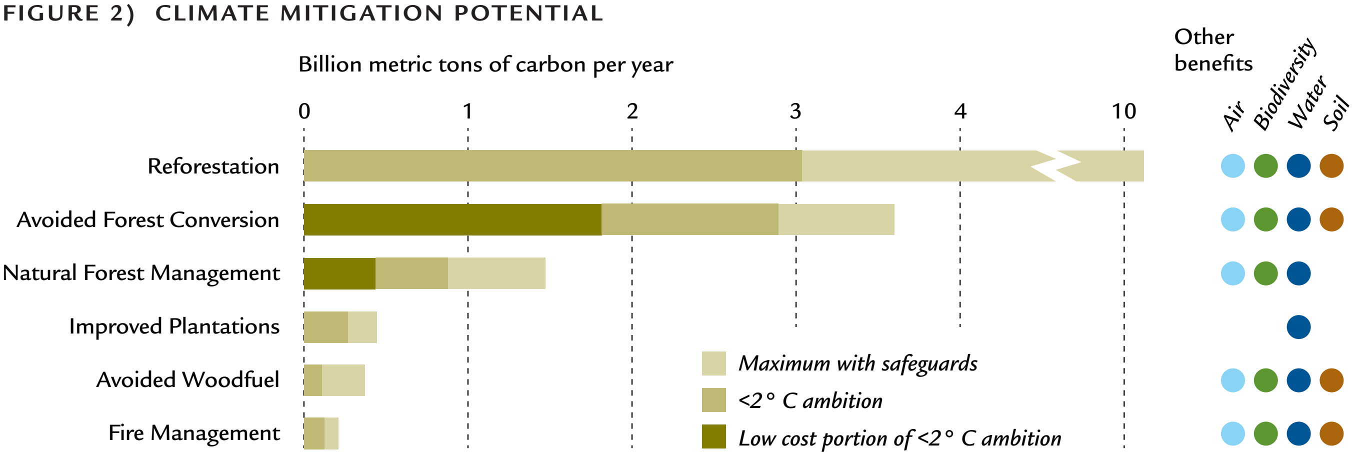
and soil carbon stock increasing significantly at an average rate of 0.61 metric tons of carbon per hectare per year (Zhou, G. et al. 2006). Their result directly challenges the prevailing belief in ecosystem ecology regarding carbon budget in old-growth forests and calls for further study.

4) Forests share carbon among and between tree species. Forest trees compete for light and soil resources, and competition for resources is commonly considered the dominant tree-to-tree interaction in forests. However, recent research made possible by stable carbon isotope labeling indicates that trees interact in more complex ways, including substantial exchange and sharing of carbon. In 2016, Tamir Klein and colleagues applied carbon isotope labeling at the canopy scale, and found that that carbon assimilated by a tall spruce was traded with neighboring beech, larch, and pine trees via overlapping root spheres. Aided by mycorrhiza networks, **interspecific transfer accounted for 40 percent of the fine root carbon** totaling roughly 280 kilograms per hectare per year tree-to-tree transfer (Klein et al. 2016). In a subsequent study, Morrie et al. (2017), found that mycorrhiza soil networks become more connected and take up more carbon as forest succession progresses even without major changes in dominant species composition.

A large old tree accumulates impressive amounts of carbon every year while also releasing oxygen, filtering pollution, and creating food and habitat for wildlife.

5) Forest carbon can help slow climate change. There has been debate about the role of forests in sequestering carbon and the role of land stewardship in achieving the Paris Climate Agreement goal. In 2017, Bronson Griscom and colleagues systematically evaluated twenty conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions. They found the maximum potential of these natural climate solutions was almost 24 billion metric tons of carbon equivalent per-year while safeguarding

FIGURE 2) CLIMATE MITIGATION POTENTIAL



Climate mitigation potential of six forest pathways estimated for reference year 2030. Bars represent maximum possible with safeguards (i.e. constraints applied to safeguard the production of food and fiber and habitat for biological diversity). Darker portions represent cost-effective mitigation levels assuming a global ambition to hold warming to <2° C. Darkest portions indicate low cost portions. Ecosystem service benefits linked with each pathway are indicated by colored dots for biodiversity, water (filtration and flood control), soil (enrichment), and air (filtration). (Adapted from Griscom et al. 2017.)

food security and biodiversity. About half of this could be delivered as cost-effective contributions to the Paris Agreement, equivalent to about **30 percent of needed mitigation as of 2030**, with 63 percent coming from forest-related actions (Figure 2). **Avoided forest conversion** had the highest carbon potential among the low-cost solution (Griscom et al. 2017). New research suggests this strategy is the most cost-feasible option by a large margin (Busch et al. 2019) and it should receive high priority as a policy consideration in the U.S. (McKinley et al. 2011). An analysis of 18,507 forest plots in the Northeast found that old forests (greater than 170 years) supported the largest carbon pools and the highest simultaneous levels of carbon storage, timber growth, and species richness (Thom et al. 2019). In addition to carbon, old forests also build soil, cycle nutrients, mitigate pollution, purify water, release oxygen, and provide habitat for wildlife.

CONCLUSION

Recently published, peer-reviewed science has established that unmanaged forests can be highly effective at capturing and storing carbon. It is now clear that trees accumulate carbon over their entire lifespan and that old, wild forests accumulate far more carbon than they lose through decomposition and respiration, thus acting as carbon sinks. This is especially true when taking into account the role of undisturbed soils only found in unmanaged forests. In many instances, the carbon storage potential of old and wild forests far exceeds that of managed forests. We now know that the concept of overmature forest stands, used by the timber industry in reference to forest products, does not apply to carbon.

In the Northeast, a vigorous embrace of natural climate solutions to mitigate global overheating does not require an either/or choice between managed and unmanaged forests. **Conserving unmanaged wild forests is a useful, scalable, and cost-effective complementary strategy to the continued conservation of well-managed woodlands.**

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REQUESTED CITATION

Anderson, M.G. 2019. *Wild Carbon: A synthesis of recent findings*. Northeast Wilderness Trust. Montpelier, VT USA.

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EXHIBIT S7

Clear-cutting destabilizes carbon in forest soils, study finds

Date: April 15, 2016

Source: Dartmouth College

Summary: Clear-cutting loosens up carbon stored in forest soils, increasing the chances it will return to the atmosphere as carbon dioxide and contribute to climate change, a new study shows.

FULL STORY

Clear-cutting loosens up carbon stored in forest soils, increasing the chances it will return to the atmosphere as carbon dioxide and contribute to climate change, a Dartmouth College study shows.

The findings appear in the journal *Soil Science*.

Soil is the world's largest terrestrial carbon pool. In northern hardwood forests in the United States, mineral soil pools store up to 50 percent of total ecosystem carbon. Logging and other land-use changes are a major cause of soil carbon release, but there has been recent interest to further understand soil carbon dynamics in forested ecosystems after logging. This is of particular importance in the northeastern U.S. because of the great potential for the use of biomass as part of a diversified renewable energy portfolio.

The Dartmouth researchers explored whether clear-cutting changes the strength of the chemical bonds of carbon stored in mineral soils in hardwood forests in the northeastern United States. Clear-cutting involves harvesting all timber from a site at once rather than selectively culling mature trees. Carbon is stored in soil by binding only to certain soil structures.

The researchers collected soils from recently clear-cut forests and from older forests, and pulled carbon from the soil in a sequence of gentle to stronger extractions. The results showed that mature forest stands stored significantly more soil organic carbon in strongly mineral-bound and stable carbon pools than did soils from cut stands.

"Clear-cutting forests has an effect of mobilizing the carbon, making it more likely to leave the soil and end up in the atmosphere," says senior author Andrew Friedland, a professor of environmental studies. "These findings are important because differences in the relative distribution of carbon in organo-mineral pools in mature and cut forests may inform our understanding of soil organic matter stability and bioavailability, microbial decomposition and carbon dioxide production in ecosystems after clear-cutting."

Story Source:

Materials provided by **Dartmouth College**. *Note: Content may be edited for style and length.*

Journal Reference:

1. Lacroix, Emily M.; Petrenko, Chelsea L.; Friedland, Andrew J. **Evidence for Losses From Strongly Bound SOM Pools After Clear Cutting in a Northern Hardwood Forest**. *Soil Science*, April 2016 DOI: 10.1097/SS.0000000000000147

Cite This Page:

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Dartmouth College. "Clear-cutting destabilizes carbon in forest soils, study finds." ScienceDaily. ScienceDaily, 15 April 2016. <www.sciencedaily.com/releases/2016/04/160415125925.htm>.

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EXHIBIT T-7

A CLIMATE ACTION PLAN FOR MAINE 2004

A Report to the Joint Standing Committee on Natural Resources of the Maine Legislature Pursuant to PL 2003 Chapter 237

Department of Environmental Protection December 1, 2004

ACKNOWLEDGEMENTS

The Department of Environmental Protection gratefully acknowledges the following organizations for their financial support of the Climate Action Plan project:

- The United States Environmental Protection Agency, for a facilitation grant to develop the stakeholder process;
- The Energy Foundation, for funds to support modeling and analytic activities;
- The Kendall Foundation, for funds to support modeling and analytic activities;
- The Maine Department of Transportation, for a grant to further the work of the Transportation and Land Use Working Group;
- The Governor's Office of Energy independence and Security, for funds to support modeling in the energy sector.

Several organizations represented in the stakeholder process were gracious in making their facilities available for meetings of the Stakeholder Advisory Group and Working Groups:

- The Natural Resources Council of Maine
- The Maine Pulp and Paper Association
- The Maine Motor Transport Association
- The Chewonki Foundation

The preparation of this report was assisted by the Muskie School of Public Service at the University of Southern Maine under the Cooperative Agreement with the Maine Department of Environmental Protection.

The Department expresses its particular thanks to Jonathan Raab and Peter Wortsman, of Raab Associates, for their tireless efforts and many useful suggestions, without which this *Plan* would not have come to fruition.

TABLE OF CONTENTS

OVERVIEW

A 2003 Maine law (PL 237) required the Department of Environmental Protection (DEP) to develop and submit a *Climate Action Plan* (*CAP* or *Plan*) for Maine. The goals of the *CAP* are to reduce greenhouse gas (GHG) emissions to1990 levels by 2010, 10% below those levels in 2020, and by a sufficient amount to avert the threat of global warming over the longer term, which could be as much as 75%. This law was built on a New England Governors and Eastern Canadian Premiers resolution calling for similar reductions. Several New England states have adopted or are in the process of drafting their own plans. The law also directed the DEP to undertake “Lead by Example” initiatives, including conducting emissions inventories for state facilities and programs; obtaining voluntary carbon reduction agreements with private sector businesses and non-profit organizations; participating in a regional GHG registry; and establishing an annual statewide GHG emissions inventory.

For the past year and a half, the Department has worked with approximately 100 stakeholders to develop the Plan. In addition to a core group of 30 stakeholders comprising the Stakeholder Advisory Group (SAG), four different Working Groups (Transportation and Land Use; Buildings, Facilities, and Manufacturing; Energy and Solid Waste; and Agriculture and Forestry segments) consisting of approximately 100 individuals, met to identify measures, develop baselines, analyze pros and cons, and draft recommendations to the Stakeholder Advisory Group, and ultimately, the Department.

The first task was to establish a baseline of Maine’s actual (1990) GHG emissions, and forecast numbers to 2020. The forecast is based largely on projections of Maine’s economic growth and energy use (including both overall consumption and fuel mix), as well as Maine’s solid waste, forestry, and agricultural practices. A particular effort was made to assure stakeholder consensus on the assumptions to be used for baseline and reduction calculations so that the *CAP* would be as Maine-specific as possible. The results show that, under a business as usual scenario, Maine’s emissions in 2020 are projected to be 9,238,000 metric tons, or 34 percent, higher than the goal of the GHG legislation.

After a year of development, and based on the work of stakeholders, the Department is recommending fifty-four actions that will be needed to fill the gap between the baseline and the legislative targets. The Department's decision to include these options was based primarily on the assessment of saved carbon, and accompanying costs. Almost half of the options either reduce carbon at a negative cost (*i.e.,* "save" money over the program life) or cost very little. The recommended actions would, if taken together and implemented, make significant progress toward the statutory emission reduction targets, and may even meet them.

There are multiple actions for each of the four sectors. The report presents the actions in a variety of ways: by the amount of greenhouse gases saved; by cost-effectiveness; and grouped by sector. The Report also indicates next steps to implement the actions. Some actions require further legislation, while others can be implemented through executive order, rulemaking, or voluntary activity. Some will need further discussions and development before implementation.

A number of the included actions are initiatives that are already well under way. Maine's 2001 "Clean Government" initiative requires state agencies to incorporate environmentally sustainable practices into their planning, operations and regulatory functions. Many of the actions address GHG mitigation options, particularly in areas such as energy efficiency, building standards, and transportation fleet upgrades.

Maine's Office of Energy Independence and Security has calculated Maine State Government's GHG emissions for FY 02, 03 and 04. Over that time period the Government has reduced its own GHG emissions by 8%, through increased purchase of renewable power and fuels, and increased focus on energy conservation and efficiency in the transportation and building sectors.

To date, other state agencies have taken such actions as converting traffic lights at intersections to more efficient light-emitting diode (LED) lighting; administering a program whose focus is to increase electrical energy efficiency throughout the Maine economy; and requiring Maine's retail electricity suppliers to have 30% of all power coming from renewable sources. This is the highest such "renewable portfolio standard" in the United States.

Every effort was made to reach consensus on the actions. Many actions achieved consensus and for the few that did not, a number achieved consensus as "principled goals": that is, stakeholders agreed on the numerical target for the amount of carbon to be saved for that option. For the few that did not achieve consensus, the Report describes the pros and cons expressed by stakeholders.

The stakeholders paid careful attention to using the best available data for modeling and calculation. It was necessary, though, to choose certain values for key variables (such as economic growth), which are sensitive over the relevant time period (2005 to 2020) to relatively small initial differences in assumptions, or to subsequent changes. While the Department is confident that the data and assumptions used to calculate the forecast carbon savings and cost information are as refined as possible at this point, we are also aware that additional information, or more sophisticated analysis, is likely to change specific numbers. In addition, the final policy design and implementation strategy for each option may require changes to the projected carbon savings and cost estimates. Since we view the CAP as a continuing and living document, we will expect to modify the specifics as better information becomes available. The Legislature clearly had this in mind in the enabling legislation, which calls on the Department to evaluate the State's progress toward meeting the reduction goals specified and amend the action plan as necessary by January 1, 2006, and every two years thereafter. Beginning in 2008, the DEP may recommend that the reduction goals be increased or decreased.

The Plan contemplates public education and outreach efforts. There is an Education and Public Awareness Working Group to assist the Department to offer public sessions at which this Climate Action Plan can be presented to wider audiences. The Department, along with other agencies of this administration, will work with the legislature to refine and implement the Plan, a leadership role that Maine frequently takes.

HIGHLIGHTS

Forestry Benefits. One of the more interesting and groundbreaking issues involves the forestry sector, which presents significant opportunities for carbon savings through sequestration. Extensive analysis of data from Federal and State sources, combined with careful exploration of assumptions about, for example, the role of forest soils in the carbon cycle, brought the Working Group to conclude that certain forms of active management already well-understood by the forest industry were capable of producing real carbon savings at very low or negligible cost. The options, voluntary in nature, would improve silviculture to produce more and higher-quality wood as an important co-benefit. It will be important to develop incentives needed to increase markets of this wood. The modeling of the carbon savings and costs suggest the likelihood that, taken together, these options would be close to cost-neutral, and could produce new landowner revenue streams and/or cost savings over time. Since Maine's is the first Climate Action Plan in the United States to fully consider the forest carbon cycle and active management options as a significant part of the overall GHG mitigation effort, further research and modeling will be necessary as part of implementation planning.

Efficiency Rewards. By establishing a baseline based on an earlier period, the Plan allows for higher production through economic efficiency. Industry is rewarded for both GHG reductions and more efficient production methods.

Trade Possibilities. The Plan gives Maine a competitive advantage by establishing a GHG baseline and registry. As more states develop GHG plans, along with the many countries with existing or contemplated plans, Maine may be in a position to "trade" carbon allowances if aggressive policies are pursued.

Co-benefits. Most of the recommended actions are expected to produce significant co-benefits in addition to saving carbon. Of particular significance are those will have a positive impact on human health, will save consumers money through energy conservation and efficiency, will reduce our dependence on foreign oil and gas, will create jobs, and/or can be expected to promote economic growth and development. Many of these occur in the realm of air quality affecting human health, since lessening the emission of carbon dioxide from combustion of fossil fuels for electricity or transportation will also lead to reductions in other air pollutants. These include smog-producing sulfur and nitrogen oxide, and those fine particulates implicated in asthma and other respiratory diseases. Other co-benefits are expected to arise from the development of new technologies, particularly in the forestry sector, which in turn will produce additional economic benefits.

Energy Efficiency. Many of the electricity demand management options, such as energy efficiency measures, will save Maine people and businesses significant dollars, while contributing to Maine's energy security. Finally, a number of the options would work hand-in-hand with existing State policy goals such as forest and farmland protection.

GLOSSARY

AF	Agriculture and Forestry Working Group
BFM	Buildings, Facilities, and Manufacturing Working Group
CAP	Climate Action Plan 2004
CHP	Combined Heat and Power
CO2	Carbon Dioxide
ESW	Energy and Solid Waste Working Group
GHG	Greenhouse Gas
HFC	Hydro-fluorocarbon compounds
IPCC	Intergovernmental Panel on Climate Change
KmtCO2	Thousand(s) of metric tons (tonnes) of carbon dioxide equivalent
LEED	Leadership in Energy and Environmental Design
LEV	Low Emission Vehicle
NEG/ECP	Conference of New England Governors and Eastern Canadian Premiers
PUC	Public Utilities Commission
PV	Photo-voltaic
RPS	Renewable Portfolio Standard
SAG	Stakeholder Advisory Group
SBC	System Benefit Charge
SPO	State Planning Office
TLU	Transportation and Land Use Working Group
VMT	Vehicle Miles Traveled
WG	Working Group
ZEV	Zero emission vehicle

A CLIMATE ACTION PLAN FOR MAINE:
THE PROPOSAL

Background

In order to meet the requirements of the 121st Maine State Legislature's L.D. 845, "An Act to Provide Leadership in Addressing the Threat of Climate Change," the Maine Department of Environmental Protection convened a group of over thirty stakeholders representing business, industry, environmental groups, and other government agencies in the autumn of 2003. The purpose was to develop a Climate Action Plan (CAP) for Maine.[1] Maine's CAP development process builds on the 2001 agreement among the governors of New England states, and premiers of Eastern Canadian provinces to reduce greenhouse gases in the region. The goals are to reduce emissions to 1990 levels by 2010, 10% below those levels in 2020, and by as much as 75% over the longer term.[2] Under the terms of the legislation, the Department must submit a Plan recommending steps needed to meet these reduction targets to the legislature's Natural Resources Committee. The present document is intended to meet that obligation.

During the course of the stakeholder process, the core group (known as the Stakeholder Advisory Group (SAG) met on five occasions to set overall direction, review recommendations, and advise the Commissioner. SAG members served with other stakeholders on five different Working Groups (Transportation and Land Use; Buildings, Facilities, and Manufacturing; Energy and Solid Waste; Agriculture and Forestry; Education and Public Outreach) that each met on four occasions. The Working Groups (WG) were charged with discussing multiple GHG reduction initiatives, programs, and policy options in consultation with technical advisors representing a number of different disciplines. They were also charged with making recommendations to the SAG and DEP. Their work forms the central core of this Plan.[3]

Establishing the Baseline

Much of the initial effort on the part of the Department and stakeholders centered on the establishment of a "Baseline" of Maine's actual (to 2002) and forecast (to 2020) GHG emissions. The baseline establishes the framework for planning the reductions needed to meet the mandated goals.

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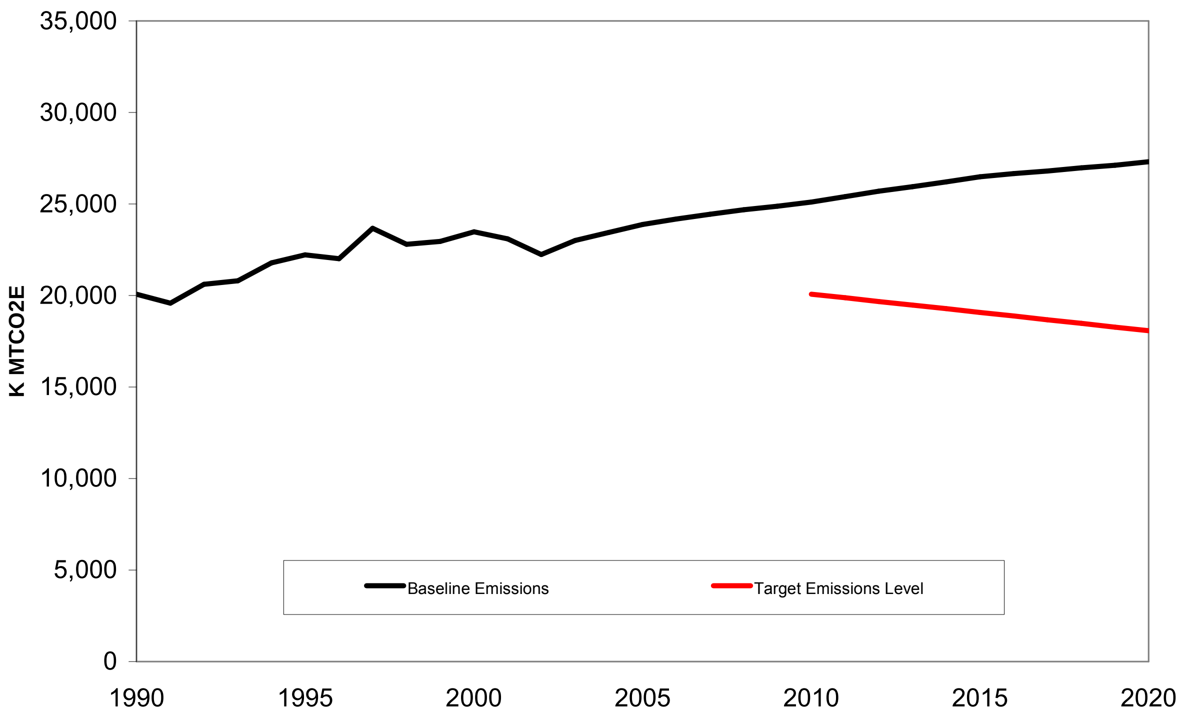
[1] See below, pp. 29 ff., for a description of the stakeholder process.
[2] See below, pp. 23-4.
[3] The entire *CAP*, together with all materials associated with the stakeholder process, is found at http://maineghg.raabassociates.org/

Figure 1 shows the baseline path for Maine's greenhouse gas emissions: that is, the expected growth in GHG emissions absent new initiatives. It also shows the path needed to meet the 2010 and 2020 targets. The gap between these paths must be filled by the initiatives, programs, and policies detailed in the following pages.

Figure 1: Emissions Baseline and Target



Calculation of Maine's baseline forecast was developed by Maine DEP and the Tellus Institute, a consulting firm engaged to provide modeling services on technical issues. The forecast is based largely on projections of Maine's energy use, as well as Maine's solid waste, forestry, and agricultural practices. The developers utilized U.S. Department of Energy energy-use information for Maine, supplemented by Maine-specific calculations based on information supplied by stakeholders representing the forest industry, the Public Utilities Commission, etc. Each stakeholder had multiple opportunities to provide data, which were reviewed by the technical consultants and Working Groups. A particular effort was made to assure stakeholder consensus on the assumptions to be used for baseline and reduction calculations so that the CAP would be as Maine-specific as possible. Further details on the assumptions underlying the development of the baseline, the modeling approach used by Tellus, etc., may be found in Appendix 2.2. Additional baseline graphs may be viewed below, pp. 98-9.

Recommendations

Based on the work of stakeholders in both the Working Groups and SAG processes, the Department is recommending the following fifty-four actions as necessary to fill the gap between the baseline and the targets.[4] Items in the table are ranked based on expected GHG emission savings in the year 2020. The number in the first column, which indicates the option's position in the rank ordering of 2020 carbon savings, is also used to identify the option elsewhere in the document. This is followed by the short title of the option. In the third and fourth columns, the estimated annual savings to be realized by 2010 and 2020, respectively, are presented in terms of "KmtCO_2," or "thousands of metric tons of carbon dioxide equivalent," a metric which allows other GHGs such as methane to be presented in terms equivalent to CO_2. The 2020 savings number is then applied to the costs (or savings) that the option entails, measured in dollars *per* unit of saved CO_2 equivalent. In this column, numbers less than –"$0"- indicate measures that, if implemented, would save more than they cost over time. Finally, the Working Group identification number is given to allow easy reference to the working group reports found in the Appendices. These present information about assumptions and calculations, as well as fuller descriptions than are found in the Detailed Option Descriptions on pp. 37 to 92.[5]

TABLE 1: CONSOLIDATED OPTIONS RANKED BY CO_2 SAVINGS

GW #	Measure (Sector)	KmtCO2 saved in 2010	KmtCO2 saved in 2020	Cost per ton CO2	Workgroup ID
1	Offset Requirements	**365.0**	**1022.0**	10	ESW 1.12
2	Implement Tailpipe GHG Emissions Standards	**137.5**	**933.6**	-48	TLU 1.1a
3	Regional Cap and Trade	**376.0**	**755.0**	-90	ESW 1.9b
4	Clean Diesel/Black Carbon	**383.8**	**740.0**	14	TLU 8.1
5	Renewable System Benefit Charge	**334.0**	**689.0**	30	ESW 1.2

[4] Original option #12 has been removed; see below, p. 50 for a complete explanation.
[5] Several of the options listed above are essentially alternative paths toward the same goal. Each is listed separately here for purposes of comparison; however, the carbon savings in 2020 have been adjusted when compiled to produce Figure 1 to avoid double counting. For example, as described in the option summaries, Options 5 (System Benefit Charge) and 11 (Renewable Portfolio Standard) each seek to support the development of renewables. Similarly, the desired outcomes of Options 1 and 7 (Offset Requirements; Emission Standards) would be partially met if Option 3 (Regional Cap and Trade) were implemented.

6	Set a Low GHG Fuel Standard	**63.5**	**639.5**	34	TLU 3.1
7	Emission Standards	**484.0**	**609.0**	23	ESW 1.10
8	Biomass Generation: Existing Units	**574.0**	**574.0**	15	ESW 1.5a
9	Landfill Gas Management: Energy Production	**210.0**	**550.0**	NE	ESW 2.1a
10	Increased Stocking With Faster Growing Trees	**531.7**	**531.7**	1	F 2.0 (A 8.0)
11	Renewable Portfolio Standards	**247.0**	**527.0**	10	ESW 1.1
13	Pay as You Drive Insurance	**6.9**	**379.0**		TLU 2.4d
14	Forestland Protection	**376.0**	**376.0**	-6	F 1.0 (A7.0)
15	Recycling/ Source Reduction	**168.0**	**374.0**	0	ESW 2.3
16	Early Commercial Thin	**331.7**	**331.7**	1	F 3 (A5.2a)
17	Slowing VMT Growth (TLU 2.2, TLU 2.3, unquantified measures in TLU 2.4)	**87.5**	**286.4**		TLU 2.0
18	Biomass Restart Nonoperating Units	**269.0**	**269.0**	15	ESW 1.5a
19	Improve Electricial Efficiency:Commercial / Institu-tional	**181.9**	**250.8**	-139	BFM 3.8
20	Timber Harvest to Capture Anticipated Mortality	**239.5**	**239.5**	4	F 7 (A5.2b)
21	Biomass Electricity Feedstocks	**228.4**	**228.4**	0	F 5.0 (A 6.1)
22	Electrical Efficiency Measures: Manufacturing	**156.5**	**207.2**	-30	BFM 4.1
23	Fossil Fuel Efficiency Measures	**76.6**	**204.4**	-34	BFM 5.5
24	Low-GHG Fuel for State Fleets	**19.1**	**157.5**	10	TLU 3.2
25	Expanded Use Of Wood Products	**129.8**	**129.8**	3	F 6 (A5.5)
26	Appliance Standards	**84.3**	**128.7**	-134	BFM 1.1
27	Landfill Gas Management: Flaring	**109.0**	**109.0**	2	ESW 2.1b
28	Active Softwood Increase	**73.2**	**73.2**	3	F 4 (A5.2e)
29	Increase Public Expenditures for Electrical Efficiency	**25.0**	**71.1**	-55	BFM 5.2
30	Improve Residential Building Energy Codes	**24.7**	**64.1**	-35	BFM 2.1
31	Voluntary Partnerships and Recognition Programs	**34.5**	**57.5**	0	BFM 5.9
32	Add ZEV Mandate to LEV II Standards	**0.0**	**53.0**	0	TLU 1.1b
33	Local Grown Produce	**34.9**	**52.1**	TBD	A 6.0
34	State Green Power Purchases	**31.0**	**45.0**	28	ESW 1.3
35	Efficient Use of Oil and Gas: Home Heating	**29.3**	**39.1**	-6	BFM 2.6
36	Combined Heat and Power Incentive Policy	**86.0**	**38.0**	-185	ESW 1.8
37	Enforce Commercial Building Energy Code	**12.0**	**33.6**	-61	BFM 3.7
38	Solar Hot Water Heater Program	**12.0**	**33.1**	16	BFM 5.7
39	Soil Carbon Buildup	**15.4**	**31.0**	28	A 2.0
40	Green Campus Initiatives	**11.0**	**29.8**	-18	BFM 3.6
41	Encourage Anti-Idling Measures: Freight	**12.0**	**29.7**		TLU 4.2d
42	Voluntary Green Building Design Standards	**23.5**	**28.0**	-45	BFM 2.3
43	Waste-to-Energy	**24.0**	**24.0**	9	ESW 2.2
44	Agricultural Land Protection	**15.9**	**22.7**	13	A 5.0
45	Energy Savings in State Buildings	**7.9**	**21.0**	-37	BFM 3.3
46	GHG Feebates (state or regional)	**3.8**	**18.8**	0	TLU 1.3b
47	Procurement Preference for Concrete Containing Slag	**18.0**	**18.0**	0	BFM 3.9

48	Promote energy efficiency buildings	**4.3**	**11.3**	-19	BFM 3.2
49	Specification C150 Portland Cement	**9.0**	**9.0**	0	BFM 4.8
50	Reduce HFC Leaks from Refrigeration	**1.2**	**9.0**	1	BFM 5.10
51	Increase Organic Farming	**4.4**	**8.9**	28	A 3.0
52	Maine Biodiesel	**5.5**	**5.5**	40	A 1.0
53	Low-GHG Fuel Infrastructure (CNG, LPG)	**0.4**	**2.0**	1,482	TLU 3.3
54	Nutrient Management	**1.8**	**1.8**	0	A 4.0
55	PV Buy Down Program	**0.1**	**0.2**	NE	BFM 5.6

The Department's decision to include these options was based primarily on the assessment of saved carbon, and accompanying costs. The recommended actions would, if all taken together and implemented, make significant progress toward the statutory 2010 emission reduction targets and would meet them by 2020. However, each one of them will require a separate plan of implementation, ranging from legislative action, rule-making or executive order, to encouraging voluntary activity on the part of Maine people, organizations, and businesses. Some options are presented in a manner that clearly identifies a specific approach to implementation, such as the adoption of a certain standard for construction materials.[6] Others will require additional study and planning to arrive at a robust, cost-effective, and publicly acceptable means to put in place the action(s) necessary to reduce emissions.

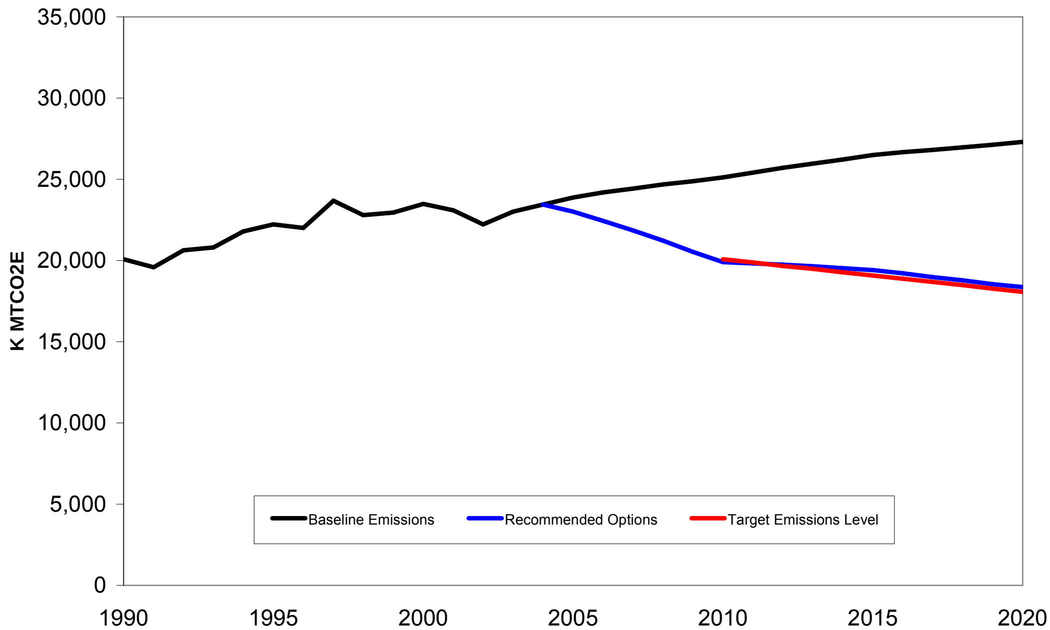
The stakeholder process of reviewing and recommending these options (and removing others from an original list) was carried out in a way that identified whether an action received consensus approval or not. At the June 30, 2004 meeting, Commissioner Gallagher concluded that all the options presented here, even when taken together, might not reach the statutory target. The Commissioner then determined that all should be preserved and presented here regardless of whether they achieved consensus.[7] When there was a lack of consensus at the Working Group or Stakeholder Advisory Group level, the detailed Option Descriptions on pp. 37 to 92 indicate that and delineate the reasons put forward by those who could and could not support the option. The complete Working Group reports in Appendix 5 identify more specifically those organizations unable to support a given recommendation.

When the 54 recommended options are summed, and compared to the forecast baseline and targets in Figure 1, the results are as follows:

[6] See Option 49.

In figure 2, the projected carbon savings are presented without considering the baseline

Figure 2: Emissions Baseline and Target without Black Carbon



forecast of the factor "black carbon."[8] In figure 3, the original baseline, as shown in figure 1, begins and ends at a higher point to account for this factor; correspondingly, the recommended options include mitigation Option #4, "Clean Diesel / Black Carbon," which would address this.

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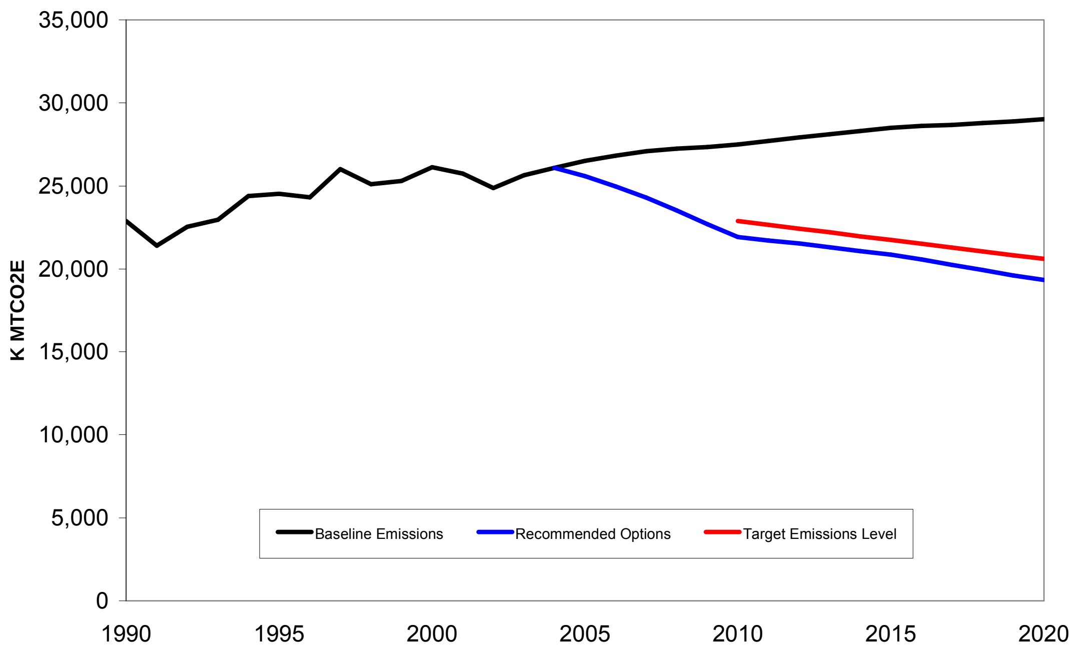
[7] Several additional forestry options, as well as the overall methodology for estimating GHG savings from the forestry sector resulting in additional GHG savings to help Maine meet the targets, were finalized subsequent to that Stakeholder meeting.

[8] Impact of Black Carbon has not been fully modeled for this reason information is presented with and without this factor. The impact of Black Carbon understood in the transportation sector is well understood, but has not been fully modeled in the other sectors. See Appendix 3.1, for a complete description of this factor.

Figure 3: Emissions Baseline and Target with Black Carbon



As can be seen above, carbon savings sufficient to meet the statutory goals can be attained if all these options are implemented. The savings exceed the goal by approximately 5% in the first calculation; and by approximately 12.5% if black carbon and its corresponding mitigation options are included. Moreover, the continuing trend downward approaching 2020 indicates that continuation of these options would produce additional reductions in subsequent years.[9] However, several cautionary notes are in order:

- The stakeholders' and DEP paid careful attention to using the best available data for modeling and calculation, but the data are subject to change. For instance, it was necessary to choose certain values for key variables such as economic growth which are sensitive over time (2005 to 2020, for example) to relatively small initial differences in assumptions, or to subsequent changes.
- Each of the recommended options contains assumptions about the "best case" for speed of implementation: that is, the option would be put in place and begin to save emissions as soon as possible given the technical requirements of the option. Each year of delay in implementing an option, for whatever reason, slows its impact. Since a number of the most important options are already expected to

[9] At present, the data are not sufficient to determine whether this downward slope would meet the eventual goal of eliminating danger to the climate.

take longer to implement than others, and several would require an extended period of time before their effects were fully realized, the actual timetable for implementation will have a direct effect on whether or not the projected carbon savings are realized by 2010 and 2020.

- Several of the options are presented as "principled goals": that is, stakeholders agreed on the numerical target for saved carbon for an option, without agreement as to appropriate implementation.[10] Forms of implementation different from those modeled are likely to produce different results.
- The CAP is a living document. The implementation plans for some options will need to identify appropriate measures, and how to gather the data needed for measurement. Since the statute specifies that the DEP shall report to the Legislature bi-annually on progress beginning in 2006,[11] the Department can identify and modify, if needed, measurement and savings data.

With these considerations in mind, particularly given the possibility that the options, either individually or in combination with others, may not save as much carbon as projected, *the Department is forwarding this Plan in the expectation that all the recommended mitigation options*, as well as others for which the analysis is not yet complete, *will be needed over time to meet the statutory targets.* As will be noted, several of the most significant recommendations depend on regional agreement and action, while others could be negatively affected by actions on the federal level or decisions made in other states.[12] As a consequence, we believe that adopting and implementing a combination of actions that exceeds the minimum statutory requirements is both prudent and desirable.

[10] For example, there was strong stakeholder support for the goals of Option #11, "Renewable Portfolio Standards" in terms to fostering growth in renewable energy production, but no consensus on whether or not this should be implemented by increasing the current RPS standard.
[11] 38 MRSA §578.
[12] See, *e.g.,* Options 2, 3, 6.

DISCUSSION

Overview: Cost Considerations

The enabling legislation calls for the *CAP* to "address reduction *in each sector* (emphasis added) in cost-effective ways…."[13] However, comparison with similar plans generated in other states, and discussion with the consultants, identified that these particular sectors do not lend themselves to discrete analysis for purposes of calculating carbon savings. Instead, the Stakeholder Advisory Group re-aligned the sectors into Energy and Solid Waste; Transportation and Land Use; Buildings, Facilities, and Manufacturing; and Agriculture and Forestry, with Working Groups for each. The resulting recommended Options do, however, identify which of the NEG/ECP sectors will be affected by implementation.

In Table 2, the 54 recommended Options are presented in order of cost effectiveness, beginning with those forecast to produce the highest cost savings. The "cost of saved carbon" is the *net* cost of the option: that is, cost of implementing the option minus avoided costs or offsetting gains.[14] In general, where the modeling or other analysis produced a range of potential costs dependent on a number of variables, the cost number in Table 2, and in the individual option descriptions, is the more *conservative* value: that is, the higher cost (or lower negative cost).

TABLE 2: OPTIONS RANKED BY COST

GW #	Measure (Sector)	KmtCO2 saved in 2010	KmtCO2 saved in 2020	Cost $/tCO2	Workgroup ID
36	Combined Heat and Power Incentive Policy	**86.0**	**38.0**	-185	ESW 1.8
19	Improve Electricial Efficiency:Commercial / Institutional	**181.9**	**250.8**	-139	BFM 3.8
26	Appliance Standards	**84.3**	**128.7**	-134	BFM 1.1
3	Regional Cap and Trade	**376.0**	**755.0**	-90	ESW 1.9b
37	Enforce Commercial Building Energy Code	**12.0**	**33.6**	-61	BFM 3.7
29	Increase Public Expenditures for Electrical Efficiency	**25.0**	**71.1**	-55	BFM 5.2
2	Implement Tailpipe GHG Emissions Standards	**137.5**	**933.6**	-48	TLU 1.1a
42	Voluntary Green Building Design Standards	**23.5**	**28.0**	-45	BFM 2.3
45	Energy Savings in State Buildings	**7.9**	**21.0**	-37	BFM 3.3
23	Fossil Fuel Efficiency Measures	**76.6**	**204.4**	-34	BFM 5.5
22	Electrical Efficiency Measures: Manufacturing	**156.5**	**207.2**	-30	BFM 4.1

[13] 38 MRSA §577, referencing the sectors in §574.2 identified by the NEG/ECP plan: transportation, industrial, commercial, institutional, and residential.
[14] For instance, the cost of implementing forestry management options that sequester carbon can be offset by revenues from sales of removed biomass.

48	Promote energy efficiency buildings	**4.3**	**11.3**	-19	BFM 3.2
40	Green Campus Initiatives	**11.0**	**29.8**	-18	BFM 3.6
35	Efficient Use of Oil and Gas: Home Heating	**29.3**	**39.1**	-6	BFM 2.6
14	Forestland Protection	**376.0**	**376.0**	-6	F 1.0 (A7.0)
32	Add ZEV Mandate to LEV II Standards	**0.0**	**53.0**	0	TLU 1.1b
47	Procurement Preference for Concrete Containing Slag	**18.0**	**18.0**	0	BFM 3.9
49	Specification C150 Portland Cement	**9.0**	**9.0**	0	BFM 4.8
54	Nutrient Management	**1.8**	**1.8**	0	A 4.0
21	Biomass Electricity Feedstocks	**228.4**	**228.4**	0	F 5.0 (A 6.1)
15	Recycling/ Source Reduction	**168.0**	**374.0**	0	ESW 2.3
31	Voluntary Partnerships and Recognition Programs	**34.5**	**57.5**	0	BFM 5.9
46	GHG Feebates (state or regional)	**3.8**	**18.8**	0	TLU 1.3b
16	Early Commercial Thin	**331.7**	**331.7**	1	F 3 (A5.2a)
10	Increased Stocking With Faster Growing Trees	**531.7**	**531.7**	1	F 2.0 (A 8.0)
50	Reduce HFC Leaks from Refrigeration	**1.2**	**9.0**	1	BFM 5.10
27	Landfill Gas Management: Flaring	**109.0**	**109.0**	2	ESW 2.1b
28	Active Softwood Increase	**73.2**	**73.2**	3	F 4 (A5.2e)
25	Expanded Use Of Wood Products	**129.8**	**129.8**	3	F 6 (A5.5)
20	Timber Harvest to Capture Anticipated Mortality	**239.5**	**239.5**	4	F 7 (A5.2b)
43	Waste-to-Energy	**24.0**	**24.0**	9	ESW 2.2
1	Offset Requirements	**365.0**	**1022.0**	10	ESW 1.12
11	Renewable Portfolio Standards	**247.0**	**527.0**	10	ESW 1.1
24	Low-GHG Fuel for State Fleets	**19.1**	**157.5**	10	TLU 3.2
44	Agricultural Land Protection	**15.9**	**22.7**	13	A 5.0
4	Clean Diesel/Black Carbon	**383.8**	**740.0**	14	TLU 8.1
8	Biomass Generation: Existing Units	**574.0**	**574.0**	15	ESW 1.5a
18	Biomass Restart Nonoperating Units	**269.0**	**269.0**	15	ESW 1.5a
38	Solar Hot Water Heater Program	**12.0**	**33.1**	16	BFM 5.7
7	Emission Standards	**484.0**	**609.0**	23	ESW 1.10
34	State Green Power Purchases	**31.0**	**45.0**	28	ESW 1.3
39	Soil Carbon Buildup	**15.4**	**31.0**	28	A 2.0
51	Increase Organic Farming	**4.4**	**8.9**	28	A 3.0
5	Renewable System Benefit Charge	**334.0**	**689.0**	30	ESW 1.2
6	Set a Low GHG Fuel Standard	**63.5**	**639.5**	34	TLU 3.1
30	Improve Residential Building Energy Codes	**24.7**	**64.1**	35	BFM 2.1
52	Maine Biodiesel	**5.5**	**5.5**	40	A 1.0
53	Low-GHG Fuel Infrastructure (CNG, LPG)	**0.4**	**2.0**	1,482	TLU 3.3
9	Landfill Gas Management: Energy Production	**210.0**	**550.0**	NE	ESW 2.1a
55	PV Buy Down Program	**0.1**	**0.2**	NE	BFM 5.6
33	Local Grown Produce	**34.9**	**52.1**	TBD	A 6.0
13	Pay as You Drive Insurance	**6.9**	**379.0**		TLU 2.4d
17	Slowing VMT Growth (TLU 2.2, TLU 2.3, unquantified measures in TLU 2.4)	**87.5**	**286.4**		TLU 2.0
41	Encourage Anti-Idling Measures: Freight	**12.0**	**29.7**		TLU 4.2d

Based on the current underlying assumptions, including those relating to economic growth and energy prices, it appears reasonable to estimate is that we can accomplish the 2020 goals at a net negative cost. *That is, if all the recommended options* *were implemented, the aggregate overall cost per unit of saved carbon would be less than zero.* It should be noted that these data, including cost estimates, are inherently uncertain, and depend on many variables such as population and economic growth projections, discount rates, etc. The data represent the best possible estimate of these uncertainties at the time the inventory is completed. The inventory will be reviewed, and modified when necessary, on a regular basis, so that the carbon and cost numbers are part of a living document. Any changes to these assumptions that emerge in the future will have the effect of altering either the projected carbon savings, or the cost characteristics of saved carbon, or both. The complete presentation and discussion of the assumptions which produced cost/savings numbers is found in the final reports of the Working Groups in Appendix 5.

Overview: Options by Working Group Sector

Energy and Solid Waste Options

These options focus on actions to be taken in the areas of electrical energy supply (generation) and solid waste management. The workgroup felt that whenever possible Maine specific data would be preferred. These were essential in two areas: 1) forecasting future electrical supply and demand; and 2) moving towards a consumption-based accounting system. The Stakeholder Advisory Group determined that the median economic forecast provided by Professor Charles Colgan should be used, although some stakeholders were concerned that the projected economic growth rates were too high.[15]

The discussion of the production/consumption issue concerned which methodology best represents Maine's electrical demand for greenhouse gas planning purposes. Although the workgroup favored a consumption-based approach it became clear that this could not easily be modeled. Two major problems are that 1) without a regional approach the possibility of leakage or double counting exists; and 2) that the current methods of collecting consumption data needed to be updated to serve this need. As discussed in Appendix 2.3, the CAP relies on a modified version of the production method, one using instate production figures, adjusted to reflect import and export trends during the period of the modeling. Over the longer term, the Workgroup and SAG believe it is in Maine's best interest to have a regional consumption-based approach adopted for future GHG accounting.

[15] See Appendix 2.1 for a complete description.

Buildings, Facilities, and Manufacturing Options

These options focus on actions to be taken in the commercial, residential and industrial building management and operation area; and in manufacturing processes. The workgroup concentrated on developing an inventory and baseline for residential, commercial, and industrial buildings and facilities that fairly represented the sectors. Workgroup members supplied facility numbers and other sources of data that replaced the initial baseline results with Maine-specific data to the greatest possible extent. The resulting options achieved a very high degree of consensus. The workgroup identified several areas of concern or modification as the CAP moves forward:

- Allowing facilities to use carbon intensity targets, which would allow them to increase production as long as the pollution *per* unit of production was reduced from current levels. The difficulty with this approach in the context of this *Plan* is that the legislative goal is based on absolute reduction targets. Since measured levels of GHGs could increase using this approach, the legislative dictate would potentially need to be changed.
- The discount rate for payback on investment was left unresolved. The workgroup thought that the discount rate should be different for each sector. While in the industrial sector a discount rate of less than one year is often expected, a 5 to 7 year payback is probably acceptable in the residential sector.
- Mechanisms to implement some of the options in this area are not specified, or would depend on funds for initial capital investment which are not presently identified. The Working Group recommends that the entities responsible for implementing these options take into account the pros and cons of each of the following mechanisms, including the effectiveness and political viability of each:
    1. Education;
    2. Recognition Programs;
    3. Financial Incentives;
    4. Mandatory Programs.

Transportation and Land Use Options

The interactive relationship between land use (siting of residential and commercial areas; managing growth, etc.) and transportation (vehicle use) suggested that these options be analyzed by the same Working Group. This sector represents the largest source of GHG pollution in Maine. The recommended options address actions to be taken by individual consumers, such as a Zero Emission Vehicle mandate and Feebates (Options 32 and 46) on the one hand; and land use strategies to reduce VMT growth on the other. As was true in the other workgroups, Maine-specific data were provided by the stakeholders to assure the truest possible picture of Maine's situation.

Workgroup members were concerned that any transportation option take market fairness into consideration. This fairness could be reached by making sure a regional approach was used to implement options, like Tailpipe Standards (Option 2) or Feebates. A regional approach would address issues such as boundary issues with close proximity states and special products for a relatively small market.

The transportation group discussed "black carbon" because current work on the subject will affect the diesel transportation segment. The group was concerned about making recommendations in this area without considering all black carbon-producing combustion sources and thus requested the Departments of Environmental Protection and Transportation to study the matter further.

Agriculture and Forestry Options

Because they were thought to represent management of natural resource areas, particularly as directed toward increasing carbon sequestration,[16] representatives of these interests shared the same Working Group. As time went on, however, it became clear that significantly different options applied to each. As a result, the Options are divided between five Agricultural options, and seven Forestry options.

As seen in Table 1, the forest sector presents significant opportunities for carbon savings through sequestration. Early in its analysis, the Agriculture and Forestry Working Group was surprised to discover that Maine's forests were currently emitting more carbon than was being taken up. Extensive analysis of data from Federal and State sources, combined with careful exploration of assumptions about, for example, the role of forest soils in the carbon cycle, brought the WG to the conclusion that certain forms of

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[16] §577, "The action plan…must allow sustainably managed forestry, agricultural and other natrual resource activities to be used to sequester greenhouse gas emissions."

active management already well-understood by the forest industry were capable of producing real carbon savings at very low or negligible cost.

Information about the carbon savings and costs for the Forestry options differs from all the others. The 2010 / 2020 template for setting carbon emission reductions, required by the statute and mirroring the NEG/ECP regional *Plan*, does not accurately account for the reality of a living system, Maine's forests. Thus, for example, a forestry management option to increase the sequestration of carbon that is put in place in 2005 might actually *increase* GHG emissions for the first ten years, but result in substantial carbon savings over the lifetime of the forest. After considering and comparing the calculations for carbon savings and costs over a 15-year span (2005-2020), and then a 95-year span (through 2100), the Working Group adopted a 58-year time horizon as best representing the life-span of a typical managed forest. In order to report data comparable with that for the non-forest options, the projected carbon savings were then "levelized": that is, total carbon savings over 58 years were averaged to an equal annual number for purposes of modeling. The Working Group and its technical advisors recognize that this is an artificial construct, but were agreed that it best represents the contribution of the forest sector to the long-term reduction of GHG emissions in Maine.[17]

Six of the recommended Forest sector options (10, 16, 20, 21, 25, 28) constitute an interactive package of forest management practices which primarily apply to Maine's large industrial and other actively managed woodlands. The options would improve silviculture to produce more and higher-quality wood as an important co-benefit. As can be seen, implementation of the options would depend primarily on voluntary actions by landowners, all of which would depend on a variety of incentives needed to increase markets. The modeling of the carbon savings and costs suggest the likelihood that, taken together, these options would be close to cost-neutral, and could produce new landowner revenue streams and/or cost savings over time. Since Maine's is the first Climate Action Plan in the United States to fully consider the forest carbon cycle and active management options as a significant part of the overall GHG mitigation effort, further research and modeling will be necessary as part of implementation planning.[18]

[17] For a fuller discussion of the process by which this standard was adopted, and its implications for the calculation of carbon savings and costs, see the Working Group report in Appendix 5.4.
[18] In 2004, the Maine Forest Service received a Federal grant to explore management options more fully, in order to identify which measures hold the greatest promise. An initial report is expected early in 2005.

Overview: Carbon Savings / Costs

As an aid to comparing the carbon savings and costs of the recommended actions, the following matrix may be helpful:

TABLE 3: DECISION / IMPLEMENTATION MATRIX

Number in ( ) is estimated $ per tonne of saved carbon

	> 200 KMT Carbon saved	**< 200 KMT Carbon saved**
Options costing less than -$20 per ton (saves money)	19: Commercial/institutional energy efficiency [BFM 3.8] **(-139)** 3: Regional Cap and Trade [ESW 1.9b] **(-90)** 2: Tailpipe GHG [TLU 1.1a] **(-48)** 23: Fossil fuel efficiency measures BFM 5.5] **(-34)** 22: Mfg. electrical efficiency [BFM 4.1] **(-30)**	36: CHP incentive policy [ESW 1.8] **(-185)** 26: Appliance standards [BFM1.1] **(-134)** 37: Commercial building energy code [BFM 3.7] **(-61)** 42: Voluntary green building standards [BFM 2.3] **(-45)** 29: Public expenditure elec. efficiency [BFM 5.2] **(-55)** 45: State buildings energy savings [BFM 3.3] **(-37)** 30: Residential building energy codes [BFM 2.1] **(-35)**
Options costing between -$20 and $0 per ton (saves money)	14: Forestland Protection [F 1.0] **(-6)** 21: Biomass electricity stocks [F 5.0] (**0**) 15: Recycling / source reduction ESW 2.3] **(0)**	48: Promote energy efficient buildings [BFM 3.2] **(-19)** 40: Green campus [BFM 3.6] **(-18)** 35: Home heating efficiency [BFM 2.6] **(-6)** 47: Slag concrete procurement preference [BFM3.9] **(0)** 49: Portland cement ASTM specification [BFM 4.8] **(0)** 54: Agriculture nutrient management [A 4.0] **(0)** 31: Voluntary partnerships [BFM 5.9] **(0)** 32: ZEV Mandate [TLU 1.1b] **(0)** 46: GHG vehicle feebates [TLU1.3b] **(0)**
Options costing more than $0 and less than $20 per ton	16: Early commercial thinning [F. 3.0] **(0 - 1)** 10: Increased stocking fast growth [F 2.0] **(1)** 20: Timber Harvesting [F 7.0] **(3.5)** 4: Clean diesel [TLU 8.1] **(6-14)** 1: Offset requirements [ESW 1.12] **(10)** 11: RPS [ESW 1.1] **(10)** 8, 18: Bio-mass re-start, subsidy [ESW 1.5a] **(15)**	41: Encourage freight anti-idling [TLU 4.2d] **(>0)** 50: Reduce HFC refrigeration leaks [BFM 5.10] **(1)** 27: Landfill methane flaring [ESW 2.1b] **(2)** 25: Expand wood products use [F 6.0] **(3)** 28: Softwood increase [F 4.0] **(3)** 43: Waste to energy [ESW 2.2] **(9)** 24: State fleet low GHG fuel [TLU 3.2] **(10)** 44: Agricultural land protectoin (**13**) 38: Solar hot water heater [BFM 5.7] **(16)**
Options costing more than $20 per ton	7: Emissions standards [ESW 1.10] **(23)** 5: System Benefit Charge [ESW 1.2] **(30)** 6: Low GHG fuel [TLU 3.1] **(34)**	39: Soil carbon buildup [A 2.0] **(28)** 51: Organic farming [A 3.0] **(28)** 34: State green power purchase [ESW 1.3] **(28)** 52: Promote Maine bio-diesel [A 1.0] **(40)** 53: Low GHG fuel infrastructure **(1482)**

Overview: Co-Benefits

Most of the recommended actions are expected to produce significant co-benefits *in addition to saving carbon*. Of particular significance are those will have a positive impact on human health, are likely to reward efficiency, and/or can be expected to promote economic growth and development. Many of these occur in the realm of air quality affecting human health, since lessening the emission of CO_2 from combustion of fossil fuels for electricity or transportation will also lead to reductions in other air pollutants. These include smog-producing sulfur and nitrogen oxide, and those fine particulates implicated in asthma and other respiratory diseases. Other co-benefits are expected to arise from the development of new technologies, particularly in the forestry sector, which in turn will produce additional economic benefits. Many of the electricity demand management options, such as energy efficiency measures, will save Maine people and businesses significant dollars, while contributing to Maine's energy security. Finally, a number of the options would work hand-in-hand with existing State policy goals such as forest and farmland protection. The Options are presented here in several categories of co-benefits:

TABLE 4: GHG OPTIONS SORTED BY CO-BENEFIT

Reduce Other Air Emissions: multiple benefits, especially human health	Economic Development, including new technologies, new markets for existing products, increase value of resources, etc.	Consumer, Business, Institutional, and/or Municipal Savings
2: Tailpipe GHG standards	1: Offset requirements	2: Tailpipe GHG standards
3: Regional cap & trade	5: Renewable SBC	12: Energy efficiency measures
4: Clean Diesel	6: Low GHG fuel standard	15: Recycling/ source reduction
6: Low GHG fuel standard	8: Biomass generation	19: Electrical efficiency of commercial buildings
7: Emission standards	10: Forest stocking increase	22: Mfg. Electrical efficiency
13: Pay as you drive insurance	11: Renewable portfolio	26: Appliance standards
17: Slowing VMT growth	16: Early forest thinning	30: Residential building codes
32: ZEV standards	20: Light forest harvest	35: Efficient home heat
41: Freight anti-idling	21: Biomass feedstocks	37: Commercial codes
46: GHG vehicle feebates	23: Fossil fuel efficiency	40: Green campus
53: Low GHG fuel infrastructure	25: Wood products use	41: Freight anti-idling
	28: Active softwood incr.	42: Green buildings
	38: Solar water rebate	45: State buildings
	42: Green building standards	47: Concrete with slag
	52: Bio-diesel	48: Energy efficient buildings
		49: Cement standards
		50: Reduce HFC leaks

Energy Security	Other
1: Offset requirements	9: Landfill methane: avoided landfill site odors
5: Renewable SBC	14: Forestland protection: habitat protection, sprawl reduction
11: Renewable portfolio standard	20: Regular light harvest: improved forest health
17: Slowing VMT growth	21: Biomass feedstocks
29: Electrical Efficiency invest.	33: Locally grown produce
34: Green power purchase	44: Agricultural land protection
52: Bio-diesel	51: Organic farming

Information about, and discussion of, co-benefits is presented qualitatively, since only some of them can be quantified. This is unfortunate, because in many cases the real cost savings to the economy are significant. Using one of the examples above, for instance, public health organizations point to significant savings in avoided health care costs and lost work time consequent on lessening the number of chronic health problems associated with air pollutants.

NEXT STEPS

In presenting this *Climate Action Plan,* the Department is aware that even if all the options are approved in principle by the Legislature and stakeholders, implementation will not be immediate or uniform. As previously noted, each of the options will have its own associated implementation steps. The different anticipated implementation approaches are summarized in Table 5.

TABLE 5: GHG OPTIONS BY TYPE OF IMPLEMENTATION

Legislation	Executive Order	Rule	Voluntary Action[19]
1, Offset Req. 6, Low GHG fuel 8, Biomass subsidy 11, RPS 26, Appliance standards 30, Residential building codes 37, Comm. energy codes 38, Solar water heat rebate 46, GHG feebates	24, Low GHG fuel, state fleets 34, State green power purchase 45, State buildings energy savings 47, Concrete procurement	2, Tailpipe GHG[20] 7, Emission Standard 9, 27 Landfill CH_4 32, ZEV 36, CHP incentives 49, Cement standards	9, 27 Landfill CH_4 10, Forest Stocking 13, PAYD Insurance 16, Early Comm. Thin 20, Forest Harvest 28, Softwood increase 31, Partnerships and recognition programs 39, Soil carbon 41, Anti-idling 42, Green building design 43, Waste to energy 48, Energy efficient buildings 50, HFC leaks

Regional or Federal Participation	Multi-part[21]	Enhance Existing Program
2, Tailpipe GHG 3, Cap and Trade 6, Low GHG fuels 24, Low GHG state fleet fuels 46, Feebates 49, Cement standards	4, Diesel/Carbon 5, SBC 14, Forest Protection 15, Recycling 17, Slow VMT growth 21, Biomass stocks 22, Manufacturing Energy Effic. 23, Fossil Fuel Efficiency 25, Wood products 33, Local produce 44, Farmland protection 51, Organic farming 52, Bio-diesel 53, Fuel infrastructure	19, Commercial / Institutional Energy Efficiency 29, Increase Electricity Efficiency Measures 35, Home heating 40, Green campus 54, Nutrient management 55, Solar PV

[19] "Voluntary Action" is assumed to require some combination of support activities such as educational programs; training; public outreach, etc. These activities may be eligible for offsets, market-based incentives, or use of SBC-type funding.
[20] Could be seen as a "major substantive" rule, requiring legislative action.
[21] Some combination of preceding approaches, including development of an implementation plan. May include incentive programs for which specific funding was not identified by SAG.

The implementation process overall will require several additional considerations. First, while the Department is confident that the data and assumptions used to calculate the forecast carbon savings and cost information are as refined as possible at this point, we are also aware that additional information, or more sophisticated analysis, is likely to change specific numbers. In addition, the final policy design and implementation strategy for each option may require changes to the projected carbon savings and cost estimates. Since we view the *CAP* as a continuing and living document, we will expect to modify the specifics as better information becomes available. The Legislature clearly had this in mind in the enabling legislation, which calls on the Department to "evaluate the State's progress toward meeting the reduction goals specified…and amend the action plan as necessary" by January 1, 2006, and every two years thereafter.[22] Beginning in 2008, the DEP may recommend that the reduction goals be increased or decreased. In order to meet this standard, some of the recommended options will need further determination of performance measures, and accompanying data gathering and analysis activities, as part of implementation.

Since many of the recommended options would have, when implemented, direct effects on individual citizens, institutions, organizations, and businesses in Maine, further efforts will be needed in the area of public education and outreach. Many of these options already identify key groups to engage in implementation, but the *Plan* as a whole must also be presented to the people of Maine. The Commissioner has asked the Education and Public Awareness Working Group to continue its work, in particular by planning and assisting the Department to offer one or more public sessions at which this *Climate Action Plan* can be presented to wider audiences. Maine citizens must be invited to join the effort to reduce Maine's GHG emissions through their individual choices and actions if Maine is to be successful in meeting the challenging goals set by statute.

As has been noted, Maine's actions will be taken, and should be understood, in the broader context of regional, national, and international activity. A number of the options that are most significant (in terms of potential for carbon reduction) either depend upon, or have effects that would be enhanced by, the actions of other jurisdictions.[23] The implementation and effectiveness of several others, particularly those involving the

[22] §578, "Progress evaluation."
[23] Chief among these are Options 2 (Tailpipe GHG Standards); 3 (Regional Cap and Trade); 4 (Clean Diesel/Black Carbon); 6 (Low GHG Fuel Standards); and 1 (Offsets) and 7 (Emission Standards) to the extent that these interact with Regional Cap and Trade.

development of, and demand for, renewable electricity supplies, will be affected by similar actions taking place in other New England states. Finally, the NEG/ECP jurisdictions have yet to agree on important items related to the long-term counting and crediting of emission reductions, particularly in the electricity sector, where agreed common assumptions would allow more accurate calculation of carbon savings and costs. It will be important for Maine to continue to lead these efforts.

The Report, as required by law, will be delivered to the Natural Resources committee of the Maine Legislature. The Department will bring to the attention of the legislature those proposed actions that require further legislative activity. While many of these would come under the jurisdiction of the Natural Resources committee, there are others that would likely be directed to other committees such as Utilities and Energy, or Transportation. The Department expects to ask the leadership of the 122nd Legislature, and the House and Senate chairs of the relevant committees, to appoint a group of legislators representing the committees. This group could be charged with reviewing the *CAP* and determining which of the recommended actions may require additional legislative action. It could then coordinate the process of moving the measures through the legislative process. It would also be asked to oversee implementation of aspects of the *CAP*, including the establishment of priorities for action.

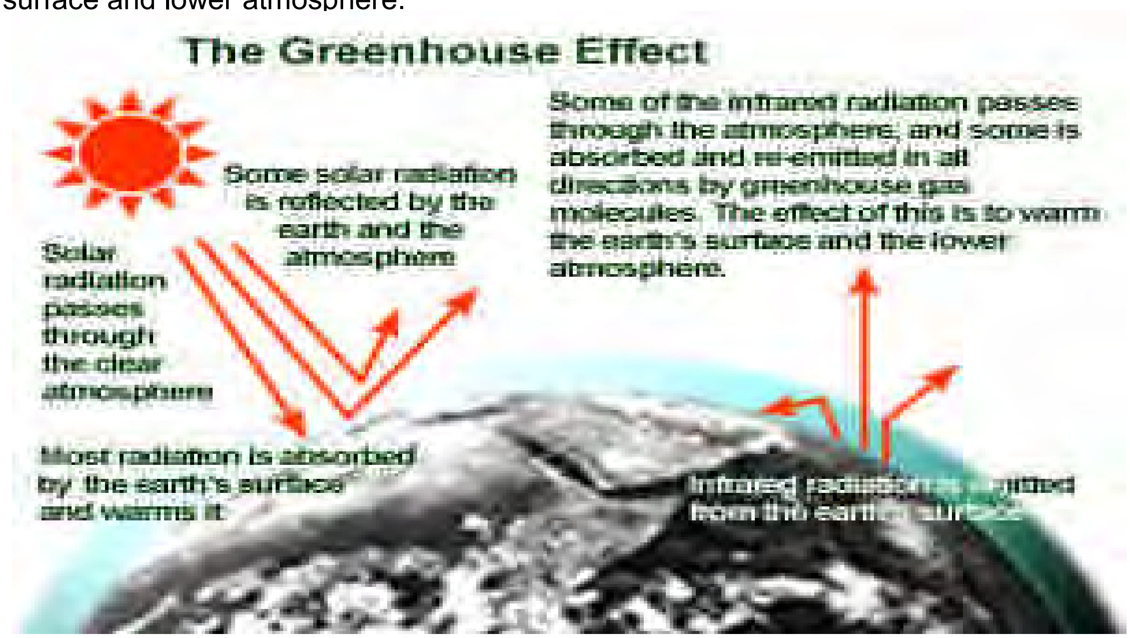
The *Plan* will also be delivered to the Office of the Governor. Some of the recommended actions, such as state purchases of renewable energy, are currently under way in the executive branch. The Department, or other appropriate agency, will continue to implement these measures. The Department will begin implementation of other actions for which it currently has authority. The Department will work with other executive branch agencies to implement recommended actions in their purview.

There are additional issues that may require additional work by the Department over the course of the next year. For example, the carbon status of biomass for purposes of the recommended actions is an issue that needs further clarification and definition before moving forward. The Department expects that the legislative group chosen to oversee the implementation of the *CAP* will provide input on how the legislature would like to see issues of this sort dealt with.

GREENHOUSE GASES AND THE PROBLEM OF GLOBAL CLIMATE CHANGE

The global climate system that produces local weather and seasonal change is a highly complex entity. It is by its nature highly variable: that is, small changes in factors such as Earth's orbital track around the sun or natural variation in the sun's intensity can have large consequences, including the advance and retreat of ice ages. Thus, until recently, studies of climate change focused primarily on natural causes and cycles.

Among the physical causes of climate change is the prevalence in the atmosphere of so-called "greenhouse gases (GHG)." These include naturally occurring components of terrestrial life such as water vapor, carbon dioxide, and methane; and human-made compounds such as SF_6.[24] As solar radiation passes through the clear atmosphere, most of it is absorbed by Earth's surface and warms it. Some is reflected by the earth and the atmosphere, and this infrared radiation passes back through the atmosphere. As it does so, a portion is absorbed and re-emitted in all directions by GHG molecules, just as the glass of a greenhouse maintains the heat created by the warming of the inside when the sun's rays pass through. The effect is further to warm the Earth's surface and lower atmosphere.[25]



[24] Sulfur hexaflouride, commonly used as an insulating compound in the electrical distribution system.
[25] Current understandings of climate science cannot easily be summarized in a *Report* such as this. A convenient website with the most comprehensive international reports on the causes and consequences of climate change is that of the Intergovernmental Panel on Climate Change, http://www.ipcc.ch.

While natural phenomena such as volcanic explosions can add significantly to the GHG in the atmosphere, the burning of fossil fuels, the clearing of forests, and other human interventions appear to be destabilizing the global climatic system which has been gradually changing (in this case, warming) since the end of the last Ice Age, about 12,000 years ago. This has been exacerbated in recent times, so that the United Nations Intergovernmental Panel on Climate Change (IPCC) concluded in its *Third Assessment Report* that "(t)here is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[26] To cite one of the most commonly used measures of change, atmospheric concentration of carbon dioxide (CO_2) has increased from a pre-industrial level of 280 parts *per* million (ppm) to the current level of 360 ppm, 31 *per cent* higher than the pre-industrial levels. Unless steps are taken to lessen further releases of GHGs, these levels are projected to increase to 450 ppm by 2025, and 550 ppm by 2050. The current level of CO_2 in the atmosphere has not been exceeded in the past 420,000 years, and probably not in the past 20 million years.[27]

Since CO_2 molecules persist in the atmosphere for more than a century, their effect on climate cannot be quickly halted or reversed. However, long-term climatic changes are difficult to predict with certainty because of the complexity of the climate system. The IPCC's increasingly sophisticated modeling results suggest that by 2100, the effects of climate change could include increased global average surface temperature of 2.5 to 10.4° F. This and other changes will not be evenly distributed over time or geography, and may include rapid and unexpected changes in temperature and water cycles.[28]

If no action is taken, the IPCC identifies as likely consequences some or all of the following:

- Increase in the incidence and severity of extreme weather events such as storms, droughts, floods, and heat waves;
- Rise in global sea level, including stresses on estuaries, bays, and wetlands;
- Changes in precipitation rates impacting water supplies and food production;
- Shifts in and/or expansion of certain disease and pest vectors; and
- Further stress on already vulnerable species and eco-systems.

[26] *Climate Change 2001: The Scientific Basis.* Report of Working Group I: Summary for Policy Makers. Cambridge, 2001: 10.
[27] *IPCC 2001*: 12.

All of these effects would be potentially profound for Maine's, and the Northeast's, natural resources in the areas of agriculture, forestry, and fisheries, as well as for human infrastructure, particularly in coastal regions.[29]

The anticipated human health effects of global climate change are profound, if less easy to quantify. Both the IPCC and World Health Organization have agreed that significant effects are likely. These include temperature-related illnesses and death; health effects related to extreme weather events; air pollution-related health problems; water- and food-borne diseases; and insect-borne diseases such as malaria, dengue, Lyme disease, and encephalitis.

In Maine, there is not yet evidence of significant warming, for reasons that are thus far unclear. However, there are already measurable changes in seasonal variation, and in patterns of precipitation, with particular impacts on groundwater, which can reasonably be associated with climate change.

Even in the face of uncertainties regarding the precise consequences to be expected from increasing levels of atmospheric CO_2, there has been increasing world-wide interest in taking steps to reverse the trend.[30] In 1992, the United States and other parties (187 countries to date) to the United Nations Framework Convention on Climate Change agreed to adopt the long-term goal of stabilizing GHG concentrations at a level that would prevent "dangerous anthropogenic interference" with the climate system. While the United States has thus far not ratified the 1997 Kyoto Protocol, which sets targets for the total quantity of GHGs that industrialized countries would be allowed to emit, a number of states and local jurisdictions have developed climate action plans centered on steps to be taken to lessen GHG emissions.[31]

In July 2000, the Conference of New England Governors and Eastern Canadian Premiers (NEG/ECP) adopted Resolution 25-9 on global warming and its impacts on the environment. The Conference recognized that global warming, given its harmful consequences to the environment and the economy, is a joint concern for which a regional ap-

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[28] *IPCC 2001*: 10.

[29] For an older but still useful summary of possible effects for Maine, see the 1998 EPA evaluation at http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BUT6R/$File/me_impct.pdf

[30] For a summary of these uncertainties, and associated policy implications, see David G. Victor, *Climate Change: Debating America's Policy Options* (NY: Council on Foreign Relations), 2004: 12-16.

proach to strategic action is required. Its Committee on the Environment was charged with presenting a summary of findings and a recommended action plan to the 2001 annual meeting of the NEG/ECP. The resulting NEG/ECPClimate Change Action Plan was subsequently ratified by each of the governors and premiers. Governor Angus King was a signatory to the Plan, and Maine's participation was subsequently endorsed by Governor John Baldacci. The plan

> (p)resents a set of near-term options for our region that would help protect the climate, reduce GHG emissions and other pollutants, cut energy demands, and promote future job growth by harnessing sustainable energy resources and advanced technologies. … By focusing on a set of concrete, achievable, near-term opportunities, we hope to demonstrate leadership and build a foundation from which more dramatic progress can be realized.[32]

The NEG/ECP *Plan* commits each member jurisdiction to participate in the achievement of regional goals which mirror those proposed in the UN Framework Convention and Kyoto Protocol, namely

- Reduce regional GHG emissions to 1990 levels by 2010;
- Reduce regional GHG emissions to at least 10% below 1990 levels by 2020; and
- Reduce regional GHG emissions sufficiently "to eliminate any dangerous threat to the climate" as a long-term goal, date unspecified.

Under the terms of the agreement, there will be varying approaches among the jurisdictions to achieving the regional goals, and an understanding that the targets might not be reached in equal measure by each jurisdiction.[33]

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[31] See Barry G. Rabe, *Statehouse and Greenhouse: The Emerging Politics of American Climate Change Policy* (Washington, D.C.: Brookings Institution), 2004.
[32] NEG/ECP *Climate Change Action Plan 2001*: 2.
[33] NEG/ECP *Plan*: 6-7.

MAINE'S POLICY RESPONSE TO THE CHALLENGE OF CLIMATE CHANGE

The Department of Environmental Protection issued its first report on GHGs in the *Maine's Greenhouse Gas Emissions Inventory for 1990.* The inventory, which was updated in 2000, is a "current, comprehensive listing, by source, of air pollutant emissions."[34] Such an inventory is necessary to establish baselines from which emissions reductions such as those called for in the subsequent legislation can be calculated. The Department has subsequently revised its Emission Statement Regulation (DEP Chapter 137) to include the reporting of GHGs for inclusion in the Emissions Inventory, making Maine the first jurisdiction in the region to mandate the reporting of GHG emissions.
In June 1998, the State Planning Office (SPO) released a draft report*, Responding to Global Climate Change and Achieving Greenhouse Gas Emission Reductions in Maine: Roles for Industry, Business, and Citizens*. The following April, a non-governmental organization, Maine Global Climate Change Inc., sponsored a two-day conference, "Global Climate Change in Maine – The Risks and Opportunities." Partly as a result of the conference, SPO then issued (January 2000) a State of Maine Climate Change Action Plan, which provided a menu of options for reducing the state's GHG emissions, but did not commit the State to specific actions. A number of the options in the SPO Climate Change Action Plan are, however, mirrored in the commitments and options for action in the NEG/ECP Plan.

The 2001 "Clean Government" initiative created a legislative mandate requiring, among other things, that state agencies incorporate environmentally sustainable practices into their planning, operations and regulatory functions. Many of the actions subsequently planned and adopted within Maine State Government directly or indirectly address GHG mitigation options, particularly in areas such as energy efficiency, building standards, and transportation fleet upgrades. This initiative precisely matches one of the action items set out in the NEG/ECP *Plan,* "Lead by Example," which commits the jurisdictions to meeting the goal of "reduc(ing) end-use emissions of GHGs through improved energy efficiency and lower carbon fuels within the public sector by 25% by 2012,…." By statute,[35] a similar target has been mandated for state buildings. To meet the re-

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[34] *On the Development of a Greenhouse Gas Emissions Inventory & Registry*. Report of the Joint Standing Committee on Natural Resources, Maine Legislature, January, 2002:1
[35] 5 MRSA § 1770, "Energy Conservation of Buildings," sets a goal of a 25% reduction in energy consumption relative to a 1998 baseline by 2010.

quirements of the Clean Government Initiative mandate, executive orders have been issued to all state government entities requiring:

- adherence to LEED building standards for all construction and renovation projects;
- procurement of fuel efficient and hybrid technology vehicles: and
- procurement of environmentally friendly goods and services.

Governors King and Baldacci have used their office to further these goals. In 2003, Governor King formally directed state agencies to pursue the purchase of low emission and more fuel-efficient vehicles. Governor Baldacci, by his March 17, 2004, Executive Order, built on his predecessor's action, ordering that state agencies:

- track state vehicle fleet fuel economy;
- track and develop plans to reduce state employee vehicle miles traveled (VMT);
- purchase and use cleaner and/or renewable fuels in state vehicles; and
- measure the GHG emissions from the state transportation sector.

To date, other state agencies have also been active in measures to reduce energy use, and thus, greenhouse gas emissions. The Department of Transportation has converted traffic lights at intersections in its span of control from conventional to LED (light emitting diode) lamps, and has made funds available to municipalities to promote similar conversion.

The Public Utilities Commission (PUC) has primary responsibility for managing state-led energy efficiency programs. The PUC's Energy Programs Division administers the State Energy Program, a United States Department of Energy funded effort whose goal is to promote energy efficiency and renewable energy. The PUC's Energy Programs Division also administers the Efficiency Maine program whose focus is to increase electrical energy efficiency throughout the Maine economy. Efficiency Maine was created to implement the legislature's Conservation Act and is funded through electric utility rates.

In the area of renewable electrical generation, Maine has been a significant national leader. Since 2000, Maine electricity producers have been required to meet a standard of 30% of all power coming from renewable sources. This is the highest such "renewable portfolio standard" in the United States.[36]

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[36] See below, Option 11 for further discussion. Recent efforts to increase over time the percentage of renewable energy in the RPS have been unsuccessful. For comparison with other states' efforts, see Rabe 2004: 53.

The 2003 State Legislature enacted L.D. 845, "An Act to Provide Leadership in Addressing the Threat of Climate Change," signed by Governor Baldacci on May 21 of that year.[37] It established State GHG emission goals identical to those of the NEG/ECP *Plan*, and directed the DEP to undertake two specific actions toward that end:

1. A group of "Lead by Example" initiatives, including:
   - emissions inventory for state facilities and programs;
   - voluntary carbon reduction agreements with private sector businesses and non-profit organizations;
   - participation in a regional GHG registry; and
   - establishment of an annual statewide GHG emissions inventory.
2. Adopt a state climate action plan "with input from stakeholders" to meet the reduction goals.

The present document is intended to meet that requirement.

The Department believes that the Climate Action Plan for Maine (proposed herein) builds on the foundation of the earlier SPO document and offers a comprehensive group of cost-effective actions needed to meet the statutory requirements. The 54 options create a solid policy basis on which to proceed toward the long-term reduction targets. This *Plan* also identifies significant co-benefits to mandated GHG emission reductions, including many that would promote innovation and economic development for Maine, support Maine's energy independence, have a positive impact on the health of Maine citizens, or all three.

The Department also believes that the title of the enabling legislation is particularly instructive. Since actual GHG emissions from Maine sources constitute a very small portion even of US national emissions, so that Maine ranks 43rd among the states,[38] actions taken within the state will have little direct impact on the global problem of GHG build-up in the atmosphere and resultant climate change. Instead, as suggested by "An Act to Provide *Leadership* …", the legislature recognized that in the absence, thus far, of Federal actions to address the threat of climate change, Maine's initiative, in company with those of other states and Canadian provinces in the region, would signal others as to the importance Maine people place on a healthy and sustainable environment.[39] From a policy point of view, this is acting on a "clean hands" basis: that Maine

[37] 38 MRSA §§ 574-578. See Appendix 1 for complete text.
[38] Rabe 2004: 2, citing USEPA inventories.
[39] This belief was affirmed in a lecture by Professor David Victor in Augusta on September 13, 2004. Victor pointed out in particular that Maine's leadership can provide powerful leverage on

cannot ask other states and nations to reduce GHG emissions until we have taken these steps ourselves.

both the Federal government, and the private sector, in developing long-term strategies and offering incentives for market-driven innovations to address climate change.

CLIMATE ACTION PLAN STAKEHOLDER PROCESS

As specified in the Legislation, the Department of Environmental Protection was charged with developing a *Climate Action Plan* (*CAP*) "with input from stakeholders." To that end, Commissioner Gallagher convened an informal advisory committee, the Climate Action Plan Convenors' group, to assist her in developing the stakeholder process. The group met for the first time on July 24, 2003.[40]

During the same period, the Department explored various options for assuring the technical and process expertise necessary to staff *CAP* development. After review of the parallel GHG/Climate plan processes in Rhode Island and Connecticut, and consultation with leaders in other states, the DEP entered into contracts (though the Muskie School of Public Service at the University of Southern Maine) with Raab Associates, Ltd., Boston, MA, for overall process coordination and facilitation; and with the Center for Clean Air Policy, Washington, D.C., and with Thomas D. Peterson, LLC, for technical consultation.[41] Raab Associates also developed a Web site dedicated to Maine's *CAP* process, on which background and working papers, *agendae* and meeting summaries, etc. were made available to stakeholders and the public.[42] All written materials developed during the process, or submitted by stakeholders for consideration, will be maintained on this site for the immediate future, since limitations of space precluded them from being included in the written *Appendix* to this report.

Using funds provided by the US Environmental Protection Agency, Raab Associates worked with the Convenors' Group and the DEP to design a stake-holder process which would produce the *CAP* called for by the Legislature. Commissioner Gallagher solicited interested participants through direct mail and an open invitation on the Web site. Ultimately, it was agreed that the process would best be served by a relatively small (30-35) group of "core" stakeholders representing the public sector, the private sector, and advocacy groups.[43]

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[40] Members included Rep. Ted Koffman; Wendy Porter, Interface Fabrics Group; Chris Hall, Maine Chamber and Business Alliance; Sue Jones, NRCM; and Pam Person, Coalition for Sensible Energy.

[41] Additional process facilitators Ann Gosline, Jonathan Reitman (Gosline, Reitman) and Jack Kartez (USM) were hired to support the Working Groups. CCAP sub-contracted modeling work, particularly in the electricity sector, to the Tellus Institute. Steve Winkelman, Karen Lawson and Matt Ogonowski of CCAP were the principal, and much-appreciated, technical consultants.

[42] http://maineghg.raabassociates.org/

[43] For lists of organizations and their representatives, see Appendix 5.2.

TABLE 6: STAKEHOLDER ADVISORY GROUP MEMBERSHIP

Government	Industry	NGO
Department of Agriculture	Dragon Products	The Chewonki Foundation
Department of Economic and Community Development	Florida Power and Light	Coalition for Sensible Energy
Department of Environmental Protection	Interface Fabrics Group	Environment Northeast
Department of Human Services: Bureau of Health	Industrial Energy Consumers Group	Maine Organic Farmers and Gardeners Association
Department of Conservation: Maine Forest Service	Independent Energy Producers of Maine	Maine Center for Economic Policy
Department of Transportation	J.D. Irving Corporation	Maine Lung Association
Office of Energy Independence and Security	Maine Automobile Dealers Association	Maine Public Health Association
Public Utilities Commission	Maine Better Transportation Association	Natural Resources Council of Maine
The University of Maine	Maine Chamber & Business Alliance	Maine Council of Churches
Androscoggin Valley Council of Governments	Maine Farm Bureau	The Nature Conservancy
Legislators *ex officio* 1. Sen. Tom Sawyer 2. Rep. Bob Daigle 3. Sen. Chris Hall 4. Rep. Ted Koffman	Maine Oil Dealers Association	Prof. Robert Kates, resource panel Co-chair, *ex officio*
	Maine Pulp & Paper Association	Karl Braithwaite, Dean, Muskie School, resource panel Co-chair, *ex officio*

Four representatives of the State Legislature were invited to serve *ex officio.* This group, named the Stakeholder Advisory Group (SAG), would assist the DEP to set general direction and review recommendations for mitigation options. Members of the SAG, supplemented by additional stakeholder representatives, also served on Working Groups charged with closer investigation of options in each of four general areas:

1. Transportation and Land Use;
2. Buildings, Facilities, and Manufacturing;
3. Energy and Solid Waste; and

4. Agriculture and Forestry.[44]

A fifth Working Group, Outreach and Public Awareness, was convened later in the process.

Commissioner Gallagher also invited distinguished representatives of Maine's academic community to serve on a technical and scientific advisory panel, co-convened by Dr. Robert Kates, a member of the Intergovernmental Panel on Climate Change, and Dean Karl Braithwaite of the Muskie School. Members of the group were to be available on an as-needed basis to provide second-party review of economic, scientific, technical or policy issues. While a number of members did contribute in this way, special note should be made of the participation of: Professors Charles Colgan, Muskie School, USM, and Tom Tietenberg, Colby College, who were particularly helpful in providing economic forecast data needed in order to model emissions over time; Jonathan Rubin, University of Maine, on the Transportation and Land Use Working Group; and Mark Battle, Bowdoin College, and Ivan Fernandez, University of Maine, for their service on the Agriculture and Forestry Working Group;. In addition, Jim Smith of the U.S. Forest Service provided invaluable assistance during the modeling of the forestry sector options.

In preparation for an initial meeting of the SAG, Raab Associates conducted interviews with a number of potential participants to identify key issues to be considered in designing the process. The Convenors' Group also assisted in drafting ground rules that would guide subsequent activities.[45]

The Stakeholder Advisory Group met for the first time on November 6, 2003, at the Chewonki Foundation in Wiscasset, where Governor John E. Baldacci gave it an initial charge. Commissioner Gallagher made clear that the stakeholders' primary mission was to advise the Department in identifying a suite of mitigation options which, taken together, would meet the 2010 and 2020 GHG emission reduction targets. The Department retained ultimate decision-making responsibility for the *CAP* and its recommendations. The SAG first reviewed the goals, missions and objectives of the process, and held an initial discussion of the forecast emissions baseline for Maine GHG emissions. They also agreed on the ground rules governing their activities. At a second

[44] Final reports from each Working Group, together with attendance lists and select working papers, may be found in Appendix 5.

meeting, in December, the SAG reviewed an extensive list of possible options gathered from a wide range of sources, and identified those it thought worthy of further consideration to be forwarded to the Working Groups. The SAG met on three further occasions, concluding its work on September 29, 2004 with a final review of the draft proposed *CAP.*

The four primary Working Groups each met for three or four day-long meetings (supplemented with conference calls and sub-committee work) to identify options in specific areas, working with consultants to assure that basic assumptions governing each option were agreed in advance. Some of the options in each group were based on existing activities or programs in Maine, while others were completely new. For each option, the Working Groups were presented with information describing the action to be taken, the GHG reductions associated with the option's impact, and the option's overall costs, savings, and potential co-benefits where available. Each option was then modeled for its behavior over time. The working Groups presented the options to the SAG in the form of reports identifying the extent of agreement / consensus in recommending a given option, together with additional thoughts and concerns regarding each. It should be noted that there was no requirement that an option reach consensus or majority approval in order to be passed on to the SAG, although in most cases, options not receiving at least majority approval were dropped from the list, or deferred for further study. In a number of cases, sub-committees and individuals within the Working Groups prepared white papers on specific topics; several of these are included in the Appendices.

Beginning in May 2004, an additional Working Group, "Education and Public Awareness," met on several occasions to identify a strategy for making the *CAP* accessible to the legislature and the general public. They also evaluated the individual mitigation options in terms of their impact on affected groups, likely co-benefits, and public components. Their analysis is included in the description of each mitigation option. The Department expects that this group may be re-convened during 2004-2005 to assist in public outreach efforts associated with the implementation of this *Plan.*

[45] The Ground Rules, together with other documents related to the work of the SAG, may be found in Appendix 4.1.

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PART 2: DETAILED OPTION DESCRIPTIONS

Introduction

Based on consideration of a list of potential GHG mitigation options originally presented to the Stakeholder Advisory Group in December, 2003, each of the four Working Groups (Transportation and Land Use; Buildings, Facilities, and Manufacturing; Energy and Solid Waste; Agriculture and Forestry) worked with the technical consultants to identify and refine those options which appeared to have the greatest potential for cost-effective carbon savings. Each of those recommended by DEP for possible adoption, or suggested for additional study and modeling, is summarized in the following pages. More extensive information about the assumptions underlying the calculations of cost, carbon benefit, etc., may be found in the Appendix volume, where the complete final reports of the Working Groups are printed.

The GHG mitigation options are designed to change technologies and practices in ways that reduce the emission of GHGs to the atmosphere. Each option sets out a key strategy that would need to be refined and specified further at the level of state implementation. Some policy approaches are broad, affecting many processes and technologies, while others are more specific.

The 54 (options included in Group I below are arranged in the same order as found in Table 1 (“Summary Table of Recommended Options”) on page ##; that is, from highest to lowest in terms of estimated 2020 carbon savings. While the Working Group and Stakeholder Advisory Group processes identified some options as having reached consensus (defined as unanimous support), and others for which consensus was not reached, Commissioner Gallagher determined at the June 30, 2003, meeting that since all the modeled options taken together were not at that time projected to reach the legislative targets, the Department’s *CAP* would include these without distinction.[46]

Even if all options taken together met the targets, it would be imprudent not to pursue most or all of them. Some benefits come after 2020 (especially for some of the Forestry options); the assumptions behind the expected reductions are likely to change when and if each option’s design is finalized and it is implemented; and most impor-

[46] Each option summary includes identification of consensus or its absence. Where a summary is silent, consensus is assumed. The complete Working Group reports in Appendix 5 identify more specifically the organizations that did not agree with a particular recommendation, as required by the agreed Groundrules.

tantly, there will likely be many unexpected delays causing the options to be implemented later than planned.

The characterization of each option contains a number of key measures or indicators:

- **The reduction in emission of carbon to the atmosphere in 2020.** This indicates the total impact in 2020 as a result of implementing all the measures from 2005 (or later) and on through 2020, expressed in thousands of metric tons of carbon dioxide equivalent.

- **The cost *per* unit of saved carbon** is the *net cost* of the option (cost of saved carbon minus avoided costs) divided by the carbon reductions for the option. The costs and carbon reductions are computed through a discounted cash flow and "carbon flow" analysis over the 15-year time period.[47] There are many options (largely energy efficiency and demand reduction in buildings, facilities, and transportation) that result in *net savings* (*i.e.*, avoided costs from saved energy or other resources are greater than the cost of implementing the measure). Thus, this cost can be a negative number, indicating a very promising option that reduces carbon emissions and saves money.

- **Performance measures** are quantitative or qualitative metrics that can be used to monitor the effectiveness of the option once implemented.

- **Implementation method(s)** vary widely among options. If implementing an option would require legislative or regulatory action, or State Executive order, it is indicated here.

- **Co-benefits** are defined as the results from implementing an option which produce a benefit in addition to reducing carbon emissions. For instance, many of the recommended actions would also decrease emission of other air pollutants with significant human health effects such as fine particulate matter and air toxics. Other co-benefits and side effects, such as the potential for economic development, are more difficult to quantify and are here described qualitatively.

For many of the options, additional notes below the summary provide general background and further details about the option, including information on specific comments made by Stakeholders in working group or SAG meetings.

The 54 options in Group 1 constitute the core of the DEP's recommendations to meet the 2010 and 2020 emissions mitigation goal, *i.e.,* a level of Maine GHG emissions

[47] As explained in further detail in the Forestry Working Group report (Appendix x), the carbon savings and costs for the forestry options have been calculated using a 58-year time horizon (approximately through 2063) instead of the 15-year time period utilized for all other options. The Working Group agreed on this approach as better representing the real life cycle of the forest.

no greater than 10% below those emitted in 1990.[48] As noted above, not all of these are proposed on the basis of consensus by the Stakeholders to the *CAP*. They have in common that the technical consultants and Stakeholders were generally agreed on the assumptions underlying the calculation of carbon to be saved if the option were to be implemented as described, and these calculations have produced a "saved carbon" number. If all of them were implemented, they would, taken together, produce 11,332,617 metric tons of projected carbon savings, slightly exceeding the reductions needed to meet the statutory target.

A few options, most notably that related to so-called "black carbon" (4), clearly require a greater depth of understanding of both technical and policy implications than could be achieved in time for complete stakeholder review. Others (5, 11) are noted as having been approved in principle by stakeholders, but which there were differences of opinion about the details of implementation. These will require additional research, technical modeling and policy consideration. The Department will make every effort, within resource constraints, to complete the evaluation of these options in consultation with stakeholders.

Some options (2, 3, 6, 46, 49) would either require a regional or multi-jurisdictional approach to be implemented, or at least would be most effective if implemented in a broader context.

The 40+ options in Group 2 ("Non-quantified Options") are briefly identified as those potential emissions mitigation actions which seemed particularly promising to the stakeholders and the DEP, but for which at the moment the data, particularly the calculation of amounts of saved carbon and/or cost of saved carbon, are incomplete. Others in this group identify actions to educate and inform specific groups and the public at large about greenhouse gas issues. These options will be studied further in the immediate future, and included in updates to the present *CAP*. In cases where the Department would be able to begin implementation of such an option on its own authority, it would be likely to do so. This group also includes additional options that have been presented by stakeholders, or identified by the Department, since the June 30, 2003 SAG meeting at which a final list was presented. Since these have not been subjected to the same analysis and review process as those in Group1, the Commissioner did not wish to include them in the list of primary recommendations.

[48] Unless otherwise specified, the calculation of carbon savings assumes that a given option is implemented in 2005. In many cases, time is allowed for the effects of an activity to be fully real-

Several of the non-quantified options identify state actions necessary to the implementation of the Group 1 options. These items would not by themselves produce carbon savings, so they are not included in Table 1. However, they were identified by stakeholders as part of the critical path forward. Briefly, they are

- *Inter-connection Rules and Transmission Barriers* (ESW 1.11);[49]
- *GHG Registry* (ESW 1.13);[50]
- *Public Education* (ESW 1.14); and
- *Improve GHG Data Collection* (TLU 7.2).

The table of Additional Options provides additional information about each of these.

For each of the Group I options, the title is followed by an indication of the option's comparative ranking with others in two categories: anticipated carbon savings, and cost effectiveness. These indicators are derived from the information in Table 2, where options are grouped in a 4x2 matrix. This information is presented as follows:

Carbon Savings Potential

High = expected carbon savings of more than 200 KMT annually in 2020;
Moderate = expected carbon savings between 25 and 200 KMT in 2020.
Low = expected annual carbon savings less than 25 KMT in 2020.

Savings / Costs

High Savings = cost savings of $20 or more *per* KMT saved in 2020;
Low Savings = cost savings of $0 to $20 *per* KMT saved in 2020.
Neutral = no identifiable costs or cost savings
Lower Costs = costs of $0 - $20 *per* KMT saved in 2020; and
Higher Costs = costs of $20 or more *per* KMT saved in 2020.

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ized, and for cumulative effects.
[49] This Option would directly influence the implementation of Options 9, 18, 27, and 36.
[50] Participation in a New England regional registry is called for in §575.3 of the statute.

OPTION #1-- Offset Requirements

Carbon Savings Potential: High

Costs / savings: Low cost

Category	Description
Working group	Electricity and Solid Waste 1.12
Option name	Offset Requirements
Sector(s)	Electricity
Policy / program elements	Requirement to offset a given percentage of CO_2 emissions through projects that reduce emissions indirectly, such as forest management practices in Options 16, 20 *et al.*; new renewable energy projects, or incremental energy efficiency projects.[51]
Rationale	Provides a way to ensure no net increase in emissions from new generation sources. May also provide a means for existing sources to offset emissions in addition to savings achieved through regional cap and trade (Option 3).
Existing policy/program	None
Significant co-benefits	Provides opportunities for increasing development or market penetration of renewable capacity.
Carbon saved 2020	1022.0 (without Option #3) (549.3 in conjunction with Option#3)
Cost *per* unit saved carbon	10[52]
Performance measure	
Implementation method(s)	Could require legislative action.
Implementation / outreach considerations	May be used in conjunction with a GHG cap and trade program or an emission standard (see 3 and 7). The utility of this option for the state could be affected by the potential adoption of a regional or national GHG reduction program in the future. Under such a plan, the state might not receive credit for offsets required by the state government.

Most Stakeholders agreed that Emission Standards and Offset Requirements should be included in the plan if they are not duplicative with the Regional Greenhouse Gas Initiative (RGGI), or if RGGI does not happen. Others could not support these two options without more information or wanted the numbers re-analyzed to ensure they were actually incremental to RGGI. These could be applied to non-electricity generation facilities, but stakeholders noted concerns over market fairness issues.

As noted above in Figure 1,[53] the consolidated options calculations only include the incremental difference between what RGGI would accomplish, and the additional savings from this and Option #7.

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[51] The types of renewable generation ultimately utilized could change the costs *per* unit of saved carbon.

[52] This number was calculated on the assumption that the option would be implemented in its entirety. Should Option 3 be implemented, it's not presently known whether the cost of achieving the marginal difference would be higher or lower.

[53] Above, p. 3.

OPTION #2 -- Tailpipe GHG Emissions Standards

Carbon Savings Potential: High

Costs / savings: High savings

Category	Description
Working group	Transportation and Land Use 1.1a
Option name	*Implement Tailpipe GHG Emissions Standards*
Sector(s)	Transportation: Vehicle Technologies
Policy / program elements	Adopt California GHG tailpipe standards for passenger vehicles. [54]
Rationale	Advances in vehicle technology offer significant opportunities to reduce GHG emissions from motor vehicles.
Existing policy/program	None at present
Significant co-benefits	Improved vehicle GHG performance is matched by reductions in other pollutant emissions, and reduces consumer fuel expenditures.
Carbon saved 2020	933.6
Cost *per* unit saved carbon	-48
Performance measure	Numbers of vehicles meeting the standard sold in Maine.
Implementation method(s)	Maine could propose amending Chapter 127 to include the new CARB regulation.
Implementation / outreach considerations	California GHG tailpipe standards are likely to face legal challenge from automakers on the basis that vehicle CO_2 regulation is preempted by federal fuel economy regulation. New York, Massachusetts, Connecticut and Rhode Island have indicated an interest in implementing the California motor vehicle GHG standards once finalized.

It is important to reduce vehicle GHG emissions rates in the short term because significant vehicle-fleet turnover and associated GHG savings can take a decade or more. This measure serves as a crucial complement to VMT reduction measures (see 17). This measure would follow California's lead on regulating emissions from new light-duty vehicles, which, according to the Clean Air Act, Maine can do. The measure produces cost savings based on the assumption that any vehicle meeting the emission standard would be significantly more fuel efficient than other vehicles, thus saving money for consumers over the operating life of the vehicle.

The Working Group was divided over this measure. Supporters noted that Maine would join other states, New York, Massachusetts and Connecticut, in the region that have in-

[54] On September 24, 2004, the California Air Resources Board (CARB) unanimously voted to direct automakers to reduce automobile CO_2 emissions starting with 2009 models of cars and light trucks and large trucks and minivans. The rule requires a 30% reduction in CO_2 by 2016. If there are no legislative changes, the regulation will take effect in 2006.

dicated interest in adopting CA GHG standards, once finalized.[55] Opponents expressed concerns that Maine's market share is too small to influence the market, about competitiveness impacts in Maine, and about potential legal exposure for the State, and were unable to support the measure in the SAG.

At the June 30 meeting of the Stakeholder Advisory Group, there was significant support to "wait and see" how the CA standards are defined and the outcome of the likely lawsuit in CA. All SAG members except one supported one of the alternatives explored, *viz.*, a "trigger" mechanism where Maine would adopt the standards after a certain number of other states in the northeast region did.

[55] In addition to Maine, New York, Massachusetts, and Vermont, three additional states, Connecticut, Rhode Island, and New Jersey, have recently adopted the LEV 2 tailpipe emission standards.

OPTION # 3-- Regional Cap and Trade

Carbon Savings Potential: High Costs / savings: High savings

Category	Description
Working group	Electricity and Solid Waste 1.9
Option name	Regional Cap and Trade
Sector(s)	Electricity
Policy / program elements	Set a mandatory cap on the amount of CO_2 emitted by the electricity generation sector. Reductions in emissions below cap levels result in tradable credits. Entities polluting at levels higher than permitted by the cap are required to purchase these emission credits. This option shows the impact of a cap and trade program in New York and six New England states. The regional CO2 emission cap was set at 25% below 1990 levels for New York in 2010, plus 1990 levels for New England in 2010.
Rationale	Market based emission reduction strategy
Existing policy/program	SO_2 and NOx trading programs
Significant co-benefits	Avoids other pollutant emission
Carbon saved 2020	755.0
Cost *per* unit saved carbon	-90
Performance measure	NA
Implementation method(s)	Regional RGGI Initiative
Implementation / outreach considerations	If implemented, would displace the need for some of the savings proposed in Options 1 and 7.

Cap and Trade is a market based policy tool for protecting human health and the environment. A cap and trade program first sets a cap, or maximum limit, on emissions. Sources covered by the program then receive authorizations to emit in the form of emissions allowances, with the total amount of allowances limited by the cap. Each source can design its own compliance strategy to meet the overall reduction requirement, including sale or purchase of allowances, installation of pollution controls, implementation of efficiently measures, among other options. Individual control requirements are not specified under a cap and trade program, but each emissions source must surrender allowances equal to its actual emissions in order to comply. Sources must also completely and accurately measure and report all emissions in a timely manner to guarantee that the overall cap is achieved.

Maine is currently involved in a Regional Greenhouse Gas Initiative (RGGI) with six New England States, NY, NJ, and Delaware. Model design and projected savings and costs should be available in 2005. Previous modeling of six New England states plus NY showed significant potential savings.

Carbon reductions and the cost estimates in this document will change based on the final design of the RGGI program. ICF Consulting's IPM model was used to estimate the impact of a cap and trade program in New York and six New England states. The regional CO_2 emission cap was set at 25% below 1990 levels for New York in 2010, plus 1990 levels for New England in 2010.

OPTION # 4-- Clean Diesel Technologies to Reduce Black Carbon

Carbon Savings Potential: High Costs / Savings: Low cost

Category	Description
Working group	Transportation and Land Use 8.1
Option name	Clean Diesel Technologies to Reduce Black Carbon
Sector(s)	Transportation
Policy / program elements	This program would accelerate the use of lower sulfur diesel and provide incentives to accelerate adoption of engine improvements and tailpipe control technology to reduce emissions of black carbon.
Rationale	Scientists have identified black carbon, a component of diesel particulate matter (PM), as having a large and fast-acting warming impact on the atmosphere.[56, 57] While there is still significant uncertainty on the exact climate impacts of black carbon emissions, the Working Group decided that the issue is worth serious consideration given the magnitude of the potential impact.
Existing policy/program	Clean School Bus USA Grant is funding diesel oxidation catalysts retrofits for 266 Maine school buses.
Significant co-benefits	Air quality improvements (particulate and toxics reductions), resulting in positive health effects.
Carbon saved 2020	740.0
Cost per unit saved carbon	14
Performance measure	Currently set for further study
Implementation method(s)	Would require definition of Best Available Control Technology (BACT) by vehicle type, vintage, duty cycle to promote appropriate use of fuels and new or retrofitted engines. Needs further study to identify a mixture of potential actions. Would likely require legislative action to establish standards, timelines, etc.
Implementation / outreach considerations	Dependent on availability of support funding for fleets to retrofit or replace. Maine's largest diesel fleet is the school buses, second largest is Maine DOT. For these sources the added expense would be a significant burden unless it could be supported by an offsets/trading funding mechanism.

Diesel engines emit roughly half of the black carbon in the United States. This option was recommended for further study by the working group, a position endorsed by the

[56] James Hansen and Larissa Nazarenko, "Soot climate forcing via snow and ice albedos," *Proceedings of the National Academy of Sciences*, vol. 101, no. 2, 423-428, January 2004.
[57] Mark Z. Jacobson, "Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming," *Journal of Geophysical Research*, Vol.107, No.D19, p. ACH 16, 1-22, 2002.

SAG. There was consensus to approve the option if it was modified to include only the following:

- Gather statewide data on heavy-duty mobile diesel engines and emissions;
- Establish working group to analyze: data, fuel issues, emission control technologies, costs, benefits, opportunities, case studies, pilot projects;
- Develop recommendations for a Maine Clean Diesel Program;
- Regional initiatives – Recommend to the NEG-ECP that bi-national black carbon emissions be studied and considered for inclusion in the GHG inventories and baselines.
- Federal initiatives – Work with its federal delegation and EPA to increase funding for diesel retrofit programs, with particular focus on trans-boundary and international diesel sources (marine, interstate trucking).

The Working Group was divided on how to implement this option, and what incentives should be provided, which will affect cost and carbon savings. The Department has included this in the list of recommended options because of the large potential GHG savings associated with it. DEP understands that further effort will be required to develop implementation approaches, particularly because the exact impacts of black carbon remain the subject of ongoing research and analysis.

OPTION #5 – Renewable Energy System Benefit Charge (SBC)

Carbon Savings Potential: High *Costs / savings: Higher costs*

Category	Description
Working group	Electricity and Solid Waste 1.2
Option name	*Renewable Energy System Benefit Charge (SBC)*
Sector(s)	Electricity supply and demand side green power purchases
Policy / program elements	Under a system benefit charge program, the state would collect funding as a charge on electricity rates or as a lump-sum payment from utilities, and then redistribute the money to projects such as wind farms, fuel cell deployment programs, and solar energy systems.[58]
Rationale	Reduce emissions of carbon and other air pollutants by promoting increased use of renewables.
Existing policy/program	Consumers may make voluntary contributions to an R&D fund for renewable resources when paying their electric bills
Significant co-benefits	Increase security of state's energy supply; economic development impetus for emerging technologies which could be eligible for funding.
Carbon saved 2020	689.0
Cost *per* unit saved carbon	30[59]
Performance measure	
Implementation method(s)	
Implementation / outreach considerations	An SBC funds the same categories of units as the RPS, or it can be structured to fund other categories of renewables that would not overlap with an RPS, or both. For purposes of this analysis it has been modeled to fund the same renewables as the RPS, but only the reductions from the RPS itself have been included in the reduction totals to avoid overlap.

No specific mechanism for funding an SBC was proposed by the Working Group or Stakeholder Advisory Group.

Some Stakeholders suggested that the SBC may not necessary if it is redundant with the RPS, but no one disagreed with the Working Group recommendations to estimate the range of GHG savings and cost of saved carbon for using the SBC to support an RPS or to support emerging technologies not covered by the RPS.

[58] The present modeling assumes annual funding for each category is allocated at the following levels:

Wind: 45% of total funding

Landfill Gas: 45% of total funding

Solar: 10% of total funding

[59] System benefit charge set at $0.0005 / kWh, based on Massachusetts level.

OPTION # 6-- Set a Low-GHG Fuel Standard

Carbon Savings Potential: High Costs / savings: Higher costs

Category	Description
Working group	Transportation and Land Use 3.1
Option name	*Set a Low-GHG Fuel Standard*
Sector(s)	Transportation
Policy / program elements	Require minimum low-GHG fuel content in all fuel sold in the state
Rationale	Reduce dependence on gasoline, reduce GHG emissions
Existing policy/program	None at present
Significant co-benefits	Reduce local air pollution; increase energy security. Some economic development may ensue as resources move to the ethanol/bio-diesel infrastructure, particularly feedstock from Aroostook county and other agriculture / waste wood areas.
Carbon saved 2020	639.5
Cost *per* unit saved carbon	34
Performance measure	Sales of substitute fuels
Implementation method(s)	Requires legislative authority. Likely to be part of a larger regional effort.
Implementation / outreach considerations	There are significant infrastructure changes to be considered as part of this measure. There is the potential for a border issue with New Hampshire if a regional approach is not adopted

This measure would mandate the substitution of E-10 (ethanol) for a progressively increasing volume of gasoline; and a comparable substitution of B-5 (bio-diesel) for diesel fuel. The goal would be 100% of all fuels by 2020.

Opinions on this option were divided. Some stakeholders preferred passage of a Federal renewable fuel standard, or at least as part of a regional approach initiated through the Northeast States Consolidated Air Use Management organization. Several state agencies noted that they did not have explicit authority to support this measure. Opponents expressed concerns about supply, distribution and price volatility.

All representatives to the SAG could support this measure if adopted regionally, but were not in agreement if implementation was limited to Maine. The SAG also unanimously supported federal renewable fuel standards.

OPTION 7 -- ESW 1.10 Emission Standards

Carbon Savings Potential: High

Costs / savings: Higher cost

Category	Description
Working group	Electricity and Solid Waste 1.10
Option name	*Emission Standards for Electricity Generation*
Sector(s)	Electricity
Policy / program elements	Output-based emission standard (emission limit) for CO_2 is applied to all fossil-fired plants in Maine (both new and existing units) beginning in 2008.
Rationale	Sets specific limits on GHG emissions.
Existing policy/program	None at present.
Significant co-benefits	Health and eco-system benefits associated with overall lessening of air emissions.
Carbon saved 2020	609.0 (without Option #3) (326.7 in conjunction with Option#3)
Cost *per* unit saved carbon	23
Performance measure	
Implementation method(s)	Change in licensing standard with authority that already exists with DEP.
Implementation / outreach considerations	Note that an emission standard may be used in conjunction with a program to offset the CO_2 emissions (see Option 1) through investment in afforestation / reforestation or new renewable energy projects. This limit could be met by averaging emissions across all fossil-fired units online in each year, so not every unit would be required to meet the standard. This is equivalent to a policy that allows entities to meet standards by purchasing and selling emission credits.

A CO_2 emission standard often limits the tons of CO_2 per kWh produced. A generation performance standard, or GPS, is an emission standard covering several pollutants in one policy / regulation, and can include CO_2. Emission standards may allow generators to meet all or part of the emission limit through purchases of offsets; the carbon sequestered or reduced is then deducted from the actual CO_2 emissions from the plant to help meet the standard. The standards could be placed on the consumer, or on the generator, with different results in either case. Emission standards were assumed to be 900 lb. CO_2/MWh in modeling the option.

Most Stakeholders agreed that Emission Standards and Offset Requirements should be included in the plan if they are not duplicative with the Regional Greenhouse Gas Initiative (Option 3), or if RGGI does not happen. Others could not support these two options without more information or wanted the numbers re-analyzed to ensure they were actually incremental to RGGI. One Stakeholder asked that Emission Standards be better defined.

As noted above in Option #1, the consolidated options calculations only include the incremental difference between what RGGI would accomplish, and the additional savings from this and Option #1.

OPTIONS #8, 18 -- Biomass Generation

Carbon Savings Potential: High *Costs / savings: Low costs*

Category	Description
Working group	Electricity and Solid Waste 1.5a
Option name	*Biomass Generation: Existing Units*
Sector(s)	Electricity
Policy / program elements	Two related options are combined here.[60] In the first scenario, three existing biomass-fired plants that are currently not in operation are restarted and then subsidized with a production tax credit. In the second scenario, six existing biomass-fired plants are subsidized with a production tax credit to enable them to continue operating.
Rationale	Electricity generation from biomass-fired plants can reduce greenhouse gas and other emissions.
Existing policy/program	None.
Significant co-benefits	Enables fuller utilization of existing biomass feedstock; may provide incentive to develop additional feedstocks from forests and farms.
Carbon saved 2020[61]	Scenario 1 - 269.0 Scenario 2 – 574.0
Cost *per* unit saved carbon	Scenario 1 - 15 -17 Scenario 2 – 15
Performance measure	Operating plant generation numbers.
Implementation method(s)	Production tax credit. Would require legislative action. Biomass subsidy assumed to be $10 per MWh based on information in Maine PUC Report
Implementation / outreach considerations	Full implementation would also depend on Non-quantified Option ESW 1.11, "Barriers to Interconnection." The Working Group noted that some non-operating plants may be restarting and some existing plants may become economical because of other states' RPS policies and increasing gas prices. Therefore a targeted program may not be necessary.

The Working Group supports these options if a subsidy is needed, and recommends that if state funds are used to subsidize existing units, a competitive bidding process should be explored (*e.g.,* evaluating bids' costs and benefits, or on a needs basis). As modeled here, this Option does aim to increase available renewable energy sources, but stands alone by using a different mechanism than that in Options 5 and 11 (SBC; RPS). As a result, the carbon savings are not double-counted.

[60] The carbon savings are entered separately in Table 1.

[61] Biomass is not inherently carbon neutral, since different fuels have different carbon emissions; and there has been some debate in the Working Group and SAG on this matter. For modeling purposes, biomass has been assumed to be carbon neutral. For further discussion, see Appendix 3.2.

For purposes of this Option, qualifying biomass fuel needs to be clearly defined so as to include clean biomass only (e.g., wooden debris) originating from sustainable managed forests.

OPTIONS #9, 27-- Landfill Gas Management

Carbon Savings Potential: High *Costs / savings: Low cost*

Category	Description
Working group	Electricity and Solid Waste 2.1a, 2.1b
Option name	*Landfill Gas Management*
Sector(s)	Waste Management
Policy / program elements	Landfills naturally create methane gas (CH_4, a GHG) as a by-product. Rather than being released into the air, methane can be captured and utilized as a fuel to produce energy or burned off (flared). Element 1 - *Small electric generating units (total potential 16 MW) are installed at four large landfill which currently flare their methane.* Element 2 – *Eight smaller landfills are required to flare their methane emissions.*
Rationale	Methane is 22 times more potent a GHG than CO_2. Both program elements reduce this to CO_2
Existing policy/program	Flaring is occurring at the larger active landfill sites, and studies/planning are underway toward active utilization.
Significant co-benefits	Avoided landfill site odors.
Carbon saved 2020[62]	Element 1 – 550.0 Element 2 - 109.0 Total: 659.0
Cost *per* unit saved carbon	Element 1 – NA Element 2 - 2
Performance measure	Calculated volumes of gas collected and either flared or converted to electricity.
Implementation method(s)	Element 1 is voluntary on the part of landfill operators. Element 2 would require additional regulations under the DEP's existing rule-making authority.
Implementation / outreach considerations	Both scenarios require capital investment. There may also be barriers in Scenario 1 to making resulting electricity available to the grid,[63] either because of transmission constraints, or "net metering" issues.

Some landfills are already required to manage methane emissions, principally to avoid local odors. In the first scenario, the state's largest landfill sites would continue to install gas collection systems, convert the gas to electricity, and either utilize the electric power locally, or sell it into the power grid. This option thus not only avoids intense GHG emissions, but generates renewable power. The second element focuses only on avoided

[62] Listed separately in Table 1.
[63] See Non-quantified Option ESW 1.11.

emissions, since collection and flaring does not produce electricity, but does reduce carbon emissions.

OPTION #10 – Increased Stocking with Faster Growing Trees

Carbon Savings Potential: High *Costs / savings: Low cost*

Category	Description
Working group	Agriculture / Forestry: Forestry 2.0
Option name	*Increased Stocking Of Poorly Stocked Forest Stands With Faster Growing Trees*
Sector(s)	Forestry
Policy / program elements	Manage and promote 25,000 acres per year from the Poorly Stocked Class (10-34% stocked) to Moderately Stocked Class (35-64% stocked) stands over the next 15 years through the use of select faster-growing nursery stock.
Rationale	Increasing coverage in existing stands increases active carbon storage in both standing timber and forest soils.
Existing policy/program	Public and private reforestation is required on many lands and practiced routinely in the state, but does not always result in full stocking of all stands.
Significant co-benefits	Harvest value of increased stocking.
Carbon saved 2020	531.7[64]
Cost *per* unit saved carbon	1
Performance measure	MFS annual forest inventory.
Implementation method(s)	Specific projects for enrichment and inter-planting; education and outreach; cost sharing.
Implementation / outreach considerations	All landowner groups can participate. May be a good candidate for pilot project funding support for planning and evaluation.

For this and a number of following options in the Forestry area (14, 16, 20, 21, 25, 28), the Working Group reached consensus in recommending them according to the following standard:

1. There is a carbon benefit gained over the long-term in actual on-ground implementation;
2. There is no adverse impact on bio-diversity and sustainability;
3. There is ongoing research and adaptive management conducted to determine the appropriate site specifications and realized Carbon benefits of the mitigation technique.
4. The mitigation technique is economically feasible for forest landowners.[65]

For this option in particular, some stakeholders raised concerns about the possible effects of introducing genetically-altered species.

[64] See above, p. 14, for the methodology used to calculate carbon savings for this and the other Forestry options.
[65] At the 9/29 SAG meeting, there was some discussion of whether the above standard should include other issues discussed at WG meetings, *e.g.*, introduction of "non-native" species. However, the minutes as approved by the stakeholders include only the four items above.

OPTION #11 -- Renewable Portfolio Standard (RPS)

Carbon Savings Potential: High   Costs / savings: Low cost

Category	Description
Working group	Electricity and Solid Waste 1.1
Option name	*Renewable Portfolio Standard (RPS)*
Sector(s)	Electricity
Policy / program elements	An incremental increase in the current RPS of at least 5% by 2010, and 10% by 2020.
Rationale	Reduce carbon emissions by substituting renewable fuel sources.
Existing policy/program	Currently, at least 30% of total kWh sales from each competitive electricity provider in Maine must come from eligible renewable sources. Latter may include municipal solid waste plants, and combined heat and power units regardless of fuel type.[66]
Significant co-benefits	Reduced dependence on out-of-state and non-domestic electrical energy resources (fuel and trans-mission). Increased economic development in Maine to provide this alternative energy.
Carbon saved 2020	527.0
Cost *per* unit saved carbon	10
Performance measure	Compliance with mandated standard.
Implementation method(s)	Would require legislative increase in existing RPS.[67]
Implementation / outreach considerations	At the 6/30 meeting of the Stakeholder Advisory Group, several members stated that while they sup-ported the overall goal of promoting increased renew-able generation, they did not agree that increasing the RPS was necessarily the appropriate mechanism.

A Renewable Portfolio Standard (RPS) is a market-oriented policy for accelerating the installation of new renewable resources and technologies into the electricity sector. Renewable portfolio standards mandate a certain minimum percentage of annual electricity production or sales come from new renewable energy sources. Sources of qualifying renewable energy are delineated in the legislation, as are increased percentage requirements over time. RPS policies typically include wind and solar, and may include biomass, hydrogen (produced with renewable energy), tidal and small hydroelectric generation. At present in Maine, wind technologies seem likely to offer the greatest potential.

The Working Group agreed that higher levels should be modeled and explored further; and costs to consumers should be fully analyzed. Renewable Standards are currently in place in most other New England States, and New York mandated a 25% RPS by 2013 in September 2004.

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[66] Fossil-fuel co-generation would not be eligible for the incremental RPS under the terms of proposed legislation.

[67] Legislation to increase Maine RPS in stages was introduced in 2004, but did not come to a vote. For the PUC *Report and Recommendations on the Promotion of Renewable Resources* (12/31/03), see http://www.state.me.us/mpuc/2004legislation/2004reports.htm.

OPTION #12 -- BFM Energy Efficiency

This item has been removed from the list of options and calculations because it originally summarized the savings counted in other BFM options. It represented the impact of the implementation of all demand-side energy efficiency measures considered in the Buildings, Facilities and Manufacturing (BFM) working group. It was included in the ESW sector because the NEMS model calculates the saving in this sector. However, treating it as a separate item created confusion as to whether the carbon savings were a separate addition to the total, which they were not. Thus, it was eliminated to avoid the appearance of "double counting."

OPTION #13 -- Pay As You Drive Insurance

Carbon Savings Potential: High   Costs / savings: Not yet modeled

Category	Description
Working group	Transportation and Land Use 2.4d
Option name	*Allow Maine Car Insurance Companies to Experiment with Voluntary PAYD Pricing Programs*
Sector(s)	Transportation: Slowing VMT growth
Policy / program elements	Pay-As-You-Drive Insurance (also called Distance-Based Vehicle Insurance, Mileage-Based Insurance, Per-Mile Premiums and Insurance Variabilization) means that a vehicle's insurance premiums are based directly on how much it is driven.
Rationale	Provides a direct cost-savings incentive to consumers to lessen vehicle miles traveled.
Existing policy/program	Insurers typically reduce a premium for low-mileage customers, but a pay-as-you drive scheme ties the premium to actual, measured VMT, either through odometer readings or GPS.
Significant co-benefits	Other benefits associated with lessening VMT
Carbon saved 2020	379.0
Cost *per* unit saved carbon	Not yet modeled. Cost figures will be added after additional study.
Performance measure	Industry reports on market penetration.
Implementation method(s)	Pilot project with a recruited volunteer insurance provider.
Implementation / outreach considerations	The stakeholder advisory group expressed some skepticism regarding the market penetration assumptions. Some specific vehicle user groups might need an adjusted approach.

This assumes a market penetration rate of 1% of Maine vehicles in 2010 (pilot program) and 50% in 2020. There was near consensus in the working group to recommend this measure, with some objections related to specific hardships that might be associated with, *e.g.*, agricultural and commercial vehicle users. Several representatives to the SAG could not support this option, in particular because the modeling assumptions were inconsistent with existing underwriting criteria. Pilot programs for this option are currently under way in Oregon, and by several insurance providers.

OPTION #14 -- Forestland Protection

Carbon Savings Potential: High **Costs / savings: Low costs**

Category	Description
Working group	Agriculture/Forestry: Forestry 1.0
Option name	*Protection of Forestland from Conversion to Non-forested Land Uses*
Sector(s)	Forest; Land Use Planning
Policy / program elements	Reduce ten percent of forestland conversion by 2010, and 20 percent by 2020 (against a baseline rate of 141,600 acres projected loss from 2005-2020).
Rationale	Protection of forestland cover from conversion to developed uses significantly reduces the atmospheric conversion of carbon stored in biomass and soils on undeveloped lands.
Existing policy/program	Large number of existing programs, including Land for Maine's Future[68]; USDA Forest Legacy Program; Tree Growth Tax Law; etc.
Significant co-benefits	More efficient growth patterns: it may have the effect of directing growth to more efficient locations and reducing transportation emissions. Future opportunities for production and use of biomass for energy and wood products are also protected. Habitat protection. Supports Maine's forest-based economy.
Carbon saved 2020	376
Cost *per* unit saved carbon	-6
Performance measure	Documented accounting of land protected from loss.
Implementation method(s)	A number of potential implementation mechanisms exist, including regulatory and market-based land use standards and goals; direct incentive payments (easements and acquisitions); cluster zoning requirements or incentives (also known as conservation design or low impact development); revised transportation infrastructure investments; improvements to forest management profitability; and education.
Implementation / outreach considerations	Would need further state agency and stakeholder planning to adopt a comprehensive approach.

Implementation of this option would translate into protection of 2832 acres of natural forest cover *per* year that otherwise would have been lost to development. The Working Group did not recommend a specific implementation approach.

According to recent calculations by Thomas D. Peterson, the total volume of carbon lost from forestland conversion to non-forest uses in Maine from 1990-2000 was 18.53 MMTC compared to growth in emissions from all sectors of about 22 MMTC during the same period. In other words, the carbon emitted from forestland conversion was almost

[68] Currently not funded.

as large as that off all other sectors combined. Fortunately, some of this was mitigated through afforestation and stand recovery, but the flow of carbon from forestland conversion appears to be significant.

Calculation of cost savings is based on the assumption of savings from the costs of public infrastructure and services not expended away from urban centers. See Appendix 5.4 for further discussion.

OPTION #15 -- Increase Recycling/Source Reduction

Carbon Savings Potential: High Costs / savings: Low to moderate savings

Category	Description
Working group	Electricity and Solid Waste 2.3
Option name	*Expand and Increase Recycling/Source Reduction Efforts*
Sector(s)	Waste Management
Policy / program elements	Create programs to reduce the amount of waste being put in landfills and/or waste-to-energy facilities, thereby reducing the amount of methane and CO_2 generated.
Rationale	Avoid / reduce direct carbon emissions; increase carbon sequestration opportunities.
Existing policy/program	The Maine Legislature has established a goal of recycling 50% of the state's municipal solid waste by 2003. Maine residents and businesses achieved a 37.3% statewide recycling rate in 2001.[69]
Significant co-benefits	Cost savings for consumers and municipalities through reduction in waste volume requiring disposal; reducing burden on limited disposal capacity; the providing of 'raw materials' for the secondary materials market. Can reduce the need for petroleum-derived materials. Can reduce source emissions by reducing the need for virgin materials.
Carbon saved 2020	374.0
Cost *per* unit saved carbon	0
Performance measure	Volume of waste tipped at waste-to-energy facilities or landfills; tonnage of recovered, recycled and/or composted discards; tons of GHG reduced/avoided.
Implementation method(s)	Utilization of existing public & private recycling and composting programs; increased effort, assisted by grants, to assist in developing additional capture/processing capabilities; developing markets for collected recyclables 'closer to home' (which encourages recycling and decreases transportation necessary for the recycling of the materials.
Implementation / outreach considerations	Increase public information / education campaign on value of recycling, both from environmental as well as economic sides; target public audiences as well as the commercial sector, both with broad topics as well as targeted messages for specific commercial operations.

"Pay-as-you-throw" pricing for residential waste services has proven to be successful as a recycling incentive program in Maine. Mandatory recycling programs are also being used or developed in some areas, as well as backyard composting of food waste (in the residential sector). Pay-as-you-throw is now used in130 Maine communities. Food waste composting, as a commercial sized venture, is being promoted and implemented in several regions in Maine.

[69] See also Non-quantified Option BFM 4.5 for information about beneficial use and recycling of solid waste.

OPTION #16-- EARLY COMMERCIAL THINNING

Carbon Savings Potential: High   Costs / savings: Very low costs

Category	Description
Working group	Agriculture / Forestry: Forestry 3.0
Option name	*Early Commercial Thinning*
Sector(s)	Forestry
Policy / program elements	Intentional thinning takes advantage of anticipated mortality, and concentrates growth on the better remaining timber. Treat 50% of available acreage to this practice over next 5 years.
Rationale	Carbon sequestration, with remainder used as a renewable energy source, or as building materials that displace higher emissions alternatives (steel and concrete).
Existing policy/program	A number of existing programs support improved management of private non-industrial forests in Maine.
Significant co-benefits	Enhanced value of longer-standing timber. Reduction in dead and dying timber through improved overall forest management. Expanded economic development options in rural economies.
Carbon saved 2020	331.7
Cost *per* unit saved carbon	1
Performance measure	
Implementation method(s)	Voluntary, supported by education and outreach. Market development needed.
Implementation / outreach considerations	Federal cost share programs support the development of forest and harvest management plans for Maine woodlot owners on acreage of 10-999 acres include) the Forest Land Enhancement Program (FLEP); and Forest Stewardship Assistance Program (FSA).

By definition this option meets market criteria and does not involve new costs to producers beyond planning and evaluation. Based on estimated Forest Product Output, products of thinning are directed to 20% durable wood products; 60% pulp/OSB (oriented strand board), and 20% biomass energy.

This and other forest management options may be linked to the development of emerging markets for sequestration as described in Options 1, 3, and 7. See Option 10 for the standard for implementation recommended by the Forestry Working Group.

OPTION #17 -- Slowing VMT Growth

Carbon Savings Potential: High Costs / savings: Not yet modeled

Category	Description
Working group	Transportation and Land Use 2.0
Option name	*Slowing Growth in Vehicle Miles Traveled* (combines TLU 2.1 *Develop Policy Packages to Slow VMT Growth*; 2.2 *Land Use & Location Efficiency*; 2.3 *Increase Low-GHG Travel Options*
Sector(s)	Transportation; land use
Policy / program elements	Develop policy packages to slow vehicle miles traveled (VMT) growth and increase the availability of low-GHG travel choices, such as transit (rail and bus), vanpools, walking, and biking. Included in the packages are a number of complementary land-use and location efficiency policies, and transit-based incentives to improve the attractiveness of low-GHG travel choices.
Rationale	Reduce dependence on gasoline; reduce GHGs, congestion, and local air pollution.
Existing policy/program	Executive Order 11, 3/17/04 calls for reductions in VMT by State employees, promotion of carpools, vanpools, teleconferencing, and study of telecommuting. A variety of existing DOT initiatives, including the State Transportation Plan, support these options.
Significant co-benefits	Reduction in time spent in travel between different locations; reduced human-hours lost to congestion; cost savings from reducing need for additional road capacity; reduction in non-point source pollution from impervious surface growth; preservation of open space/wildlife habitat (from compact growth); improved health of citizens with access to transit-served walking communities.
Carbon saved 2020	286.4
Cost *per* unit saved carbon	See more complete discussion in Appendix 5.1.
Performance measures	Transit ridership; quantity of open space lost; air and water quality; rate of growth of VMT.
Implementation method(s)	Requires establishment of a multi-agency and stakeholder working group to identify the best combination of options for Maine. Could be chartered by legislative resolve.
Implementation / outreach considerations	Must be approached from a regional perspective. State or regional planning agency involvement in land use/transit planning, water and sewer infrastructure investment is essential. Transit option must be made attractive and be adequately promoted. Compact growth may require publicly-funded incentives.

Given the interactive natural of land use and transportation measures it is difficult to estimate impacts of many of these policies on their own. So-called “smart growth” studies and projects in other parts of the country consistently show potential regional and statewide VMT reductions ranging from around 3-10 percent (below business-as-usual projections) for actions of this sort. The VMT savings are a result of a combination of transit improvements, land use modifications (Transportation Oriented Development; infill, etc.) and complementary policies such as open space protection and Travel Demand Management.

OPTION #19 -- Improve Electrical Efficiency in Commercial and Institutional Buildings

Carbon Savings Potential: High Costs / savings: High savings

Category	Description
Working group	Buildings, Facilities and Manufacturing 3.8
Option name	*Improve Electrical Efficiency in Commercial and Institutional Buildings*
Sector(s)	Commercial
Policy / program elements	Technical and financial assistance to encourage replacement of inefficient equipment
Rationale	Improving electrical efficiency in commercial and institutional buildings provides large carbon savings while working with a small set of facilities.
Existing policy/program	"Efficiency Maine" C&I Program, available to businesses with > 50 FTEs, includes three components: (1) business practices training, (2) information and end-use training opportunities, and (3) financial grants to assist in the purchase of EE equipment.
Significant co-benefits	Improves productivity of commercial buildings, which may translate into incentives for maintaining or establishing business in Maine
Carbon saved 2020	250.8
Cost *per* unit saved carbon	-139
Performance measure	Specific goal of saving 124K mwH in 2005, probably based on PUC measurement
Implementation method(s)	With Options 22, 29, and 37, builds on and expands current "Efficiency Maine" C&I Program
Implementation / outreach considerations	Funding may be available from savings in Option 29. Targeted audience: owners of commercial buildings. Outreach through identification of bellwether property owners and property management groups. Some form of "leadership excellence" awards / gubernatorial proclamation may be useful. Formal marketing effort may be required.

Included in this measure, which is based on the Office of Public Advocate *Optimal Energy Study*[70], are items such as efficient appliances, lighting and air conditioning; building system controls; high efficiency motors and variable frequency drives, etc.

[70] "The Achievable Potential for Electric Efficiency Savings in Maine" , Optimal Energy Full report: http://www.state.me.us/meopa/02-162%20Optimal.pdf
Report summary by the PUC: http://www.efficiencymaine.com/orders-documents/2002-162%20EE%20Pot%20Sum%20V5%202.htm

OPTION #20 – Timber Harvesting to Capture More Anticipated Mortality

Carbon Savings Potential: High

Costs / savings: Low costs

Category	Description
Working group	Agriculture/Forestry: Forest 7.0
Option name	*Timber Harvesting to Capture More Anticipated Mortality*
Sector(s)	Forestry
Policy / program elements	Remove standing biomass with minimal impact on forest floor and soils. Goal: within 15 years capture 50% of tree biomass that otherwise is lost to natural mortality and decays on forest floors. Apply to all forest types and all landowner classes on 1,700,000 total acres over a 15-year period (113,333 acres per year).
Rationale	Reducing volume of decaying wood enhances carbon sequestration. Increased use of forest biomass for energy generation, paper production, and building materials displaces fossil based energy use of conventional alternatives.
Existing policy/program	Some support from federal cost-share programs
Significant co-benefits	Use of forest biomass to displace non-renewable energy and material sources. Improved forest management and health. Expanded economic development opportunities.
Carbon saved 2020	239.5
Cost *per* unit saved carbon	3.5
Performance measure	MFS forest sustainability benchmarking (Criterion 3, Timber Supply and Quality)
Implementation method(s)	This program potentially will require new administration and program costs associated with education and technical assistance to landowners, managers, and businesses, and identification or expansion of markets for low quality wood.. Program costs include the need for planning, implementation, and evaluation of programs and, potentially, individual projects.
Implementation / outreach considerations	By definition this option meets market criteria and likely will not involve new costs to landowners and managers. Timber harvests will remove anticipated mortality if it is more profitable than alternative management options.

This option is intended to support timber harvesting that removes anticipated mortality from the forest with minimal impact to the forest floor and soils, and to use the harvested wood for energy generation, paper and solid wood production to reduce carbon dioxide emissions from energy generation and materials production.

See Option 10 for the standard for implementation recommended by the Forestry Working Group.

OPTION #21 -- Biomass Electricity Feedstocks

Carbon Savings Potential: High   Costs / savings: Neutral

Category	Description
Working group	Agriculture / Forestry: Forestry 5.0
Option name	*Biomass Electricity Feedstocks*
Sector(s)	Forestry; Electricity
Policy / program elements	Measured by simple addition of biomass energy sub-options from other forestry management options including: early commercial thinning (16), more lighter harvests (20), and active management of stands for softwood re-establishment (28).
Rationale	Incentives to make greater use forest products or forest waste as a fuel (in solid or gas form) or for co-firing with fossil fuels may reduce net emissions from power supply if it replaces higher emissions supply sources.
Existing policy/program	Presently biomass is used for about 24 percent of the state's power generation, and is also a significant source of combined heat and power for wood products' manufacturing facilities. Biomass is heavily used for home heating with wood stoves.
Significant co-benefits	Removals of overstocked, unhealthy, or otherwise unmarketable trees may improve forest health and reduce emissions from dead and dying trees. Supports Maine's forest-based economy.
Carbon saved 2020	228.4
Cost *per* unit saved carbon	-0-
Performance measure	
Implementation method(s)	
Implementation / outreach considerations	Biomass energy under current capacity and technology is marketable, but new capacity and new technology (biomass gasification and combined cycle) may require market intervention. Stakeholders identified a currently increasing demand for biomass in the market, which could produce a shortage in the intermediate future.

See Option 10 for the standard for implementation recommended by the Forestry Working Group.

OPTION #22 -- Manufacturing Electrical Efficiency Measures

Carbon Savings Potential: High

Costs / savings: High savings

Category	Description
Working group	Buildings, Facilities and Manufacturing 4.1
Option name	*Promote Electrical Efficiency Measures for Manufacturing in Maine*
Sector(s)	Industrial
Policy / program elements	Offer financial incentive/rebates for EE improvements for manufacturing in Maine.
Rationale	Continue to encourage replacement of energy inefficient equipment
Existing policy/program	"Efficiency Maine" has established a new Commercial and Industrial Program for Maine businesses that provides a combination of services, including energy efficiency information and training, business practice assistance, and direct financial incentives in the form of grants. The components of the program are designed to encourage businesses to adopt energy efficient business practices, to include consideration of energy costs and energy efficiency in their business decisions, and to purchase and install energy efficient products.
Significant co-benefits	Very high cost effectiveness, with rapid payback on investment to achieve significant operational savings
Carbon saved 2020	207.2
Cost *per* unit saved carbon	-30
Performance measure	Analysis of "Efficiency Maine" data.
Implementation method(s)	Can include: • Tax incentives, such as Investment Tax Credit or shortened depreciation periods for installation of energy efficient systems and equipment • Creative financing mechanisms • Rebates and grants • Technical assistance and training • Interruptible power programs • Real time pricing
Implementation / outreach considerations	May be able to take advantage of existing programs such as Building Operator Certification program.

Potential areas for energy efficiency improvement include

- Efficient Lighting
- Efficient Ventilation and Cooling
- Efficient Process Controls
- Building System Controls
- Variable Frequency Drives
- High Efficiency Air Compressors

While the Work Group reached consensus in recommending this option, it did not reach agreement on a specific funding mechanism or level.

OPTION #23 -- Fossil Fuel Efficiency Measures

Carbon Savings Potential: High   ***Costs / savings: High savings***

Category	Description
Working group	Buildings, Facilities and Manufacturing 5.5
Option name	*Increase Public Expenditures for Fossil Fuel Efficiency Measures*
Sector(s)	Residential, Commercial, Industrial
Policy / program elements	Develop mechanisms to raise public funding for fossil fuel efficiency measures. Enhance existing programs to promote weatherization and insulation measures.
Rationale	Encourage replacement of energy inefficient equipment providing space, water, and process heating.
Existing policy/program	None
Significant co-benefits	Funds could support research and development for new energy technologies with wider applications in Maine.
Carbon saved 2020	204
Cost *per* unit saved carbon	- 34
Performance measure(s)	Would require an evaluation program to measure funds collected and expended, efficiency mechanisms installed, ease of implementation, user end point savings, number of participants etc.
Implementation method(s)	To be determined.
Implementation / outreach considerations	Involvement of key stakeholders in developing of specific mechanisms is particularly important. Probably a good candidate for pilot programs.

Could include actions such as rebates or financing subsidies for efficient boilers for space, water, and process heating, steam system optimization, etc. Could also be funded from a commercial/industrial loan program to help businesses retrofit projects in their facilities. For example, monies from New York's system benefits charge (SBC) are used to write down the interest on loans to businesses for energy efficiency projects. Revolving loan funds are also an option.

Option 35, *Efficient Use of Oil and Gas: Home Heating*, is a specific example of this approach which is listed and modeled separately.

Some members of the working group and the SAG were not in agreement with this option because no definition of "public expenditures" was presented, and/or because potential funding mechanisms were not specified.

OPTION #24 -- Low GHG Fuel for State Fleets

Carbon Savings Potential: Medium Costs / savings: Low costs

Category	Description
Working group	Transportation and Land Use 3.2
Option name	*Low GHG Fuel for State Fleets*
Sector(s)	Transportation
Policy / program elements	Maximize use of non-petroleum, renewable fuel or other low GHG-fuels for State Fleets where feasible.
Rationale	Fleets provide opportunities to develop a market for more fuel-efficient vehicles to reduce GHGs and air pollution.
Existing policy/program	In 2003 the 121st Maine Legislature passed a *Resolve* requesting the Maine Departments of Environmental Protection and Transportation to conduct a comprehensive study of the costs and benefits of various alternative energy sources for state government actions (S.P. 388 - L.D. 1184). MDOT has begun a trial program utilizing bio-diesel in one facility. The Department of Administrative and Financial Services (DAFS) was charged with developing recommendations for fuel efficiency and emissions standards for heavier duty vehicles by January 1, 2004, and agencies are directed to promote the procurement of dedicated alternative fuel vehicles, dual-fuel vehicles and fueling infrastructures to support such vehicles. DAFS was also given until January 15, 2003 to ensure that these policies are reflected in the procurement policies of the State.
Significant co-benefits	Similar to others in transportation sectors.
Carbon saved 2020	157.5
Cost *per* unit saved carbon	10
Performance measure	Measured volume of alternative fuel used.
Implementation method(s)	Executive order.
Implementation / outreach considerations	May require installation of additional local fuel storage tanks.

Similar policies are already in effect in many cities around the US. Stakeholders were not unanimous in endorsing this option, citing potential difficulties in the marketing of diesel light vehicles, but almost all the stakeholders could support the option if it was adopted in a regional approach through the New England Governors and Eastern Canadian Premiers.

OPTION #25 – Expanded Use of Wood Products

Carbon Savings Potential: Medium   Costs / savings: Low costs

Category	Description
Working group	Agriculture / Forestry: Forestry 6.0
Option name	*Increase Wood Products Use*
Sector(s)	Forestry
Policy / program elements	This option is the simple addition of biomass to wood products sub-options evaluated under forest management options, including: early commercial thinning (16), more lighter harvests (20), and active management of stands for softwood reestablishment (25).
Rationale	Durable wood products in construction of furnishings and buildings can sequester carbon for long periods of time depending on the type of harvesting practices and end use of the wood products. The substitution of wood products building materials for steel and concrete reduces embedded energy and carbon dioxide emissions.
Existing policy/program	None at present.
Significant co-benefits	Wood products are often less energy-intensive in production and use than other materials. Supports Maine's forest products-based economy.
Carbon saved 2020	129.8
Cost *per* unit saved carbon	3
Performance measure	
Implementation method(s)	
Implementation / outreach considerations	The carbon savings associated with this option may be increased if additional technologies and markets for wood products come into active use.

The policy options that contribute to expanded wood products use assume marketable harvests of biomass and no additional costs of market penetration. The only additional costs are those associated with stewardship and harvest planning by landowners.

See Option 10 for the standard for implementation recommended by the Forestry Working Group.

OPTION #26-- Energy Efficiency Appliance Standards

Carbon Savings Potential: Medium

Costs / savings: High savings

Category	Description
Working group	Buildings, Facilities, and Manufacturing 1.1
Option name	*Energy Efficiency Appliance Standards*
Sector(s)	Residential, Commercial
Policy / program elements	Legislation proposed, never passed.
Rationale	For appliances not covered under federal standards, the state may set minimum efficiency standards for appliances to reduce power consumption
Existing policy/program	Federal "Energy Star" program identifies some affected products. LED (Light-emitting Diode) kits for traffic signals have been purchased for replacement traffic lights in Maine, funded in part through existing PUC and DOT programs.
Significant co-benefits	Consumer, municipality, and commercial business cost savings.
Carbon saved 2020	128.7
Cost *per* unit saved carbon	-134
Performance measure	Number of energy efficient appliances purchased
Implementation method(s)	Will require legislative mandate.[71]
Implementation / outreach considerations	Demonstrable life-of-products cost savings will be a major incentive.

The working group has identified a group of appliances not currently subject to Federal efficiency standards. These are:

Dry type transformers
Commercial refrigerators & freezers
Exit signs
Traffic signals
Torchiere lamps
Set-Top boxes
Unit heaters (therm savings)
Commercial Clothes Washers

The impacts from this option would accumulate gradually as existing equipment is retired and replacements acquired, and as new buildings are built.

[71] The PUC has reported (2004) to the Legislature on cost effectiveness, and is engaged in further analysis on different mechanisms (including standards) for accelerating the adoption of more efficient technologies. A report is expected in January, 2005.

OPTION #28 -- Active Softwood Increase

Carbon Savings Potential: Medium Costs / savings: Low costs

Category	Description
Working group	Agriculture / Forestry: Forestry 4.0
Option name	*Maintain and Increase the Softwood Component of Forest Stands*
Sector(s)	Forest
Policy / program elements	Structured conversion from lands currently classified as hardwood to softwood to increase soil sequestration values. Goal: transition 33,333 acres per year over 15 years currently classified as a hardwood forest type on native softwood sites to a softwood forest type by 2020.
Rationale	Softwood stands provide higher merchantable biomass use rates and can reduce greenhouse gas emissions by increasing biomass use rates for energy generation and building materials. Biomass removals can also reduce emissions from decay of dead and dying timber.
Existing policy/program	Non-industrial forests: various MFS, etc., technical and financial assistance programs to promote better forest management practices; Tree Growth tax law
Significant co-benefits	Generation of additional bio-mass for wood products or energy; mitigate forest health risks as a result of improved forest management practices. Supports Maine's forest-based economy.
Carbon saved 2020	73.2
Cost *per* unit saved carbon	3[72]
Performance measure	Acres converted from hardwood to softwood classification: MFS annual inventory
Implementation method(s)	Implementation of appropriate practices by large industrial forest managers; utilization of existing non-industrial forest initiatives (see above)
Implementation / outreach considerations	By definition this option meets market criteria for the acreage involved in biomass harvest, and does not involve new costs to producers.

Significant percentages of Maine's original softwood forests have shifted to hardwoods as a result of forest practices. With long-term forest succession they are likely to return to softwoods in the very long term, but this process can be accelerated with practices that remove hardwood stocks by thinning or harvest and replace them with longer-lived softwoods.

See Option 10 for the standard for implementation recommended by the Forestry Working Group. There were significant differences of opinion in the Working Group as to the efficacy of this Option, particularly due to the possibility of herbicide use.

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[72] This option also includes application of herbicides to 3,000 acres of hardwood to promote natural stand release and regeneration of softwoods. Costs here ($200/acre est.) would increase the cost per unit of carbon saved, but are not included in the above calculation since they would be incurred whether or not saving carbon is a goal.

OPTION #29 -- Increase Public Expenditures for Electrical Efficiency Measures

Carbon Savings Potential: Moderate

Costs / savings: High savings

Category	Description
Working group	Buildings, Facilities and Manufacturing 5.2
Option name	*Increase Public Expenditures for Electrical Efficiency Measures*
Sector(s)	Residential, Commercial, Industrial
Policy / program elements	Develop mechanism(s) to raise public funding for electrical EE measures. This proposed measure would support several other options (19, 22, 37).
Rationale	Electrical efficiency measures frequently require initial investments in new or replacement equipment which cannot always be borne by property owners, even though the payback period is relatively short. Public funding bridges this gap.
Existing policy/program	Efficiency Maine is funded by electricity consumers and administered by the Maine Public Utilities Commission (current funding level ~$16 million per year); no sunset date.
Significant co-benefits	Direct and indirect electrical energy savings provides either additional capacity for development, or displacement of marginal (costly and environmentally less-preferred) energy production.
Carbon saved 2020	71.1
Cost *per* unit saved carbon	-55
Performance measure	Utilization of additional funds.
Implementation method(s)	No particular method suggested by stakeholder group.
Implementation / outreach considerations	Current program is funded by consumers. There will likely be opposition to increasing the current rate.

Estimates reflect the savings associated with putting $15 million into this effort beyond business-as-usual. It does not specify a funding mechanism.

OPTION #30 -- Improved Residential Building Energy Codes

Carbon Savings Potential: Moderate

Costs / savings: High savings

Category	Description
Working group	Building and Facilities 2.1
Option name	*Improved Residential Building Energy Codes*
Sector(s)	Residential
Policy / program elements	Require new buildings or substantial reconstruction to meet the most recent energy code efficiency/ performance standards established by the International Code Council and ASHRAE 6.2 ventilation standards,
Rationale	More energy efficient residential buildings save both money and energy.
Existing policy/program	Residential: State-developed code, less stringent than 1992 MEC, mandatory statewide; Voluntary IECC 2000. The PUC has initiated model energy code rule-making (9/04) to require ASHRAE 62.2-2003.
Significant co-benefits	Significant cost savings over life of building; improved air quality.
Carbon saved 2020	64.1
Cost *per* unit saved carbon	-35
Performance measure	Number of new/reconstructed buildings using the new requirements.
Implementation method(s)	Legislative mandate, followed by outreach to building contractors, local code enforcement officers/ building inspectors, etc.
Implementation / outreach considerations	Would require compliance records and effective enforcement, as recommended through the PUC process. Some increase in initial price for buildings or improvement. Over time, energy efficiency certification can become a value-added aspect of home sales.

OPTION #31 -- Voluntary Partnerships and Recognition Programs

Carbon Savings Potential: Moderate

Costs / savings: High savings

Category	Description
Working group	Buildings, Facilities and Manufacturing 5.9
Option name	*Participate in Voluntary Partnerships and Recognition Programs*
Sector(s)	Comprehensive
Policy / program elements	Recognize voluntary programs and reward actions for GHG reduction in the appropriate sectors.
Rationale	Developing additional programs in Maine increases the range of voluntary participation in saving energy and reducing emissions, and heightens public awareness.
Existing policy/program	Several programs already exist at the national level: EPA Climate Leaders, DOE Industries of the Future (Maine Industries of the Future currently includes pulp and paper, secondary wood, and metals industry), EPA Energy Star Benchmarking Program, Climate Vision, DOE Rebuild America; Maine STEP-UP program, Carbon Challenge
Significant co-benefits	
Carbon saved 2020	57.5
Cost *per* unit saved carbon	0
Performance measure	Number of new companies, institutions, etc., participating in formal agreement programs.
Implementation method(s)	Formal voluntary agreements; Memoranda of Understanding/Agreement with businesses, industries, institutions, etc.
Implementation / outreach considerations	Energy audit program sponsored by the PUC may provide a baseline for participants.

Existing voluntary programs such as those identified above have already generated agreements to significantly reduce GHG emissions and/or save energy. The success of these programs could be increased by broadening participation.

The Department of Energy identified the following possibilities for expanding Maine's participation in "Industries of the Future":

- Include agriculture and plastics and potentially welding;
- Additional publicity;
- The Maine legislature might consider creating a mini state grant program that could provide funds to Maine businesses for feasibility studies to determine whether to adopt new energy-efficient technologies;
- Discuss energy and EE technologies as part of technology cluster project.

The carbon savings quantified above assume that companies representing 10% of GHG emissions voluntarily reduce these by 15% by 2010, and 25% in 2020.

OPTION #32 -- Adopt Advanced Technology Component (Formerly ZEV) of LEV II Standards

Carbon Savings Potential: Moderate

Costs / savings: Neutral

Category	Description
Working group	Transportation and Land Use 1.1b
Option name	*Adopt Advanced Technology Component (formerly ZEV) of LEV II Standards*
Sector(s)	Transportation
Policy / program elements	Adopt Advanced Technology component of California LEV II Standards
Rationale	Maine already has LEV II but opted (2000) not to include ZEV mandate because of concerns over limited number of non-electric vehicles that complied with zero-emission standard. New alternative path allows ZEV requirement to be met with current hybrid technology.
Existing policy/program	Maine adopted CA LEVII for criteria pollutant emissions, without ZEV.
Significant co-benefits	Reduction in other pollutants, especially hazardous air pollutants like benzene.
Carbon saved 2020	53.0
Cost per unit saved carbon	0
Performance measure	Increase in number of hybrids available for purchase in Maine
Implementation method(s)	Rulemaking
Implementation / outreach considerations	In late 2004, the Board of Environmental Protection held a Public Hearing on re-instituting the ZEV requirement as a revision to Chapter 127 of the Department's rules. This is expected to be considered by the Legislature, with earliest possible implementation affecting model year 2009 vehicles.

The ZEV program was designed to catalyze the commercialization of advanced-technology vehicles that would not have any tailpipe or evaporative emissions. Originally, the ZEV program required that 2 percent of new vehicles produced for sale in1998 and10 percent of new vehicles produced for sale in 2003 would be zero emission vehicles. The automakers convinced the California Air Resources Board (CARB) that they could not meet the 1998 deadline, and full implementation of the program was delayed until 2003. In 2002, automakers sued the state over the program and were granted a preliminary injunction barring its implementation pending a final court ruling. California has adopted a revision to its ZEV program, with the aim of restoring it by 2005.
In the Working Group and SAG, a few stakeholders mentioned the following considerations:

1) Dealers being forced to stock vehicles that would be difficult to sell;
2) Minimal CO_2 benefit of the option;
3) If not part of this program limited availability of hybrid vehicles.

OPTION # 33 Support Purchase of Locally Grown Produce

Carbon Savings Potential: Moderate *Costs / savings: Low or no Costs*

Category	Description
Working group	Agriculture / Forestry Agriculture 6.0
Option name	Support Purchase of Locally Grown Produce
Sectors	Agricultural; Transportation
Policy / program elements	Increase availability and purchase of locally produced agricultural products by shifting production location and transportation demand.
Rationale	Lower transportation emissions
Existing policy/program	Current Dept. of Agriculture "Buy Real – Buy Maine" and similar programs; also NGO programs to promote local production/consumption. Existing state and federal programs could assist in this effort, including the USDA Resource Conservation and Development (RC&D) program and recently promulgated organic food standards by USDA.
Significant co-benefits	Encourages local farming; prevents loss of farmland.
Carbon saved 2020	52.1
Cost *per* unit saved carbon	To be determined: probably > 0
Performance measure	Surrogate: Sales numbers of specific products, based on household surveys/
Implementation method(s)	Identify likely high-value product shifts; target specific marketing at producers and consumers. Good candidate for pilot program.
Implementation / outreach considerations	Further study to identify differential production costs of specific food categories. Likely to be perceived positively by general public. Food distribution and retail sector would need to be involved, and potentially provided with incentives.

Organic farming techniques can build up soil carbon levels in farmed acreage. Consistent with the broader policy option to increase soil carbon, the working group did not formulate an implementation mechanism for increased acreage in organic farming, and instead suggested simple acreage goals. About 20,000 acres of farmland in Maine are presently in organic farming out of 155,000 acres of total cultivated cropland. The Maine Organic Farming Association expects this to grow to 30,000 acres by 2010 and then cease to increase. They believe that aggressive public policy could increase this acreage level to 70,000 acres by 2020 (a 40,000 acre increase).

There is currently no inventory of existing market share of locally grown food in Maine for a baseline. The goal of 10% of every food dollar was derived from an Iowa study. The Working Group proposes to increase to this to 15% by 2020.

OPTION #34 -- State Green Power Purchases

Carbon Savings Potential: Moderate

Costs / savings: High costs

Category	Description
Working group	Electricity and Solid Waste 1.3
Option name	*State Green Power Purchases*
Sector(s)	Electricity
Policy / program elements	A requirement that State government and universities meet a minimum percent of their power needs with renewable energy. The renewable energy percentage may be set to increase over time.
Rationale	Reduce carbon emissions from electrical generation, using a "lead by example" approach.
Existing policy/program	Governor of Maine has set a goal for the State government to purchase 50% of its electricity from renewable sources.
Significant co-benefits	Increased incentive for the development of renewable resources.
Carbon saved 2020	45.0
Cost *per* unit saved carbon	28
Performance measure	Direct reporting of State facilities energy portfolio mixture.
Implementation method(s)	Executive order.
Implementation / outreach considerations	Has the potential to add to State government costs at a time of increased budget stringency.

Implementation of this option would aim to increase state government purchase level to 50% in 2010 and 60% in 2020, all from 100% renewable sources. A policy of purchasing green tags from renewable energy providers that feed the New England Power Pool could serve as an additional means of increasing future renewable energy procurement. New York, Maryland and New Jersey have already adopted this approach.

OPTION # 35-- Efficient Use of Oil and Gas: Home Heating

Carbon Savings Potential: Moderate

Costs / savings: Moderate savings

Category	Description
Working group	Buildings, Facilities and Manufacturing 2.6
Option name	*Efficient Use of Oil and Gas: Home Heating*
Sector(s)	Residential
Policy / program elements	Develop energy efficiency programs for heating and hot water systems of all fuel types. Replace inefficient boilers/furnaces with Energy Star rated.
Rationale	Relative to mid-efficiency equipment, over 10% of the fossil fuel consumed and carbon emitted can be saved if high-efficiency equipment is installed instead.
Existing policy/program	LIHEAP, WAP, REACH Central Heating Improvement (CHIP) Programs for low-income residents. (Energy Advisors, LLC, 2003)
Significant co-benefits	Long-term operating cost savings.
Carbon saved 2020	39.1
Cost *per* unit saved carbon	-6
Performance measure	Would require an evaluation program to measure funds collected and expended, efficiency mechanisms installed, ease of implementation, user end point savings, number of participants etc.
Implementation method(s)	Could be included in actions taken to implement Option 23.
Implementation / outreach considerations	Maine should review market and regulatory barriers to identify best opportunities for increasing installation of cost-effective efficiency measures, and review potential incentives for implementing these measures. This option provides good opportunities to utilize pilot projects.

The most efficient furnaces and boilers for home heating use far less energy than those which current dominate the market. High-efficiency products have a higher capital cost, but lower annual operating costs. Further, there are changes that can be made to existing systems (*e.g.*, pipe insulation, nozzle reduction) to achieve significant savings without full system replacement.

22 states have natural gas conservation programs. In the Northeast, NH, VT, MA, NY, NJ, PA, MD and WV have natural gas conservation programs. ME, RI, CT and DE do not. Vermont's natural gas conservation program has saved 1,000 cubic feet/year (typically lasting 20 years) for every $29 spent.
Programs include:

- ✓ promoting ENERGY STAR heating equipment;
- ✓ promoting ENERGY STAR-rated water heaters;
- ✓ promoting ENERGY STAR-rated programmable thermostats;
- ✓ increasing the efficiency of residential new construction.

OPTION # 36-- Combined Heat and Power (CHP) Incentive Policy

Carbon Savings Potential: Moderate Costs / savings: High savings

Category	Description
Working group	Electricity and Solid Waste 1.8
Option name	*Combined Heat and Power (CHP) Incentive Policy*
Sector(s)	Electricity
Policy / program elements	Reduce barriers and implement programs to increase clean CHP in the state. CHP is a high efficiency method of distributed generation that utilizes both the steam and electricity produced by the electricity generating process, rather than just the electricity
Rationale	Increases overall energy generation efficiency.
Existing policy/program	CHP units are included as eligible renewable sources under the state Renewable Resource Portfolio Requirement. See full option description for efforts currently underway.
Significant co-benefits	
Carbon saved 2020	38.0
Cost *per* unit saved carbon	-185
Performance measure	Direct reporting of CHP facility output.
Implementation method(s)	Developing uniform and consistent interconnection standards can allow units to be connected to the electricity grid faster and reduce the cost of interconnection.
Implementation / outreach considerations	Utility regulations may need to be changed to encourage CHP; however, this could have the effect of transferring costs to other ratepayers.

CHP systems, also known as co-generation systems, make use of heat that would be wasted in conventional electric generating plants.

The Working Group agreed that this option should be pursued by exploring the barriers to CHP, including inter-connection standards,[73] environmental standards, and back-up rates. Any back-up rate proceedings should look at impacts and benefits on CHP owners and other ratepayers.

There may be more opportunities in the institutional and commercial sectors than modeled above and should be further explored. For instance, USM and Eastern ME Medical are currently installing CHP.

In addition to the implementation methods above, other methods include:

- awarding of emission reduction credits to CHP units for emission reductions realized as a result of their high efficiency;
- consumer choice, which allows electricity customers to purchase CHP-generated electricity; and
- direct subsidies, provided to CHP units on a per unit, efficiency or energy production basis, which can improve the depreciation allowance for CHP equipment.

[73] See NQ Option ESW 1.11 for further discussion of inter-connection rules and transmissions barriers.

OPTION #37 -- Improve Enforcement of Commercial Energy Codes

Carbon Savings Potential: Moderate Costs / savings: High savings

Category	Description
Working group	Buildings, Facilities and Manufacturing 3.7
Option name	*Improve Enforcement of Commercial Energy Codes*
Sector(s)	Commercial
Policy / program elements	Improve enforcement of the requirement that new construction and substantial renovations of commercial buildings meet the most recent energy code efficiency/performance standards established by the International Code Council.
Rationale	Build in higher efficiency levels at the point of construction to realize lower energy operating costs and reduced carbon emissions.
Existing policy/program	Commercial: ASHRAE/IESNA 90.1-2001, mandatory statewide (includes all institutional buildings such as schools and hospitals).
Significant co-benefits	Operating cost savings for commercial businesses that utilize lower-energy construction methods.
Carbon saved 2020	33.6
Cost *per* unit saved carbon	-61
Performance measure	Reports from local building inspectors.
Implementation method(s)	Legislature must pass "housekeeping legislation" whenever the State wants to update to the most recent building energy codes.[74] Requires training for building inspectors. #29, *Increase Public Benefit Fund,* supports this option.
Implementation / outreach considerations	There may be a need to avoid conflict with existing rehabilitation codes. A well-publicized “Leadership Excellence” program for the commercial sector could be utilized for this and other sector options.

Current building codes have requirements affecting the level of energy used in new and renovated buildings.

Any process to upgrade enforcement of building codes would entail some funding requirements for standards evaluation and development, implementing code revisions as these occur, training for contractors and inspectors, etc.

[74] 10 MRSA c. 214, §1415-D: Mandatory standards for commercial and institutional construction.

OPTION #38 -- Solar Water Heat Rebate

Carbon Savings Potential: Moderate *Costs / savings: Moderate savings*

Category	Description
Working group	Buildings, Facilities and Manufacturing 5.7
Option name	Solar Water Heater Program
Sector(s)	Residential, institutional, commercial: new or existing buildings.
Policy / program elements	Funding for SWH systems incentives and marketing
Rationale	To promote the use of renewable energy through the installation of solar water heating systems.
Existing policy/program	No current program.
Significant co-benefits	Support of local businesses for purchase and installation
Carbon saved 2020	33.1
Cost *per* unit saved carbon	16
Performance measure	Number of installed systems
Implementation method(s)	Legislative action to establish tax credit or revolving loan fund. Specific approach to be determined.
Implementation / outreach considerations	Relatively high up-front costs may discourage potential adopters. Rebate system might need to be scaled to income.

Active solar water heating systems collect and store thermal energy from the sun in order to heat water for domestic and small commercial / institutional use. They are usually installed on roofs. To provide backup, a conventional water heater must be installed along with the SWH. Under this proposal, the state would promote through education, rebates, tax credits, etc. the procurement and installation of solar water heating systems for residential applications. To qualify, the system owner must have an inspector confirm the conservation measure is an efficiency upgrade.

The modeled carbon savings assume a 0.5% market penetration by 2020.

OPTION # 39-- Build Up of Soil Organic Carbon

Carbon Savings Potential: Moderate Costs / savings: Moderate cost

Category	Description
Working group	Agriculture / Forestry Agriculture 2.0
Option name	*Buildup of Soil Organic Carbon (Agriculture)*
Sector(s)	Agriculture
Policy / program elements	Conservation tillage and related cropland soil management toward improving *per* acre soil carbon storage rate. Goal: Bring 140,000 existing acres of cropland into new management practices.
Rationale	Practices that result in less disruption of the soil or increase organic content through carbon deposition can increase the carbon content (stock) of soil or reduce its rate of loss (flow) to the atmosphere.
Existing policy/program	A variety of support / incentive programs exist to encourage conservation tillage or no till agriculture through installation of best management practices.
Significant co-benefits	Soil conservation maintains land productivity, reduces water quality impairment, and loss of wildlife habitat.
Carbon saved 2020	31
Cost *per* unit saved carbon	28
Performance measure	Acreage brought into new management practice yielding per acre soil carbon storage rate improvements from1.5 percent to 3.5 percent over a 10 year time period.
Implementation method(s)	Development and deployment of Best Management Practices.
Implementation / outreach considerations	

OPTION #40 -- Green Campus Initiatives

Carbon Savings Potential: Moderate *Costs / savings: Moderate savings*

Category	Description
Working group	Buildings, Facilities and Manufacturing 3.6
Option name	***Green Campus Initiatives***
Sector(s)	Institutional
Policy / program elements	Promote a "Green Campus" initiative with all Maine colleges, universities, private/secondary schools to minimize environmental impact
Rationale	Educational institutions are discrete entities in which energy and GHG usage can be measured, monitored, and effected more easily than in other parts of the sector.
Existing policy/program	Currently underway on college campuses (USM, Other Campuses)
Significant co-benefits	Institutional cost reduction
Carbon saved 2020	29.8
Cost *per* unit saved carbon	-18
Performance measure	Typical energy saving indicators
Implementation method(s)	Further promotion of existing programs, including special attention to active support by senior administrators. Can be integrated with environmental management systems already being developed on some campuses.
Implementation / outreach considerations	Existing programs already well underway, with significant connections to the educational mission.

"Green campus" initiatives are well underway throughout the region. At present, these primarily involve post-secondary institutions, where both administrators and student action groups are promoting a wide range of environmentally-preferable activities. The above carbon savings and cost numbers are limited to colleges and universities.

Transferring these efforts to the public school group has not yet begun. Here, the active agents will change, to include not only school administrators and students, but also local school boards and the state Department of Education.

OPTION #41 -- Encourage Anti-Idling Measures: Freight

Carbon Savings Potential: Moderate

Costs / savings: Low cost

Category	Description
Working group	Transportation and Land Use 4.2d
Option name	*Encourage Anti-Idling Measures: Freight*
Sector(s)	Transportation -- Freight
Policy / program elements	Support programs to fund infrastructure or develop incentives to reduce truck, locomotive, and marine engine idling through electrification and other technologies, enforcement, and congestion management.
Rationale	Lessening idle time reduces emissions directly.
Existing policy/program	Maine DOT Intelligent Transportation System Commercial Vehicle Operation work group is working on a system for pre-clearance at scale houses.
Significant co-benefits	Fuel cost savings (lowered consumption). Lessened emissions of fine particulate matter: direct human health benefits (asthma).
Carbon saved 2020	29.7
Cost *per* unit saved carbon	> 0
Performance measure	Surrogate: estimates of diesel consumption
Implementation method(s)	Installation of technology; education to promote best practices, inform truckers of alternative routes, etc.
Implementation / outreach considerations	Further information needed to identify potential for Truck Stop Electrification (~30% GHG emissions reductions) and list of freight rail commodities in Maine that could be shifting to TSE (refrigerated goods, etc). Good candidate for pilot project, either with specific firms or in partnership with other states for particular routes.

Vehicles at idle are performing no useful work, but are nonetheless consuming fossil fuels, and emitting both GHG and other substances associated with ground-level air pollution. The rationale for such idling frequently relates to the importance of maintaining heat in diesel engines; maintaining electric power to support ancillary motors (refrigeration, *e.g.*); and cab comfort.

Changes in diesel technology, and the availability of alternate power sources (so-called “truck stop electrification”), both act to reduce idling. Non-quantified Option TLU 8.2, “Highway Weight Limits,” could have a positive effect on implementing this option.

OPTION #42 -- Voluntary Green Building Design Standards

Carbon Savings Potential: Moderate Costs / savings: High Savings

Category	Description
Working group	Buildings, Facilities and Manufacturing 2.3
Option name	Voluntary Green Building Design Standards
Sector(s)	Residential
Policy / program elements	Promote voluntary high efficiency and sustainable building standards that builders can follow (*e.g.,* Energy Star, LEED residential building standard as it becomes available, Built Green™). In addition to an energy efficiency requirement, require procurement standard for concrete containing up to 20% recovered mineral component (see #47).
Rationale	This program encourages better building practices, which have a high cost/benefit return for homeowners while saving energy in both construction and operation.
Existing policy/program	None
Significant co-benefits	Economic development related to increased use of energy efficient products; lessened use of toxic materials.
Carbon saved 2020	28.0
Cost *per* unit saved carbon	-45
Performance measure	Possible reporting through local CEO, building permits, etc.
Implementation method(s)	Voluntary change, requiring education and outreach; could be linked to state procurement requirements. Builder/constructor associations are the first clients.
Implementation / outreach considerations	Availability of specialized materials, and training of builders/contractors in sustainable construction: special license or certification may be needed. May be linked to special mortgage rates for meeting the standard. Will take time to implement. Excellent candidate for pilot programs.

Owning (*i.e.,* mortgage amortization) and operating (*e.g.,* utility bills) an Energy Star-labeled home costs less than owning and operating a non-Energy Star labeled home. Energy-saving measures are not recommended unless the amortized cost of implementing those measures is less than the utility bill savings resulting from them.

OPTION #43 -- Waste to Energy

Carbon Savings Potential: Moderate

Costs / savings: Moderate - High

Category	Description
Working group	Electricity and Solid Waste 2.2
Option name	*Waste to Energy*
Sector(s)	Waste Management
Policy / program elements	Increase capacity factor at waste-to-energy facilities.
Rationale	Burning waste instead of landfilling can reduce the amount of methane generated from waste and can create a source of energy that avoids emissions from other energy sources.
Existing policy/program	Electric generating plants fired by municipal solid waste (MSW) are included as eligible renewable sources under Maine's Renewable Resource Portfolio requirement (see Option 11).
Significant co-benefits	
Carbon saved 2020	24.0
Cost *per* unit saved carbon	9
Performance measure	Volume of waste being utilized for energy production.
Implementation method(s)	Voluntary action by existing plan owners.
Implementation / outreach considerations	Expansion of existing facilities is likely to generate local opposition that would have to be overcome.

Current status of MSW incineration in Maine indicates that construction of new plants is unlikely due to environmental concerns and local opposition. Plant operators have indicated that potential increases in generation at existing plants may be possible through upgrades. Total cost of upgrading plants assumed to be about $2 million, based on information provided by plants. Costs were annualized over the 2005-2020 time period, assuming a 7% interest rate.

The Working Group had concerns about increasing capacity of waste to energy facilities if it would reduce potential for recycling, source reduction, and landfill gas development.

OPTION # 44—Agricultural Land Protection

Carbon Savings Potential: Moderate Costs / savings: Moderate cost

Category	Description
Working group	Agriculture / Forestry: Agriculture 5.0
Option name	*Agricultural Land Protection*
Sector(s)	Agriculture
Policy / program elements	A goal of saving ten percent of projected farmland loss by 2010, and 20 percent by 2020 (950 acres *per* year over 15 years).
Rationale	Maintains soil from disruption that releases carbon to the atmosphere.
Existing policy/program	A variety of programs exist that potentially affect land conversion rates, including Land for Maine's Future program[75]; USDA Farm and Ranchland Protection Program; *etc.*
Significant co-benefits	May also reduce transportation emissions by directing growth to more efficient locations.
Carbon saved 2020	22.7, including a portion allocated to VMT reduction effects
Cost *per* unit saved carbon	13
Performance measure	
Implementation method(s)	Regulatory and market-based land use standards and goals; direct incentive payments (easements and acquisitions); cluster zoning requirements or incentives (also known as conservation design or low impact development); revised transportation infrastructure investments; improvements to farm profitability; and education.
Implementation / outreach considerations	Requires some form of proactive "smart growth" program.

[75] Currently unfunded.

OPTION #45 -- Energy Savings in State Buildings

Carbon Savings Potential: Moderate

Costs / savings: High Savings

Category	Description
Working group	Buildings and Facilities 3.3
Option name	*Implement the Most Cost-effective Energy Savings in State Buildings*
Sector(s)	Institutional (Government)
Policy / program elements	Implement cost-effective savings in state buildings at a level of 1% per year above the existing legislative mandate. Specifically, implement the most cost-effective Harriman study recommendations such as appropriately adjusting building temperatures and turning off unneeded lights. Further evaluate emerging technology, such as the pilot program for bio-diesel.
Rationale	State has the opportunity and leverage to led in energy efficiency and GHG reduction in its own facilities. This is aligned with the NEG/ECP "Lead by Example" theme, and supported by current "Clean Government" initiative in Maine.
Existing policy/program	25% energy reduction goal by 2010 (relative to 1998 baseline) added to Energy Conservation Building Act for Public Buildings. This legislation established a pilot program to achieve that level of energy savings in ten facilities of over 40,000 square feet. Under the pilot program, energy savings are to be achieved through performance contracts with energy service companies. However, existing mechanisms have not been fully implemented.
Significant co-benefits	Healthier work environment for employees and public visitors; operating cost savings. Very cost effective.
Carbon saved 2020	21.0
Cost *per* unit saved carbon	-37
Performance measure	Energy use tracking by State Bureau of General Services
Implementation method(s)	May require additional mandates and resources.
Implementation / outreach considerations	Excellent opportunity for public education and outreach, through branding visible to the public, etc.

This option involves a comprehensive effort to minimize energy-related GHG emissions in public facilities through measures such as best technology in new construction; comprehensive retro-fitting, and using lower carbon fossil fuels for space heat.

OPTION #46 -- GHG Feebates

Carbon Savings Potential: Low

Costs / savings: Neutral

Category	Description
Working group	Transportation and Land Use 1.3b
Option name	*GHG Feebates (state or regional)*
Sector(s)	Transportation
Policy / program elements	Under a GHG Feebate system, consumers would be charged a fee on purchases of relatively high-emitting (more CO_2 *per* mile) vehicles and would receive a rebate on the purchase of relatively low-emitting, higher-efficiency vehicles. The program is intended to apply to all light-duty vehicles.
Rationale	Reduce carbon emissions as well as oil dependence.
Existing policy/program	The Cleaner Cars for Maine Program is a consumer-labeling and financial incentive/disincentive program that enables individuals seeking to purchase an automobile to easily identify the cleanest vehicles on dealer lots.
Significant co-benefits	Reduction in other vehicle fuel emissions.
Carbon saved 2020	18.8[76]
Cost *per* unit saved carbon	0
Performance measure	Comparisons of number of vehicles in each classification sold.
Implementation method(s)	Requires legislation.
Implementation / outreach considerations	Administering the Feebates at the time of registration would avoid any potential "leakage" (*i.e.,* if Maine residents were to buy high-GHG vehicles in another state to avoid paying the fee, or if out-of-state residents were to buy low-GHG vehicles in Maine in order to get the rebate).

Both in the Working Group, and the SAG, supporters noted that this program will help "market transformation" toward more fuel efficient, lower GHG cars, and that the measure should be crafted so as to be revenue neutral. It is part of the Action Plan for the GHG plans in Massachusetts, Rhode Island, Connecticut, and New York. Opponents noted that this program is a "tax," which hits working people hardest and would be politically unpopular. There was no consensus on recommending this option.

Savings could be significantly higher in a multi-state or national program, since a larger market would enhance the effect of price signals. However, a state- or regional-level plan can serve the important purpose of informing consumers about the characteristics of different vehicles and their pollution consequences.

[76] This calculation is based on Costs and savings schedule shown in Appendix 5.1, p.12, Table 1.3.b, a sample feebate schedule. Savings based on \$40/MMTCO$_2$. Many stakeholders believe that, depending on program design, this option could be much more aggressive in reducing carbon emissions and producing larger CO_2 savings.

OPTION #47 -- Procurement Preference for Concrete Containing Slag

Carbon Savings Potential: Low

Costs / savings: Neutral

Category	Description
Working group	Buildings, Facilities and Manufacturing 3.9
Option name	*Procurement Preference for Concrete Containing Slag*
Sector(s)	All
Policy / program elements	Specify procurement preference for concrete and concrete products that contain a minimum of 20% of ground granulated blast furnace slag for publicly funded projects, as long as this is cost-effective.
Rationale	Avoid a portion of direct emissions associated with cement manufacture.
Existing policy/program	ASTM specifies standards for the inclusion of slag to concrete. MDOT specifications allow for the inclusion of slag in concrete.
Significant co-benefits	
Carbon saved 2020	18.0
Cost *per* unit saved carbon	0
Performance measure	Slag sales, combined with construction industry activity reports.
Implementation method(s)	Executive order for state procurement.
Implementation / outreach considerations	

Slag is derived from a by-product of the steel industry. It is processed and grounds to meet strict specifications and sold as a cementitious (cement-like) product. Slag has cementitious properties and can be used to offset a portion of the cement used in concrete mixtures.[77] How much can be offset is dependent on season (winter/summer), set requirements and other factors.

[77] Although fly ash is another concrete admixture that wold lower the carbon intensity of concrete, it was not included as part of this Option due to concerns expressed by several Working Group members as to the nature of fly ash.

OPTION #48 -- Promote Energy Efficient Buildings

Carbon Savings Potential: Low

Costs / savings: Moderate Savings

Category	Description
Working group	Buildings, Facilities, and Manufacturing 3.2
Option name	*Promote Energy Efficient Buildings*
Sector(s)	Commercial and Institutional
Policy / program elements	Encourage privately financed new construction and renovation to be high performance buildings by certifying to 20% above existing code. Voluntary program; no public funds intended.
Rationale	New construction and renovation present a strong opportunity to transform building practices and influence equipment markets.
Existing policy/program	No current program.
Significant co-benefits	Long-term operational energy savings offset initial capital cost.
Carbon saved 2020	11.3
Cost *per* unit saved carbon	-19
Performance measure	Information from building inspectors, etc.; voluntary registration program.
Implementation method(s)	Development of a voluntary sign-on or registration program, including educational and technical materials, technical assistance, etc.
Implementation / outreach considerations	Adds $3-$5 *per* sq. ft. to construction costs. Builders and architects who follow "green" guidelines could be recognized with some sort of state designation, included in a directory through Efficiency Maine for customers wishing to find builders/architects if they want to build green.

This program addresses both electrical energy use/savings, and fossil fuel (heat) combustion. The range of potential efficiency measures is broad, including building shell, lighting, HVAC and chiller systems, motors, refrigeration, and process heating and cooling.

This measure could be enhanced through development of a financing program to assist participants, and/or through direct subsidies in the form of tax credits, loan funds, etc. Such measures have not been included in the calculation of saved carbon or cost.

OPTION # 49-- Portland Cement Specifications

Carbon Savings Potential: Low

<u>Costs / savings: Low Costs</u>

Category	Description
Working group	Buildings, Facilities and Manufacturing 4.8
Option name	*Accept ASTM Specification C150 for Portland Cement*
Sector(s)	Manufacturing
Policy / program elements	Specify ASTM (American Society for Testing and Materials) specification C150 for Portland cement rather than AASHTO (American Association of State Highway Officials).
Rationale	The amended specification lowers the overall carbon intensity of Portland cement through direct reduction of emissions from cement production.
Existing policy/program	N/A
Significant co-benefits	
Carbon saved 2020	9.0
Cost *per* unit saved carbon	0
Performance measure	Production information from manufacturers.
Implementation method(s)	Department of Transportation rule amendment.
Implementation / outreach considerations	Estimates of avoided CO_2 emissions would need to be adjusted regularly on the basis of recorded production. Maine would need to work with MA, NH to harmonize across the region so all cement companies could begin to implement.

ASTM is the American Society for Testing and Materials, the largest voluntary standard development system in the world. The manufacturing of portland cement is outlined in ASTM standard C150. ASTM C 150 was recently amended to allow for the inter-grinding of up to 5% limestone in Portland cement while maintaining all performance specifications. This standard is consistent with standards already in place in Mexico and Canada. US EPA supports this revised standard due to the potential for CO_2 reductions.

OPTION #50 -- Reduce HFC Leaks from Refrigeration

Carbon Savings Potential: Low

Costs / savings: Low Costs

Category	Description
Working group	Buildings, Facilities and Manufacturing 5.10
Option name	*Reduce HFC Leaks from Refrigeration*
Sector(s)	Commercial and Industrial
Policy / program elements	Reduce HFC leaks from refrigeration
Rationale	Leaking hydrofluorocarbons have many times the global warming value of carbon dioxide.
Existing policy/program	None.
Significant co-benefits	More efficient use of existing refrigeration equipment in commercial and industrial applications. Lower cost of use.
Carbon saved 2020	9.0
Cost *per* unit saved carbon	1
Performance measure	Reduction in reported emissions
Implementation method(s)	Maine Greenhouse Gas reporting requirement in Chapter 137.
Implementation / outreach considerations	Outreach to commercial and industrial users to promote voluntary inspection/servicing.

Hydroflourocarbons (HFCs) are primarily used in refrigeration and air-conditioning units to effect heat transfer. When these gases leak from faulty or inadequately serviced equipment, they ascend into the atmosphere. They carry with them a CO_2 equivalent value; for example, CFC-12 has a Global Warming Potential (GWP) of 10,600 and HCFC-22 has a GWP of 1,700. In other words, these compounds have 10,600 and 1,700 times the global radiative forcing impact of CO_2.

OPTION #51 -- Organic Farming

Carbon Savings Potential: Low

Costs / savings: Moderate Cost

Category	Description
Working group	Agriculture / Forestry Agriculture 3.0
Option name	*Increase Maine's organically Farmed Acreage*
Sector(s)	Agriculture
Policy / program elements	Programs to increase acreage in organic cultivation relative to current expected growth
Rationale	Organic farming techniques can build up soil carbon levels in farmed acreage.
Existing policy/program	Some existing state and federal programs could assist in this effort, including the USDA Resource Conservation and Development (RC&D) program and recently promulgated organic food standards by USDA.
Significant co-benefits	Farmland protection
Carbon saved 2020	8.9
Cost *per* unit saved carbon	28
Performance measure	New acreage brought into organic cultivation
Implementation method(s)	To be determined.
Implementation / outreach considerations	

The Working Group did not suggest any particular implementation methods.

OPTION #52 -- Maine Bio-diesel

Carbon Savings Potential: Low

Costs / savings: High Cost

Category	Description
Working group	Agriculture / Forestry Agriculture 1.0
Option name	*Maine Bio-diesel*
Sector(s)	Agriculture; Transportation
Policy / program elements	The working group did not develop a detailed policy proposal for this potential action, and instead suggested a general proposal that assumed expanded use of bio-diesel in farm equipment and off-road diesel vehicles.
Rationale	Substitution of renewable vehicle fuel for petroleum.
Existing policy/program	Pilot production programs; some business fleet use.
Significant co-benefits	Economic development in both agriculture and fuel processing industries; lessen dependency on imported vehicle fuels; renewable and bio-degradable product; lessen criteria pollutant emissions.
Carbon saved 2020	5.5
Cost *per* unit saved carbon	40
Performance measure	Volume of state and regional production; volume of consumer use.
Implementation method(s)	Expand pilot projects to target vehicle fleets. Expand distribution network for product.
Implementation / outreach considerations	Some bio-diesel already available in Maine. Encouragement of domestic renewable fuel production likely to be positively received by public. Some existing barriers: fuel performance, current price premium, public confidence in fuel properties.

Adoption of this option would assist expansion of in-state and regional production capacity, including development of bio-fuel feed stocks (direct growth; agricultural by-product; wood waste).

OPTION #53 -- Low-GHG Fuel Infrastructure (CNG, LPG)

Carbon Savings Potential: Low

Costs / savings: Very High Costs

Category	Description
Working group	Transportation and Land Use 3.3
Option name	*Low-GHG Fuel Infrastructure (CNG, LPG*)
Sector(s)	Transportation
Policy / program elements	Expand infrastructure for compressed natural gas, propane, and other low GHG fuels.
Rationale	The complex inter-relationship among supply, infrastructure, and purchase/use of alternative fuel vehicles requires some investment in infrastructure as an incentive.
Existing policy/program	Pilot project Portland area Council of Governments
Significant co-benefits	See other transportation measures.
Carbon saved 2020	2.0
Cost *per* unit saved carbon	1482[78]
Performance measure	
Implementation method(s)	See below.
Implementation / outreach considerations	Due to the high cost of implementation, identification of funding sources is necessary before action can be taken.

The measures included focus on investing in and providing incentives for fueling infrastructure for low-GHG fuels (biodiesel, ethanol, CNG, LPG) such as:

- Establishing CNG infrastructure in other metropolitan areas and along the Turnpike;
- Taking advantage of existing propane fueling infrastructure;
- Expanding incentives for in-State production of biofuels;
- Providing incentives for the sale of low-GHG fuels;
- Providing incentives for the purchase of low-GHG vehicles (E85, CNG);
- Considering use of CNG vehicles at any LNG port.

[78] Cost numbers used to calculate include both CNG and LNG. CNG costs account for roughly 90%, because the initial investment costs of a CNG infrastructure are extremely high. Thus, cost *per* unit would be significantly lower if implementation focused on LNG.

OPTION #54 -- Nutrient Management

Carbon Savings Potential: Low

Costs / savings: Neutral

Category	Description
Working group	Agriculture / Forestry Agriculture 4.0
Option name	*Nutrient Management*
Sector(s)	Agriculture
Policy / program elements	Improve efficiency of fertilizer application by reducing over-application resulting from incorrect timing. Substitute organic fertilizer (primarily manure) for synthetic fertilizer, by altering the timing of applications, by altering cover crops and rotational schemes, or by increasing soil testing to improve efficiency (and reduce unnecessary applications). Specific proposal for potato fertilization: bring 25% of current acreage into new application practice.
Rationale	A portion of nitrogen applied to the soil and not incorporated into plants and soil organic material is emitted as N_2O (a GHG); therefore, a reduction in the quantity of fertilizer applied or measures that improve uptake can reduce N_2O emissions.
Existing policy/program	Nutrient Management Law in 1998 (7 M.R.S.A. Chapter 747, Nutrient Management Act); various state and Federal support programs.
Significant co-benefits	Reduces threats to water quality.
Carbon saved 2020	1.8
Cost *per* unit saved carbon	-0-
Performance measure	Number of acres brought into new practice.
Implementation method(s)	Utilize existing programs to encourage voluntary adoption of preferred methods. Would require development of a specific education/outreach program.
Implementation / outreach considerations	

Since this process does not reduce the net amount of fertilizer applied, but increases use in the crop and soil organic layer versus over-application in one large dose, the result is a savings of 40 pounds per acre of fertilizer. This will be fully incorporated by crops and not applied in excess (660,000 pounds nitrogen saved).

OPTION #55 -- Solar Photovoltaic Buy Down Program

Carbon Savings Potential: Low

Costs / savings: Not estimated

Category	Description
Working group	Buildings, Facilities, and Manufacturing 5.6
Option name	*Solar Photovoltaic (PV) Buy Down Program*
Sector(s)	Residential, Commercial, and Industrial
Policy / program elements	Create a "Maine PV Buydown" program
Rationale	To promote and encourage the use of renewable energy through the installation of photovoltaic (PV) systems by offering a rebate, or "buying down," the high up-front cost of PV systems.
Existing policy/program	None.
Significant co-benefits	Contributes to the "learning curve" for this technology. Support of local business for purchase and installation.
Carbon saved 2020	0.2
Cost *per* unit saved carbon	Not estimated
Performance measure	Identified number of installed units; calculation of displaced non-renewable electricity.
Implementation method(s)	Will need a new vehicle, not yet identified.
Implementation / outreach considerations	A good candidate for pilot program implementation, especially in business and institutional (campus; healthcare facility) settings.

Solar photovoltaic cells systems (PVs) convert sunlight into electricity, producing direct current which is then converted to alternating. Since such systems continue to be relatively expensive *per* kW, many states have implemented policies to promote further market penetration of this renewable approach to electrical generation.

ADDITIONAL GHG MITIGATION OPTIONS NOT YET QUANTIFIED OR DEFERRED FOR FURTHER STUDY

Work Group Identifier	Title	Description	Further Action Needed
ESW 1.4	Carbon Capture and Sequestration	Several technologies allow carbon dioxide to be removed from flue gases for storage in geologic formations or in the ocean. May be a more long-term measure	Based on discussions with Maine DEP, it is proposed that this option be transferred from immediate to long-term consideration for ongoing monitoring and future analysis.
ESW 1.5b	Biomass Gassification	Pressurizing agricultural and forestry biomass to produce a synthesis gas for combustion.	Based on discussions with Maine DEP, it is proposed that this option be transferred from immediate to long-term consideration for ongoing monitoring and future analysis.
ESW1.6	Repowering Old Generating Plants	Converting old plants to natural gas combined cycle (NGCC) or coal integrated gasification combined cycle (IGCC) technology. Both technologies have the potential to provide efficiency improvements and lower emissions per kWh.	The chief plant considered for repowering was the oil-fired William Wyman facility, which accounted for 37% of emissions from electric power in 2000. However, subsequent research has indicated that the plant is likely a poor candidate for repowering due to the fact that it operates as a peaking unit with a low capacity factor and the high potential costs involved. Other potential fossil facilities in Maine are either closed or used for peaking only, making repowering impractical.
ESW 1.7	Hydrogen	Hydrogen is a clean burning fuel that may be produced by IGCC and other power sources and can be used to generate electricity. The magnitude of the resulting emission reductions depends on how the hydrogen is produced.	Based on discussions with Maine DEP, it is proposed that this option be transferred from immediate to long-term consideration for ongoing monitoring and future analysis.
ESW 1.11	Inter-connection Rules and Transmission Barriers	Standardized rules to enable clean, distributed generation to receive authorization to connect to the local grid. Transmission pricing and technical issues are often barriers to renewable and other clean distributed generation (DG), as well as power from independent power producers (IPPs).	Information on potential costs and emission benefits for this option are not readily available. This option is discussed further in the discussion of the Combined Heat and Power (CHP) incentive policy.
ESW 1.13	Registry	Encourage further research and development of regional systems for reporting and tracking of GHG emissions. This would cover electricity and other sectors. Voluntary GHG emissions registry that requires participating entities to separately report direct and indirect emissions or emission reductions. Registries may be used to provide public recognition, baseline protection, and support future emissions trading regimes.	A GHG registry can be an important component of the supporting infrastructure in the Maine GHG Initiative. Current DEP policy is to work with a regional effort headed by NESCAUM.

ADDITIONAL GHG MITIGATION OPTIONS NOT YET QUANTIFIED OR DEFERRED FOR FURTHER STUDY

Work Group Identifier	Title	Description	Further Action Needed
ESW 1.14	Public Education	Any of a variety of methods, including public service announcements and education in schools, that make the public aware of the GHG emissions that come from fossil-fueled electricity generation and the actions people can take to reduce GHG emissions.	This option was referred to the Education Working Group.
ESW 1.15	Hydroelectric Power Development	Three areas were explored: the addition of capacity to existing hydroelectric units; the development of new hydroelectric units at existing dams; and development at undeveloped sites.	Based on discussions with Maine DEP, it is proposed that the third area under this option be transferred from immediate to long-term consideration for ongoing monitoring and future analysis.
BFM 2.7	Fuel Switching	Study opportunities in Maine to switch from electric heat and/or electric hot water systems to lower greenhouse gas alternatives using high efficiency oil or natural gas fired systems.	It was the workgroup's feeling that this matter needed further researched.
BFM 3.5	Load Management Techniques	Maine should fully examine the usefulness of TOU electric meters, rates, and related technologies to allow consumers to respond to price signals and to shift consumption.	Need to see if there is a CO2 benefit to option.
BFM 4.4	Substitution for High GWP Gases	State should explore the use of high GWP (Global Warming Potential) gases. These gases are used as replacements for OSD (Ozone Depleting Substances) mainly used in refrigeration.	Further study of the cost/benefit of this option is needed to evaluate its merits.
BFM 4.5	Industrial Ecology	Beneficial Use in Maine's Industrial Ecology program and is regulated under Chapter 418. Agronomic Use of waste materials is a similar program and is not discussed here. DEP convened a multi-year stakeholder process with the task of reviewing issues related to beneficial use with the overall goal of increasing beneficial use in Maine. The stakeholders' group funded a pilot project through the University of Maine to compile data related to beneficial use of certain materials.	Proposed bill developed by the Maine Beneficial Use Stakeholder Group was intended to promote and encourage beneficial use and recycling of solid waste by providing liability protection under relevant State laws to persons who engage in such activities in accordance with a permit or exemption:
BFM 4.6	Negotiated Agreements	Include GHG reduction projects as acceptable Supplemental Environmental Project (SEP). A SEP is an environmentally beneficial project that a company performs in exchange for a reduction in penalty associated with violation of an environmental regulation or statute, but it is in addition to the actions necessary to bring the company into compliance.	LD845 Climate Change: This bill requires new sources of greenhouse gases to be reported to the Department of Environmental Protection. The bill also requires the department to enter into carbon emission reduction agreements with nonprofit organizations and businesses.
BFM 5.4	Incentives for Green Power Purchases	Study the potential of promoting green power purchasing beyond State owned and operated buildings.	The BFM workgroup thought that there may be merit in expanding #34, State Green Power Purchases, to included residential and commercial consumers.

ADDITIONAL GHG MITIGATION OPTIONS NOT YET QUANTIFIED OR DEFERRED FOR FURTHER STUDY

Work Group Identifier	Title	Description	Further Action Needed
BFM 5.8	REC Purchase Program	To help reduce the cost of renewable energy by brokering the renewable energy credits (RECs) purchased from commercial and residential owners of renewable energy systems. The State will offer owners of renewable energy systems the opportunity to sell their renewable energy credits (RECs) to the State, which can then broker these RECs on the open market. The amount of the payments depends on the current market demand for the type of renewable energy technology, the amount of electricity produced by the system, and the length of the contract period.	Not determined at this time.
BFM 5.11	Natural Gas Leak Reduction	Study the potential for the reduction from leaks from LNG systems. Existing federal program – EPA Natural Gas Star Program - aims to reduce methane leaks from natural gas pipelines	Needs more study to analyze CO2 benefits and cost to implement.
TLU 1.1d	Add-on Technology (Low Friction Tires / Low Friction Oil)	Support technologies that improve efficiency in vehicles	Voluntary program with education effort to inform consumers on the benefits of technologies.
TLU 1.2b	Vehicle Maintenance / Driver Training	Encourage more energy efficient driving habits and increase awareness of maintenance issues that cause an increase in vehicle operating cost and increase pollution.	Not determined at this time.
TLU 1.2c	Transportation System Management	Use Technology, signage and other measures to mitigate traffic congestion	Not determined at this time.
TLU 1.3d	Provide Tax Credits for Efficient Vehicles	Offer tax credits for car buyers to purchase a low-GHG emitting car.	Not determined at this time.
TLU 2.4a	Commuter Choice	Promoting employer-based commuter incentives for transit and carpooling (includes transit benefits, parking cash-out, telecommuting, vanpools, preferential parking)	Workgroup needed more time to identify cost of individual options and CO2 benefits. But recommend this option as a voluntary program.
TLU 2.4b	VMT Tax	Tax on the number of miles driven per year per vehicle with revenues targeted towards low-GHG travel alternatives	Workgroup dropped this from the initial list of options because of time constraints.
TLU 2.4c	Fuel Tax with targeted use of revenues	A fuel targeted to a low-GHG option such as funding transit, hybrid vehicles, etc with revenues targeted towards low-GHG travel alternatives.	Workgroup dropped this from the initial list of options because of time constraints.
TLU 2.4e	Road Pricing	Toll pricing to encourage multi-occupant vehicles and travel during lower congestion periods	Not determined at this time due to time constraints.

ADDITIONAL GHG MITIGATION OPTIONS NOT YET QUANTIFIED OR DEFERRED FOR FURTHER STUDY

Work Group Identifier	Title	Description	Further Action Needed
TLU 2.4f	Location Efficient Mortgage	Location-Efficient Mortgages (LEM) – is a discounted mortgage that recognizes the savings available to people who live in location efficient communities, mixed-use communities near public transportation.	Workgroup dropped this from the initial list of options because of time constrains. Was also referred to BFM workgroup.
TLU 2.4j	VMT Offset Requirements from large developments	Require developer to offset automobile emissions attributed to their development (e.g., through transportation infrastructure changes, incentives for low-GHG modes, building efficiency improvements, tree planting, purchases of emission credits, etc.)	Workgroup dropped this from the initial list of options because of time constrains.
TLU 3.4	Hydrogen Infrastructure	Support research on low-GHG hydrogen vehicle technology and infrastructure. This could include such components as: fuel cells, how best to facilitate the development of alternative fuel infrastructure and refueling networks, pilot projects and R&D and /or incentives.	Workgroup was interested in this option as a future technology option, but felt it is too new an option.
TLU 5.3	Aircraft Emission	More efficient operation of aircraft	Not determined at this time.
TLU 5.4	Airport Emissions	Use of low GHG airport equipment and better runway management	Not determined at this time.
TLU 6.4	Incentives to purchase low GHG recreation vehicle alternatives	Offer tax breaks or rebates for purchase of low GHG recreation vehicles. (4 stroke vs. 2 stroke)	Not determined at this time due to time constraints of process.
TLU 7.2	Improve GHG Data Collection	Make available local data sets to replace regional and national data. The closer to the source the better the data and the more accessible that data is.	Coordinate data collection efforts and make recommendations to state agencies to supply better data for evaluating GHG performance measures.
F 8.0	Increased Age of Forest Stands	Over the next 15 years, identify hardwood stands under relatively short pulpwood rotations that can be shifted to significantly longer saw timber rotations.	Support development of durable wood products markets targeted to hardwood saw timber. Identify marginal economic sites for all stands that can be removed from production and maintained in permanent forest cover, particularly in areas with high environmental attributes. Focus forest preservation programs on mature timber stands to reverse the disproportionate clearing of this land, and reduce disease and pest risks as possible to maintain continuous growth of existing stands.

OPTIONS FOR FUTURE CONSIDERATION ADDED BY STAKEHOLDERS OR DEP AFTER 6/30 STAKEHOLDER MEETING

Work Group Identifier	Title	Description	Further Action Needed
BFM 6.1 (new)	Educate and encourage landscaping practices that reduce energy use	Educate homeowners and landscaping professional on methods that well planned and maintained landscape can help reduce energy use	Not determined at this time.
BFM 6.2 (new)	Educate homeowners on energy saving options and cost saving	Provide information to homeowners on options that reduce energy use when retrofitting, renovating and new construction.	Not determined at this time.
BFM 6.3 (new)	Tax credits or rebates to purchase low energy alternative appliances	When purchasing a new appliance offer incentives to making a low energy appliance purchase.	Not determined at this time.
BFM 6.4 (new)	Energy Audits	Offer an energy audit program to all sectors (residential, commercial and industry) effective energy savings options.	Not determined at this time.
TLU 8.2 (new)	Highway Weight Limits	Increase the current weight limit on state highways to reduce VMT by heavy diesel vehicles	Not determined at this time. Suggested as an adjunct to Option #41, but not modeled.
TLU 9.0 (new)	CAFÉ	Support federal efforts to increase CAFÉ standard.	Provide support for the Maine delegation and work with of interested parties in requesting an increase in the national CAFÉ standard.
F 9.0	Short Rotation Woody Cropping	Over the next 15 years, explore the use of short rotation woody crops using hybrid willow or poplar species on non forested sites, including cropland, riparian zones, eroded lands, rights of ways, and pasture. Manage crops for wood products and bioenergy to displace fossil energy emissions. Use waste manure where possible for fertilization to minimize nitrous oxide emissions from synthetic fertilizers.	Additional research and development and commercialization programs may be needed. Costs of producing carbon credits have not yet been estimated for Maine, although preliminary investigation in New Brunswick suggests use of hybrid poplars sequesters 30-75 metric tons of CO_2 *per* acre-year at a cost of $2-3 *per* tonne. This Option could be utilized with the following one (F 10.0, Afforestation).
F 10.0	Afforestation	This option calls for establishment of forests on underutilized or abandoned cropland and pastureland.	The Maine Woods WISE program estimates tree planting costs for afforestation at $170 per acre.[79] Total future carbon sequestration from increased stocking of faster growing trees on poorly stocked sites is estimated at 26.90 MT carbon per acre. This translates into a cost of saved carbon equal to $6.31 per ton carbon, or $1.72 per ton CO2 saved.

[79] Guidelines and data from the Woods Wise program to support private forestland owners are available at: http://www.maine.gov/doc/mfs/woodswise/steward.html

ADDITIONAL BASELINE GRAPHS

Figures 4 and 5 present the emissions baseline based on the proportionate share of Maine emissions associated with each of four sectors: Transportation; Buildings, Facilities, and Manufacturing; Energy and Solid Waste; and Agriculture and Forestry. It should be pointed out, however, that there was no legislative requirement or Departmental intent that the recommended mitigation options exactly correspond to each sectors' emissions. Rather, the emphasis has been on identifying a suite of options sufficient to meet the *overall* emissions reduction target.

Figure 4: All-Sector Emissions Baseline without Black Carbon

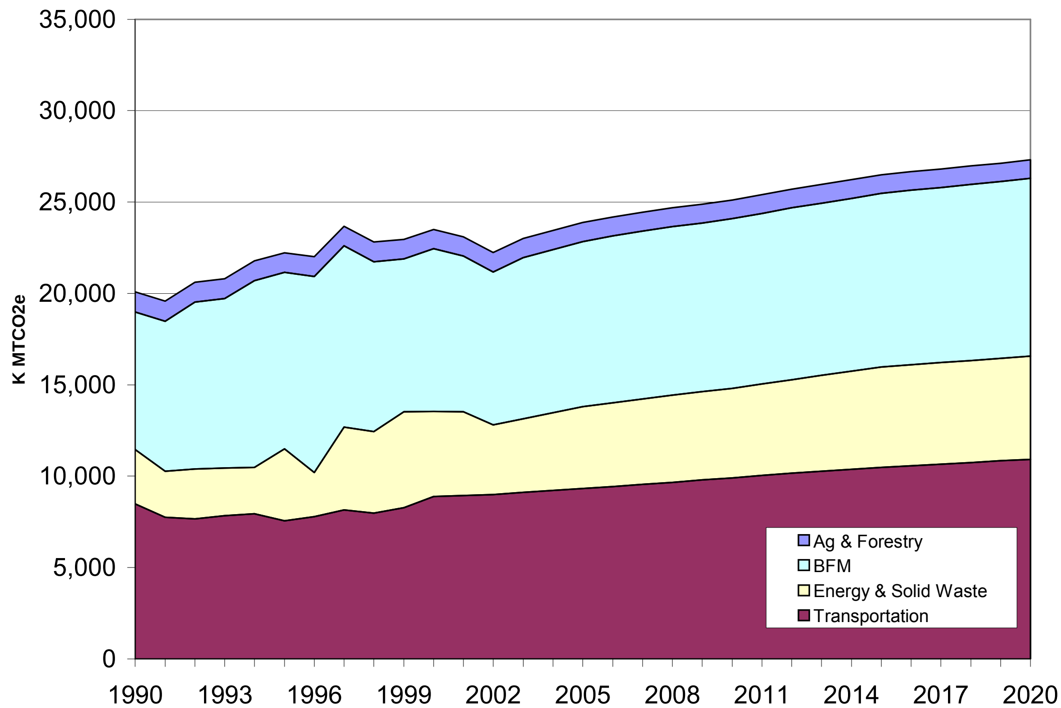
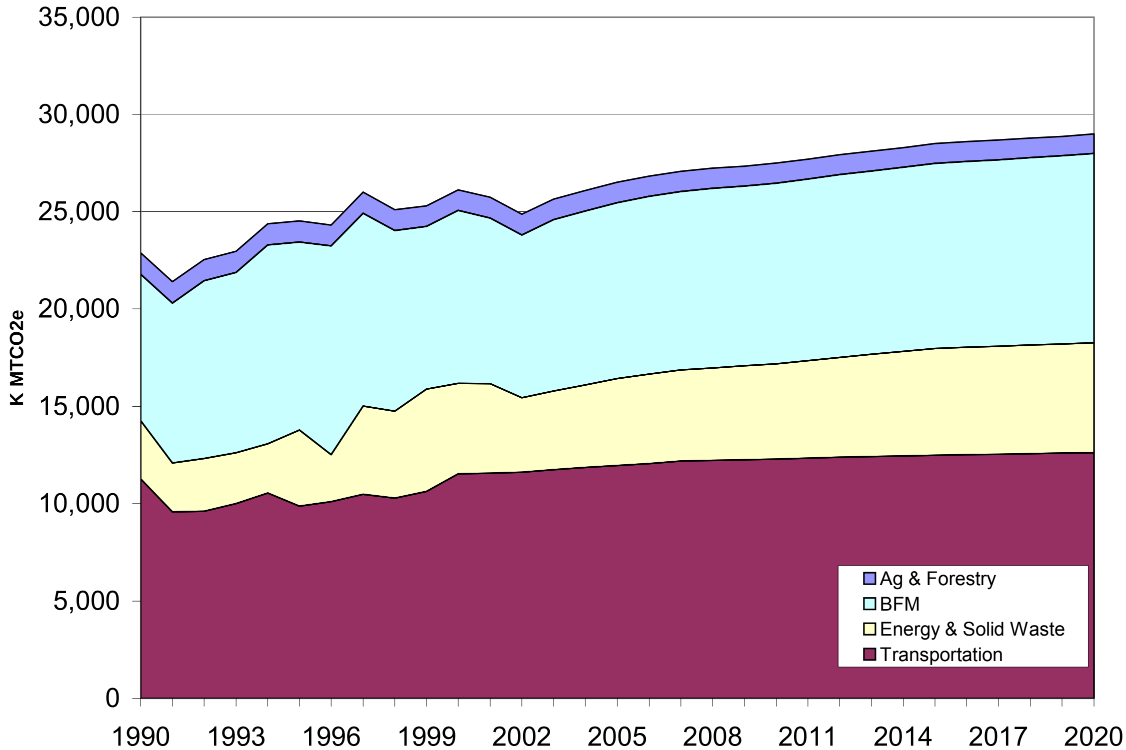


Figure 5: All-Sector Emissions Baseline with Black Carbon



MAINE CLIMATE ACTION PLAN 2004

VOLUME TWO: APPENDICES

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APPENDIX 1: AN ACT TO PROVIDE LEADERSHIP IN ADDRESSING THE THREAT OF CLIMATE CHANGE (L.D. 845, 2003)

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PUBLIC LAWS OF MAINE
First Regular Session of the 121st

CHAPTER 237
H.P. 622 - L.D. 845

An Act To Provide Leadership in Addressing the Threat of Climate Change

Be it enacted by the People of the State of Maine as follows:

Sec. 1. 38 MRSA c. 3-A is enacted to read:

CHAPTER 3-A
CLIMATE CHANGE

§574. Definitions

As used in this chapter, unless the context otherwise indicates, the following terms have the following meanings.

1. Greenhouse gas. "Greenhouse gas" means any chemical or physical substance that is emitted into the air and that the department determines by rule may reasonably be anticipated to cause or contribute to climate change. "Greenhouse gas" includes, but is not limited to, carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride. Rules adopted by the department pursuant to this subsection are routine technical rules as defined in Title 5, chapter 375, subchapter 2-A.

2. Sector. "Sector" means one of the 5 sectors identified in the climate change action plan adopted by the Conference of New England Governors and Eastern Canadian Premiers in August 2001. The 5 sectors are the transportation, industrial, commercial, institutional and residential sectors.

§575. Lead-by-example initiative

The department shall establish a lead-by-example initiative under which the department shall:

1. Greenhouse gas emissions inventory for state-owned facilities and state-funded programs. Create an inventory of greenhouse gas emissions associated with state-owned facilities and state-funded programs and create a plan for reducing those emissions to below 1990 levels by 2010;

2. Carbon emission reduction. By January 1, 2006, seek to establish carbon emission reduction agreements with at least 50 businesses and nonprofit organizations;

3. New England greenhouse registry. Participate in a regional effort to develop and adopt a greenhouse gas registry that includes 3rd-party verification; and

4. Statewide greenhouse gas emissions inventory. Create an annual statewide greenhouse gas emissions inventory.

§576. Reduction goals

The State's goals for reduction of greenhouse gas emissions within the State are as follows:

1. Reduction by 2010. In the short term, reduction to 1990 levels by January 1, 2010;

2. Reduction by 2020. In the medium term, reduction to 10% below 1990 levels by January 1, 2020; and

3. Long-term reduction. In the long term, reduction sufficient to eliminate any dangerous threat to the climate. To accomplish this goal, reduction to 75% to 80% below 2003 levels may be required.

§577. Climate action plan

By July 1, 2004, the department, with input from stakeholders, shall adopt a state climate action plan to meet the reduction goals specified in section 576. The action plan must address reduction in each sector in cost-effective ways and must allow sustainably managed forestry, agricultural and other natural resource activities to be used to sequester greenhouse gas emissions. The department shall submit the action plan to the joint standing committee of the Legislature having jurisdiction over natural resources matters.

§578. Progress evaluation

By January 1, 2006 and by that date every 2 years thereafter, the department shall evaluate the State's progress toward meeting the reduction goals specified in section 576 and shall amend the action plan as necessary to ensure that the State can meet the reduction goals. Starting no earlier than January 1, 2008, the department may recommend to the joint standing committee of the Legislature having jurisdiction over natural resources matters that the reduction goals specified in section 576 be increased or decreased.

Effective September 13, 2003, unless otherwise indicated.

APPENDIX 2: ECONOMIC AND MODELING ASSUMPTIONS

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Appendix 2.1

MEMORANDUM

TO: Maine GHG Stakeholder Group
FROM: Center for Clean Air Policy
DATE: April 1, 2004

RE: **Population and Economic Forecasts, Discount Rates**

The intent of this memo is to outline the Work Group discussions and recommendations regarding (1) the underlying population and economic assumptions that will be used to forecast greenhouse gas emissions and (2) the selection of a discount rate that will be used to analyze the cost-effectiveness of the priority measures to reduce GHG emissions.

Population Forecast

The population forecast will be used in the baseline forecast of greenhouse gas emissions and in evaluation of mitigation options. Several Work Groups discussed the forecast of population growth and considered the following sources: EIA's Annual Energy Outlook (national), 2004; Charles Colgan, University of Southern Maine; and the Maine State Planning Office (SPO). The Buildings, Facilities and Manufacturing Work Group felt most comfortable with the Charles Colgan medium forecast because it used Maine data and covered the time period of the analysis. This was supported by the Energy and Solid Waste Work Group.

	EIA's Annual Energy Outlook 2004 [1]	Charles Colgan, USM [2,3]	Maine State Planning Office [2]
Forecast Period	2004-2025	2004-2025	2004-2017
POP (low)	0.60%	1.00%	
POP (med)	0.80%	1.15%	0.70%
POP (high)	1.00%	1.30%	

[1] National
[2] State of Maine
[3] Preliminary

Economic Forecast

The economic forecast will be used in the baseline forecast of greenhouse gas emissions and in evaluation of mitigation options. The forecast of economic growth was discussed in the Buildings, Facilities and Manufacturing Work Group and the Energy and Solid Waste Work Group. The Work Groups considered the following forecasts: EIA's Annual Energy Outlook (national), 2004; Charles Colgan, University of Southern Maine; and the Maine State Planning Office (SPO) (see table below). The EIA GDP forecast extends from 2004 to 2025, as does the Charles Colgan GSP forecast. However, the SPO only has a short-term economic forecast to 2007. The Buildings, Facilities and Manufacturing Work Group felt most comfortable with the Charles Colgan medium forecast because it used Maine data and covered the time period of the analysis. This was supported by the Energy and Solid Waste Work Group.

	EIA's Annual Energy Outlook 2004 [1]	Charles Colgan, USM [2,3]	Maine State Planning Office [2,3]
Forecast Period	2004-2025	2004-2025	2004-2007
GDP (low)	2.40%	3.0%	
GDP (med)	2.97%	3.5%	2.85%
GDP (high)	3.45%	4.0%	

[1] National Gross Domestic Product

[2] Gross State Product

[3] Preliminary

The BFM Work Group is in the process of investigating the industrial sector component of this economic forecast. The BFM WG believes that the economic indicator for industrial growth should be constant or declining over time (with the exception of the tourism sector). Once forecast is determined, it will be used to estimate future emissions from fossil fuel combustion in Maine's industrial sector.

Discount Rate

The Maine Department of Environmental Protection has recommended the use of a consistent discount rate across all sectors (e.g., transportation, industry, residential, etc.). Consistency is important for policy analysis as it allows decision-makers to compare the cost-effectiveness of different measures across various sectors.

One option for a consistent discount rate is the Federal Reserve Prime Rate, the average over the last five years (1999-2003) is 6.58% and the 2003 rate is 4.12%. The US Federal Government Office of Management and Budget recommends using a discount rate of 7% for regulatory analysis. The 7% rate, an estimate of the average before-tax rate of return to private capital in the US economy, reflects the returns to real estate and small business capital as well as corporate capital.

Due to their tax exempt status, states have a lower discount rate – about 5%. Note that the Maine State Planning Office does not currently have a recommended discount rate that they use for policy analysis. As a point of reference, Rhode Island used a discount rate of 5% in analysis of greenhouse gas mitigation options that the Rhode Island Legislature's Policy Offices uses for all legislative and policy analysis, whereas Connecticut used a discount rate of 7%.

The Buildings, Facilities and Manufacturing Work Group had a lengthy discussion regarding the selection of a discount rate. They pointed out that the private sector uses higher discount rates to evaluate investments. This discount rate reflects the capital constraints and preference for short payback periods, and high internal rates of return that are often required by the private sector. For example, the BFM Work Group suggested a 12% discount rate for the residential sector, 30% discount rate for the commercial sector, and a 50% discount rate for the industrial sector. However, this process will not delve into the details of which sectors the investments will come from (i.e. government v. private). Therefore, application of a private discount rate might be more appropriate in the future during the stage of final program design as a check regarding whether expected levels of customer investment/contribution are likely to occur.

Appendix 2.2

Electricity Sector Modeling Approach

The Tellus Institute worked with the Center for Clean Air Policy in developing the baseline emissions for the electric sector and to estimate the emissions and costs for the following policies: Renewable portfolio standard, system benefits charge, energy efficiency, combined heat and power, GHG emission standards and GHG emission offsets.

Develop preliminary electricity supply baseline. Tellus developed the baseline for the electric sector in Maine using the output from the National Energy Modeling System (NEMS). NEMS is the primary mid-term modeling tool used by the Energy Information Administration. CCAP worked with members of the Maine electricity working group to review and identify any changes to the assumptions in NEMS for the performance characteristics (capacity, costs, efficiency, fuel mix) of existing and potential new plants. Tellus applied the identified adjustments to NEMS and ran the model under reference case conditions (ie. assuming no additional policies). Tellus then calculated the GHG emissions for Maine (accounting for both emissions that occur in-state and net emissions from imports or exports). See next section for further details on this approach for calculating electricity emissions at the state-level. In addition to GHG emissions Tellus used NEMS output to estimate electric sector generation and capacity (including new builds), fuel consumption, and costs. All results were calculated for the 2005 to 2025 period.

Modeling of key policies. Tellus used NEMS (including the adjustments from the base case) to model the set of electric supply policies identified by the working group. NEMS allows the user to change parameters for total electricity demand, incentives for renewables, and disincentives for GHG emissions. Tellus adjusted these parameters to reflect each of the electric supply policies. Emission reductions and costs reflect the differences between each policy case and the base case, based on changes in Maine, rather than to the whole NERC region. As in the base case, the policy case results account for any changes in net exports.

Appendix 2.3

Production and Consumption Emissions:
The Implications for Greenhouse Gas Mitigation in the Electricity Sector
Center for Clean Air Policy
March 2004

Introduction

The decision of whether to measure emissions from the electric power industry on the basis of production or consumption has important implications for greenhouse gas (GHG) mitigation programs. It can significantly impact the total reductions required and the estimation of the performance of GHG mitigation measures such as renewable portfolio standards. This memo presents an analysis of these issues.

The issue of production versus consumption arises in restructured electricity markets, where electric power plants all generate and sell power into a single local grid. Unlike traditional commodities, after electricity is produced, it is physically impossible to track from individual power plants to the final destination. It therefore cannot physically be identified as meeting the demand of particular customers. The total generation of each individual plant and of the entire region, state or locality can be determined, however, as can the total demand in aggregate.[*] In some self-contained electricity markets, the total demand is equal to the total generation. In most markets, however, electricity is transmitted for sale across borders, and the total generation within the territory therefore differs from the total demand. In cases where the generation exceeds total demand the state is a net exporter selling power to other regions; where generation is lower than demand the state is importing power.

Total emissions can be estimated based either on total generation or total demand. When transmission of electricity between states is significant, these production and consumption emissions will in general be different due to the difference in total kilowatt-hours. They will also differ if the fuel mix of generation in the state and the surrounding areas has different emissions characteristics. The estimation methods and the issues associated with production and consumption emissions are discussed below.

Production versus Consumption Emissions

Production-based emissions are based on the total level of electricity generation within a state. They are estimated by taking 100% of emissions from all electric generating units located within the state. The production approach is the generally accepted method for estimating emissions. All emission trading systems implemented thus far in the United States and elsewhere to regulate SO_2, NO_x and CO_2 have been production-based. Since it is based on taking all emissions within a given territory, the production standard is also consistent with the methodology used by the Intergovernmental Panel on Climate Change (IPCC) for estimating national GHG emissions, as well as with computer models used for national and regional analysis of the US electric power industry (e.g., ICF Consulting's Integrated Planning Model (IPM), US Energy Information Administration's National Energy Modeling System [NEMS]). Its key strength is that the methodology used

[*] In this memo, to avoid confusion it is assumed that the electricity market is an individual state that may also export or import power to or from surrounding states or regions.

is simple, accurate and widely accepted, and the data required (usually total fuel consumption) is readily available. In states where the number of emission sources is small, production-based estimation may allow for independent verification of emission estimates: emissions calculated from fuel use can be verified using continuous emissions monitoring at the exhaust stack, and vice versa.

Another advantage of using a production-based standard at the state or regional level concerns its compatibility with a potential national GHG regulation program. While the exact structure of a future US GHG cap and trade program is uncertain, based on the experience of the SO_2 and other programs in the United States it is expected that national GHG regulation would employ a production-based standard. Each individual generating unit would therefore be responsible for 100% of its total GHG emissions, regardless of consumption levels. The use of a production standard by states would therefore be consistent with the national program, while a consumption approach would not. This could ease the transition from state to national regulation, and could potentially reduce the costs incurred by the states in the process.

Despite the strengths of the production approach, it may nonetheless be deemed unsuitable for some GHG mitigation programs. In states with significant interstate transmission, the production approach will fail to account for all emissions (and therefore the environmental impact) from the total consumption of electricity within the state. Electricity consumption within a state that imports power, for example, will account for some of the emissions produced in the exporting areas, but this impact will not be captured under a production approach. In the case of a state that exports power, generation will exceed demand, so a production approach would cause the state to account for emissions that have been produced to meet the demand of consumers in other regions. In such cases the use of a production approach may give rise to questions of equity and responsibility for emissions. The use of a consumption approach may be more appropriate in such cases.

Consumption emissions are based on total electricity demand within a state, and thus account for imports (or exports) of power from (or to) other areas. As discussed above, the key benefit of a consumption approach is that in cases where electricity transmission flows are significant, it provides a method of estimating and accounting for a level of emissions representing all and only those that arise from consumption within the state itself. A consumption approach has drawbacks, however. One issue is that the consumption standard is controversial. It has not been employed for GHG regulation, and no generally accepted estimation method exists. The data required is also likely to be more difficult to obtain than in the case of production emissions. A consumption approach may give rise to responsibility questions of its own, since an exporting state could employ consumption-based estimates to hold other states or regions accountable for some of the emissions from the exporting state. In all but a few special cases (e.g., power plants are connected to a single transmission line sending all of the power into a neighboring state), the total electricity consumption and emissions cannot be traced to a group of specific plants, so consumption emissions cannot be verified. Emission estimates based on consumption therefore typically represent allocations on paper rather than actual physical emissions that can be measured.

In restructured markets, at least two general methods for estimating emissions on a consumption basis exist:

- One approach is to treat the state market as a unified part of a larger market to or from which it imports or exports power (e.g., the Maine market is taken as a component of the New England Power Pool). The annual emissions are then taken as the product of the total state demand and the average regional emission rate (method #1). This is the approach that the Tellus Institute appears to have used in developing Rhode Island's GHG Plan.

- A second approach treats the state as a distinct unit, with emissions from the power imported or exported added or subtracted from the total production emissions (method #2). In states that import power it is assumed that all of the generation in the state is consumed within the state, and the emissions for imports only are estimated by adding the product of the net power imports and the average regional emission rate to the production emissions. In exporting states all of demand is assumed met by in-state generation, and the product of the net power exports and the average state emission rate is subtracted from the production emissions to obtain the consumption emissions. Unlike the first approach, with this approach the consumption emissions will always exceed production emissions in importing states, and will be lower than them in exporting states.

These two approaches will produce different estimates of consumption emissions due to differences between the average emission rate of the state and that of the surrounding region. For example, in the case of an exporting state that has an average emission rate that is lower than the regional rate (perhaps due to a higher level of renewable energy generation), the consumption emissions estimated using method #1 will be higher than those obtained with method #2. (This has typically been the case with Maine in most years since 1990, as will be discussed below.)

Implications for GHG Mitigation

The decision of whether to adopt a production versus a consumption approach for estimating emissions will have significant implications for a state, as well as for the surrounding region. In New England, for example, the regional effort to regulate GHG emissions to meet the NEGA/ECP targets ultimately will need to ensure that each state adopts a consistent standard for estimating GHG emissions. In selecting a standard for a GHG reduction program a state may wish to consider the level of total reductions required and the mitigation measures to be employed. Goals for GHG mitigation programs are typically set in terms of emission levels to be achieved in a future year (e.g., 2010) equal to a share of the total emissions in a past baseline year (typically 1990). Since the selection of a production or consumption approach will typically produce different estimates in any given year, the total reductions that would be required in a GHG program may be significantly different under each approach. It should be further noted that with a consumption approach, the estimated reductions required may also vary depending upon the particular method used to estimate the consumption emissions.

The table below displays estimates of the annual emissions in the state of Maine from 1990 through 2000. The emissions have been estimated using a production approach, a consumption approach using method #1, and a consumption approach using method #2. The total kilowatt-hours associated with both approaches are displayed as well. Consumption emissions with method #1 exceed production emissions in all years due to the much higher regional (compared to the state) emission rate. Maine was a net exporter of power in most years, and consumption emissions with method #2 were typically lower than production emissions. It should also be noted that the consumption emissions are significantly higher when estimated using method #1 than with method #2, again due to the difference between the regional and state emission rates.

The table shows that over the 1990-2000 period, GHG emissions are estimated to have increased by 1.2 MMTCO$_2$e under the production approach, by less than 0.1 MMTCO$_2$e under a consumption approach using method #1, and by 1.5 MMTCO$_2$e using method #2. Therefore, if the state had adopted a policy of lowering electric power emissions in 2000 to 1990 levels, the reductions required under each approach would have been significantly different. It should be noted that under a consumption approach using method #2, the total reductions required would have been 0.3 MMTCO$_2$e higher than under a production approach even though the annual emissions are lower in both 1990 and 2000 in the former case. The use of a consumption approach with method #1 would have enabled the state to meet the 1990 target with only minimal reductions.

Maine CO_2 Emissions and Generation (MMTCO$_2$e)					
Year	**From Production**		**From Consumption**		
	Generation (million MWh)	**Emissions (MMTCO$_2$e)**	**Generation (million MWh)**	**Emissions (MMTCO$_2$e) #1**	**Emissions (MMTCO$_2$e) #2**
1990	15.9	3.1	11.5	4.8	2.2
1991	17.3	2.6	11.4	4.8	1.7
1992	15.7	2.6	11.5	4.5	1.9
1993	15.6	2.3	12.0	4.2	1.7
1994	16.5	2.4	11.6	4.2	1.6
1995	9.8	2.3	11.6	4.4	3.0
1996	14.9	2.0	11.7	4.6	1.5
1997	10.3	2.8	12.0	6.0	3.6
1998	11.0	3.3	11.6	5.6	3.6
1999	12.7	4.6	11.9	5.2	4.4
2000	14.0	4.3	12.2	4.9	3.7
Total	153.8	32.2	128.9	53.2	28.9

Another important issue concerns the impact of the emissions standard selected on the performance of the specific GHG mitigation measures. Measures taken to reduce GHG emissions within a given state will often affect the electric power industry in surrounding areas. In such cases, the use of a production approach may not capture the full emission impacts in these areas. For example, the adoption of a state renewable portfolio standard may alter the structure of the regional power market, perhaps by encouraging the development of new renewable facilities in other areas hoping to export power to the state. Another example would be the adoption of a generation performance standard on all plants within the state. Such a policy would likely increase the cost of generating electricity from in-state plants, and could therefore decrease in-state generation and increase the level of power imported from surrounding areas. In such a case the use of a production approach would show a drop in total emissions even if total state demand does not change. Consumption-based emissions may therefore allow a state to better estimate the total regional impact of in-state programs. In all cases, however, the specific impacts of selecting a production or consumption approach will depend upon the structure of the electricity market and the interactive effects of the policies adopted. Thus, while in many cases a consumption standard may be a more appropriate method of estimating the regional impacts of in-state GHG policies or programs, in others a production standard may be just as useful.

The key attributes of production and consumption emissions are summarized in the following table.

Estimate	Basis	Imports/ Exports Included	Benefits	Drawbacks	Accounts for Out-of-State Activities
Production	Generation	Exports only	Simple, direct estimation method; widely accepted; consistent with other emission regulation programs and computer models; can be verified	Does not account for interstate or interregional transmission	Typically not
Consumption	Demand	Imports Only	Accounts for interstate transmission; allows responsibility for all and only those estimated emissions from in-state consumption	No generally accepted method of estimation; cannot be independently verified; more difficult to obtain data	Yes

APPENDIX 3: ISSUE DISCUSSIONS

3.1 Black Carbon

3.2 Carbon Accounting for Bio-mass

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Appendix 3.1

Memorandum

TO:	Stakeholder Group, Maine GHG Initiative
FROM:	CCAP, Environment Northeast
SUBJ:	Overview of Black Carbon
DATE:	4/1/2004

This memo provides an overview of black carbon (BC) emissions, which are the result of incomplete combustion of carbon-based material, including transportation, power generation and biomass combustion.

Sources of Black Carbon

Black carbon is defined as the absorbing component of carbonaceous aerosols (fine particles in the air) in soot (particulate matter or PM). The latest science on BC indicates it may be responsible for as much as 25% of global warming to date.[1] Up to half of BC emissions result from transportation, with the remainder occurring from power plants, industrial processes and the burning of vegetation.[2] Estimating transportation BC emissions is more straightforward than in other sectors. BC emissions arise from solely from diesel fuel (e.g., trucks, buses and off-road/construction equipment), and the data is more readily available. Of the remainder (e.g., black carbon in the electric power industry), more research is necessary determine the amount of BC generated, including industrial boilers and commercial home heating, where wood-burning stoves and heating oil may contribute significant BC emissions. Finally, biomass burning likely has a considerable impact on BC, but defining specific sources and relative contributions has proven challenging and has not yet been addressed.

Baseline and Emissions Forecasts

Developing a black carbon baseline requires three steps, including: 1) calculating historic BC emissions, developing a forecast of BC emissions and, 3) converting BC emissions to CO_2-equivalent emissions. Roughly speaking, black carbon warming impacts are determined by estimating the insoluble organic fraction of carbon-based PM generated by combustion of diesel fuel in Maine's transportation sector and converting to equivalent metric tons of CO_2.[3] Given the uncertainty inherent surrounding BC production from electricity generation and residential and commercial it may be necessary to adjust these GHG sector baselines in the future, as data become more precise. At that time, it is anticipated that the GHG baselines will need to be adjusted using the process likely to be adopted by the NEG/ECP (i.e., every three years).[4]

[1] Jacobson, M.Z. (2002). Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. Journal of Geophysical Research, 107(D19), ACH 16, 1-22. Other leading climate scientists (e.g., James Hansen) have measured atmospheric conditions driven by black carbon aerosols that generally support Jacobson's modeling-based estimates of the magnitude of BC climate impact.

[2] Recent research from has found that up to half of black carbon is from the transportation sector (Streets, Bond).

[3] While much work has been done on this by Environment Northeast, Energy and Environmental Analysis, Inc, and others, such estimates are still a source of uncertainty. Further refinement will be necessary as the scientific understanding of black carbon evolves.

[4] The issue of black carbon will be taken up formally at the upcoming NEG/ECP meeting scheduled for summer 2004.

Potential for Control Technologies to Reduce Transportation BC

Recent federal engine and fuel regulations will play a role in reducing black carbon emissions. Specifically, these include: 1) current U.S. Environmental Protection Agency (EPA) rules which set standards for all new on-road engines that will achieve 90 percent reductions in PM beginning in 2007; 2) pending EPA rules requiring similar reductions for all new nonroad engines (to phased in between 2008 and 2014); and 3) federal fuel standards for low sulfur and ultra low sulfur. This combination of engine and fuel standards will allow for the use of new advanced retrofit technologies, which can reduce BC emissions by 90% (and in some cases up to 99%). Successful integration and use of new PM-control technologies can maximize the BC benefits in Maine while providing health benefits from reduced exposure to diesel exhaust, which is linked to lung cancer and respiratory ailments.

For Maine to achieve these levels of BC reduction from transportation sources will require the adoption of advanced technologies such as particulate traps and catalyzed filters and allow the state to achieve the levels of BC reductions as a result of new federal engine and fuel regulations mentioned above.[5] Doing so will require a statewide process (e.g., a system of incentives and regulations) that incorporates engine turnover rates, the availability of low sulfur fuels and the market availability of the various control technologies.[6] However, the climate benefits from such initiatives will still take considerable time to achieve, given that average vehicle turnover for heavy-duty trucks is 30 years. Of interest, the Maine Transportation Working Group has raised the fact that Maine truck engine turnover rates may be considerably lower, (i.e., 10 year lifetime) which may offer further incentive to reduce transportation BC emissions in the state.

Black Carbon in the Connecticut GHG Reduction Process

The Governor's Steering Committee (GSC) asked Connecticut (CT) stakeholders to formulate policy recommendations to help the State to make progress toward or beyond GHG targets established by the New England Governors/Eastern Canada Premiers (NEG/ECP) Climate Change Agreement of 2001. As part of this process, stakeholders formulated recommendations to include black carbon as another GHG toward NEG/ECP targets. The CT Transportation Working Group agreed to make an adjustment to the baseline to include BC emissions, which increased the absolute baseline but total percentage difference between 1990 and 2020 transportation GHG emissions remains the same. Other sectors did not account for BC due to the lack of data.

Black Carbon Questions for Maine Stakeholders

Stakeholders must decide whether or not to quantify BC in the state and if so,

- Should we include BC in the Transportation sector baseline?
- Given data limitations, is it appropriate to analyze BC in the Transportation sector and not in the others?

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[5] Cost estimates developed during in the Connecticut GHG process indicate an estimated cost of \$6 – 14 per $MTCO_2e$ reduced.

[6] Environment Northeast, which contributed to this memorandum, has developed a suggested approach to integrate new PM control technologies into Maine's current fleet of on-road and off-road vehicles. This will be shared with the Transportation Working Group and other interested parties.

- If BC is included in the baseline, should BC savings be estimated from all existing options?
- Should we formulate new options specifically designed to reduce BC?

Appendix 3.2

TO: Maine DEP, Maine GHG Initiative
FROM: Thomas D. Peterson, LLC, Agriculture and Forestry Working Group consultant
SUBJ: Maine Forestry Carbon Accounting
DATE: 11/18/2004

This memo details the accounting systems used in the Forestry Technical Working Group in the Maine Stakeholder Advisory Group process, including consistency with and adjustments to IPCC and US National Communications guidelines.

The Maine Stakeholder Advisory Group (SAG) and Technical Working Groups (TWGs) used generally accepted accounting principles and guidelines from other state and substate greenhouse gas mitigation plans (CT, NY, Puget Sound, RI) with adjustments for specific new issues in Maine. These guidelines are based upon and consistent with emissions inventory guidelines of the Intergovernmental Panel on Climate Change (IPCC) and US National Communications of mitigation actions.[7] However, in key areas the IPCC guidelines and National Communications are incomplete or inconsistent when applied at a state level (*e.g.*, treatment of imports and exports, treatment of displacement effects across sectors).[8] The Forestry TWG worked closely with the US Forest Service Northern Global Change Research program to apply and develop accounting practices consistent with national forest carbon inventory and modeling systems, and to create adjustments for state application that can be institutionalized in future by the US Forest Service.[9]

The Maine SAG process augmented or adjusted existing principles and guidelines based on the generally accepted principal that *states are responsible for emissions and emissions reductions that occur as a result of actions taken within the state boundary*, even if the emissions impacts occur outside the boundary. Conversely, states are not responsible for exported emissions associated with import actions by other states. For instance, emissions from electricity consumption within a state are counted even if they result from the import of power or raw material generated outside the state (a consumption based system). States are not responsible for emissions from exported electricity that is generated in the state. As a consequence, emissions associated with imports were included, and emissions associated with exports were excluded in the inventories and mitigation analyses for all sectors in the Maine SAG process.[10] For information purposes calculations of production-based emissions were developed in some sectors.

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[7] See following memo, pp. 24 ff. from Wiley Barbour, Managing Director, Environmental Resources Trust, Washington DC, 2004.

[8] K. Pingoud a, B. Schlamadingerb, S. Grönkvistc, S. Brownd, A. Cowiee, and G. Marland. *Task 38: Greenhouse Gas Balances of Biomass and Bioenergy Systems Approaches for inclusion of harvested wood products in future, GHG inventories under the UNFCCC, and their consistency with the overall UNFCCC inventory reporting framework.* IEA Bioenergy, July 13, 2004. See footnote 7 and the description of double counting problems that exist under current IPCC guidelines.

[9] Jim Smith, US Forest Service Northern Global Change Research Program, initial Maine data available at: http://www.fs.fed.us/ne/global/pubs/books/epa/states/ME.htm

[10] See Maine SAG *Boundary and Timing Issues (Including Biomass) Memo* available at: http://maineghg.raabassociates.org/events.asp?type=grp&event=Stakeholder%20Advisory%20Group

Mitigation analysis in the Maine SAG and Forestry and Agriculture TWG used full life cycle analysis[11] of emissions reductions to ensure comprehensive accounting of positive and negative emissions impacts of policy actions, including direct and indirect impacts across sectors (also known as displacement effects),[12] all greenhouse gases, and the full impact of actions taken during the 2005-2020 compliance period time period even if they resulted in impacts beyond 2020 (also known as the duration of impacts). This approach is consistent with principles and guidelines for cost benefit analysis established in guidelines from the US EPA Science Advisory Board.[13] The EPA guidelines are not entirely conclusive on the use of discounting,[14] and the Maine SAG process chose to discount monetized costs of policy actions but not non-monetized benefits of emissions reductions.[15]

In the Maine forestry sector, a number of important accounting procedures were used to measure emissions impacts of policies affecting pre harvest and post harvest biomass from Maine forests. Pre harvest and post harvest biomass carbon accounts were integrated as needed for forest preservation and management options. For sensitivity analysis, all forest management options were evaluated using two distinct time periods for analysis. Scenario 1 only included impacts through 2020 and is, therefore, not a full life cycle analysis. Scenario 2 included full life cycle impacts past 2020, including a full 58 year generation of new tree growth (based on Maine FORCARB estimates of the average age of Maine forests).

Pre-Harvest Biomass[16]

Full life cycle accounting was used to determine net impacts of policies affecting the size and configuration of the state's forest ecosystem, including the impact of biomass removal and growth. Analysis was based on regional FORCARB data recalibrated to Maine using best available state data developed by the Forest Experts Group, including the US Forest Service, and the Technical Consultant. Forest preservation measures (land use change) included estimation of direct biomass emissions impacts of land clearing and associated above ground and below ground biomass carbon disturbance using Maine FORCARB data. Indirect effects of post harvest biomass for the merchantable portion of cleared biomass were also included using HARVCARB[17] and other data (dis-

[11] Full life cycle analysis (FLCA) is well developed in theory but not widely practiced for forestry greenhouse gas mitigation. This approach counts both positive and negative emissions for all carbon accounts over the full time period of affects from actions, and estimates transfers of carbon between accounts.
[12] Displacement effects can result in *increased or decreased* greenhouse gas flows outside the compliance boundary of the action, including impacts to other sectors or jurisdictions. Displacement effects (sometimes referred to as "leakage") should be addressed in comprehensive accounting of *direct and indirect* benefits and costs.
[13] EPA Guidelines for Preparing Economic Analyses EPA 240-R-00-003 Environmental Protection Agency, September 2000.
[14] The EPA guidance identifies several options and issues related to discounting, and recommends that discounting be applied symmetrically to costs and benefits, both monetized and non-monetized.
[15] See Maine SAG *Population Economic and Discount Rate Forecasting Memo*, Appendix 2.1.
[16] A full description of Maine Forestry Options can be found Appendix 5.4.
[17] HARVCARB (Skog and Nicholson, US Forest Service model) provides post harvest biomass accounts for pulp and saw timber wood products, landfill storage, energy recapture, and direct

cussed below). A new protocol was developed for estimation of the carbon impacts of acreage conversion from forested cover to cleared residential land cover using data from Maine FORCARB augmented with the Natural Resource Inventory (NRI) and American Housing Survey (AHS). For forest management options (e.g. density management) net impacts of biomass carbon removal, decay and regrowth were included for a full generation of tree growth (estimated at 58 years) using Maine FORCARB data for all forest carbon accounts.[18] Increased stocking options also used a full time period of tree growth for analysis. Import and export issues do not affect pre harvest biomass management.

Post-Harvest Biomass[19]

Full life cycle accounting was used to determine net impacts of policies that increase or decrease flows of wood products or biomass energy feedstocks into the market. Emissions impacts of imported biomass were included, and emissions impacts of exported biomass were excluded based on detailed data found in the Maine Wood Processor Reports from 1990 forward.[20] This adjustment to IPCC and National Communications guidelines is needed at the state level to ensure that forestry emissions are treated consistently with other sectors (particularly energy supply and manufacturing), and with other states in the region, to avoid double counting.[21]

Biomass energy emissions (from biomass combustion for electricity or direct heat) were reported in the energy supply sector, and the carbon storage associated with biomass regrowth following harvest was counted in the forestry sector under a statewide inventory framework. This is consistent with IPCC Guidelines and National Communications and allows full life cycle calculation of direct and indirect emissions impacts of biomass energy use across sectors. Direct carbon storage and emissions impacts of harvested wood products (pulp and saw timber) were estimated by use of the US Forest Service HARVCARB model using Maine specific rates, and indirect energy displacement effects were calculated using the CORIIMM model.[22] The HARVCARB model provides emissions estimates over a 100 year time period for the disposition of harvested biomass to four greenhouse gas accounts: wood products storage (the manufacturing sector); landfill storage (the waste sector); energy recapture (the energy supply sector); and direct emissions from on site combustion and decay (the forestry sector).

It should be noted that this full life cycle analysis did not assume in advance that emissions of biomass combustion for energy use would automatically be offset by equal regrowth of biomass in the future (typically referred to as a “carbon neutral” assumption). Instead, a full life cycle analysis was used to estimate *all positive and negative emissions impacts*. In sustainably managed forest system (however elusively that term is de-

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emissions from burning and or decay. Imports and exports of post harvest biomass are incorporated through supplemental data, such as state wood processor reports.

[18] FORCARB (Jim Smith, US Forest Service model) contains pre harvest biomass (ecosystem) accounts for live trees, standing dead and dying trees, forest floor and coarse woody debris, and soils.

[19] A full description of Maine Forestry Options can be found in Appendix 5.4.

[20] At present 24 percent of Maine electricity is generated from biomass feedstocks, with significant potential for increased supplies in the future that could reduce net carbon emissions.

[21] IEA Bioenergy, July 13, 2004.

22 Perez-Garcia, John, Bruce Lippke, Jeffrey Comnick, and Carolina Manriquez. CORRIM: Phase I Final Report, Module N. TRACKING CARBON FROM SEQUESTRATION IN THE FOREST TO WOOD PRODUCTS AND SUBSTITUTION. March 25, 2004.

fined) it is assumed that future conditions will allow a full regrowth of biomass that is harvested and combusted for energy recapture. A number of conditions must be met for this assumption to be realized in the future, including permanent protection of the forest from conversion to developed land uses, no long term reduction in productivity associated with forest health and or climate change, and no net carbon impact of forest harvest practices.

In addition, indirect impacts of durable wood products use are important. In the typical case of forest harvest in Maine, part of the harvested biomass is used for wood products, and part is used for biomass energy (typically logging and mill residue, or live tree chips). Harvested wood products result in long-term carbon storage in the form of durable wood, as well the displacement of energy-based emissions when wood building materials replace steel and concrete.[23] Therefore, it is critical to integrate the direct and indirect impacts of all uses of biomass from a given forestry option to fully understand its net greenhouse gas emission impact.

In summary, the use of a carbon neutral assumption in Maine would have precluded a full analysis of direct and indirect impacts, or a specific understanding of the effect of sustainability assumptions. The final analysis of forest inventories and policy options in Maine did not assume carbon neutrality, but did include an assumption of future sustainability that allowed full regrowth of harvested biomass.

[23] CORRIM, March 25, 2004.

Greenhouse Gas Accounting at the State and Regional Level: Applying International Norms for Reporting Biomass Energy

Wiley Barbour, Managing Director, Environmental Resources Trust

October 2004

Officials in state and local governments are actively developing emission inventories for greenhouse gas pollutants. In the US there are a number of different views on the best ways to measure and report emissions, and this has led to some confusion. In order to develop emission inventories in a comparable manner many have turned to the international reporting and accounting rules to ensure consistency. This paper provides some background on international accounting and reporting practices related to biomass energy and explains how international accounting practices may provide a useful model for domestic reporting.

Introduction

Over the last decade global climate change has become an important issue in Statehouses and State Agencies across the United States, prompting a number of state agencies to begin developing inventories of sources and sinks of greenhouse gas (GHG) emissions within their state boundaries. These emission inventories are used for both basic reporting and for tracking emissions performance over time to assess the effects of policies and measures.

In an effort to ensure compatibility with reporting initiatives developed by other states, many states are developing state level emission inventories that follow the rules for national-level emissions reporting under international agreements. This paper provides insight into the appropriate application of international GHG reporting practices to state inventories.

National Emission Inventory Reporting under International Rules

All of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are responsible for periodic reporting of all sources and sinks of greenhouse gases. Developed nations are required to report this information on an annual basis. The Kyoto Protocol, which is an offspring of the UNFCCC, is designed to use the annual inventory report to determine compliance with the binding limits on GHG emissions set forth by the treaty. The rules and procedures to be followed when assembling and reporting emission inventory data are spelled out in detail in UNFCCC Reporting Guidelines.[24]

In addition, the Intergovernmental Panel on Climate Change (IPCC) has developed a solid body of scientific and technical guidance related to the estimation and modelling of emissions.[25] The guidance prepared by the IPCC specifically applies to national level

[24] *Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual inventories*

[25] The IPCC guidance is contained in three key documents: The Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories; The IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories; and The IPCC Good Practice Guidance

reporting, but forms the basis for estimating emissions at the project, company and local level as well.

Fundamentally, an emission inventory is a policy relevant but policy neutral document that provides a solid basis for scientific understanding, decision making, and policy development. Distinct from a policy plan or proposal, the emission inventory in the international context is devoid of political spin and does not include projections of future emissions or scenarios of avoided emissions. It is simply an objective statement of what actually happened over the last reporting period, supported by transparent documentation.

National Action Plan Reporting under International Rules

In addition to annual inventories, Parties to the UNFCCC also are required to develop National Communications on a periodic basis (approximately every 4-5 years).[26] The National Communication is in essence a national *action plan* that describes national circumstances, identifies existing and planned policies and measures, indicates future trends in greenhouse gas emissions, outlines expected impacts and adaptation measures, and provides information on financial resources, technology transfer, and climate research. These action plans go far beyond the impartial "just the facts" approach employed by emission inventories; in fact, action plans are inherently policy documents that are analogous to the state-level action plans adopted by some northeastern States. In order to develop projections of future emissions under a given action plan, it is necessary to develop assumptions about what is likely to happen in a "business-as-usual" scenario. This business-as-usual outcome is then contrasted with projections that include assumptions about the likely effectiveness of policies and measures. The result is a policy statement that predicts the consequences of proposed actions.

An emission inventory is a fundamental element in any climate strategy. The emission inventory provides the starting point for planning and analysis and is a required input for action plans. The linkages between inventory data and policy development are important to understand for domestic and international activities, and States that develop both emission inventories and action plans would be well advised to keep a clear distinction between the two activities.

Biomass Energy Generation

The IPCC Guidelines require that net GHG emissions due to land use change and forestry activities on managed lands should be included in national GHG emissions accounting.[27] From a scientific perspective, it is important to recognize the uptake of carbon into forests and plant biomass pools as well as the subsequent release of that carbon as a result of harvesting or combustion of biomass fuels. The fundamental principle used in the IPCC methodology assumes that changes on the ground (i.e. emissions and sequestration) are equal to the changes in the atmosphere. This principle re-

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for Land Use, Land-Use Change and Forestry. All of the IPCC reports are available at http://www.ipcc-nggip.iges.or.jp

[26] The most recent version of the US national Communication can be found on EPA's website at: http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublications.html

[27] In the continental United States, all forested lands are considered managed.

quires *complete accounting for all emissions and sequestration*, so that atmospheric impact may be accurately calculated.

Accordingly, under international reporting standards, the CO_2 released during biomass energy generation **is** accounted for as an emission. These CO_2 emissions are not accounted for as a fuel-related energy source; instead, CO_2 releases due to the use of biomass energy are captured in the *Land Use Change and Forestry* category as emissions from the land use sector. The *non*-CO_2 gases emitted as a result of biomass combustion are to be included in the *Energy* category. In summary, biomass energy is not considered "carbon neutral" under international reporting guidelines; the emissions accounting is split between the land use sector and energy sector accounts.

Harvested Wood Products

When forest fires rage through timbered areas, the carbon combusted is released immediately, but when commercial timber operations harvest wood from forests the result is a complex and time dependent pattern of net fluxes to the atmosphere. The rules for accounting for uptake or loss of carbon from forests are based on the concept of a measurable change in the amount of carbon stocks in a given "pool."

Forest harvesting could result in a net uptake of carbon if the wood that is harvested is used for long-term products such as building lumber, and the regrowth is relatively rapid. This may in fact has become a response strategy identified in state action plans.

Under the IPCC Guidelines, national level emission inventories account for carbon in all wood products produced in the country, including exported products, whereas carbon in imported wood is not counted. As states develop action plans some have proposed a "life cycle" approach to carbon accounting of harvested wood products. It may be possible to track the fate of harvested wood products as they cross state boundaries but this is not a practice that is authorized under the current IPCC Guidelines.

APPENDIX 4: STAKEHOLDER PROCESS DOCUMENTS

4.1 Ground Rules

4.2 Stakeholder Membership Lists

4.3 Stakeholder Meeting Attendance Lists

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<u>Appendix 4.1</u>

Maine Greenhouse Gas Action Plan Development Process

Purpose, Charge, and Ground rules

11/6/03

Purpose and Charge:

The purpose of the Stakeholder Advisory Group is to advise the Department of Environmental Protection (DEP) on creating a state climate action plan to meet the following reduction goals as specified in section 576 of state law L.D. 845:

1. **Reduction by 2010.** In the short term, reduction to 1990 levels by January 1, 2010.
2. **Reduction by 2020.** In the medium term, reduction to 10% below 1990 levels by January 1, 2020.
3. **Long Term Reduction.** In the long term, reduction sufficient to eliminate any dangerous threat to the climate. To accomplish this goal, reduction to 75% to 80% below 2003 levels may be required.

The plan will include a portfolio of program and policy options. "The action plan must address each sector (i.e., transportation, industrial, commercial, institutional, and residential) in cost-effective ways and must allow sustainably managed forestry, agricultural, and other natural resource activities to be used to sequester greenhouse gas emissions."

The final output of the Stakeholder Advisory Group will be a set of recommendations to the DEP on which program and policy options to include in it's plan. The specific recommendations will likely include a portfolio of options, and for each option, the following information:

- Description of the Option, including key design elements, implementation mechanisms, and key implementers;
- Estimated GHG savings, cost of saved carbon equivalent, and other key benefits and costs as appropriate and data is available;
- Other critical factors deemed germane to assessing the feasibility of implementing a given option.

The DEP will finalize its proposed action plan and submit it to the joint standing committee of the Legislature having jurisdiction over natural resources matters.

Stakeholder Advisory Group Members:

Membership

1. Membership to the Stakeholder Advisory Group will be determined by the DEP.
2. Each member organization of the Stakeholder Advisory Group will designate a lead representative, and, at their discretion, an alternate.

3. Only the lead representative, or the alternate in the case of the representative's absence, will participate in formal decision-making.

Roles and Responsibilities

4. Stakeholder Advisory Group members (including alternates), will make every attempt to attend all Stakeholder Group meetings, to be on-time, and to review all documents disseminated prior to the meeting. Members who can not make a meeting should let the Facilitator know prior to the meeting (by voice or e-mail).

5. Stakeholder Advisory Group members will be expected to participate in the process in good faith, including focusing on the Purpose and Charge of the process, to achieve the goals and objectives of the legislation. Members also agree to act respectfully toward each other as well as being truthful and communicative.

6. It is the responsibility of the Stakeholder Advisory Group members to keep their organizations and constituencies fully informed on the developments of the Stakeholder Group process.

7. Stakeholder Advisory Group members will not speak (e.g., to the press) on behalf of the Stakeholder Advisory Group or its members, intentionally or otherwise, without the Group's expressed permission. DEP will otherwise be the point of contact for the process.

8. Stakeholder Advisory Group members are encouraged to confer with each other, the Facilitators and the Technical Consultants in and between meetings.

9. The members of the Stakeholder Advisory Group will advise DEP on the focus, charge, and membership of the Working Groups .

Decisionmaking

10. The primary task of the Stakeholder Advisory Group will be to prepare recommendations for DEP's consideration consistent with the Purpose and Charge of the process.

11. The goal of the process will be to make major substantive recommendations including a set of individual GHG policy actions by consensus of the Stakeholder Advisory Group (excluding Ex-Officio representatives), where consensus shall mean that everyone is at least willing to live with a decision and chooses not to dissent.

12. The Group's final Report to DEP at the end of the process will include all areas of consensus, and a description of the alternative policy designs and implementation approaches preferred by Group members in areas where consensus was not reached, if any. For non-consensus issues, the Stakeholder Advisory Group members supporting each alternative approach will be listed under each alternative.

13. If unable to consent on a particular recommendation or decision, a representative

will be expected to explain why and to try and offer a positive alternative. Representatives are responsible for voicing their objections and concerns, and silence or absence will be considered consent.

14. Stakeholder Advisory Group members will be listed in the Report along with their organizational affiliations. Members should seek the endorsement from their respective organizations.

Ex-Officio Members:

Members

15. The Ex-Officio Members to the Stakeholder Advisory Group will consist of: 1) State Legislators and 2) the co-chairs of the Technical and Economic Policy Resource Panel[28], (See attached Ex-Officio List).

Roles and Responsibilities

16. Ex-Officio Members are invited and encouraged to participate in discussions in all Stakeholder Meetings, but will not be formal voting members.

17. Ex-Officio Members will be expected to participate in the process in good faith, including focusing on the Purpose and Charge of the process, to achieve the goals and objectives of the legislation. Members also agree to act respectfully toward each other as well as being truthful and communicative.

Working Groups:

Membership

18. With advice from the Stakeholder Advisory Group, membership of the Working Groups will be determined by DEP.

19. Working Group representatives can be members of the Stakeholder Advisory Group, others from member Stakeholder organizations, or other individuals with relevant interest and expertise.

Roles and Responsibilities

20. Working Group members will make every attempt to attend all workgroup meetings, to be on time, and to review all documents disseminated prior to the meeting. Members who can not make a meeting should let the Facilitator know prior to the meeting (by voice or e-mail).

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[28] The Technical and Economic Policy Resource Panel, comprised of Maine based Academics, plus Federal Agency representatives, will be available to advise the various working groups as well as the Stakeholder Advisory Group, and review policy recommendations. The panel will be co-chaired by Dr. Robert Kates, a member of the Intergovernmental Panel on Climate Change, and Dean Karl Braithwaite of the Muskie School of Public Service at the University of Southern Maine.

21. Working Group members will be expected to participate in the process in good faith, including focusing on the Purpose and Charge of the process, to achieve the goals and objectives of the legislation. Members also agree to act respectfully toward each other as well as being truthful and communicative.

22. It is the responsibility of the Working Group members to keep their organizations and constituencies fully informed on the developments in the Working Group process.

23. Working Group members are encouraged to confer with each other, the Facilitators, and the Technical Consultants in and between meetings

24. Working Groups will work under direction of the Stakeholder Advisory Group and DEP.

Decisionmaking

25. The primary task of each Working Group is to identify and analyze GHG mitigation options and alternative policy designs within the scope of that Working Group, to assist the Technical Consultants and Facilitators in a collaborative fashion, and prepare recommendations for the Stakeholder Advisory Group, and ultimately the DEP's consideration consistent with the Purpose and Charge of the process.

26. Each Working Group's recommendations to the Stakeholder Group will include all areas of consensus, and a description of the alternative options or approaches preferred by Group members in areas where consensus was not reached, if any. Consensus shall mean that everyone is at least willing to live with a decision and chooses not to dissent. Representatives are responsible for voicing their objections and concerns, and silence or absence will be considered consent. For non-consensus issues, the Working Group members supporting each alternative approach will be listed under each alternative.

Department of Environmental Protection (DEP):

Roles and Responsibilities

27. DEP is the convenor of the process and has ultimate responsibility to submit the State Climate Change Action Plan to the Legislature. The Plan will be primarily based on the recommendations from the Stakeholder Advisory Group (including all supporting analysis and documentation), especially where consensus is reached.

28. The DEP will designate a representative to participate as an active and voting member of the Stakeholder Advisory Group as well as each Working Group. Given its special role in the process, DEP may from time-to-time abstain from specific recommendations.

29. DEP will assign staff members to each Working Group to provide support and to liaise with the DEP.

30. DEP will adhere to all of the other groundrules established for both the Stakeholder Advisory Group and the Working Groups.

31. DEP will also have final oversight responsibility for the Facilitators (Raab Associates, et al.) and Technical Consultants (CCAP et al.), as well as Stakeholder Advisory and Working Group process issues (e.g., schedule, structure, etc.,).

Public Involvement:

32. The Stakeholder Advisory and Working Group meetings are open to the public. Members of the public will be given a chance to express their opinions and make suggestions at appropriate junctures as appropriate and time allows, as determined by DEP with advice from the Stakeholder Advisory Group and Working Groups and the Facilitators.

Facilitators' and Technical Consultants':

Roles and Responsibilities

33. The Facilitators' primary function is to help design and manage a productive process, including stakeholder and working group meetings. The Technical Consultants primary function is to provide technical support to the Stakeholder Advisory Group and Working Groups, including identification of options, alternative policy designs, and analysis

34. Facilitators will facilitate all meetings of the Stakeholder Group and the Working Groups to provide a constructive forum where diverse points of view are voiced and examined in a professional and balanced way. Personal attacks are not permitted.

35. The Facilitators will draft all agendas and meeting summaries and distribute to Stakeholders and Working Group members in a timely fashion (ideally, 1 week in advance, and 1 week after meetings respectively). Facilitators will also distribute documents prepared by Technical Consultants. All documents will be distributed once via email, and will then be available on a web site maintained by the Facilitators for the duration of the process.

36. Technical Consultants will prepare all memos, documents, results of analysis, and reports in a timely manner and for distribution by the Facilitators prior to meetings.

37. Facilitators and Technical Consultants will act in an impartial and non-partisan manner, and will treat confidential discussions with parties confidentially.

Appendix 4.2: Stakeholder Membership Lists

STAKEHOLDER ADVISORY GROUP

Affiliation	Representative Name
American Lung Association of Maine	Norm Anderson
American Lung Association of Maine	Ed Miller
Androscoggin Valley Council of Governments	Robert Thompson
Chewonki Foundation	Peter Arnold
Coalition for Sensible Energy	Pam Person
Department of Agriculture	Ned Porter
Department of Conservation	Donald Mansius
Department of Economic and Community Development	Brian Dancause
Department of Environmental Protection	Dawn Gallagher, Commissioner
Department of Environmental Protection	James Brooks (alternate)
Department of Human Services / Bureau of Health	Andy Smith, (alternate)
Department of Human Services / Bureau of Health	Phil Haines
Department of Transportation	Duane Scott (alternate)
Department of Transportation	Greg Nadeau
Dragon Products	Ann Thayer
Energy Independence and Security	Beth Nagusky
Environment Northeast	Michael Stoddard
FPL Energy	Allen Wiley
Industrial Energy Consumers	Tony Buxton
Independent Energy Producers	David Wilby
Interface Fabrics Group	Wendy Porter
J.D. Irving, Limited	Bill Borland
Legislative Representative	Ted Koffman
Legislative Representative	Bob Daigle
Legislative Senator	Christopher Hall
Legislative Senator	Tom Sawyer
Maine Automobile Dealers Assoc., Inc.	Tom Brown
Maine Automobile Dealers Assoc., Inc.	Virginia Davis (alternate)
Maine Better Transportation Association	Maria Fuentes
Maine Center for Economic Policy	Lisa Pohlmann
Maine Chamber & Business Alliance	Christopher Hall
Maine Council of Churches	Andy Burt
Maine Farm Bureau Association	Jon Olson
Maine Global Climate Change	Robert W. Kates, Ph.D.
Maine Municipal Association	Jeff Austin
Maine Oil Dealers Association	Jamie Py
Maine Oil Dealers Association	Pattie Aho (Alternate)

Maine Public Health Association	Saskia Janes
Maine Pulp & Paper Association	John Williams
Maine Pulp & Paper Association	Michael Barden (Alternate)
MOFGA	Russell Libby
Muskie School of Public Service	Karl Braithwaite, Dean
Natural Resources Council of Maine	Sue Jones
Public Utilities Commission	Tom Welch, Commissioner
Public Utilities Commission	Angela Monroe
The Nature Conservancy	Kate Dempsey
University of Maine	Janet Waldron

BUILDINGS, FACILITIES, AND MANUFACTURING WORKING GROUP

Affiliation	Representative Name
American Lung Association	Norm Anderson
Dead River Company	Leslie Anderson
Dragon Cement	Ann Thayer
Environment Northeast	Mike Stoddard
Industrial Energy Consumers Group	Tony Buxton
Interface Fabrics Group	Shannon Cox
International Paper Corporation	Chuck Kraske
Maine Council of Churches	Andy Burt
Maine Oil Dealers Association	Patti Aho / Jamie Py
Maine Pulp and Paper Association	Mike Barden
National Semiconductor	Dick Hall
Natural Resources Council of Maine	Sue Jones
Northeast by Northwest	Doug Baston
Public Utilities Commission	Denis Bergeron
University of Southern Maine	Dudley Greeley
Independent consultant	Brian Hubbell

Consultants, Facilitators, and Staff

Maine DEP	Mike Karagiannes
Center for Clean Air Policy	Karen Lawson
Gosline & Reitman	Ann Gosline

ENERGY AND SOLID WASTE WORKING GROUP

Affiliation	Representative Name	
Androscoggin Valley Council of Governments	Carol Fuller	
Calpine	Donald Neal	
Casella Waste Systems, Inc.	Ted Reeves	
Chewonki Foundation	Peter Arnold	
Coalition for Sensible Energy	Pam	Person
Dept. of Economic and Community Development	Brian	Dancause
Energy Research Center	John	Bastey
Energy Director	Beth	Negusky
Environment Northeast	Michael	Stoddard
FPL Energy	Doug	Whittier
FPL Energy	Al	Wiley
Independent Energy Producers	David	Wilby
Interface Fabrics	Dave	Walker
International Paper - Androscoggin Mill	Chuck	Kraske
Maine Center for Economic Policy (MECEP)	Lisa	Pohlmann
Maine DEP	Jeff	Crawford
Maine MEP	Joan	Saxe
Maine Oil Dealers Association	Patti	Aho
Maine Pulp and Paper	Dixon	Pike
Maine Power Options	Mary Lou	Gallup
Maine State Senate	Tom	Sawyer
Maine State Senate	Christopher	Hall
Natural Resources Council of Maine (NRCM)	Sue	Jones
NESCAUM	Suzanne	Watson
Physicians for Social Responsibility	Paul	Liebow
Public Utility Commission (PUC)	Angela	Monroe
Regulatory Assistance Project	David	Moskovitz
State Planning Office	George	MacDonald

Consultants, Facilitators, and Staff

Raab Associates, Ltd.,	Jonathan	Raab
Raab Associates, Ltd.,	Peter	Wortsman
Center for Clean Air Policy	Matt	Ogonowski
Tellus Institute (via phone)	Bill	Dougherty
Tellus Institute (via phone)	Alison	Bailie
Maine DEP	Mike	Karagiannes
Maine DEP	Dave	Burns

TRANSPORTATION AND LAND USE WORKING GROUP

Affiliation	Representative Name
Alliance of Auto Manufacturers	Greg Dana
Androscoggin Valley COG	Bob Thompson
Coalition for Sensible Energy	Pam Person
Dragon Products	Ann Thayer
Environment Northeast	Michael Stoddard
Greater Portland COG	Steve Linnell
Maine Automobile Dealers Assoc.	Ginger Davis (alt.)
Maine Better Transportation Assoc.	Maria Fuentes
Maine Council of Churches	Andy Burt
Maine Legislature	Rep. Ted Koffman
Maine Senate	Tatiana Brailovskaya (for Sen. Chris Hall)
Maine Department of Transportation	Duane Scott / Greg Nadeau / Anna Price / Ed Hanscomb
Maine Lung Association	Chuck Hazzard / Norm Anderson
Maine Motor Transport Association	Dale Hanington
Maine Oil Dealers Association	Patti Aho (alt.)
Maine Tourism Association	Carolyn Manson
Maine Turnpike Authority	Conrad Welzel
Natural Resources Council of Maine	Sue Jones
Physicians for Social Responsibility	Raina Rippell
State Planning Office	Paula Thomson
The Nature Conservancy	Kate Dempsey

Advisory Panel Members, Staff, Consultants

University of Maine	Jonathan Rubin
Maine DEP	Lynn Cayting
Maine DEP	John Wathen
Maine DEP	Mike Karagiannes
Maine DEP	Malcolm Burson
Center for Clean Air Policy	Steve Winkelman
Gosline & Reitman Associates	Jonathan Reitman

FORESTRY AND AGRICULTURE WORKING GROUP

Affiliation	Representative Name
Maine Farm Bureau Association	Jon Olson
International Paper	Chuck Kraske
The Nature Conservancy	Kate Dempsey
Maine Forest Service	Donald Mansius
Maine Department of Agriculture	Jonathan Chalmers
MOFGA	Russell Libby
Wild Blueberry Commission of Maine	David Bell
Environment Northeast	Dan Sosland
Environment Northeast	Mike Stoddard (alt)
Mainewatch Institute	Sherry Huber
Maine Potato Board	Timothy Hobbs
Small Woodlots Owners of Maine	Judith Merck
J.D. Irving, Ltd.	Walter Emrich
Natural Resources Council of Maine	Sue Jones
Maine Pulp & Paper Association	John Williams

Facilitators, Technical Consultants, Staff

Center for Clean Air Policy/Penn State University	Tom Peterson
Muskie School – USM	Jack Kartez
Muskie School – USM	Hugh Coxe
DEP – Commissioner's Office	Malcolm Burson
DEP – Bureau of Air Quality	Mike Karagiannes
DEP – Bureau of Air Quality	James P Brooks
DEP – Bureau of Air Quality	Kevin McDonald
Maine Forest Service	Ken Laustsen
Bowdoin College	Dr. Mark Battle
University of Maine	Dr. Ivan Fernandez
US Forest Service	Dr. Jim Smith

Guests

Independent Energy Producers of Maine	Dave Wilby
NRCM	Cathy Johnson
Maine Forest Products Council	Patrick Strauch
Unaffiliated	Bill Ferdinand
NRCM / Environmental Defense	Melissa Carey

EDUCATION AND PUBLIC AWARENESS WORKING GROUP

Affiliation	Representative Name
Chewonki Foundation	Peter Arnold
Nereus Communications	Tatiana Bailovskaya
University of Maine – Machias	Jon Reisman
Natural Resources Council of Maine	Mark Hays
Maine Council of Churches	Andy Burt
Maine Public Health Association	Saskia Janes
Advanced Management Catalyst, Inc.	Dan Thompson
Maine DEP, Green Campus Initiative	Peter Cooke
Maine DEP, Education/Outreach Committee	Debbie Avalone-King
Maine DEP Commissioner's Office	Malcolm Burson

SCIENCE, TECHNOLOGY AND ECONOMICS RESOURCE PANEL

Name	Affiliation	Subject area/ expertise
Robert Kates, co-chair	Professor Emeritus, Brown University Member, IPCC	General climate change
Karl Braithwaite, co-chair	Dean, Muskie School of Public Service, University of Southern Maine	Public policy
Bill White	EPA-New England	Energy efficiency
Jonathan Reisman	Assistant Professor Economics University of Maine - Machias	Economics, public policy
Robert Sanford	Associate Professor Of Environmental Studies, University of Southern Maine	Env. Science & policy
Charles Fitts	Associate Professor Of Geoscience, USM	Geo sciences
Lani Graham, M.D.	Former Director, Maine Bureau of Health	Public health
Tom Tietenberg	Professor of Economics, Colby College	Policy; trading
Charles Colgan	Muskie School of Public Service, USM	Public policy
Richard Barringer	Muskie School of Public Service, USM	Public policy
George Jacobson	Professor of Biology and Climate Studies, Climate Change Institute, University of Maine	Climate science; forest ecology

Mark Battle	Assistant Professor of Physics, Bowdoin College	Carbon cycle
Jonathan Rubin	Margaret Chase Smith Center for Public Policy, University of Maine	Resource economics and policy; alt. fuels
Gary King	Clare S Darling Prof. of Oceanography; Darling Center, University of Maine	Ocean science
George Hurtt	Institute for the Study of Earth, Oceans, and Space, University of New Hampshire	Land sequestration; metrics
Ivan Fernandez	Professor of Plant, Soil & Environmental Sciences; Coop Prof. of Forest Resources, University of Maine	Land sequestration
Chris Cronan	Professor of Biology and Ecology, University of Maine	Emissions baseline
Suzanne Watson	Energy and Climate Team Leader, NESCAUM	Electricity generation sector

Appendix 4.3: Attendance Lists

STAKEHOLDER ADVISORY GROUP

Attendance List

Affiliation	Name	11/6/03	12/17/03	4/8/04	6/30/04	9/29/04
American Lung Association of Maine	Norm Anderson	X				X
American Lung Association of Maine	Ed Miller				X	
Androscoggin Valley Council of Governments	Robert Thompson			X	X	X
Chewonki Foundation	Peter Arnold	X	X	X	X	X
Coalition for Sensible Energy	Pam Person	X	X	X	X	X
Department of Agriculture	Ned Porter	X			X	
Department of Conservation	Alec Giffen (alternate)					
Department of Conservation	Donald Mansius	X		X	X	X
Department of Economic and Community Development	Brian Dancause	X	X	X	X	X
Department of Environmental Protection	Dawn Gallagher, Commissioner	X	X	X	X	X (phone)
Department of Environmental Protection	James Brooks (alternate)	X	X	X	X	X
Department of Human Services / Bureau of Health	Andy Smith, (alternate)	X				
Department of Human Services / Bureau of Health	Phil Haines		X			
Department of Transportation	Duane Scott (alternate)	X	X	X	X	X
Department of Transportation	Greg Nadeau		X		X	
Dragon Products	Ann Thayer	X	X		X	X
Energy Independence and Security	Beth Nagusky	X	X	X	X	X
Environment Northeast	Michael Stoddard	X	X	X	X	X
FPL Energy	Allen Wiley	X	X	X	X	X
Industrial Energy Consumers	Tony Buxton				X	
Independent Energy Producers	David Wilby	X	X	X	X	X
Interface Fabrics Group	Wendy Porter			X	X	X
Interface Fabrics Group	Shannon Cox (alternate)		X			
J.D. Irving, Limited	Bill Borland	X	X	X	X	X
Legislative Representative	Ted Koffman	X			X	
Legislative Representative	Bob Daigle		X			
Legislative Senator	Christopher Hall	X	X			
Legislative Senator	Tom Sawyer					
Maine Automobile Dealers Assoc., Inc.	Tom Brown			X		
Maine Automobile Dealers Assoc., Inc.	Virginia Davis (alternate)	X	X	X	X	
Maine Better Transportation Associa-	Maria Fuentes	X	X	X		X

tion						
Maine Center for Economic Policy	Lisa Pohlmann	X	X	X	X	X
Maine Chamber & Business Alliance	Christopher Hall	X	X	X		X
Maine Chamber & Business Alliance	Kristine Ossenfort				X	
Maine Council of Churches	Andy Burt	X	X	X	X	X
Maine Farm Bureau Association	Jon Olson					
Maine Global Climate Change	Robert W. Kates, Ph.D.	X			X	
Maine Municipal Association	Jeff Austin	X (PM)				
Maine Oil Dealers Association	Jamie Py	X	X	X	X	X
Maine Oil Dealers Association	Pattie Aho (Alternate)	X	X		X	X
Maine Public Health Association	Saskia Janes	X		X	X	X
Maine Pulp & Paper Association	John Williams	X	X	X	X	X
Maine Pulp & Paper Association	Michael Barden	X	X	X		X
MOFGA	Russell Libby	X		X		
MOFGA	Andrew Marshall				X	
Muskie School of Public Service	Karl Braithwaite, Dean		X		X	X
Natural Resources Council of Maine	Sue Jones	X	X	X	X	X
Public Utilities Commission	Tom Welch, Commissioner	X	X		X	
Public Utilities Commission	Angela Monroe					X
The Nature Conservancy	Kate Dempsey	X	X	X	X	X
University of Maine	Janet Waldron	X	X		X	X

Other Attendees

Clean Air – Cool Planet	Bob Sheppard					X
Department of Transportation	Anna Price				X	X
Environmental Defense	Melissa Carey					X
ExxonMobil	Dan Horton					X
Maine Forest Products Council	Patrick Strauch					X
New England Petroleum Council	John Quinn					X

Facilitators / Technical Consultants / Staff

Raab Associates, Ltd.,	Jonathan Raab	X	X	X	X	X
Raab Associates, Ltd.,	Peter Wortsman	X	X	X	X	X
Muskie School – USM	Jack Kartez		X		X	X
Muskie School – USM	Hugh Cox			X		
Gosline and Reitman DRS	Ann Gosline			X		
Gosline and Reitman DRS	Jonathan Reitman					
Center for Clean Air Policy	Steve Winkelman			X	Phone	
Center for Clean Air Policy	Karen Lawson			X		
Center for Clean Air Policy	Matt Ogonowski			X	Phone	
Consultant	Tom Peterson	X	X	X	X	
Tellus Institute	Allison Bailey			X	Phone	
DEP	Malcolm Burson	X	X	X	X	X

DEP	Mike Karagiannes	X	X	X	X	X
DEP	Don Anderson	X				
DEP	Kevin MacDonald		X	X	X	X
DEP	Lynne Cayting		X			
DEP	Deb Avalone – King			X		
DEP	David Littell					X
DEP	Deb Garnett					X

TRANSPORTATION AND LAND USE WORKING GROUP

Attendance List

Affiliation	Name	2/5/04	3/9/04	5/20/04
Alliance of Auto Manufacturers	Greg Dana	x	x	
Androscoggin Valley COG	Bob Thompson	x	x	x
Coalition for Sensible Energy	Pam Person	x	x	x
Dragon Products	Ann Thayer	x	x	
Environment Northeast	Michael Stoddard	x	x	x
Greater Portland COG	Steve Linnell	x	x	
Maine Automobile Dealers Assoc.	Ginger Davis (alt.)	x	x	x
Maine Better Transportation Assoc.	Maria Fuentes	x	x	x
Maine Council of Churches	Andy Burt	x	x	x
Maine Legislature	Rep. Ted Koffman	x		
Maine Senate	Tatiana Brailovskaya (for Sen. Chris Hall)		x	
Maine Department of Transportation	Duane Scott / Greg Nadeau / Anna Price / Ed Hanscomb	x	x	x
Maine Lung Association	Chuck Hazzard / Norm Anderson	x	x	
Maine Motor Transport Association	Dale Hanington	x	x	x
Maine Oil Dealers Association	Patti Aho (alt.)	x		x
Maine Tourism Association	Carolyn Manson	x	x	x
Maine Turnpike Authority	Conrad Welzel	x	x	x
Natural Resources Council of Maine	Sue Jones	x	x	x
Physicians for Social Responsibility	Raina Rippell	x	x	x
State Planning Office	Paula Thomson	x	x	x
The Nature Conservancy	Kate Dempsey	x	x	

Advisory Panel Members, Staff, Consultants

University of Maine	Jonathan Rubin	x	x	x
Maine DEP	Lynn Cayting	x	x	
Maine DEP	John Wathen	x	x	x
Maine DEP	Mike Karagiannes	x	x	x
Maine DEP	Malcolm Burson	x		
Center for Clean Air Policy	Steve Winkelman	x	x	x
Gosline & Reitman Associates	Jonathan Reitman	x	x	x

ENERGY AND SOLID WASTE WORKING GROUP
Attendance List

Affiliation	First Name	Last Name	1/28/04	3/8/04	6/17/04
Androscoggin Valley Council of Governments (AVCOG)	Carol	Fuller	X	X	X
Calpine	Donald	Neal	X	X	
Casella Waste Systems, Inc.	Ted	Reeves			
Chewonki Foundation	Peter	Arnold	X	X	X
Coalition for Sensible Energy	Pam	Person	X	X	X
Dept. of Economic and Community Development	Brian	Dancause	X	X	PM
Energy Research Center	John	Bastey	X		X
Energy Director	Beth	Negusky			X
Environment Northeast	Michael	Stoddard	X	X	X
FPL Energy	Doug	Whittier		X	
FPL Energy	Al	Wiley	X		X
Independent Energy Producers	David	Wilby	X	X	
Interface Fabrics	Dave	Walker			
International Paper - Androscoggin Mill	Chuck	Kraske	X	X	
Maine Center for Economic Policy	Lisa	Pohlmann	X		X
Maine DEP	Jeff	Crawford	X	X	X
Maine MEP	Joan	Saxe	X		
Maine Oil Dealers Association	Patti	Aho	X	X	
Maine Pulp and Paper	Dixon	Pike		X	
Maine Power Options	Mary Lou	Gallup	X	X	X
Maine State Senate	Tom	Sawyer			
Maine State Senate	Christopher	Hall	X	X	
Natural Resources Council of Maine (NRCM)	Sue	Jones	X	X	X
NESCAUM	Suzanne	Watson	X	X	X
Physicians for Social Responsibility	Paul	Liebow	X	X	
Public Utility Commission (PUC)	Angela	Monroe	X	X	X
Regulatory Assistance Project	David	Moskovitz	X	X	
State Planning Office	George	MacDonald	X	X	X

Facilitators / Technical Consultants / Staff

Raab Associates, Ltd.,	Jonathan	Raab	X	X	X
Raab Associates, Ltd.,	Peter	Wortsman	X	X	X
Center for Clean Air Policy	Matt	Ogonowski	X	X	X
Tellus Institute (via phone)	Bill	Dougherty		X	
Tellus Institute (via phone)	Alison	Bailie		X	X
Maine DEP	Dawn	Gallagher			X
Maine DEP	Jim	Brooks			X
Maine DEP	Malcolm	Burson	X	X	
Maine DEP	Mike	Karagiannes	X	X	X
Maine DEP	Dave	Burns	X	X	X

BUILDINGS, FACILITIES, AND MANUFACTURING WORKING GROUP

Attendance Summary

Stakeholders:	Meetings Present	1/23	2/26	3/25	5/26
Anderson, Leslie	Dead River Company	X			
Anderson, Norm	American Lung Association			X	
Barden, Michael	Maine Pulp & Paper Association	X	X	X	X
Baston, Doug	Northeast by Northwest	X	X	X	X
Bergeron, Denis	Public Utilities Commission		X	X	X
Burt, Andy	Maine Council of Churches		X		X
Buxton, Tony	Independent Energy Consumers	X	X	X	X
Cox, Shannon	Interface Fabrics Groups	X	X	X	X
Greeley, Dudley	University of Southern Maine	X	X	X	X
Hall, Dick	National Semiconductor	X	X	X	X
Hubbell, Brian	independent consultant	X	X	X	
Jones, Sue	Natural Resources Council of Me	X		X	X
Karagiannes, Mike	DEP Air Quality	X	X	X	X
Kraske, Chuck	International Paper - Androscoggin	X	X	X	X
Py, Jamie/				X	
Aho, Pattie	Maine Oil Dealers	X	X		X
Stoddard, Michael	Environment Northeast	X	X	X	X
Thayer, Ann	Dragon Products	X	X	X	X
Gosline, Ann	Facilitator	X	X	X	X
Lawson, Karen	CCAP	X	X	X	X

Notes:
Ms. Lawson attended the 3rd and 4th meetings by teleconference
Working Group members who did not attend any meetings are not listed.

AGRICULTURE AND FORESTRY WORKING GROUP

Affiliation	Name	1/29/04	3/19/04	5/27/04	7/29/04
MEMBERS					
Maine Farm Bureau Association	Jon Olson	X			
International Paper	Chuck Kraske	X	X	X	X
The Nature Conservancy	Kate Dempsey	X	X	X	X
Maine Forest Service	Donald Mansius	X	X	X	X
Maine Department of Agriculture	Jonathan Chalmers	X	X		X
MOFGA	Russell Libby	X	X	X	
Wild Blueberry Commission of Maine	David Bell	X		X	
Environment Northeast	Dan Sosland	X	X	X	
Environment Northeast	Mike Stoddard (alt)				X

Mainewatch Institute	Sherry Huber			X	
Maine Potato Board	Timothy Hobbs	X		X	
Small Woodlots Owners of Maine	Judith Merck	X	X	X	X
J.D. Irving, Ltd.	Walter Emrich	X	X	X	
NRCM	Sue Jones	X		X	X
Maine Pulp & Paper Association	John Williams	X		X	X

Facilitators/Technical Consultants					
Center for Clean Air Policy/Penn State University	Tom Peterson	X	X	X	X
Muskie School – USM	Jack Kartez	X	X	X	X
Muskie School – USM	Hugh Coxe		X	X	
DEP Staff					
DEP – Commissioner's Office	Malcolm Burson	X			
DEP – Bureau of Air Quality	Mike Karagiannes	X	X	X	X
DEP – Bureau of Air Quality	James P Brooks				X (am)
DEP – Bureau of Air Quality	Kevin McDonald	X		X	X
Others (Science Advisors)					
Maine Forest Service	Ken Laustsen	X			
Bowdoin College	Dr. Mark Battle	X		X	X
University of Maine	Dr. Ivan Fernan-dez	X	X	X	X
US Forest Service	Dr. Jim Smith	X	X		

Guests					
Ind Energy Prod Me, and MeGHG-SAG	Dave Wilby			X	X
NRCM	Cathy Johnson				X
Me Forest Products Council	Patrick Strauch				X
unaffiliated	Bill Ferdinand				X
NRCM / Environmental Defense	Melissa Carey		X	X	X

APPENDIX 5: WORKING GROUP FINAL REPORTS

The weblinks for the Final Working Group Reports are below:

5.1 Transportation and Land Use

http://maineghg.raabassociates.org/Articles/Final_TLU_Reportv1.final.pdf

5.2 Buildings, Facilities, and Manufacturing

http://maineghg.raabassociates.org/Articles/BFM%20Memo%20to%20SAG_June%2015v1.pdf

5.3 Energy and Solid Waste

http://maineghg.raabassociates.org/Articles/ESW%20Memo%20to%20SAG_June%2021v5.doc

5.4 Agriculture and Forestry

http://maineghg.raabassociates.org/Articles/MEAFWG_memoto_SAG_6-21.pdf

5.4.2 Forestry Calculations, 8-25-04, from Tom Peterson

http://maineghg.raabassociates.org/Articles/Appendix%205.4%20Pt%20%20(Forestry%20calcs).pdf

5.4.3 Draft Memo on Forestry Options Costs

http://maineghg.raabassociates.org/Articles/Appendix%205.4%20Pt%203%20(Forestry%20Cost%20Table).pdf