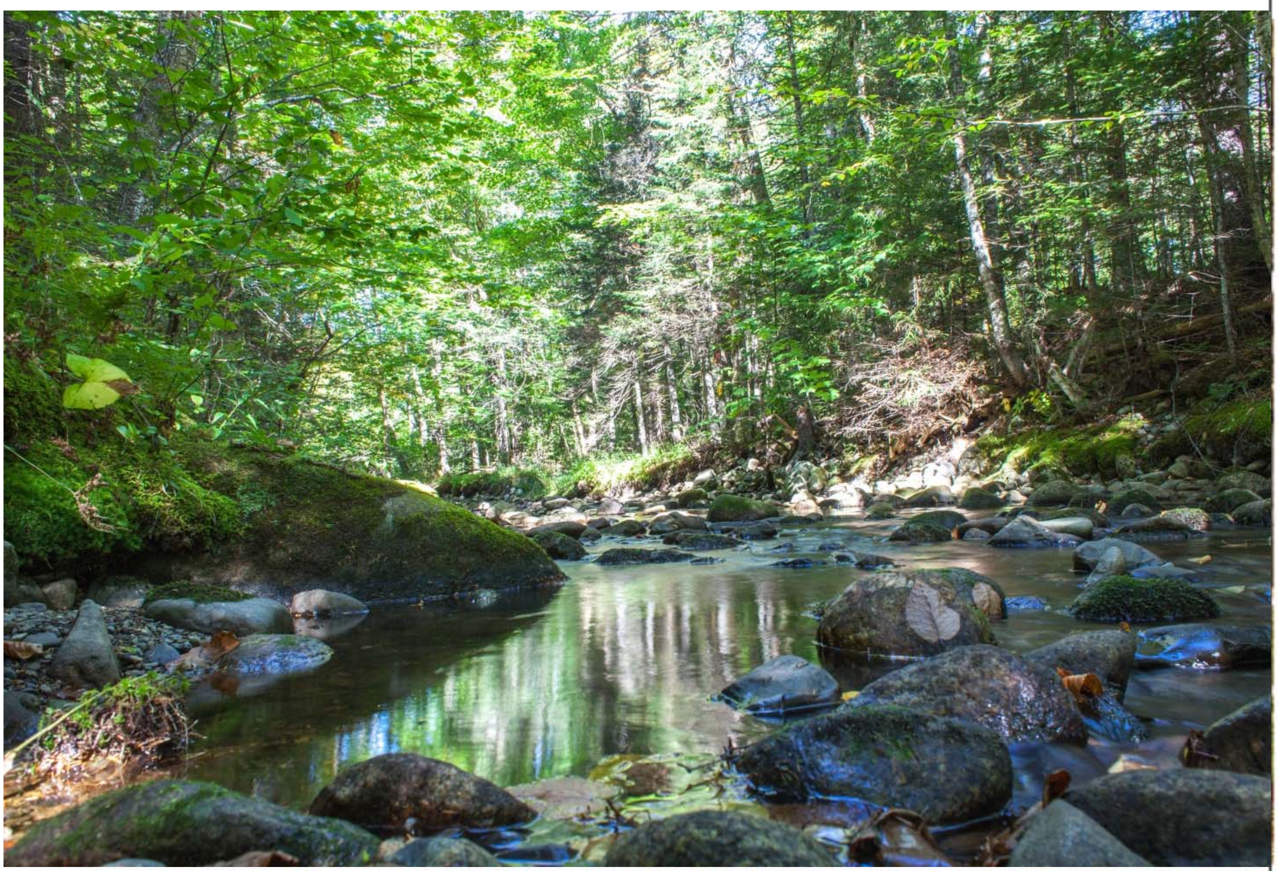
New England Forests: The Path to Sustainability

CHAPTER 4 • PROTECT US FROM CLIMATE CHANGE



A TECHNICAL REPORT BY NEW ENGLAND FORESTRY FOUNDATION

INTRODUCTION

This project documents both the existing value and potential of New England's working forest lands: Value – not only in terms of business opportunities, jobs and income – but also nonfinancial values, such as enhanced wildlife populations, recreation opportunities and a healthful environment. This project of the New England Forestry Foundation (NEFF) is aimed at enhancing the contribution the region's forests can make to sustainability, and is intended to complement other efforts aimed at not only conserving New England's forests, but also enhancing New England's agriculture and fisheries.

New England's forests have sustained the six-state region since colonial settlement. They have provided the wood for buildings, fuel to heat them, the fiber for papermaking, the lumber for ships, furniture, boxes and barrels and so much more. As Arizona is defined by its desert landscapes and Iowa by its farms, New England is defined by its forests. These forests provide a wide range of products beyond timber, including maple syrup; balsam fir tips for holiday decorations; paper birch bark for crafts; edibles such as berries, mushrooms and fiddleheads; and curatives made from medicinal plants. They are the home to diverse and abundant wildlife. They are the backdrop for hunting, fishing, hiking, skiing and camping. They also provide other important benefits that we take for granted, including clean air, potable water and carbon storage. In addition to tangible benefits that can be measured in board feet or cords, or miles of hiking trails, forests have been shown to be important to both physical and mental health.

Beyond their existing contributions, New England's forests have unrealized potential. For example, habitats for a wide variety of wildlife species could be enhanced by thoughtful forest management. Likewise, the quantity of wood produced could be increased and the quality improved through sustainable forest management. The virtues of improved forest management and buying locally produced goods are widely extolled, but what might that actually look like on the ground? More specifically, how could enhanced forest management make more locally produced forest products available to meet New Englander's own needs, as well as for export, improve the local and regional economies and provide the greatest social and environmental benefits?

The purpose of this project is to document that potential by analyzing what we know about how improved silviculture can enhance wildlife habitat, the quantity and quality of timber, recreational opportunities and the environment. The best available data from the US Forest Service, state forestry agencies and universities was used to characterize this potential.

The technical reports produced for this project document the potential for:

- Mitigating climate change and ameliorating its effects;
- Increasing timber production to support a more robust forest products industry;
- Restoring important wildlife habitat;
- Replacing fossil fuels with wood to produce thermal energy;
- Reducing greenhouse gas emissions, not only by substituting wood for other fuels, but also wood for other construction materials;

- Enhancing forest recreation opportunities and related tourism;
- Expanding production of nontimber forest products;
- Maintaining other forest values such as their role in providing clean air and potable water – taken for granted but not guaranteed;
- Enhancing the region's economy by meeting more of our own needs with New England products and retaining more of the region's wealth within the New England economy; and
- Other related topics.

These technical reports are viewed as "works in progress" because we invite each reader to bring their own contributions to this long term effort of protecting, managing and enhancing New England's forests. The entire set may be viewed at www.newenglandforestry.org. If you have suggested improvements please contact the New England Forestry Foundation to share your thoughts. These technical reports were used as the background to prepare a summary – *New England Forests: The Path to Sustainability*, which was released on June 5, 2014.

If you are not familiar with NEFF's work please visit www.newenglandforestry.org. Not already a member? Please consider joining NEFF – https://41820.thankyou4caring.org.

New England Forestry Foundation
32 Foster Street, PO Box 1346
Littleton, MA 01460

The New England Forestry Foundation is a recognized leader in conserving working forests, educating the public about forestry, and assisting landowners in the long-term protection and stewardship of their properties. For almost 70 years, we have demonstrated that well-managed working forests can provide landowners and the community with the prime ingredients for healthy living: clean air and water, sustainable production of an array of forest products, healthy forests for hiking and relaxation, a diversity of wildlife and habitats, periodic income, and renewable natural resources that help support rural economies.

Our Mission -- At the core of New England Forestry Foundation's work stands the belief that both conserving forestland and practicing sustainable forestry are essential to preserving the beauty, prosperity, wildlife habitats, and unique character of our region for future generations. Our approach strives to serve and unite people and organizations across the region to support the long-term health of New England's forests, and to guarantee their continued environmental, recreational, and economic benefits for all New Englanders.

This mission encompasses:

- Educating landowners, foresters, forest products industries, and the general public about the benefits of forest stewardship and multi-generational forestland planning.
- Permanently protecting forests through gifts and acquisitions of land for the benefit of future generations.
- Actively managing Foundation lands as demonstration and educational forests.
- Conservation, through sustainable yield forestry, of a working landscape that supports economic welfare and quality of life.
- Supporting the development and implementation of forest policy and forest practices that encourage and sustain private ownership.


THE PATH TO
SUSTAINABILITY
KEEP NEW ENGLAND FORESTED
Conserve 90% of New England's existing forests
GIVE WILDLIFE HOMES
Provide critical habitat for 338 diverse species
PROVIDE MORE RECREATION
Contribute more than $5 billion to the New England economy
GROW AS MUCH AS WE USE
Meet our consumption with wood from local forests
YOU ARE HERE
SUSTAINABILITY
PROTECT US FROM CLIMATE CHANGE
Reduce extent and impacts of heat waves, floods, and drought
CLEAN & COOL THE AIR
Save $700 million per year in health costs and crop losses
REDUCE USE OF FOREIGN OIL
Displace $1.85 billion of oil annually with wood heat
GROW MORE WOOD
Enhance quality and double wood production
PURIFY OUR WATER
Save $6 billion in water treatment costs
PROVIDE MORE WOOD FOR BUILDINGS
Save 3.5 million metric tons of carbon
CULTIVATE NEW BUSINESSES
Create new cottage industries using non-timber resources
CREATE LOCAL JOBS
Retain 30k jobs and increase exports to more than $10 billion.
New England's forests have tremendous potential to provide economic, environmental, and social benefits to the citizens of the region. Right now, we're letting some of that potential slip away. Through 12 new research reports, New England Forestry Foundation has defined the benefits our region's forests could provide, and those benefits are summarized here along the Path to Sustainability, starting with the premise that we Keep New England Forested.
NEW ENGLAND FORESTRY FOUNDATION

TABLE OF CONTENTS

PROTECT US FROM CLIMATE CHANGE

by R. Alec Giffen, Frank Lowenstein and Craig Ten Broeck

This report on the role of forests in ameliorating the effects of climate change (commonly referred to as climate adaptation) and reducing the extent of climate change (commonly referred to as climate mitigation) is part of a larger project on the potential of New England's forest lands to provide societal benefits and ecosystem services coordinated by R. Alec Giffen for the New England Forestry Foundation. Component parts of the larger effort include the following:

1. KEEP NEW ENGLAND FORESTED: Assessing the Current Conservation Status of New England's Forests by Jerry A Bley
2. GIVE WILDLIFE HOMES: Potential of New England's Working Forests as Wildlife Habitat by Jerry A. Bley
3. PROVIDE MORE RECREATION: Forest Recreation Trends and Opportunities in New England: Implications for Recreationists, Outdoor Recreation Businesses, Forest Land Owners and Policy Makers by Craig Ten Broeck and Aaron Paul
4. PROTECT US FROM CLIMATE CHANGE by R. Alec Giffen, Frank Lowenstein and Craig Ten Broeck
5. CLEAN AND COOL THE AIR: Forest Influence on Air Quality in New England: Present and Potential Value by Aaron Paul
6. PURIFY OUR WATER: The Potential for Clean Water from New England Forests by Aaron Paul
7. GROW MORE WOOD: The Potential of New England's Working Forests to Produce Wood by R. Alec Giffen, Craig Ten Broeck and Lloyd Irland
8. CREATE LOCAL JOBS: Vision for New England's Wood-Based Industries in 2060 by Innovative Natural Resource Solutions, LLC and The Irland Group
9. CULTIVATE NEW BUSINESSES: New England's Nontimber Forest Products: Practices and Prospects by Craig Ten Broeck
10. PROVIDE MORE WOOD FOR BUILDINGS: The Greenhouse Gas Benefits of Substituting Wood for Other Construction Materials in New England by Ann Gosline
11. REDUCE USE OF FOREIGN OIL: The Potential for Wood to Displace Fossil Fuels in New England by Innovative Natural Resource Solutions, LLC
12. GROW AS MUCH AS WE USE: Production versus Consumption of Wood Products in New England by Craig Ten Broeck

A. Acknowledgements

The authors of this report want to gratefully thank all of the researchers, organizations and agencies of government whose work has been relied on to write this report. Without their professional diligence we would not have been able to prepare this overview of the effects of climate change on New England, its people and its forests. We claim no original research on our part in its preparation, but rather have tried to synthesize their work into a coherent overview.

B. Executive Summary

Climate change is already causing changes in temperatures, precipitation, floods and droughts on global, national and regional scales. The National Climate Assessment foresees these changes continuing and intensifying driven largely by the amount of greenhouse gases (GHG) emitted into the atmosphere. These changes are expected to impact New England significantly. For example, there will be more very hot days. The number of days rated by the National Weather Service as being at the "extreme caution" level (90°F) is expected to occur with greater frequency, especially throughout southern New England and coastal Maine by 2090 where the number of days in the "extreme caution" range are expected to triple over 1990 levels. Other areas of northern New England that historically have not experienced such extreme heat may be subjected to 20-30 sweltering days per year.

This report by the New England Forestry Foundation on climate change documents the significant role that forests can play in both:

- Ameliorating the adverse impacts of climate change, e.g., reducing high temperatures in urban environments; and

- Mitigating the effects of climate change, e.g., reducing greenhouse gas levels by sequestering CO_2.

Research shows forests can ameliorate the adverse effect of climate change in a number of ways. Temperatures on calm clear nights in urban areas can be as much as 22°F (12°C) hotter than surrounding areas. This temperature differential is caused by the heat island effect of urban infrastructure. However, urban parks, depending on their size, can reduce air temperatures significantly and these effects can extend downwind over 600 feet into the city.

Forests can reduce high temperatures over a large area through the cooling effect of evapotranspiration. The shade from urban trees reduces fugitive emissions from parked cars and hence tropospheric ozone (a GHG). Forests can also increase water infiltration into the soils thereby reducing localized stream flooding and augmenting flows during periods of low precipitation.

Forests also afford a multitude of opportunities to mitigate climate change, including carbon sequestration. Oliver, et al. (2014) contend that using more of the wood we already grow and substituting it for other construction materials could reduce global annual GHG emissions by 14-31%. Even if this ambitious reduction is not fully realized, it is clear that using wood to replace other construction materials, like steel and concrete with higher embodied energy, could have significant climate benefits.

A thorough analysis by Matthews, et al. (2014) compare the GHG emissions from wood versus alternative construction materials, and concluded that over a 20-year period using wood for sawn wood products and the residuals for energy could reduce emissions by up to 30 MtCO2e per hectare per year when compared to the alternatives. Further, they calculated that these reductions were greater than those that would be realized by either leaving the forest unharvested or only burning the wood for energy.

New engineered wood products, such as cross laminated timber, now allow multi-story buildings to be built entirely or more substantially with wood. This provides a two-fold reduction in climate change – the avoidance of the carbon pollution caused by other more energy intensive building materials such as concrete and steel and resulting in the storage of more carbon in the wood for the long-term. The material for these products can be produced sustainably by substantially increasing the growth in New England forests (potentially doubling growth) through more intensive management for current species. It is also possible to favor species such as oak, hickory and pine that will expand further northward as the climate warms. See the report "Grow More Wood" in the "Path to Sustainability" (a series of technical reports available at http://newenglandforestry.org/connect/publications/path-to-sustainability/).

This report also documents that forests can influence global climate in many ways beyond merely sequestering carbon. There are over 30 forest influences on climate that can be organized into three categories: 1) Forest and Urban Tree Functions, e.g., reflecting and absorbing incoming solar radiation, and oxidizing methane (a potent GHG); 2) Forest and Urban Tree Management, e.g., harvesting and transporting wood products; and 3) Forest Products and Uses, e.g., reducing CO_2 emissions by substituting wood for other construction materials and burning certain sources of biomass rather than fossil fuels.

In addition, it is apparent that under some circumstances certain of these influences either collectively or individually may be more important than carbon sequestration. This means that in order to understand accurately and implement effective policy and management, we must understand the "net effects" of several influences.

> "An integrated assessment of forest influences entails an evaluation beyond albedo, evapotranspiration, and carbon to include other greenhouse gases, biogenic aerosols, and reactive gases. The interrelatedness of climate change science, climate impacts on ecosystems, and climate change mitigation policy requires that these be studied together in an interdisciplinary framework to craft strong science in the service of humankind" (Bonan 2008, p. 1449).

While it is obvious that New England's forests cannot by themselves fully mitigate global climate change or even ameliorate all of the regional impacts that are likely to occur, they could, along with the region's intellectual capital working on this issue, serve as a site for case studies that enable us to determine:

1. How to maximize the climate benefits of forests (maximize net benefits);
2. How to increase forest resilience; and
3. How to facilitate forest adaptation to species that will be favored by a warming climate.

It is imperative that we get underway with this research soon if we are to lead the way for other regions and initiate policies and practices that will take full advantage of New England's forests to ameliorate and mitigate climate change.

Existing tools, such as the latest atmospheric models, may be useful to explore some of these questions, and it is likely that new modeling tools will also be needed. This will be a fertile area for research (for an outline of the research concepts, see Attachments 4 and 5 in this report). The lives, livelihoods and wellbeing of New Englanders could depend upon the development of effective strategies to mitigate climate change and ameliorate its effects. It will take time to develop the necessary climate research tools and to employ them to find answers to challenging and complex questions about our changing climate. We are fortunate to have the Woods Hole Research Center, a world leader on this topic, and the Clean Air Task Force as partners in this enterprise.

Actions We Can Take Now!

Finally, despite the need for additional research, there are steps we can take now to capitalize on the opportunities New England's forests offer to: 1) ameliorate and 2) mitigate climate change, as well as 3) facilitate the adaption of forests to future climate conditions, so that they can ameliorate and mitigate climate change in the future. That is, for example, because we understand their consequences, we can with confidence take the following actions:

Ameliorate Climate Change

- Increase use of urban trees to shade buildings to reduce ground level air temperatures and thereby reduce emissions associated with air conditioning and block winter winds to reduce emissions from heating.
- Maintain and expand urban parks to provide cooling benefits downwind into surrounding residential areas.

Mitigate Climate Change Now

- Keep New England's forests as forests – not only to store carbon but also to reduce emissions of N_2O.
- Restore management for longer rotation ages to increase the oxidation of methane (many actively managed areas are now managed for shorter rotation ages than they were historically).
- Favor tree species best suited to grow valuable products (particularly those suitable for long-lived wood products) under future climatic conditions.
- Substitute wood in construction for other materials with higher life cycle greenhouse gas emissions.
- Productively use trees that are dead or will die in the next few decades, so that the carbon contained in them can be used in ways that most effectively reduce greenhouse gas emissions.

Facilitate the Adaptation of Forests to Future Climate Conditions (Adaptation is needed to allow forests to both amelioration and mitigation climate change in the future.)

- Thin stands to improve growth on trees targeted for management and to make them more resilient to climate change; and harvest trees that would otherwise die.
- Maintain the "connectivity" between forest areas (particularly along high elevation areas and the north/south axis) in the Northern Appalachian/Acadian Forest to allow for species migration over time.

In summary, New England's forests provide options to ameliorate, mitigate and adapt to climate change. They in turn will be strongly influenced by the actions we choose to take. If forests are managed to optimize climate benefits, considering the full range of forest-climate systems interactions without adverse climate impacts (e.g. displacing agriculture to a region where it results in greater radiative forcing), they could contribute to what Garman, et al. (2014) referred to as "climate remediation." This would be an example of employing techniques to improve our circumstances rather than simply avoiding making them worse. This can be thought of as "green" geoengineering that has multiple benefits without the risks that other more extreme geoengineering approaches could entail. This effort should include expanded urban and agroforests, as well as wildland forests.

C. Purpose of this Report

Scientists recognize that greenhouse gases generated by burning fossil fuels as well as other human activities are the primary cause of climate change. Natural variations in climate have been found in the geologic record, but occur slowly over thousands of years. Human induced changes are being seen and felt in less than 100 years. The impacts of anthropogenic climate change being seen now will continue for the New England region for the rest of this century and well beyond. While the extent of change will depend on governmental and societal decisions worldwide that control the amount of greenhouse gases emitted, trends point to hotter summers, shorter winters, longer growing seasons, more frequent and extreme heavy precipitation events, more severe flooding, increased evapotranspiration, and even periods of increased seasonal drought or aridity. These changes will affect human health and well-being as well as ecosystems—including forests which are the subject of this report. These impacts could also have major consequences for our regional economy.

The New England Forestry Foundation developed this report to inform governments, landowners and the public that:

- Forests will influence the extent of future climate change in several ways – they do far more than just store carbon, they influence the reflectance of the earth's surface and the formation of clouds which can exert a cooling effect on the earth.
- Forests ameliorate the effects of climate change by shading and cooling our cities and towns, and stabilizing and moderating storm water flows.
- Improved management of New England's forests could enhance all of these benefits.
- New England's forest could be used as the test case to determine how to optimize these benefits. New Englanders and New England's forests offer several advantages:
  - History of innovation in forest conservation
  - Tradition of management
  - Resilience – many species and physiographic settings
  - Knowledge base
  - Intellectual capital and strong interest

The available climate models lack the accuracy and resolution to fully, completely, and with certainty account for all the complexities of the climate system, particularly at the regional level and in the short term. It is not possible at this time to predict with precision the severity and timing of these types of impacts within the New England region. This report is not intended to be the several authors' independent assessment of the likely impacts of a changing climate on New England. Rather we use as a point of departure for this report the information provided in the most recent National Climate Assessment (U.S. Global Change Research Program 2014) and more specifically the chapter on the Northeast region of the U.S., which encompasses New England. After briefly summarizing information from the most recent National Climate Assessment about the likely trends of climate change on the U.S. and in New England we focus on the role forests can play in helping society adapt to and mitigate climate change. Additional information is included in the attachments on the expected nature of climate change and the positive influences forests can have on climate change and human health and well-being.

D. Overview

The IPCC Climate Change 2014 Synthesis Report Summary for Policymakers states that: **"Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely [95% confidence level] to have been the dominant cause of the observed warming since the mid-20th century."**

And, **"In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate."**

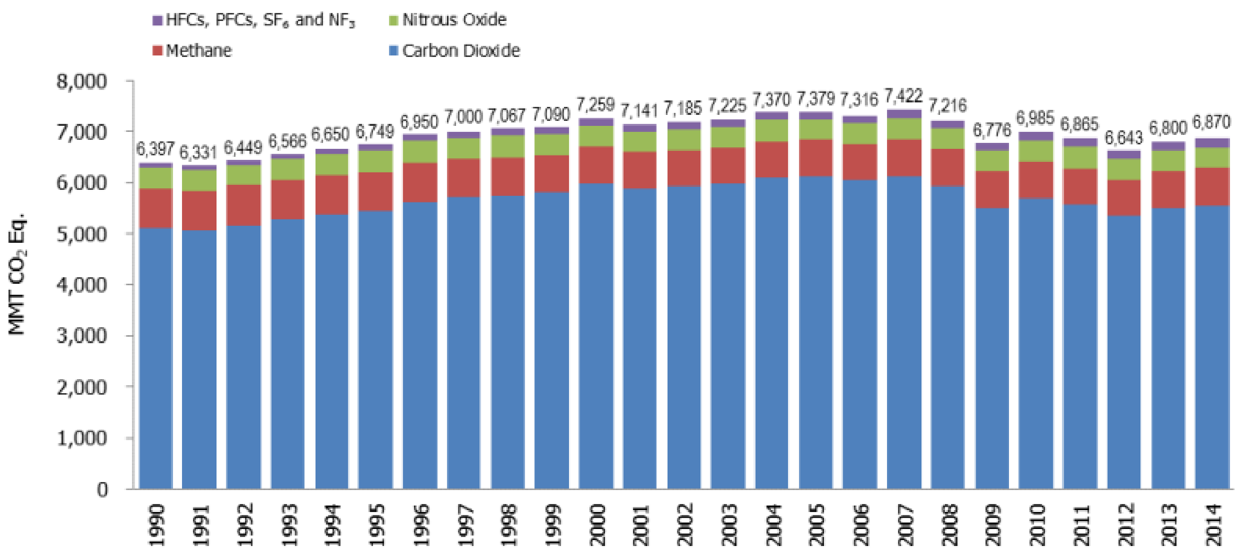
The report goes on to say that **"Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks."**

The report clearly identifies rising concentrations of carbon dioxide and other greenhouse gases in the atmosphere as the primary drivers of this change. The increased levels of carbon dioxide in the atmosphere are derived primarily from burning of fossil fuels, and to a lesser extent from deforestation and degradation of forests and other ecosystems.

The most recent U.S. EPA greenhouse gas inventory was issued in 2016. It reports that for 2014, total U.S. greenhouse gas emissions were 6,870.5 MMT or million metric tons CO_2 Eq. Total U.S. emissions have increased by 7.4 percent from 1990 to 2014, and emissions increased from 2013 to 2014 by 1.0 percent (70.5 MMT CO_2 Eq.) (see Figure 1 below).

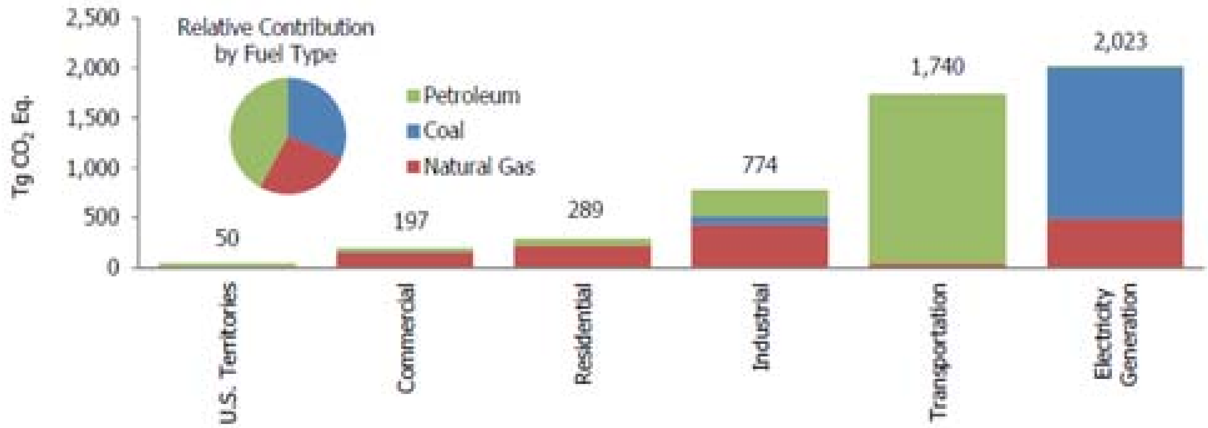
As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 76 percent of Global Warming Potential (GWP)-weighted emissions since 1990, and stayed at that same level in 2014. Emissions of CO2 from fossil fuel combustion increased at an average annual rate of 0.4 percent from 1990 to 2014. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 25 years, (2) an overall growth in emissions from electricity generation and transportation activities, and (3) a general decline in the carbon intensity of fuels combusted for energy in recent years by most sectors of the economy (see Figure 2 below).

Figure 1. U.S. Greenhouse Gas Emissions by Gas (MMT CO_2 Eq.)



Source: U.S. EPA (2016).

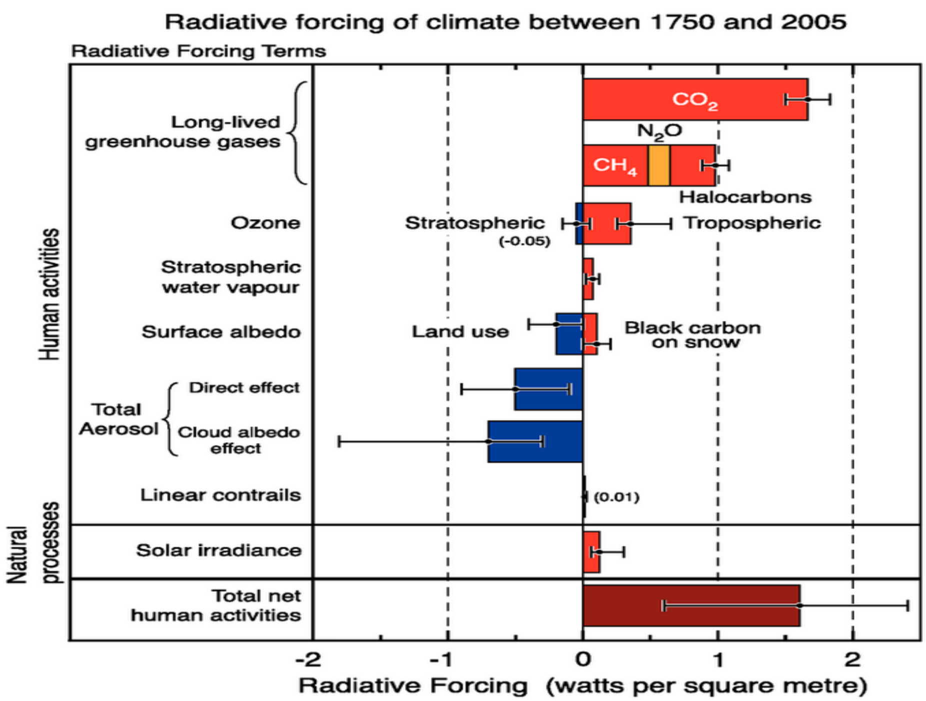
Figure 2. 2014 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type (MMT CO_2 Eq.)



Source: U.S. EPA (2016)

The Intergovernmental Panel on Climate Change (IPCC) characterizes the drivers of climate change and their relative influences in Figure 3. In the figure the effects of radiative forcing (RF) of climate are quantified in watts per square meter, as this is most commonly how these impacts are measured. Increases in RF warm the climate (on the X axis to the right ‘0’), while decreases in RF cool the climate (on the X axis to the left of ‘0’). Forests influences on climate can either result in an increase in RF, producing greater warming (e.g., forest cover absorbs more incoming solar radiation than grass or most crops thereby causing the surface of the earth to ‘heat up’) or decrease RF (e.g., forests oxidize methane – a potent greenhouse gas thereby reducing the greenhouse effect).

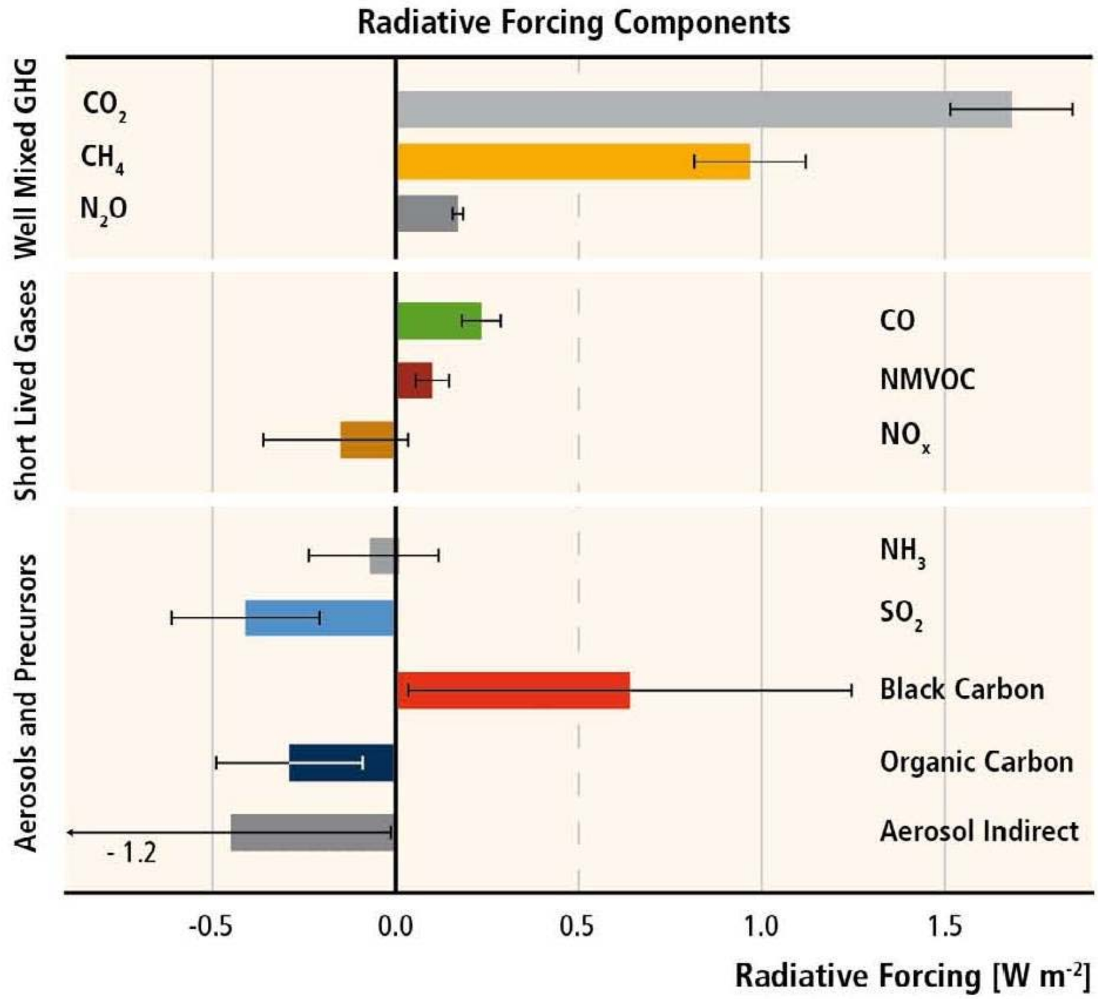
Figure 3. Radiative forcing of climate (2007 version)



Source: IPCC (2007b.).

Both a 2007 and 2014 version of similar graphics are included in this Overview section as the 2007 version includes a somewhat broader set of factors, e.g. “surface albedo” and “solar irradiance”, that were not included in the summary of GHG impacts shown in the graphic from 2014. Note that the error bars associated with each graph indicate that the influence of some factors (such as the gas nitrous oxide -- N_2O) have been fairly precisely quantified, while the impact of other factors (such as black carbon) are more uncertain.

Figure 4. Radiative forcing components (2014 version)

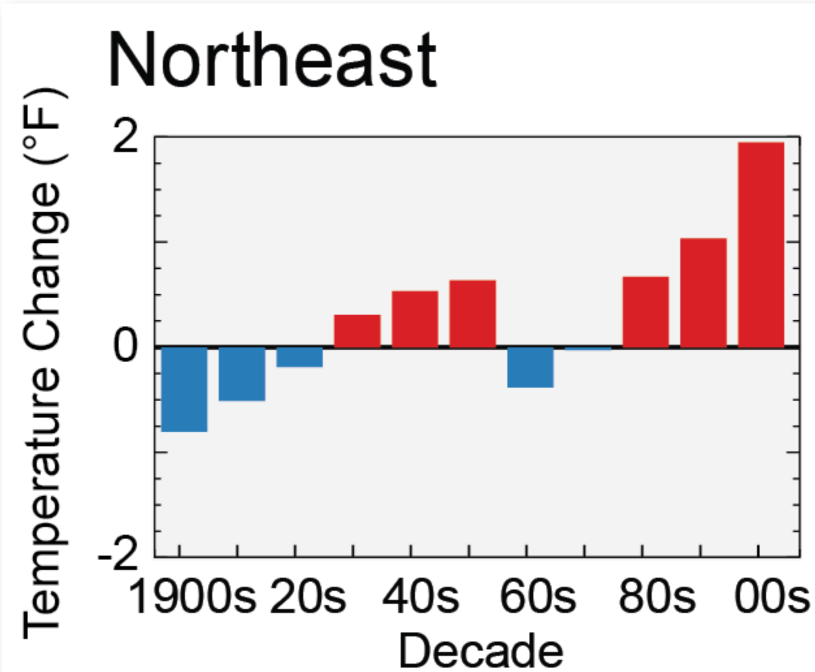


Source: IPCC (2014).

Despite the uncertainties with global climate modeling,[1] weather and climate records show that New England has clearly already experienced elevated temperatures and intensified precipitation events when compared to historical records (Melillo, et al. 2014). These are not projections based on models but actual data recorded over decades. Thus, regardless of the extent of future climate change, it is clear that we will need to adapt to the changes in climate that have already occurred to protect lives and reduce economic damage from heat waves, intense storms, floods and droughts.

[1] While the overall trends of a changing climate are clear and effects are already being experienced it is difficult to predict the rate and scale of change for any particular region precisely. David Garman and his coauthors (Garman, et al. 2014) put it this way, "It is important to also recognize that there is significant uncertainty regarding the pace, severity and consequences of the climate change attributable to human activities… There is also uncertainty regarding short-term and regional impacts, because the available climate models lack the accuracy and resolution to account for the complexities of the climate system."

Figure 5. Observed Northeast temperature change (Note: temperatures are shown in Fahrenheit)



The bars on the graphs show the average temperature changes by decade for 1901-2012 (relative to the 1901-1960 average) for the Northeast region. The far right bar (2000s decade) includes 2011 and 2012. The period from 2001 to 2012 was warmer than any previous decade.

Source: Melillo, et al. (2014).

New England's extensive forests make an important contribution to the region's ability to reduce greenhouse gas levels and stem climate change. They absorb carbon from the atmosphere and sequester it in their roots, trunks, branches and bark and contribute to carbon stored in and on the soil. Depending on management of the forest and the uses to which forest products are put that carbon can be trapped for centuries. Forests also influence climate in many other ways: albedo effects (reflectance); production of biological volatile organic compounds; oxidation of methane; physical effects; and wood substitution benefits; which are discussed later. Unfortunately, we have yet to develop tools that enable us to accurately assess the net effects of these influences, when considered comprehensively, as they can be mutually reinforcing or contradictory and interact non-linearly in complex ways. It is vitally important that we use the most accurate existing tools, and develop new analytical tools where necessary, to enable us to accurately assess the net effects of forest influences on climate change so that we have a solid basis for climate beneficial forest management and policy. In this regard, it is clear that existing policies regarding the use of forests and forest products to reduce climate change are based on consideration of only one or two of the more than 20 factors involved; and that even based on the few factors considered, those policies can have effects which exacerbate rather than mitigate climate change (e.g., policies which promote harvesting whole trees that are healthy and would otherwise persist for decades strictly for use as fuel can add to GHG levels for decades).

In most, but not all cases, conserving forests as forests is profoundly important to mitigate climate change by ensuring that the carbon stored in the roots, trunks, branches and bark of trees is not released to the atmosphere. Forests can also provide products which, when used in place of more energy-intensive alternatives, can in the near term reduce greenhouse gas levels. Over the longer term, if we are successful in decarbonizing our energy system process energy will be reduced or eliminated, but long-lived wood products will continue to store carbon. In this way, forests can be used for "green" geo-engineering to pump excess carbon out of the atmosphere and store it in buildings or other long-lived products. Forests can also ameliorate heat, floods, and droughts thereby helping us to adapt to climate change. This report identifies key roles of forests in mitigating climate change and ameliorating its effects, thereby helping us to avoid, at least to some degree, the adverse consequences.

E. The National Climate Assessment – 2014

The authors of this report relied on the National Climate Assessment -- 2014, rather than duplicating this extensive effort, as the point of departure for discussing climate change and the role of New England's forests in helping to protect us from its effects.

The National Climate Assessment documents the impacts of a changing climate on the United States and its various regions, including New England. A team of more than 300 experts guided by a 60-member Federal Advisory Committee produced the report. It has received extensive review by the public, experts, federal agencies and a panel of the National Academy of Sciences. For more information see http://nca2014.globalchange.gov/highlights/overview/overview.

The National Climate Assessment collects, integrates, and assesses observations and research from around the country to see what is happening to our climate and to understand how it will affect our lives, livelihoods and future. The report also assesses key impacts on all U.S. regions. It analyzes the impact of climate change on seven sectors: human health, water, energy, transportation, agriculture, forests, and ecosystems – and the interactions among sectors at the national level. To read the full report visit: http://nca2014.globalchange.gov/report.

The essence of the National Climate Assessment team's findings is that in general the future climate will:

- Be warmer
- Change patterns of precipitation from those currently existing
- Be characterized by more extreme weather events, e.g., extreme heat, heavy downpours, and seasonal droughts, etc.
- Challenge the capacity of natural systems to buffer the impacts of extreme events.

For the northeast they concluded:

First, as regards current trends:

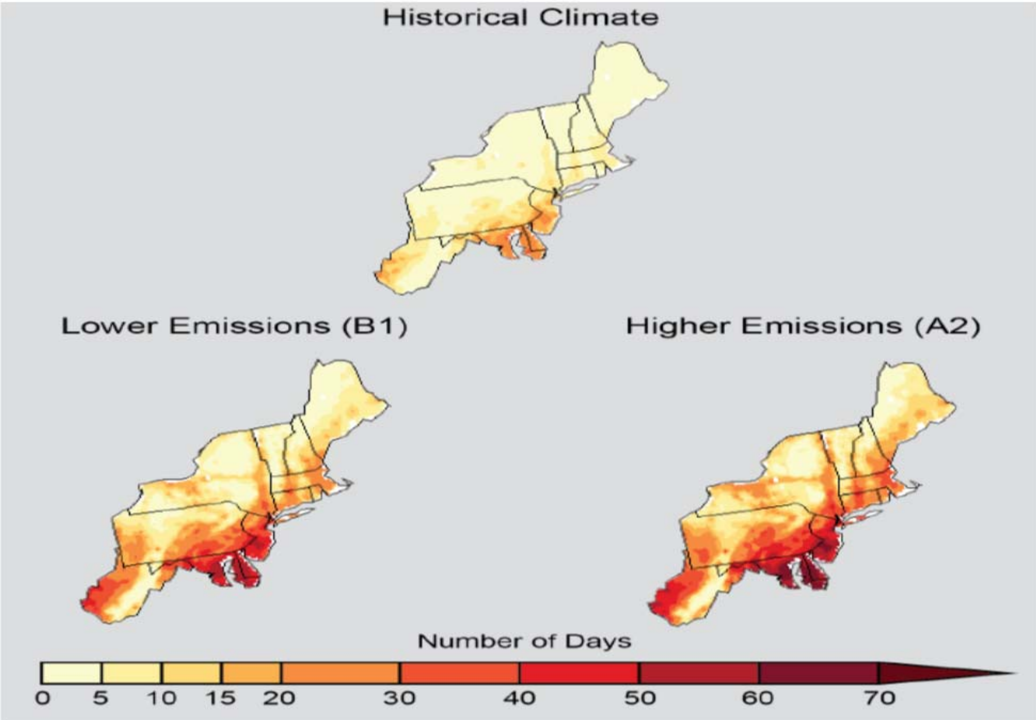
"*Between 1895 and 2011, temperatures in the Northeast increased by almost 2˚F (0.16˚F per decade), and precipitation increased by approximately five inches, or more than 10% (0.4 inches per decade). Coastal flooding has increased due to a rise in sea level of approximately 1 foot since 1900. This rate of sea level rise exceeds the global average of approximately 8 inches*" (http://nca2014.globalchange.gov/report/regions/northeast).

As to the future:

The degree of warming in the Northeast will be highly dependent on global emissions of greenhouse, heat-trapping gases, e.g., the high emissions scenario (A2) used by the National Climate Assessment, postulates temperatures above the current annual average at a level between 4.5ºF to 10ºF by the 2080s, while the lower emissions scenario (B1) projects increases of 3ºF to 6ºF.

As to one of the impacts perhaps most commonly associated with climate change, under both scenarios the frequency, intensity, and duration of heat waves is expected to increase, with larger increases under the higher emissions scenario.

Figure 6. Projected increases in the number of days over 90°F



]

Source: Melillo, et al. (2014).

Further, the frequency of heavy downpours is projected to continue to increase during this century. Seasonal drought risk is also projected to increase in summer and fall as higher temperatures lead to greater evaporation and earlier winter and spring snowmelt.

More generally, for the Northeast the report has a few key messages summarized here:

- *"Climate Risks to People - Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems. This will increase the vulnerability of the region's residents, especially its most disadvantaged populations.*
- *Stressed Infrastructure - Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding, and intense precipitation events.*
- *Agriculture and Ecosystem Impacts - Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts including seasonal droughts…, adaptive capacity, which varies throughout the region, could be overwhelmed by a changing climate.*
- *Planning and Adaptation - While a majority of states and a rapidly growing number of municipalities have begun to incorporate the risk of climate change into their planning activities, implementation of adaptation measures is still at early stages." (http://nca2014.globalchange.gov/report/regions/northeast).*

F. The Benefits of Forests in Ameliorating Effects of Climate Change

Forests play a role in maintaining the health and safety of New England residents. While they will not be able to maintain ground-level temperatures or storm intensities at historic levels, they can nonetheless ameliorate a portion of the adverse consequences of climate change. Further, with climate change these critical roles are likely to increase in importance, and conserving forests should be part of region-wide strategies for New Englanders in adapting to the impacts of climate change. Forests protect residents from heat waves, flooding and droughts in the following ways:

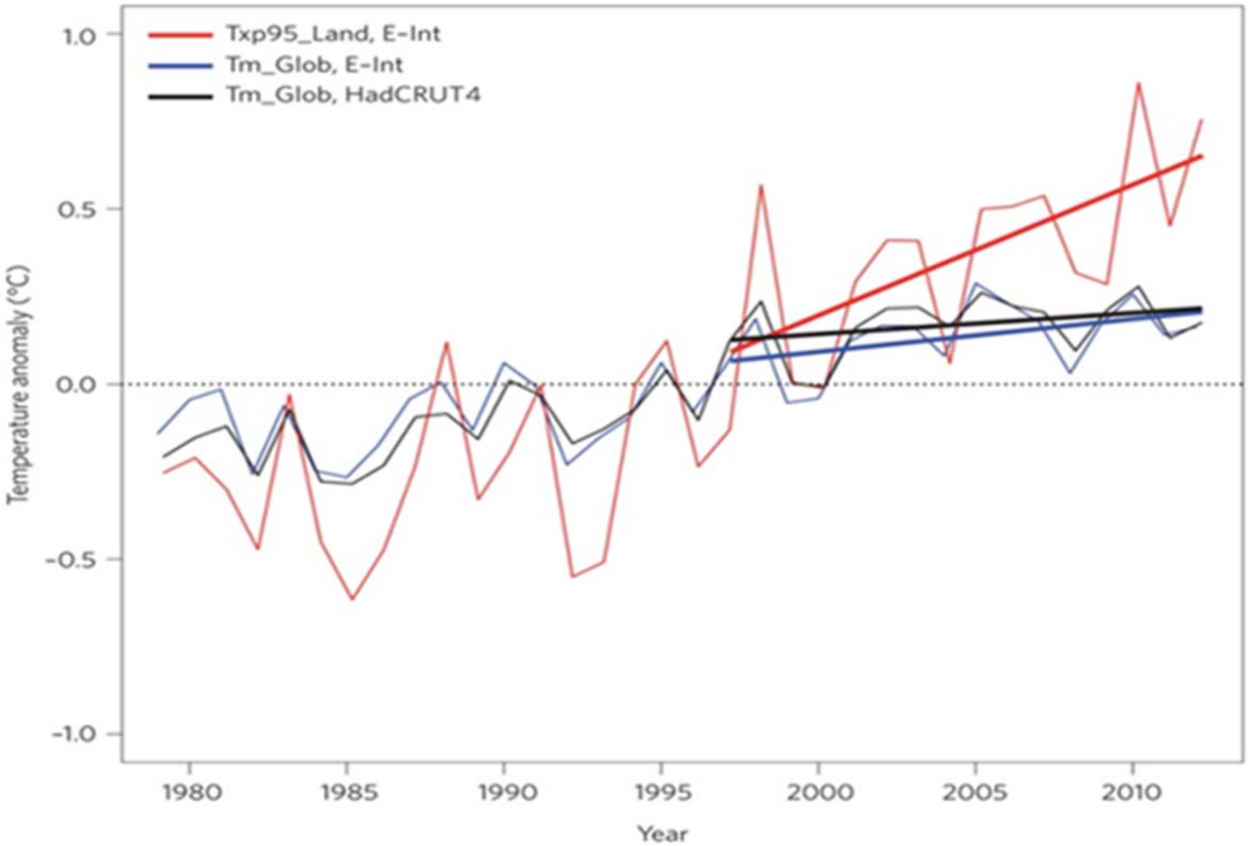
- **Regional Cooling** -- through shading and evapotranspiration of moisture that cools and increases cloud formation and rain;
- **Moderating Flooding** – by storing precipitation; and
- **Increasing Summer Low Stream Flows** -- by promoting infiltration and the steady release of ground water to streams and rivers.

Each of these beneficial aspects of forests is considered further in the following three sections.

1. Local and Regional Cooling

The frequency of very hot days in the United States has already increased by approximately 50 percent since the 1950s and even in the last 15 years -- when mean global temperatures have increased somewhat more slowly (thought to be a result of absorption and redistribution of heat in the oceans) there has been a dramatic increase in the frequency of the hottest days (Figure 7).

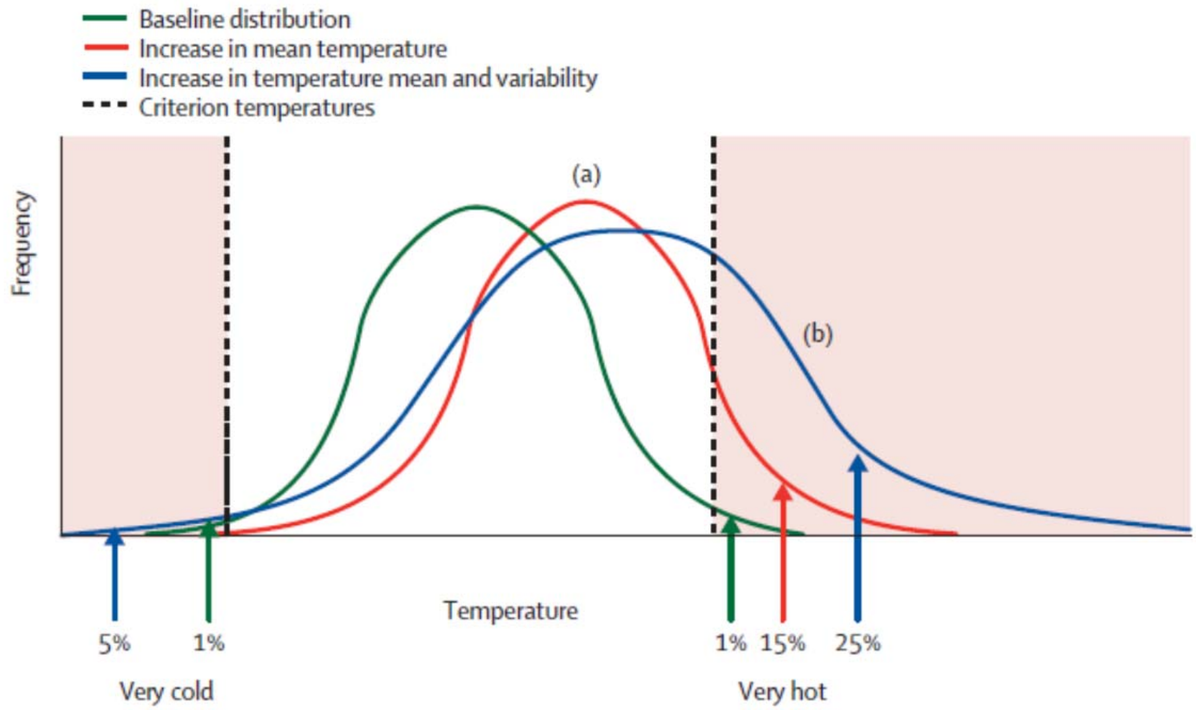
Figure 7. Time series of temperature anomalies for hot extremes over land (red) and two measures of global mean temperature (black, blue)



Source: Seneviratne, et al. (2014).

This graphic shows how hot "extremes" over land can increase significantly even as mean global temperatures rise only modestly. Climate change driven by fossil fuel emissions and deforestation, particularly in the tropics, is causing New England, like the rest of the nation, to experience rising temperatures and associated cascading impacts (Lowenstein and Girvetz 2014). These trends could accentuate impacts already documented in the region, with both elevated average temperatures and heat waves becoming more common (Figure 8). As noted earlier, considerable uncertainties exist with predicting future conditions particularly in the near term and at a regional scale.

Figure 8. The effect of increases in (a) mean temperature, and (b) temperature mean and variability*, on frequency of extreme temperature days



Arrows designate the percent of area-under-the-curve, beyond the criterion temperatures for very cold and very hot. Percentages are approximate only.

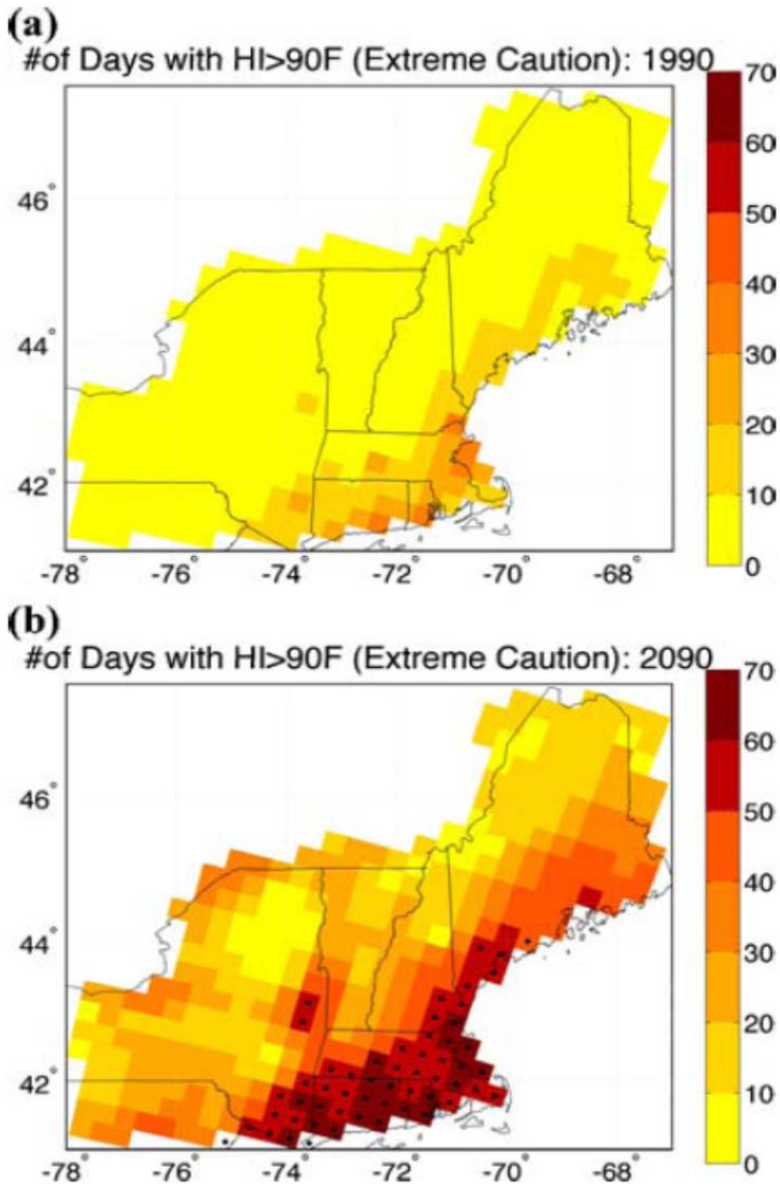
Source: McMichael, et al. (2006).

This graph illustrates that the frequency of both hot and cold extremes of temperature depend on both the mean temperature around which variation occurs and the extent of variation. The theoretical graph shows how a shift in mean temperature without an increase in variability would shift the distribution of temperatures from the green bell curve to the identically shaped red bell curve. The percentage of time experiencing extreme heat (areas to the right of the dotted line) would increase from 1% to 15%. If both mean temperature and variability increase (shown by the blue curve) then the area under the curve above the threshold for extreme heat could increase to 25% and the amount of time experiencing extreme cold could also increase! Note also that the two scenarios showing increased mean temperature also result in the occurrence of unprecedented very hot temperatures (McMichael, et al. 2006).

The increase in frequency of heat waves may place vulnerable individuals at extreme risk due to heat stress. Vulnerable individuals are most commonly found in certain socioeconomic groups including the elderly, young children, those living below the poverty level, and in people with underlying health issues that compromise their ability to cope with heat stress. Heat stress is the primary cause of weather-related deaths worldwide.

The southern third of the region could face dramatic increases in the number of days of dangerous heat indices and has less forest cover to help moderate temperatures than the northern two-thirds (Figure 9). Under these conditions, even healthy young adults could be well advised to restrict outdoor activities due to heat stress (Anderson, et al. 2010).

Figure 9. Number of days per 92-day summer season (June-August) in which the daily heat index (HI) maximum is above the National Weather Service "extreme caution" level (90°F) for (a) 1990-1999 and (b) 2090-2099. Regions with black dots are ones in which seasonal-mean daily HI maximum is above "extreme caution" level (90°F).



Source: Anderson, et al. (2010).

An increase in the frequency of heat waves would be associated with other threats to health, including increased concentrations of ground level ozone that is created by temperature-influenced chemical reactions. Ozone is likely to reach unhealthy levels on hot sunny days in urban environments, but ozone can also be transported long distances by wind. For this reason, even rural areas can experience high ozone levels (https://www.epa.gov/ozone-pollution).

Heat waves could cause cascading impacts to occur. High day time temperatures could compromise generating capacity within the electric grid at the same time that demand for air conditioning is increasing. For example heat waves in the summer of 2012 caused a shutdown of the Millstone nuclear power plant complex in Connecticut when Long Island Sound became too warm to be used as a source of cooling water for the plant. Two Midwest electric generating plants also cut back—one due to high temperatures in its cooling pond and the other when water levels fell below the plant's intake pipe. Cutbacks in hydroelectric output could also coincide with heat waves and seasonal droughts as stream flows and impoundment levels would decrease.

Heat waves also cause a feedback loop that worsens future global warming. During a heat wave, the demand for electricity increases as air conditioning systems work overtime to keep building temperatures within comfortable ranges. This causes electric utilities to bring on-line back-up power plants, increasing emissions of carbon dioxide to the extent that those plants are fossil fueled. While this is not a major factor influencing GHG emissions it has a cumulative impact.

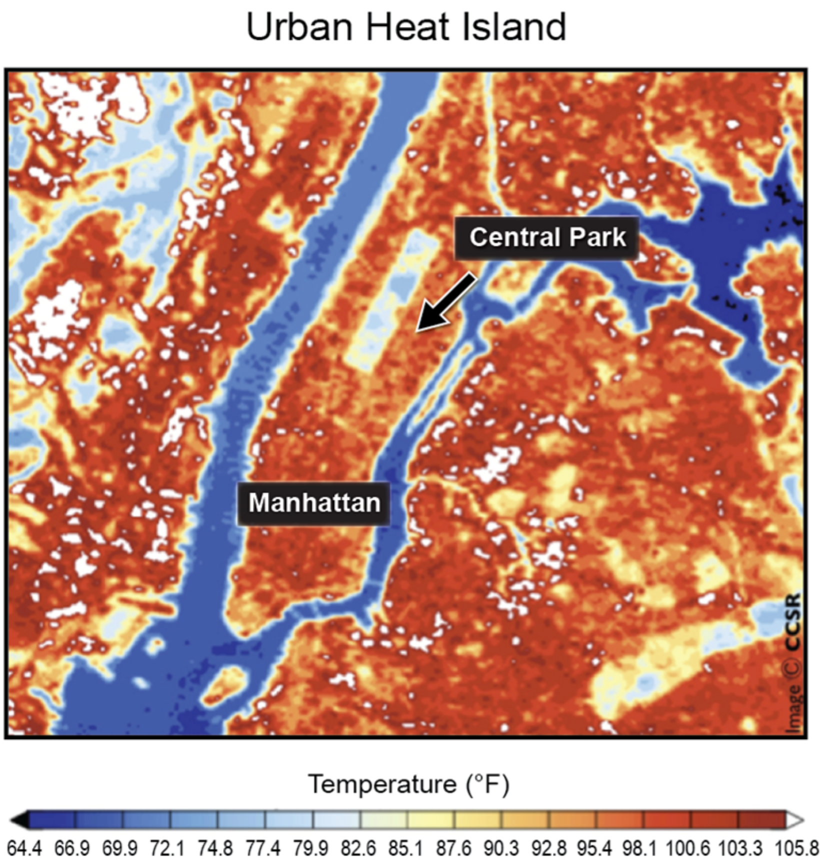
Since 1980, a number of scientific studies have documented the role of urban and suburban development in creating urban heat islands (Arnfield 2003). The heat island effect derives in part from the relative absence of vegetation to shade the ground and cool by evapotranspiring moisture (to lose water into the atmosphere by evaporation and transpiration). Adding to this effect is the heat released from car engines and air conditioning systems. The storage of heat by concrete buildings and asphalt streets also contributes to elevated temperatures. To date these heat islands often have much larger impacts on average temperatures than does existing human-induced climate change.

These effects can be at least partially mitigated by retaining and planting more trees in urban and suburban areas. Strategically located trees can reduce ground level temperatures by shading and evaporative cooling – not only making temperatures more comfortable, but also reducing the amount of heat exhausted from air conditioning. A single well positioned tree that effectively shades a building can reduce residential air conditioning by 20% or more in some settings (Akbari, et al. 2001). Temperatures in forested urban settings (e.g., parks and tree lined streets) can be up to 10^{o}F cooler than treeless areas (Horton and Yohe 2014).

Other heat island reduction efforts such as creating reflective surfaces (roofs and pavement) and green roofs have also been shown to be effective in reducing urban temperatures and emissions associated with cooling. The most effective strategies use a combination of aggressive urban forestry—planting more trees, using green roofs and creating reflective surfaces (Rosenzweig, et al. 2006).

Not only can urban forests shade buildings and thereby reduce ground level air temperature and, hence, reduce emissions associated with air conditioning, they can also block winter winds and reduce emissions from heating. These beneficial impacts of forests and trees blur the lines between mitigation—preventing climate change—and adaptation, that is reducing climate change's undesirable impacts on people and the environment.

Figure 10. New York Urban Heat Island and Effect of Central Park



"Surface temperatures in New York City on a summer's day show the "urban heat island," with temperatures in populous urban areas being approximately 10°F higher than the forested parts of Central Park. Dark blue reflects the colder waters of the Hudson and East Rivers. (Figure source: Center for Climate Systems Research, Columbia University)" (Horton and Yohe 2014).

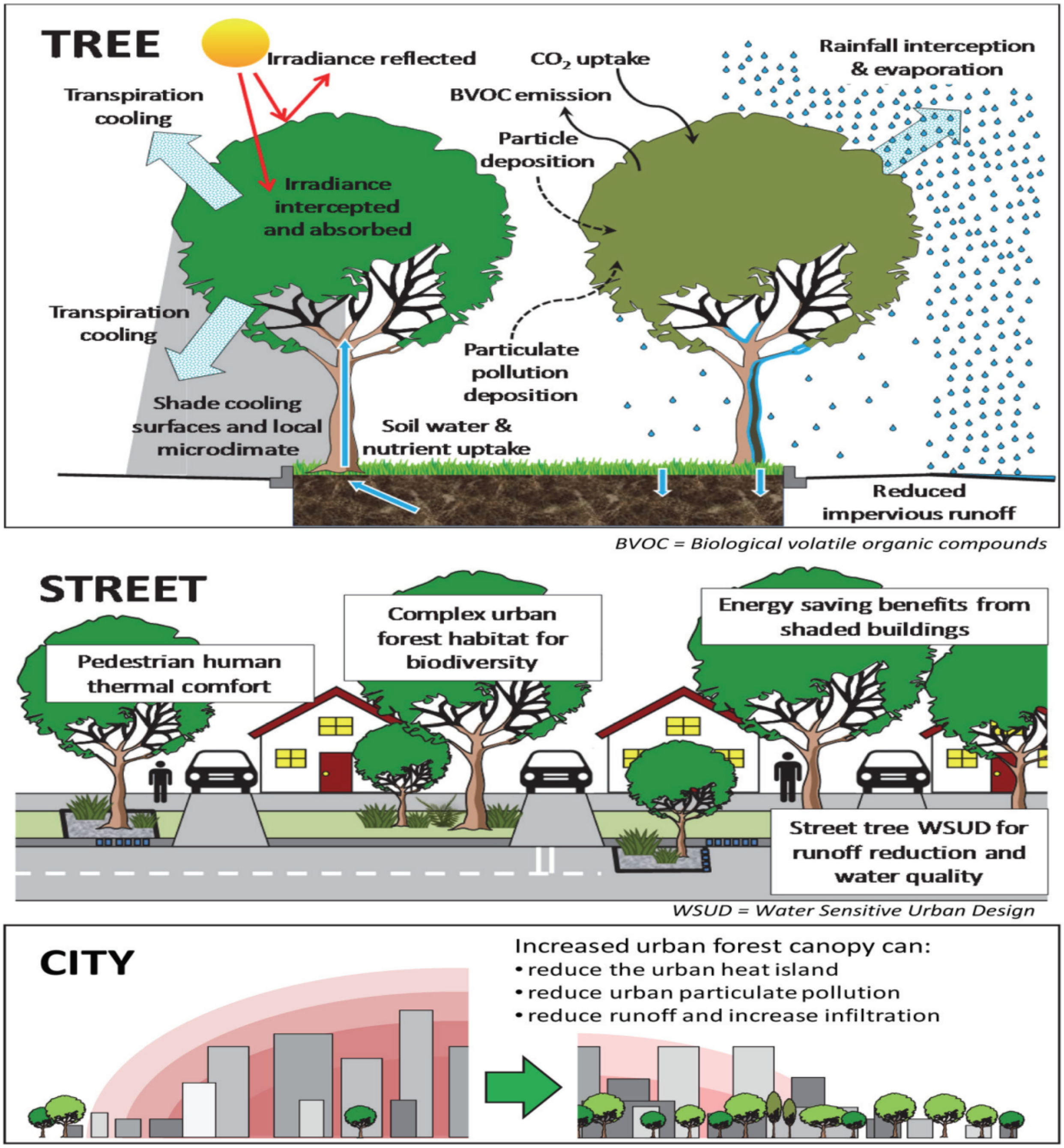
The loss of forests to urban and suburban development is expected to continue and will exacerbate the urban heat island effect. Although the Northeastern U.S. has the second lowest amount of developed area per person of any U.S. region (Alig, et al. 2003), developed area is expected to increase by nearly 73% over 1997 levels by 2025. Since urban heat island effects are increased by size of the urban area (Zhang, et al. 2012) the increase in developed area at the expense of New England's forest would be expected to have a more immediate effect on temperature increases than even global climate change, and will interact with global climate change in synergistic and damaging ways.

Similarly, Zhang et al. (2012) used remote sensing data of temperatures and size of urban area in the northeastern U. S. to document that larger urban areas have higher urban heat island effects. Heat islands occur on the surface and in the atmosphere. On a hot, sunny summer day, the sun can heat dry, exposed urban surfaces, such as roofs and pavement, to temperatures 50–90°F (27–50°C) hotter than the air, while shaded or moist surfaces—often in more rural surroundings—remain close to air temperatures. Surface urban heat islands are typically present day and night, but tend to be strongest during the day when the sun is shining. (See https://www.epa.gov/heat-islands/learn-about-heat-islands). In contrast, atmospheric urban heat islands are often weak during the late morning and throughout the day and become more pronounced after sunset due to the slow release of heat from urban infrastructure. The annual mean air temperature of a city with one million people or more can be 1.8–5.4°F (1–3°C) warmer than its surroundings. On a clear, calm night, however, the temperature difference can be as much as 22°F (12°C). The urban heat island increases exposure to heat stress and potential heat stroke. (For more on urban heat islands see https://www.epa.gov/heat-islands/learn-about-heat-islands).

Green infrastructure, defined as vegetation systems intentionally designed to promote environmental quality, can reduce the intensity of heat islands by providing shade and evapotranspirational cooling (Livesley et al. 2016). Arnfield (2003) documents empirical research showing that urban parks reduce nearby temperatures and air conditioning demand, and that the geographic extent of the effect is proportional to the size of the park. Livesley et al. (2016) report urban trees are perhaps the most effective and least costly approach to urban heat island mitigation and adaptation (Figure 11). The urban heat island also increases energy use for building space cooling. Sugawara et al. (2016) describe the cooling benefit of a large park in the hot urban environment of Tokyo, Japan. Under calm wind conditions, the cooling benefit of a large park generally extended 200 meters downwind into surrounding residential areas. It has been demonstrated that the cooling benefit of an urban green space is significantly greater when forested than if managed as more open parkland. Furthermore, the cooling effect is influenced more by the size of the forested area than its shape and many small, treed urban green spaces will not provide the same magnitude of cooling as fewer, but larger, urban green spaces with extensive tree cover (Jaganmohan et al. (2016).

In the next several decades, global warming could combine with urban heat island effects to push temperatures in many urban areas into the National Weather Service ‘extreme caution’ range, and the surrounding forest may have new value as a refuge providing respite from the heat. Regarding impacts at a broader scale, Galós, et al. (2011) used modeling studies to show that active afforestation in Hungary could reduce future mean temperature increases due to climate change by between 0.3 to 1 degree Celsius for lowland regions and to a lesser extent in mountainous areas where forest cover is more ubiquitous. Larger, less fragmented forest patches produced greater reductions in average future temperatures.

Figure 11. Urban forest ecosystem service and function: at the tree, street, and city scale



Source: Livesley et al. (2016).

In summary, urban forests can reduce temperatures in urban and suburban areas and in concert with green roofs and reflective surfaces result in significant reductions in temperatures, some reductions in air pollutants and modest reductions in greenhouse gas emissions. Although the evidence is not conclusive, current studies indicate that the forested landscape surrounding New

England cities can also help reduce urban heat island intensity, maintain lower regional temperatures and provide low cost refuges from the hottest temperatures during heat waves. These forest refuges, which can offer significant relief from high temperatures, would continue to function even in the face of cascading climate impacts that could incapacitate the electric grid.

2. Moderating Flooding

The United States has seen dramatic changes in hydrology over the last 50 years (Melillo, et al. 2014). Throughout the country more precipitation is falling in the heaviest 1% of all daily events. The epicenter of these impacts is the Northeastern US, where the amount of precipitation falling in these most intense events has increased by 71%. The heaviest 1% of precipitation events (such as intense thunderstorms) are bringing nearly twice as much water to the ground as 50 years ago. The region has also experienced a more moderate increase in the total annual amount of precipitation, with most parts of New England experiencing something less than a 15% increase. While this increase in total annual precipitation may continue, there is less congruence in climate models around this possibility. On the other hand, observed increases in extreme precipitation are expected to persist.

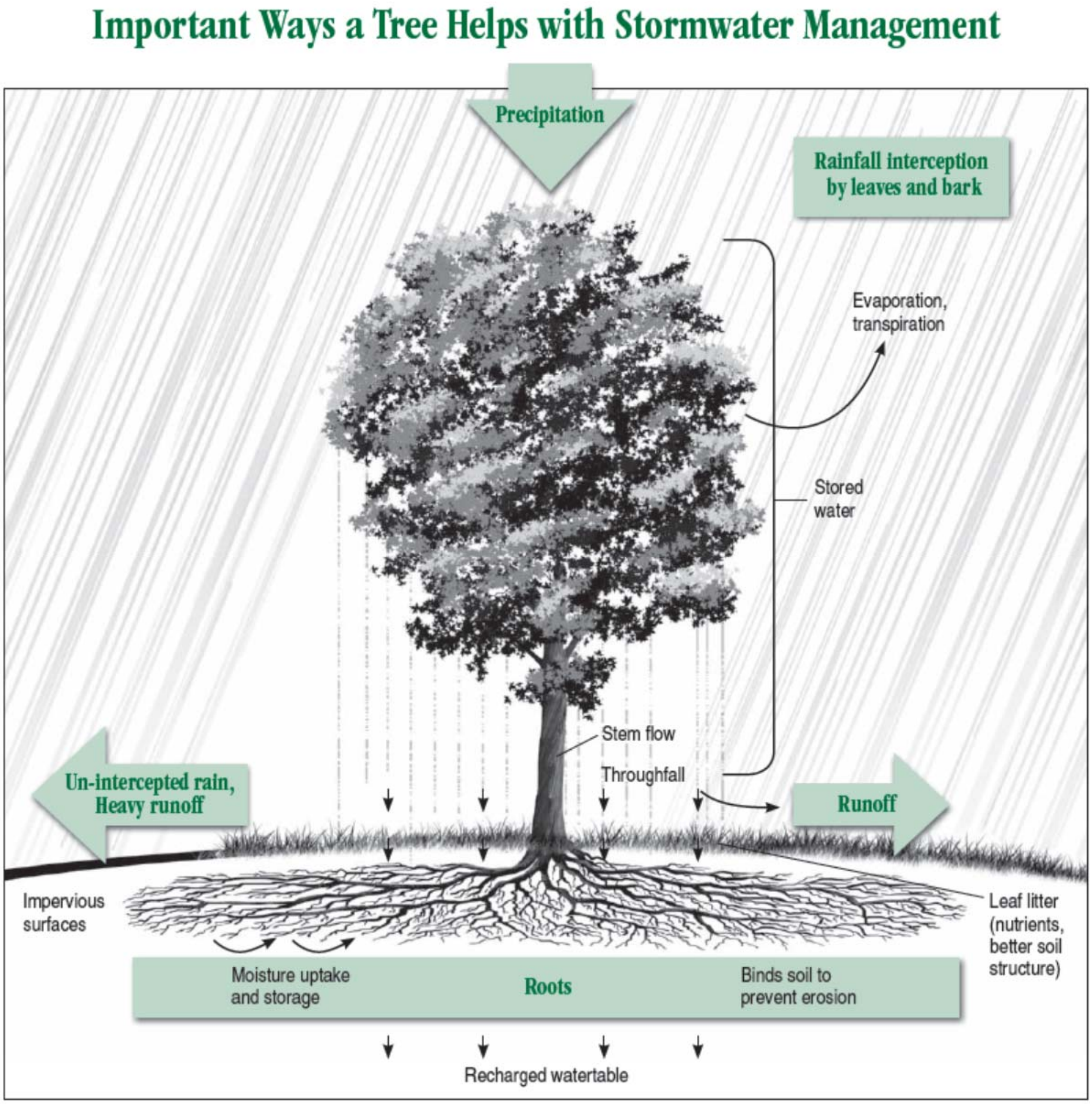
With regard to hydrology, climate change impacts interact synergistically with the loss of forest land to urban and suburban development. Urbanization increases runoff by reducing infiltration of water into soil and speeding the flow of water off the land surface (Depietri, et al. 2012). “Soil sealing” due to paving and building footprints in urban cores elevates these impacts to extremes. In urban cores with traditional development patterns and nearly continuous impervious surfaces, almost all precipitation runs off quickly and cities must devote substantial infrastructure to capture and divert storm water.

Forests by contrast promote infiltration into soils. The leafy canopy intercepts rainfall, where some water evaporates back into the atmosphere, and slows the rest from reaching the ground surface thereby allowing for gradual infiltration into soils. Falling leaves and branches along with herbaceous vegetation decays to create a highly pervious duff layer at the soil surface, which facilitates infiltration into soils where openings from roots and animal tunnels allows it to filter deeper into the ground and ultimately reach the ground water table (Figure 12). These effects result in negligible surface runoff from most forested areas unless precipitation lasts long enough to saturate the soil, or if rain falls on frozen forest soils. Under these two conditions runoff can reach nearby water bodies by overland flow.

These properties of forests can reduce runoff from rain events in small storms (Diepietri, et al. 2012), but are less effective in attenuating large floods in major river basins, which are generally driven by extended periods of heavy precipitation at a basin or sub-basin scale. For example, the 2011 500-year floods in the Mississippi River basin were caused, to great extent, by far-above-average precipitation throughout much of the Ohio River basin over a period of months.

The expansion of urban forests as “green” rather than “grey” infrastructure to handle storm water flows by infiltrating them into the ground can also help reduce peak flows in developed landscapes. These expanded urban forests can also provide a number of other benefits concurrently, e.g., shading and evapotranspiration to reduce surface temperatures.

Figure 12. Important ways a tree helps with stormwater management



Source: Fazio (2010).

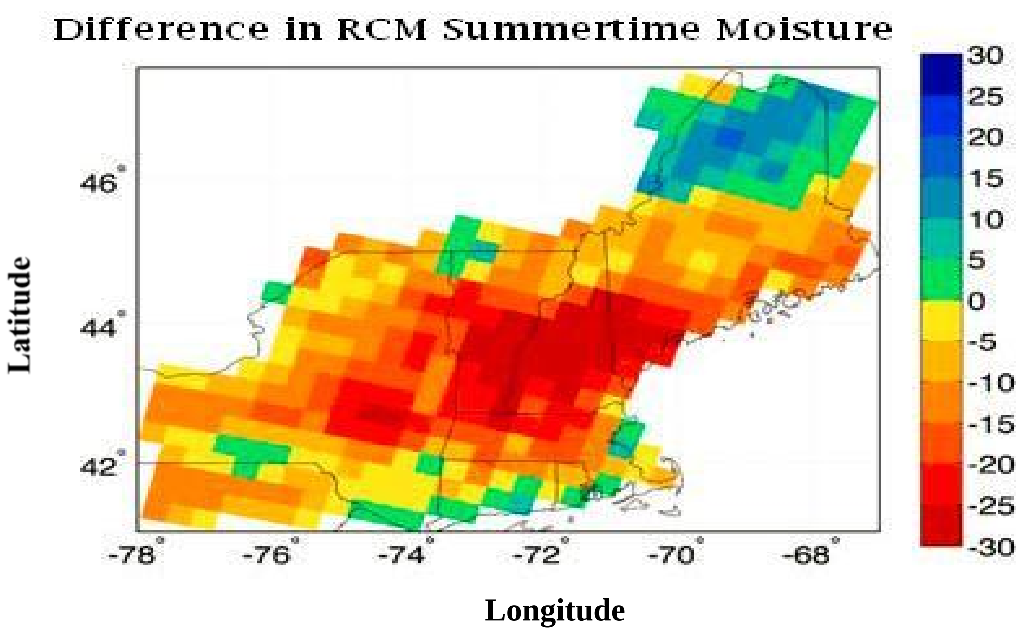
Considering all of the above, the benefits of forests in reducing impacts of intense precipitation events are therefore likely to be limited to smaller storm events, smaller watersheds, and developed landscapes.

3. Increasing Summer Time Stream Flows

Over the course of a year the region may experience more intense rainfall events and even increases in overall precipitation, but it is also possible that it will experience increased seasonal droughts during the summer and fall. The reason is that precipitation may be sporadic and increases in overall rainfall may be more than offset by rising evapotranspiration due to elevated temperatures. On a global scale this is likely to be a common pattern as the impacts of enhanced evapotranspiration due to a lengthened growing season and warmer temperatures are expected to overwhelm the effects of increases in precipitation, except in a few parts of the world (Girvetz and Zganjar 2014).

In New England the results of studies are mixed. Huntington (2003) expects the same pattern to hold for forested watersheds, with a resulting decrease in low-water stream flow, especially in the summer. Annual reduction in flow in streams draining forested basins was projected at 11-13% given a 3 degree Celsius increase in average annual temperature, with much more substantial reductions in summer flow (Huntington 2003). Huntington predicted that urban and suburban watersheds would experience more dramatic flow reductions due to the reduced infiltration associated with impervious surfaces. Similar results were obtained by Vogel, et al. (1997) and Anderson, et al. (2010) who project a decrease in soil moisture and associated stream base flow throughout all of New England except extreme northern and southern regions (Figure 13).

Figure 13. Difference in regional climate model (RCM) summer time soil moisture



Source: Anderson, et al. (2010).

However, not all studies point to the same results. Ollinger, et al. (2008) in a series of model experiments predicted runoff ranged from no change to a slight decrease, depending on future precipitation and assumptions about stomatal response to CO_2. One empirical study in the nearby

Catskills showed that the increase in evapotranspiration has been overwhelmed by increases in precipitation, resulting in increased stream runoff (Burns, et al. 2007). The Catskill study did however, show that runoff increased less than precipitation, due to the effects of increased evapotranspiration. A historical study focused on the Hubbard Brook research station in New Hampshire showed mixed results in terms of low water flows.

Lower water flows, higher ambient temperatures, and urbanization can also combine to produce dramatic increases in stream water temperatures. Water temperatures are increasing in many streams and rivers throughout the US. Sujay et al. (2010) analyzed historical records from 40 sites and found that 20 major streams and rivers have shown statistically significant, long-term warming. Annual mean water temperatures increased by 0.009–0.077˚C yr–1, and rates of warming were most rapid in, but not confined to, urbanizing areas. Long-term increases in stream water temperatures were typically correlated with increases in air temperatures. If stream temperatures were to continue to increase at current rates, due to global warming and urbanization, this could have important effects on eutrophication, ecosystem processes such as biological productivity and stream metabolism, contaminant toxicity, and loss of aquatic biodiversity. As a result, there could be dramatic impacts on cold water fisheries in New England, including potentially the endangered Atlantic salmon and New England's nationally significant wild brook trout populations.

In summary, maintaining the region's forests will have substantial hydrologic benefits. In the face of intensifying extreme precipitation events and with the potential for reduced stream base flows, the hydrologic benefits of maintaining or increasing forest cover are all the more important. By conserving forest cover we can maximize infiltration of precipitation, with the potential for reducing flood flows from small events and for increasing storage of water in soils and aquifers to sustain sufficient summer base flows for aquatic life and recreational uses. As with the temperature amelioration benefits of forests, the dollar value of this service is hard to estimate but clearly is large.

G. Benefits of Forests in Mitigating and Preventing Climate Change

Given the climate risks to New England's residents, infrastructure, agriculture and ecosystems it is important to consider how forests can mitigate and prevent climate change. Not that New England's forests could by themselves mitigate global climate change, but they can contribute and improved understanding of their potential role in New England and could inform efforts more broadly. This said, forests influence climate in many ways. The most important of these in the New England setting may prove to be:

- Carbon storage;
- Albedo effects;
- Production of biological volatile organic compounds;
- Oxidation of methane; and
- Wood substitution benefits.

See Table 1, which follows, for a more complete list of forest and urban tree influences on climate.

Table 1. Pathways by which forests and urban trees, forest and urban tree management and forest products and uses influence climate*

(Some influences are beneficial to climate leading to cooling, some are negative leading to warming and some can even be a mix of beneficial and negative e.g. forests can both produce and oxidize methane.)

Forest and Urban Tree Functions

1. Absorbing, storing and emitting CO_2 (including emissions from forest mortality and wildfires)
2. Producing and oxidizing CH_4 (methane)
3. Emitting biogenic volatile organic compounds (BVOCs) (can affect ozone levels and albedo [reflectance] both directly and indirectly)
4. Affecting NO_X, N_2O emissions by soils
5. Absorbing NO_X, CO, O_3 and SO_2
6. Transpiring H_2O
7. Increasing on-site infiltration of water (runoff control) resulting in increased transpiration
8. Intercepting (dry deposition) gases and particulate matter on leaves and branches
9. Absorbing solar radiation in canopy
10. Reflecting solar radiation and shading areas beneath
11. Shading of buildings reducing air conditioning energy use
12. Shading of parking areas and streets reducing fugitive emissions from vehicles
13. Affecting thermal inertia, defined as stored energy radiated toward the ground by overstory trees and their foliage or can be defined as resistance to change
14. Affecting air flow (roughness, length and drag)
15. Emitting black carbon and GHGs (other than CO_2) from wildfires

Forest and Urban Tree Management

1. GHG emissions from silvicultural practices intended to improve forests/urban trees
2. GHG emissions from harvesting and transporting wood products
3. GHG emissions from fertilizing, spraying for competition and pest control
4. GHG emissions from irrigating
5. GHG emissions from draining soils
6. Black carbon and GHG emissions from controlled burns and burning to dispose of forest and urban wood wastes
7. Reducing greenhouse gas emissions from use of fertilizers on agricultural crops by introducing or expanding agroforestry
8. Reducing CO_2 emissions from the conversion of forests and grasslands to agriculture by introducing or expanding agroforestry
9. GHG emissions from allowing wood wastes to decompose on and off site (e.g., slash from logging, construction debris and urban wood waste)
10. GHG emissions from managing urban trees (e.g. fertilizing, trimming, limbing, removal, etc.)

Forest Products and Uses

1. Reducing CO_2 emissions by burning certain sources of biomass (direct combustion) rather than alternative fuels
2. Reducing CO_2 emissions by producing fuels (both liquid and gas) from certain sources of biomass rather than using fossil fuels
3. Using carbon capture and storage (CCS) to sequester carbon from burning biomass as fuel or to produce biofuels
4. Long-term storage of carbon in lumber and other wood products
5. Reducing CO_2 emission by using wood for construction, rather than alternative materials (including disposal at the end of the product's useful life – reuse, burning or landfills)
6. GHG emissions of disposing of wood wastes in landfills (see further discussion below**)
7. Reducing CO_2 emissions by using wood waste such as bark and shavings for mulch rather than alternatives such as plastic films

* For literature sources and full description of the ways forests influence climate, see "A Distillation of the Many Ways that Forests Influence Climate - Far More than Carbon Sequestration", Giffen, et al. (2013, draft available upon request). The EU Joint Research Centre also identifies several, though not all, of these influences in "Carbon Accounting of Forest Bioenergy" (Agostini, et al. 2013).

** Some wood from a variety of sources (construction waste, urban wood waste, etc.) ends up in landfills despite efforts to reuse it or burn it as fuel – some researchers have suggested greatly expanding efforts to sequester carbon in landfills, belowground or deep ocean storage as a way to remove $_{CO2}$ from the atmosphere, but at this point these are thought experiments. An LCA would be required as it will take energy to transport and bury wood wastes. J. A. Micales and K. E. Skog concluded that "The placement of forest products in landfills serves as a significant carbon sink and its importance in the global carbon balance should not be overlooked." See: https://www.researchgate.net/publication/257423509_The_Decomposition_of_Forest_Products_in_Landfills

These factors can interact in complex ways both positively and negatively to impact climate change. To capitalize on the full range of benefits that forests may be able to provide, we need analytical methods to accurately assess the synergistic and cumulative effects of forest climate influences resulting from particular forest management actions and product use scenarios. However, in the New England context, there are still things that appear promising to do now to reduce climate change, which we refer to as ‘no regrets actions’.

1. No Regrets Actions

While forest climate interactions are complex (much more on this later), based on existing knowledge there are things we can undertake now with confidence to tap the potential of forests to reduce climate change. Because circumstances vary region to region, this is a New England specific list. This list assumes that Best Management Practices and other guidelines for sustainability are followed (e.g., maintaining or improving wildlife habitat).

Actions We Can Take Now!

Finally, despite the need for additional research, there are steps we can take now to capitalize on the opportunities New England’s forests offer to: 1) ameliorate and 2) mitigate climate change, as well as 3) facilitate the adaption of forests to future climate conditions, so they can both amelioration and mitigation climate change in the future. That is, because we understand their consequences, we can with confidence take the following actions:

<u>Ameliorate Climate Change</u>

- Increase use of urban trees to shade buildings to reduce ground level air temperatures and thereby reduce emissions associated with air conditioning and block winter winds to reduce emissions from heating.
- Utilize ‘green infrastructure’, defined as vegetation systems intentionally designed to promote environmental quality, to reduce the intensity of heat islands by providing shade and cooling from evapotranspiration, and increase infiltration of precipitation.
- Maintain and expand urban parks to provide cooling benefits downwind into surrounding residential areas.

<u>Mitigate Climate Change Now</u>

- Keep New England’s forests as forests – not only to store carbon but also to reduce emissions of N_2O.
- Utilize management plans developed by professional foresters to ensure that the forestry objectives outlined are realized.
- Restore management for longer rotation ages to increase the oxidation of methane (many actively managed areas are now managed for shorter rotation ages than they were historically).
- Reforest marginal agricultural lands in areas that are not likely to be used for agriculture. (Note: Some of these lands could be used for short rotation production of biomass fuels if demand warrants it).
- Minimize soil disturbance during logging, unless needed for intentional regeneration of desired species.

- Regenerate logged areas as quickly as possible to the desired species.
- Favor tree species best suited to grow valuable products (particularly those suitable for long-lived wood products) under future climatic conditions.
- Employ intensive management practices on the most productive forest lands to increase sustainable production of wood per acre – this will result in storing more carbon on-site and will provide more wood for long-lived purposes.
- Substitute wood in construction for other materials with higher life cycle greenhouse gas emissions.
- Productively use trees that are dead or will die in the next few decades, so that the carbon contained in them can be used in ways that most effectively reduce greenhouse gas emissions.
- Prevent and control wildfires (note that controlled burns may be appropriate to create or maintain certain habitats).
- Use limbs and tops from logging, forest manufacturing waste, and urban wood waste for biomass fuel, favoring heating and combined heat and power over biomass electrical generation.
- Allow forest waste to naturally decompose onsite when it cannot be used for a climate beneficial purpose or when it is needed to maintain desirable site conditions rather than burning onsite (attenuates release of CO_2, increases soil carbon and reduces black carbon emissions).

<u>Facilitate the Adaptation of Forests to Future Climate Conditions (Adaptation is needed to allow forests to both amelioration and mitigation climate change in the future.)</u>

- Thin stands to improve growth on trees targeted for management and to make them more resilient to climate change; and harvest trees that would otherwise die.
- Manage for species that will be favored by a warming climate (e.g., oak, hickory and pine) over much of New England.
- Create a strategically designed system of reserves to maintain the values of older forests and provide ecological benchmarks that can be used to qualify and quantify impacts due to a changing climate.
- Maintain the "connectivity" between forest areas (particularly along high elevation areas and the north/south axis) in the Northern Appalachian/Acadian Forest to allow for species migration over time.

New England's forests provide options to ameliorate, mitigate and adapt to climate change. They in turn will be strongly influenced by the actions we choose to take. If forests are managed to optimize climate benefits, considering the full range of forest-climate systems interactions without adverse climate impacts (e.g. displacing agriculture to a region where it results in greater radiative forcing), they could contribute to what Garman, et al. (2014) referred to as "climate remediation." That is employing techniques to improve our circumstances rather than simply avoiding making them worse. This can be thought of as "green" geoengineering that has multiple benefits without the risks that other more extreme geoengineering approaches could entail. This effort should include expanded urban and agroforests, as well as wildland forests.

Before thinning

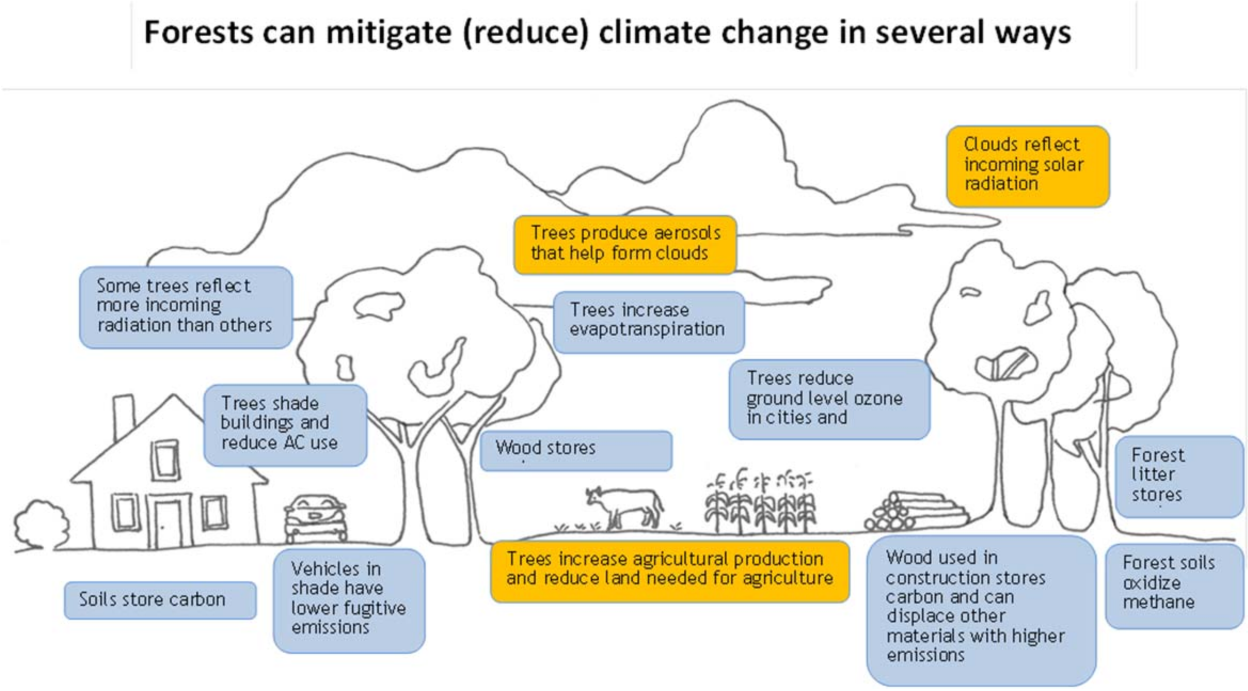
After thinning to reduce mortality to reduce mortality and increase growth on crop trees

Source: Jake Maier and the Cole Bros.

2. Beyond These Actions: We Need to Develop Analytical Methods that Can Evaluate Multiple Factors

Before getting into the details of particular influences, while carbon storage is often discussed as "the" influence forests can have on climate change, other influences collectively, or in some cases individually, may be more important than carbon storage alone in mitigating climate change. A simplified view of some of the more important influences is shown in Figure 14. A more complete listing and comprehensive description of these influences and their direct and indirect effects is shown in Table 1.

Figure 14. Forests can mitigate (reduce) climate change in several ways



Source: Alec Giffen, Clean Air Task Force.

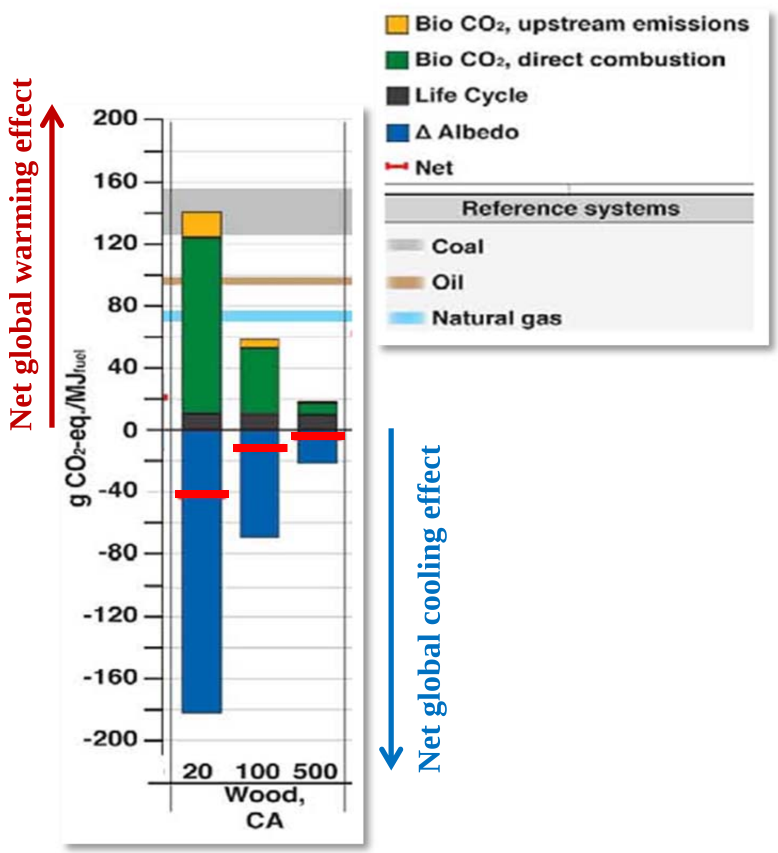
Some influences while complex are commonly acknowledged and are fairly well understood. This category includes forest carbon storage and ground surface albedo effects. Others are not generally recognized, but are reasonably well understood, such as production of biogenic volatile organic compounds (BVOCs) and their direct effects on the albedo of the atmosphere. Forest influences on the oxidation of methane also appear to be reasonably well understood. Others are not generally recognized and we are challenged to understand their effects completely. For example, we need to improve our understanding of the effects of BVOCs on cloud formation, albedo and blocking infrared emissions from earth.

Further, forests can influence climate through other mechanisms than those that are the subject of study by the natural sciences. For example, and importantly, wood products can substitute for other materials that have much higher carbon footprints such as steel and concrete. Also, forest management and the use of forest products can influence markets and land use; for example reforesting agricultural land here in New England could drive more agricultural clearing in tropical forest regions. More on these points follows later.

Thus, net climate impacts of any particular forest management regime, including preservation, are not currently clear given the many pathways for forest influences and the nonlinear relationships among them.

A recent study by Cherubini et al. (2012) underscores the importance of evaluating forest influences collectively to determine their net effects. In this study, Cherubini evaluates the impact of whole tree forest harvesting specifically for biomass fuel use in northern latitudes where there is snow cover during the winter. The study considers impacts on carbon emissions (including fossil fuel emissions avoided) from the use of the wood harvested for fuel and the effect of the harvests on albedo. The essence of the study as shown in Figure 15 is that the conclusion as to whether or not harvesting biomass for fuel is climate beneficial is different if only impacts on carbon is considered as opposed to including both the influences on carbon and albedo together. That is, some uses which are not climate beneficial strictly from a carbon perspective are beneficial when both albedo and carbon are taken into account. Cherubini et al. (2012) state that "Results show the importance of specifically addressing the climate forcings from biogenic CO2 fluxes and changes in albedo, especially when biomass is sourced from forested areas affected by seasonal snow cover. The climate performance of bioenergy systems is highly dependent on biomass species, local climate variables, time horizons, and the climate metric considered." "When compared with fossil fuel-based heat production facilities, most of the bioenergy cases outperform fossil fuel systems. For forest-based bioenergy this is due to the cooling contributions from albedo changes." (Cherubini et al. (2012) "On the global scale, the albedo effect is found to be the dominant direct biogeophysical climate forcing, particularly in areas affected by seasonal snow cover, and can be compared to the effects of GHGs using radiative forcing (RF) as a metric basis." (Cherubini et al. (2012)

Figure 15. Direct contributions to global warming of one bioenergy option for stationary applications (analysis for a portion of Canada (CA), which includes managed forest wood.) (Note that Cherubini et al. considered six options in a more complicated figured, which has been simplified for this report.)[2]



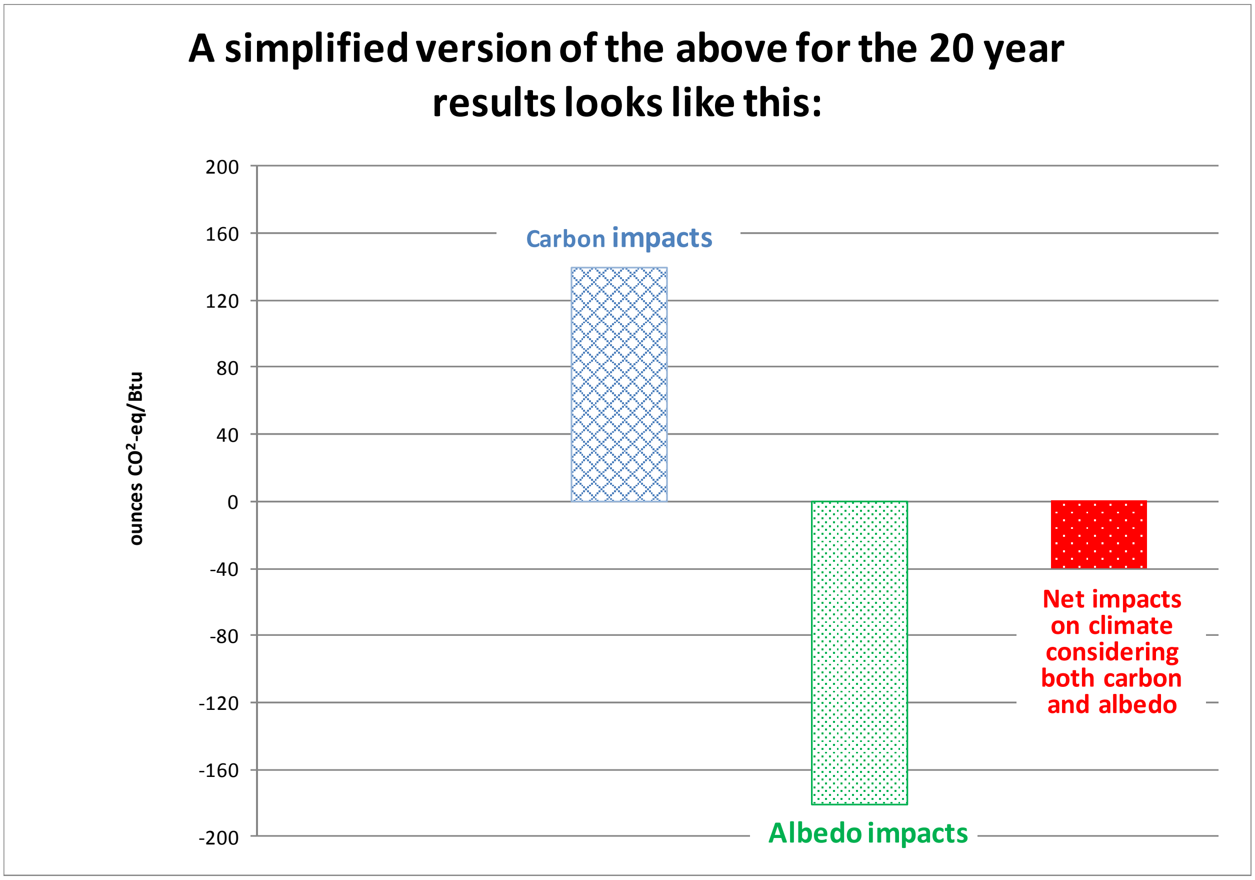
Direct contributions to global warming of one bioenergy option for **stationary applications.** GWP factors, corrected with the climate efficacies of the various forcing agents, are used to characterize emissions, including biogenic CO2. Three time horizons (TH) (20, 100, and 500 years) are considered. Fossil fuels (coal, oil, and natural gas) per MJ of fuel combusted are shown to benchmark our results. Lower and higher limits of the bands for the fossil systems represent the impact for TH 500 and TH 20, respectively. Abbreviations: Bio CO2 = biogenic CO2 emissions, i.e. emissions from oxidation of biomass harvested for bioenergy; upstream emissions = emissions from biomass losses through the value chain and biofuel processing; and direct combustion = emissions from combustion of biofuels at a plant.

Note: The red line on the bars indicates net effect by time horizon. Blue bar below zero represents the effects of albedo causing net global cooling.

Source: Cherubini, et al. 2012.

[2] Some of the other scenarios analyzed in this study did not show the same results.

Figure 16. Simplified version of direct contributions to global warming of one bioenergy option for stationary applications for the 20-Year Time Horizon



Source: Simplified by R. Alec Giffen from Cherubini, et al. (2012).

While this example clearly illustrates the importance of evaluating multiple influences simultaneously, it only includes 2 out of over 20.

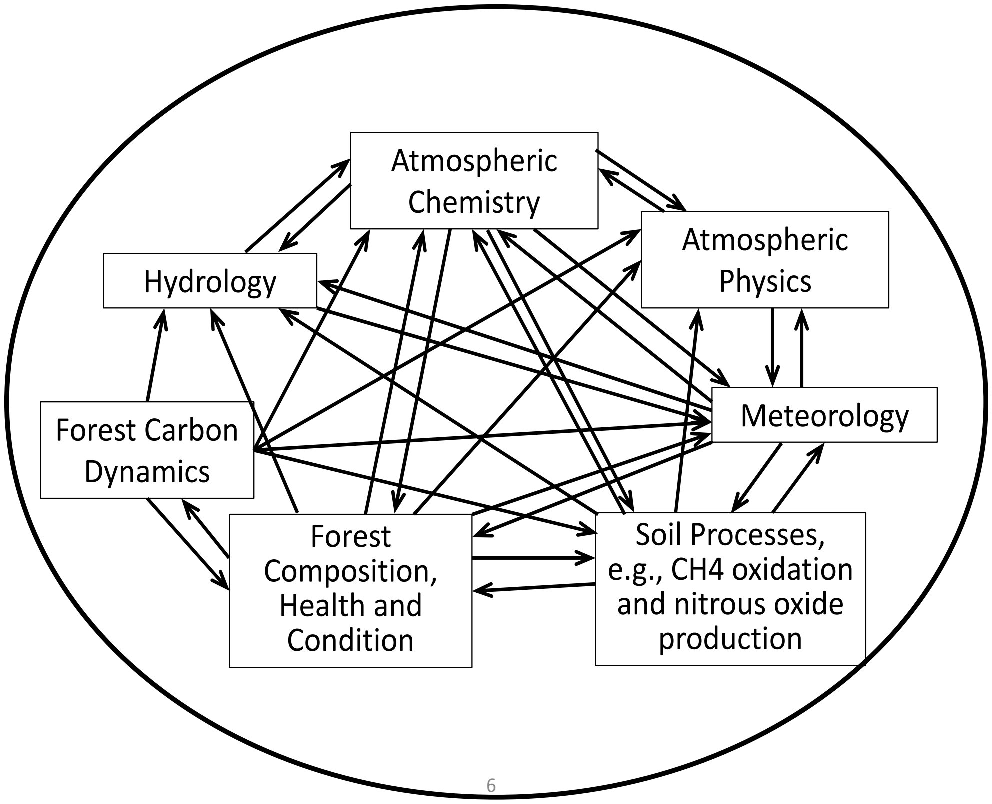
Adding to the complexity, the numerous forest influences on climate interact with one another. Some are complementary, while others are contradictory, and the nature of these relationships is complex (Figure 17).

What is needed is both additional analysis of individual influences and analysis of the net effects when considering a range of the most significant forest influences on climate.

The Influence of Conversion to Agriculture

As an example of the difference that additional carbon storage in forest ecosystems could make, Ruddiman (2003, 2005, 2013) reports that that release of carbon from deforestation and emissions from the agriculture which followed likely increased atmospheric CO_2 levels enough to forestall an ice age that if it followed geologic cycles would have started a few thousand years ago.

Figure 17. The complexity of forest impacts on climate



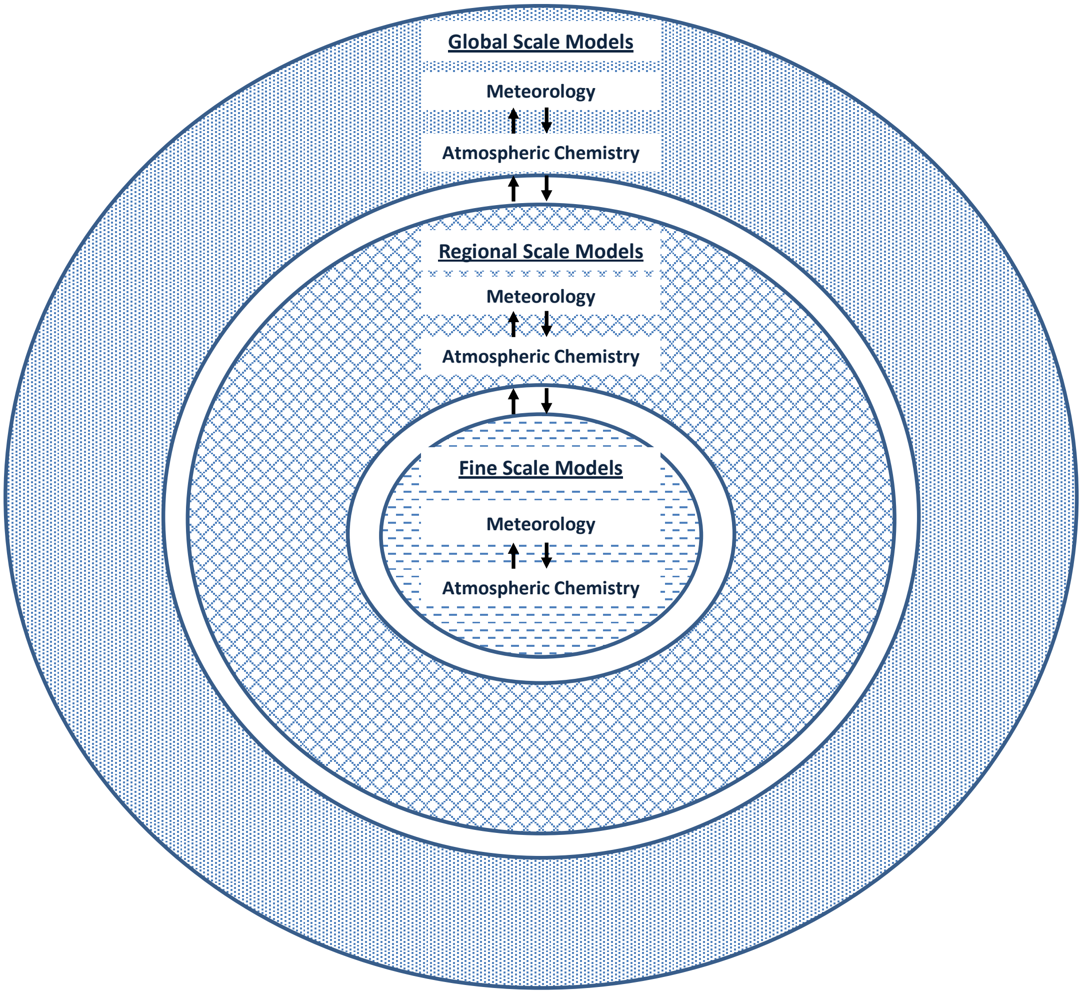
Source: Clean Air Task Force (2014).

Atmospheric models offer an opportunity to analyze these interactions. Only by understanding these relationships and net effects of a more complete range of influences can we be sure that policies and actions are certain to achieve their climate mitigation objectives. Analyzing one, or even a few forest climate influences in isolation can lead to erroneous conclusions. Pursuing policies based on those conclusions can, at the very least, prove ineffective and has in fact proven to be damaging in certain cases.[3] (Attachment 2 explains the reasons to use atmospheric modeling to understand these complex interactions.)

> "An integrated assessment of forest influences entails an evaluation beyond albedo, evapotranspiration, and carbon to include other greenhouse gases, biogenic aerosols, and reactive gases. The interrelatedness of climate change science, climate impacts on ecosystems, and climate change mitigation policy requires that these be studied together in an interdisciplinary framework to craft strong science in the service of humankind"
>
> (Bonan 2008, p. 1449).

[3] A prime example of this has been the failure to recognize that using biomass for fuel is not always a carbon neutral action as it has frequently been presumed to be in policy statements. For further discussion on this see Section 7.b. Biomass Fuels.

Figure 18. Nested, interactive sets of existing mathematical models provide an opportunity to evaluate the net effects of several influences simultaneously



Source: Giffen, R. A. 2015.

Further, the interaction of forest influences at fine, regional and global scales, needs to be assessed as effects at any one geographical scale may not be experienced at another. A number of prominent climate scientists with an interest in forestry have commented on the need. Gordon Bonan from the National Center for Atmospheric Research articulated it as shown in the sidebar on the previous page. Alternatively, Kaiguang Zhao and Robert B. Jackson of Duke and Stanford put it this way in an article in *Ecological Monographs*, "A carbon-centric accounting is, in many cases, insufficient for climate mitigation policies" (Zhao and Jackson 2013). Anderson, et al. (2011), support this view in their article "Biophysical considerations in forestry for climate protection." They summarize their own thoughts as follows: "In a nutshell:

- Forestry is becoming an important part of both voluntary carbon markets and government efforts to mitigate climate change

- Forests have biophysical effects that can enhance or counter-act their potential for carbon sequestration to reduce climate warming
- These effects can differ greatly, depending on the spatial scale involved
- Consideration of both the biogeochemical and biophysical effects of forests is necessary when designing projects that maximize climate benefits; only broad best practices can be applied at this time, given that the science in support of such an integrated approach is still under development."

And, further, "In addition to surface biophysics, many forcings and interactions for local land-use changes, such as changed lapse rate[4] and cloud feedbacks[5] should be further elucidated for quantifying the full range of biophysical forcings" (National Research Council 2005).

To make sense of all these factors when considering their "net effects," Woods Hole Research Center, a nationally known research institute, located in Falmouth, Massachusetts, with scientists investigating the causes and effects of climate change, is working to engage researchers from universities and other organizations from around the country in developing a research agenda to investigate the "net effects" of different forest influences, management systems and wood use on climate and to identify ways to fund the research needed to solidify our understanding of the full range of climate services forests can provide.

While we do not as yet know how to optimize forest management and the use of forest products to mitigate climate change, as noted earlier, we do know how some individual forest influences could be modified in ways that it appears would benefit climate change.

Now for more on the specifics for some key individual influences.

3. Carbon Storage

Reducing GHG levels and thus future climate change will require decarbonizing our energy systems. Conserving existing forests globally, in the United States and in New England is a

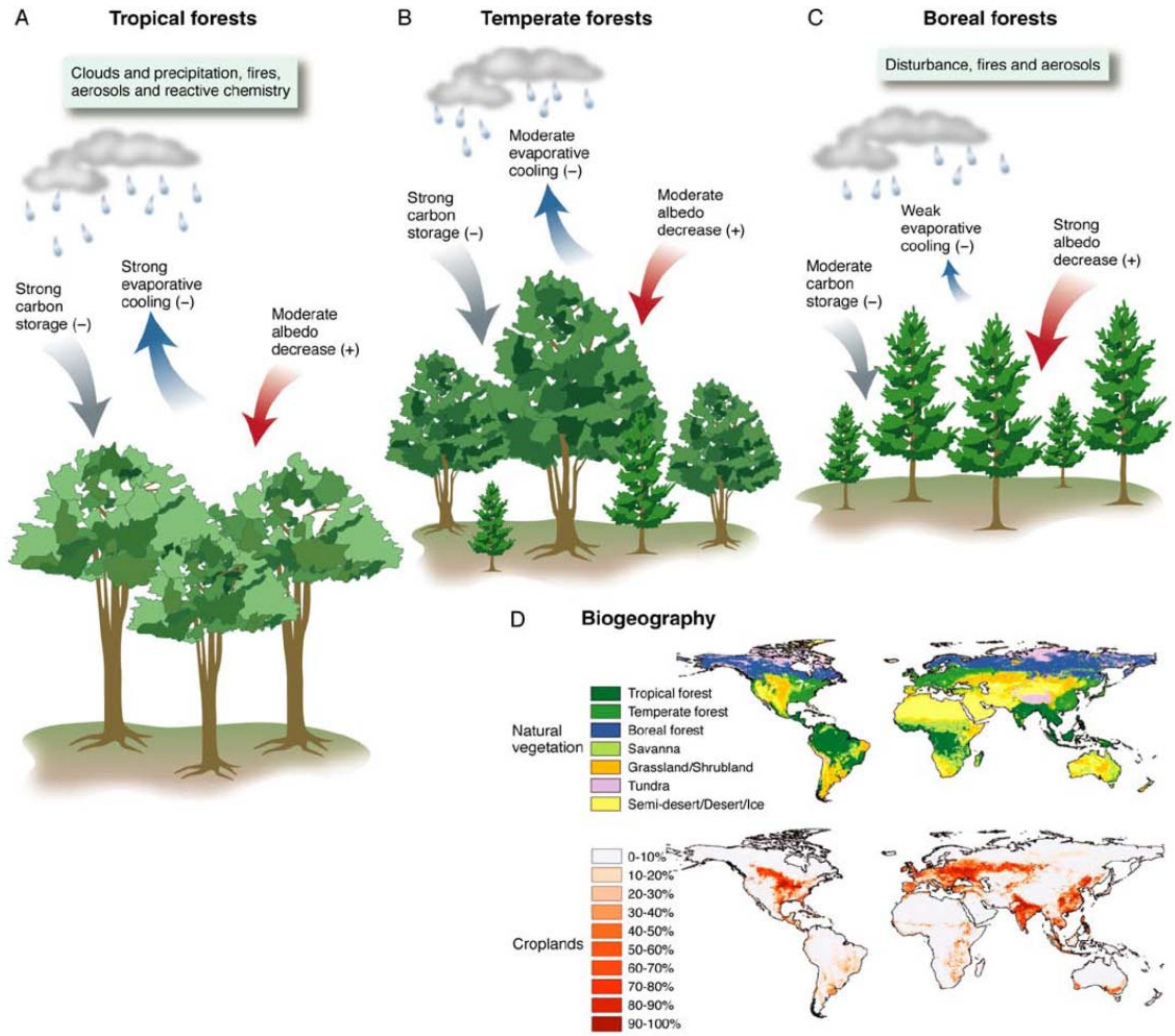
---

[4] Lapse rate feedback- The lapse rate is the rate at which atmospheric temperature decreases with an increase in altitude in the troposphere. Since emission of infrared radiation varies with temperature, long wave radiation escaping to space from the relatively cold upper atmosphere is less than that emitted toward the ground from the lower atmosphere. Thus, the strength of the greenhouse effect depends on the atmosphere's rate of temperature decrease with height. Both theory and climate models indicate that global warming will reduce the rate of temperature decrease with height, producing a negative lapse rate feedback (cooling) that weakens the greenhouse effect. Measurements of the rate of temperature change with height are very sensitive to small errors in observations, making it difficult to establish whether the models agree with observations. https://en.wikipedia.org/wiki/Climate_change_feedback.

[5] Cloud feedback - Cloud feedback is the coupling between cloudiness and surface air temperature where a surface air temperature change leads to a change in clouds, which could then amplify or diminish the initial temperature perturbation. Warming is expected to change the distribution and type of clouds. Seen from below, clouds emit infrared radiation back to the surface, and so exert a warming effect; seen from above, clouds reflect sunlight and emit infrared radiation to space, and so exert a cooling effect. Whether the net effect is warming or cooling depends on details such as the type and altitude of the cloud. High clouds tend to trap more heat and therefore have a positive feedback (warming), low clouds normally reflect more sunlight so they have a negative feedback (cooling). These details were poorly observed before the advent of satellite data and are difficult to represent in climate models. https://en.wikipedia.org/wiki/Climate_change_feedback.

necessary complement. Forests can play an important role in storing not only existing carbon, but also in sequestering additional carbon for the long term.

Figure 19. Different types of forests have varying carbon storage capacities and albedo effects

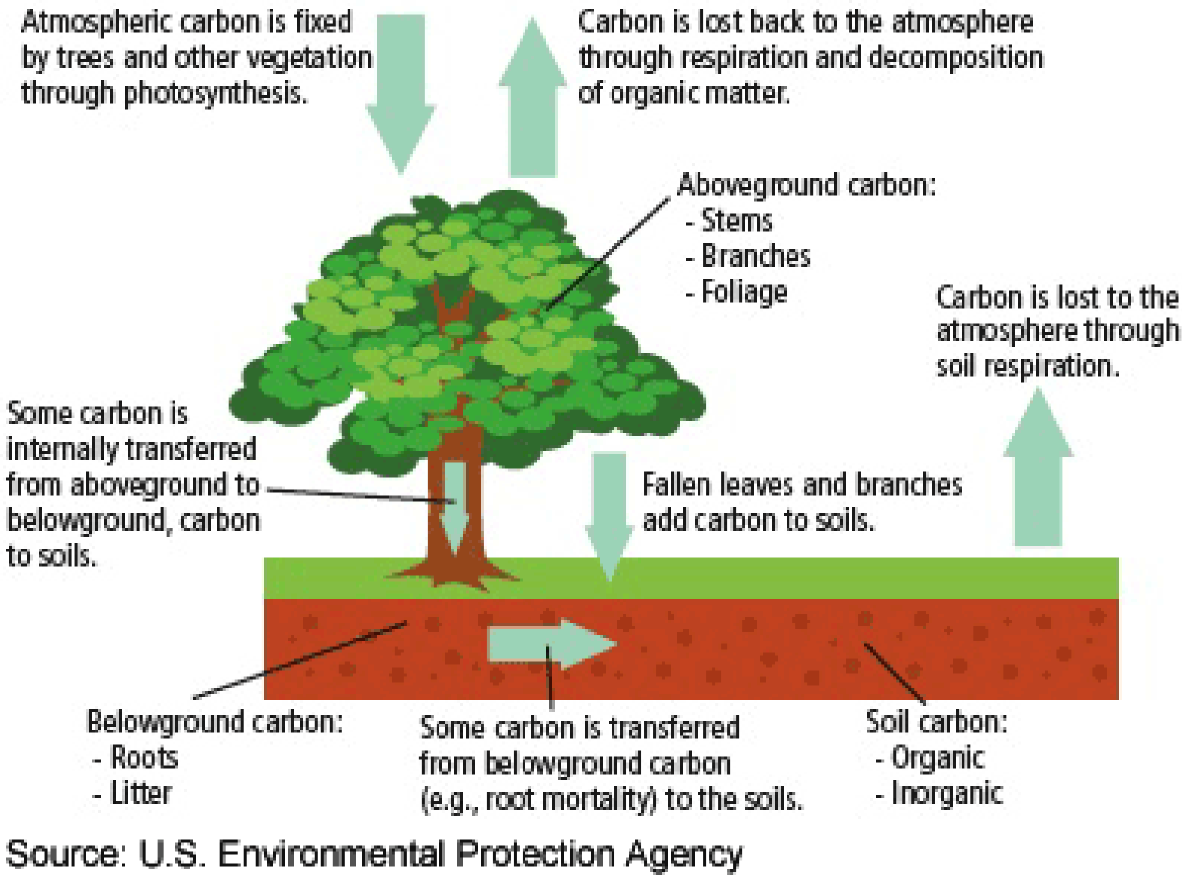


Note: The (+) and (-) signs indicate warming and cooling effects respectively. Thus storing carbon and evapotranspiration cool, while decreasing albedo (reflectance of incoming solar radiation) warms.

Source: Bonan 2008.

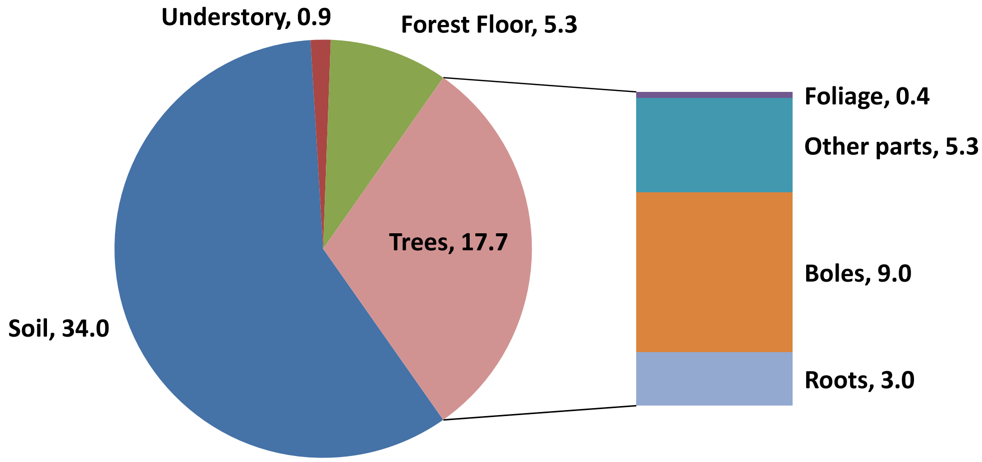
The engine behind carbon storage in forest ecosystems is that plants extract carbon dioxide from the atmosphere and combine it with water to form carbohydrates and in the process release oxygen. Chemical reactions using carbohydrates enable the synthesis of sugars and other carbon containing compounds (e.g., proteins and fats). These carbon compounds are used to form various plant tissues. As trees and other plants grow the amount of carbon stored in the plant increases.

Figure 20. Carbon storage and fluxes in forest ecosystems



Carbon storage in forest vegetation is reasonably well understood, but as reported in different studies uncertainties remain as to the impacts of changes in forests and how that will affect carbon stored in forest soils. Over time, forests store immense amounts of carbon. In the U.S. forests and forest soils make up 90% of the U.S. carbon sink (USDA 2017). U.S. forests store approximately 58 billion tons of carbon (Figure 21 – total amount of carbon in the pie chart equals 57.9 billion tons). New England's forests alone store approximately 2.4 billion tons (Will McWilliams, USDA Forest Service pers. comm.).

Figure 21. Carbon storage in billions of tons in various components of U.S. forest ecosystems (pie diagram) and in various parts of trees (bar diagram)

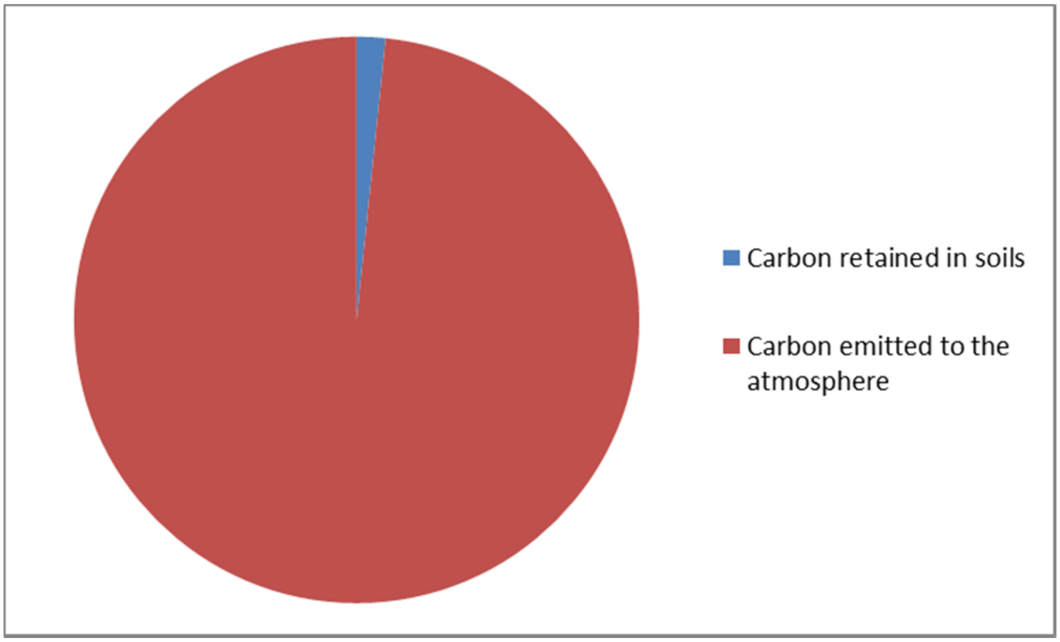


Source: Birdsey (1992).

Forest litter is composed of leaves, seeds, cones, twigs, branches, whole trees and bark. This litter carbon falls on the surface of the ground and enters a large soil carbon pool where it can stay for years. These inputs of carbon from litter are largely balanced by decomposition of soil organic matter, referred to as soil respiration. This carbon is released back to the atmosphere and a small fraction of the carbon annually enters the deep soil as depicted in Figure 22. This small fraction of litter carbon along with roots and microorganisms has built up over hundreds and thousands of years, which has made the soil underneath forests the largest carbon pool in the forest ecosystem, as depicted in Figure 21.

The amount of litter carbon entering the soil depends on many factors including temperature, precipitation, soil moisture, drainage, soil nutrients as well as the quality of litter itself. Rich soils provide the nutrients necessary to produce abundant high quality litter while trees on poor soils produce less. Seasonality of precipitation can be more important than the total amount that falls. Soils saturated with water lack oxygen for decomposition slowing organic matter breakdown. The frequency of fires and timber harvests also influence carbon stocks and the accumulation of soil carbon.

Figure 22. Fate of carbon in litter fall (Shown to depict relative fate of carbon to soils and the atmosphere.)

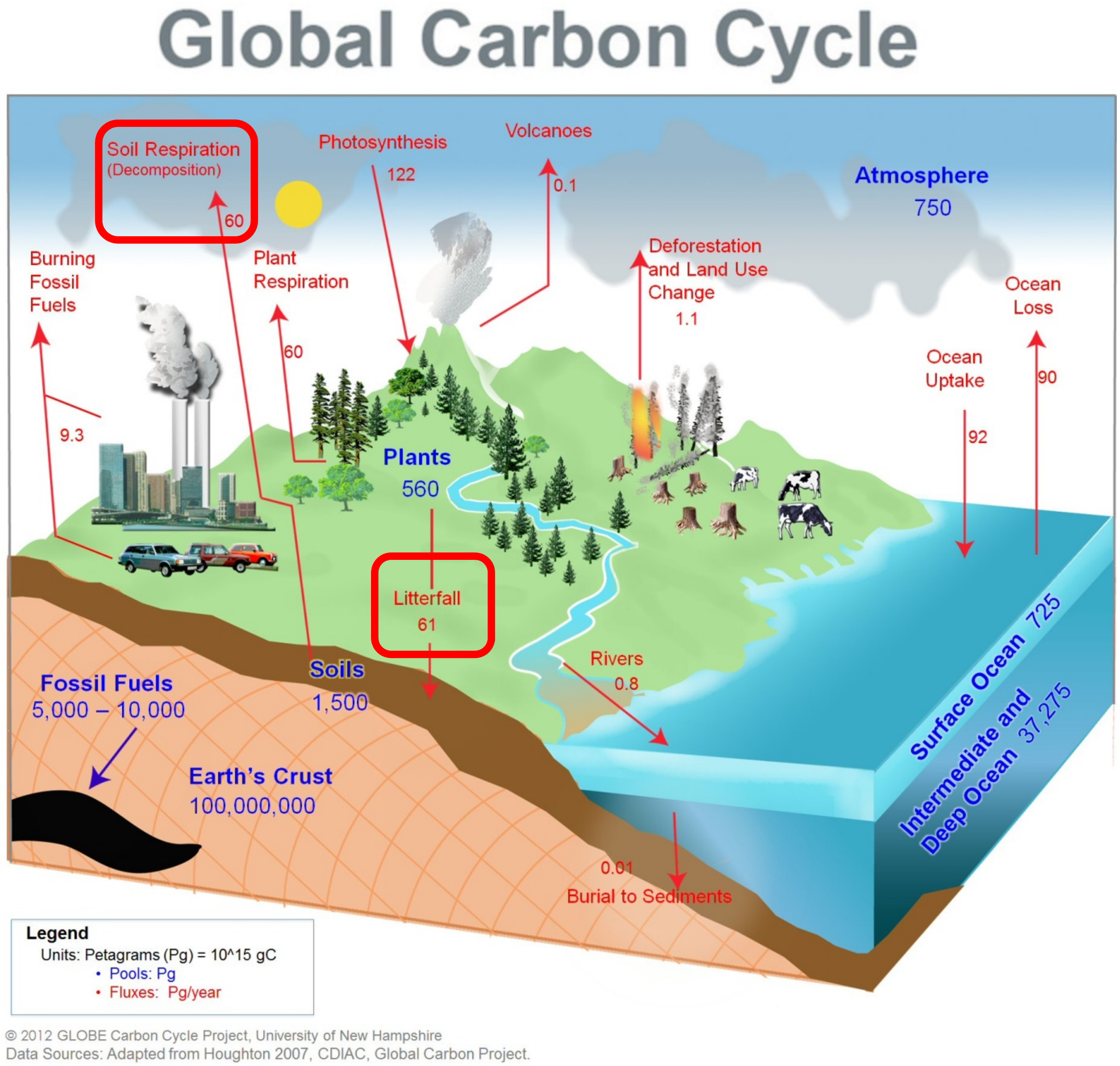


Source: Based on information in the Global Carbon Cycle diagram, see Figure 23.

Figure 23, the Global Carbon Cycle diagram, shows the carbon pools (in blue) and annual fluxes (in red) from both natural systems and human actions including burning fossil fuels, deforestation and land use changes. Units (numbers) are shown in Petagrams (Pg) of carbon. A Petagram is equal to a gigaton (Gt) (one billion tonnes or 2.2 trillion pounds). Forests annually take 122 Petagrams of carbon from the atmosphere and combine the CO_2 with water through photosynthesis to form organic materials including boles (stems), branches, foliage and roots. As shown in Figure 21 boles (stems) store the largest amount of carbon in the trees. Plants like humans, also "breathe" out CO_2 in a process called respiration, which creates the energy needed for plant growth. This plant respiration amounts to 60 Petagrams a year. Some of the organic materials produced by trees, such as leaves, seeds and branches as well as whole trees, fall as litter to the forest floor. This amounts to an additional 61 Petagrams a year. Through soil respiration – 60 Petagrams of carbon is respired back into the atmosphere.

Terrestrial ecosystems in general appear to be a net sink of about 1-2 Pg/yr of carbon (some estimates put this a little higher or lower). Whether this is in vegetation, soils or a combination is less certain. This is why carbon cycle diagrams often depict a slight imbalance somewhere in the land. (Personal communication, April 3, 2017, Dr. Scott Ollinger, University of New Hampshire, Globe Carbon Cycle Project).

Figure 23. Global carbon cycle



Source: GLOBE Carbon Cycle Project (2012). An introduction to the global carbon cycle. University of New Hampshire, Durham, NH. www.globecarboncycle.unh.edu.

Beyond storing carbon on site, wood from sustainably managed forests (forests managed for the full range of ecological, social and economic benefits) can also be used to produce wood products, which can store carbon. The USFS has conducted an analysis of how long, on average, different types of wood products store carbon that they contain. Products like dimension stock used in construction have long storage lives while materials like paper and packaging obviously have shorter useful lives. However, even once their initial useful lives are over wood products can be reused, burned to displace fossil fuels, or store significant amounts of carbon in landfills. Research has shown that the anaerobic conditions (absence of oxygen) in properly designed landfills prevent wood from decomposing and that a large portion of wood and certain papers (e.g. ground wood) will last almost indefinitely in landfills.[6]

Using wood to replaced other construction materials can reduce GHG levels because the non-wood alternatives result in greater GHG emissions (for more on this topic, see Section 7. B. Biomass Fuels). Wood could be used to remove CO_2 from the atmosphere in other ways as well. For example, some scientific studies have suggested methods for storing logs underwater or underground in anaerobic conditions. Others have suggested that in addition to burning wood to displace fossil fuels the CO_2 in emissions be captured and injected into geologic storage.

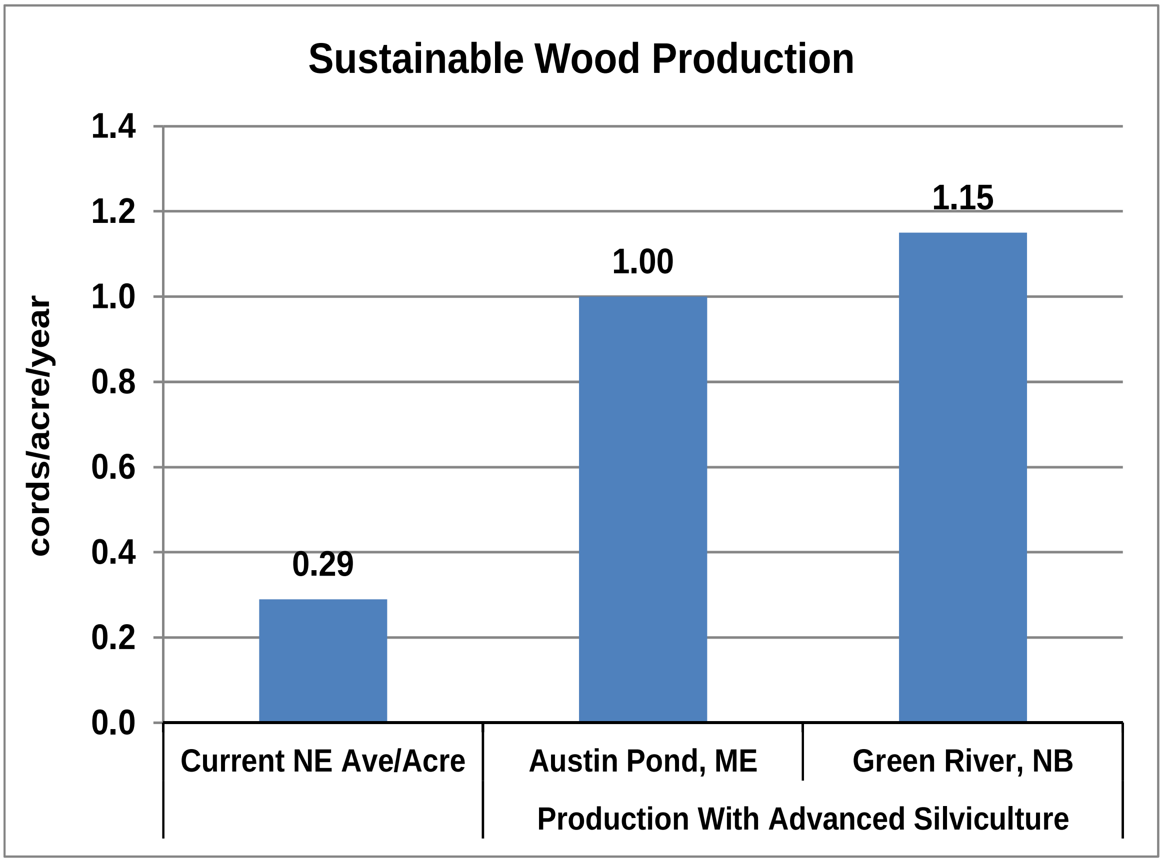
Thus, forests could be used to "pump" excess carbon out of the atmosphere as a part of "green" geo-engineering. This approach could be an alternative to other geoengineering proposals such as circling the earth with sun shields to reflect solar energy, seeding the ocean with iron to encourage the growth of plankton, or dispersing aerosols in the stratosphere to help reflect solar energy, all of which have the potential for unintended consequences. In contrast with many of the other mechanisms currently being discussed for geo-engineering we already know how to manage forests. In addition, if harvesting is done with forethought and care we know that we can benefit other forest values such as wildlife habitat, reduce the risks of catastrophic fires, and protect water quality and other forest values.

The functions of maintaining and enhancing carbon storage are vital in maintaining greenhouse gas levels below the levels established by the IPCC in the near term and in the long term. If the carbon stored in U.S. forests and carbon from forests in other parts of the world were released in any significant degree to the atmosphere (e.g., as a result of extensive insect or disease mortality, storms or catastrophic fires or droughts), it would contribute significantly to exceeding the IPCC's specifications for greenhouse gas levels required to keep temperature increases below 2^oC (3.6^oF).

It is possible through more intensive forest management to double production of tree growth (and ultimately wood products) thereby significantly increasing carbon sequestration in New England forests. We can also more intensively manage not only for current species but favor species such as oak, hickory and pine that will expand further northward as the climate warms. (See the report "Grow More Wood" in the "Path to Sustainability", a series of technical reports available at http://newenglandforestry.org/connect/publications/path-to-sustainability/). Figure 24 shows that forest production can be more than doubled based on actual data from sites in New England.

[7]Micales, J. A. and K. E. Skog. (2002). The placement of forest products in landfills serves as a significant carbon sink and its importance in global carbon balance should not be overlooked. International Biodeterioration & Biodegradation Vol. 39, No. 2–3 (1997) 145–158.

Figure 24. Potential to sustainably increase wood production in New England forests



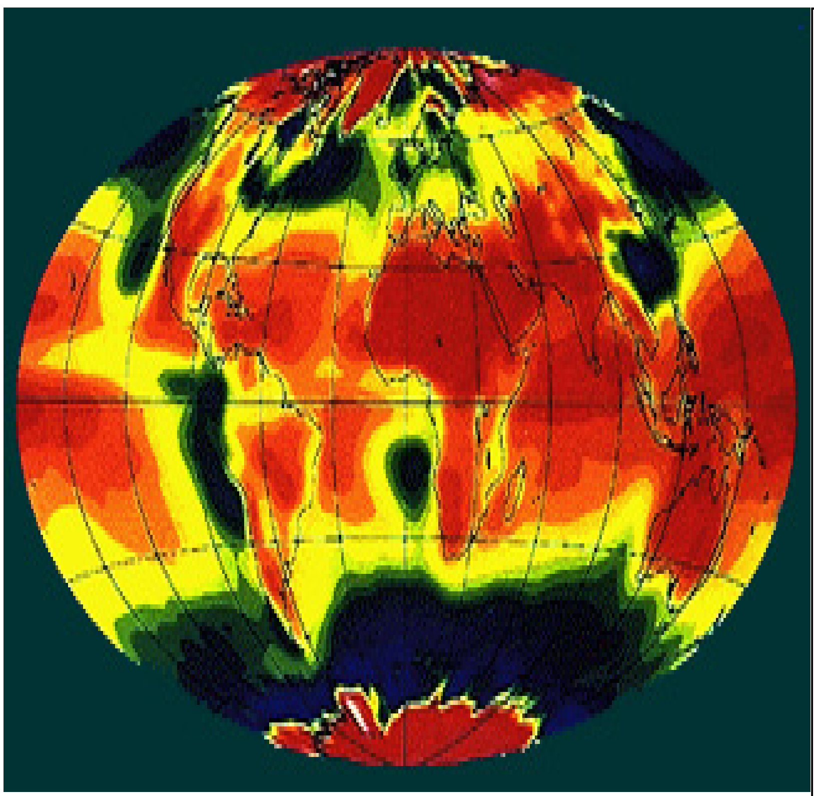
The USDA's Northern Research Station produced a publication on Carbon Sequestration that states "Slight changes in forest management practices can improve the ability of forests to store carbon while still providing other benefits. Extending the time between harvests, encouraging fast-growing species, and fertilization are a few examples of management techniques that could be used to improve forest carbon sequestration." It also emphasizes the importance of forest soils in storing carbon, noting that "In fact, northern forests can sequester twice as much carbon in the soil than aboveground." Keeping forests as forests not only maintains their important role in carbon storage in trees but also maintains the carbon storage function of the forest soils as well. (See https://www.nrs.fs.fed.us/niacs/carbon/forests/carbon_sequestration/) (Accessed March 23, 2017.)

4. Albedo Effects

The albedo of the earth involves more than just the earth's surface as aerosols and clouds both reflect incoming solar radiation and block outgoing long wave (infrared) radiation (heat loss). Clouds in turn are affected by forests both through evapotranspiration and forests' contribution to aerosols that allow water droplets to form in the atmosphere (Kurten, et al. 2003).

> Energy goes back to space from the Earth system in two ways: reflection and emission. Part of the solar energy that comes to Earth is reflected back out to space in the same, short wavelengths in which it came to Earth. The fraction of solar energy that is reflected back to space is called the albedo. Different parts of the Earth have different albedos. For example, ocean surfaces and rain forests have low albedos, which means that they reflect only a small portion of the sun's energy. Deserts, ice, and clouds, however, have high albedos; they reflect a large portion of the sun's energy. Over the whole surface of the Earth, about 30 percent of incoming solar energy is reflected back to space. Because a cloud usually has a higher albedo than the surface beneath it, the cloud reflects more shortwave radiation back to space than the surface would in the absence of the cloud, thus leaving less solar energy available to heat the surface and atmosphere. Hence, this "cloud albedo forcing," taken by itself, tends to cause a cooling or "negative forcing" of the Earth's climate. (See: http://earthobservatory.nasa.gov/Features/Clouds/ (Accessed 3/5/17)

Figure 25. Annual average net cloud radiative forcing

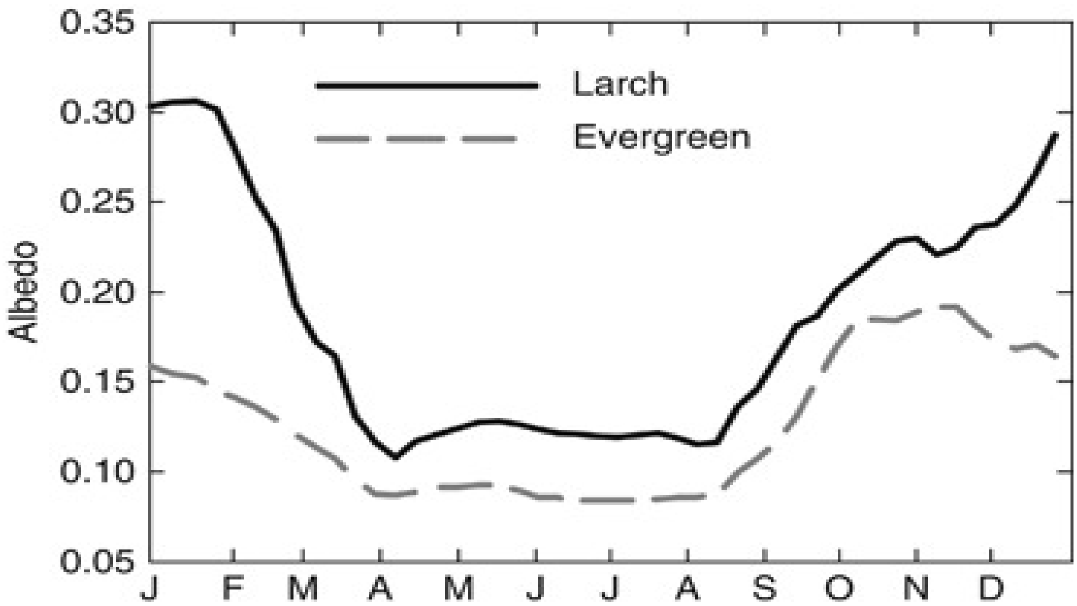


Annual average net cloud radiative forcing determined from 1985 to 1986. Net cloud forcing is the result of two opposing effects: (1) greenhouse heating by clouds (or positive forcing)--clouds trap heat coming from Earth's surface that would otherwise be lost to space, and (2) cooling by clouds (or negative forcing)--clouds reflect incoming solar radiation back to space. The relatively large areas where cooling is the greatest are represented by colors that range from yellow to green to blue. In some areas, the effect of the clouds is to produce some warming as shown by colors that range from orange to red to pink. **Overall, clouds have the effect of lessening the amount of heating that would otherwise be experienced at Earth's surface** (Earth Radiation Budget Experiment data on the Earth Radiation Budget Satellite and the NOAA-9 satellite. Data processed at NASA Langley Research Center; images produced at the University of Washington). Visit: http://earthobservatory.nasa.gov/Features/Clouds/clouds6.php

Source: NASA.

In general, trees absorb more incoming solar radiation than grasslands, crops and deserts. Absorption is measured as albedo with '1' being complete reflection and '0' complete absorption. The albedo effect of trees varies by species and location. In general, softwoods absorb more radiation and warm the earth surface more than hardwood trees, particularly in areas with winter snow cover where hardwoods typically also lose their leaves. However, even within the major types there are variations (e.g., in the New England context most softwoods don't lose their leaves, but larch do). Thus, managing for different species can influence albedo and hence global warming. Figure 26 shows that larch has twice as much albedo effect as evergreens during the winter months when snow cover is present. Evergreens absorb more radiation thereby warming the earth, but larch, because it drops its needles, allows for more reflectance of radiation when snow cover is present thereby cooling the earth.

Figure 26. Deciduous Larch Trees increase Albedo and cooling when compared to other Softwoods



Source: Shuman, et al. (2011).

5. Production of Biological Volatile Organic Compounds

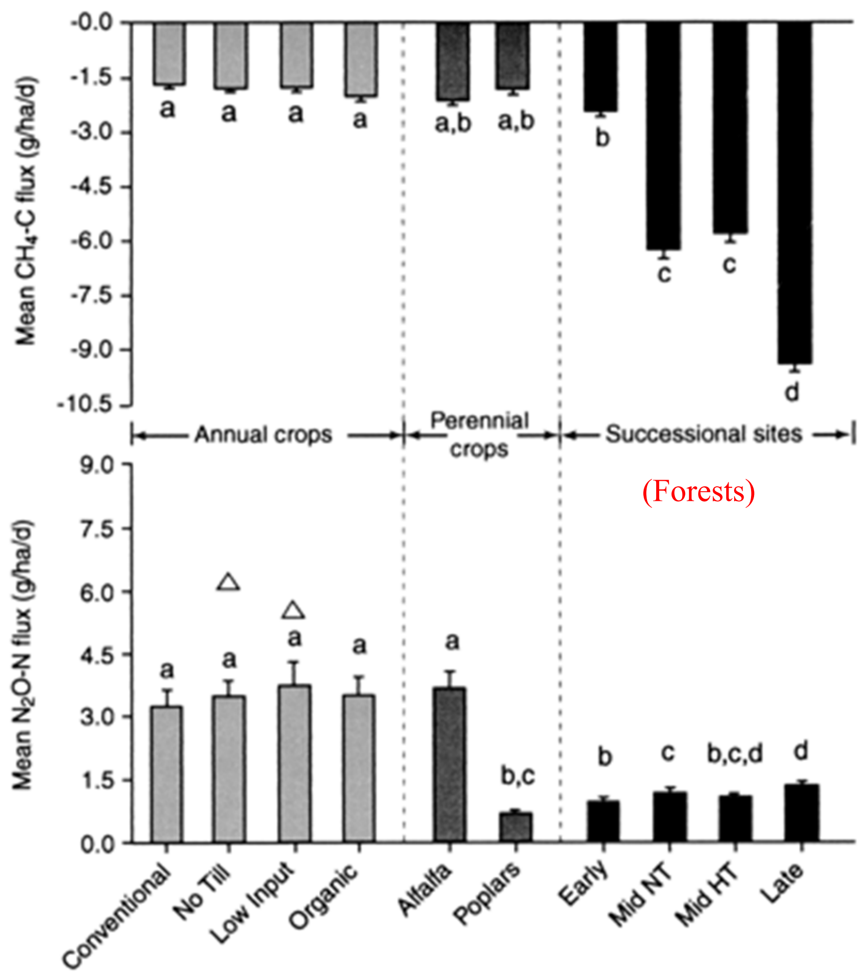
Biogenic volatile organic compounds (BVOCs) in the form of aerosols play an important role in reflecting incoming solar radiation, thereby reducing warming of the atmosphere. This role is reasonably well understood. The type and volume of BVOCs produced varies from tree species to species. Softwoods typically produce more terpenes while hardwoods produce more isoprenes. These in turn vary in their propensity to result in aerosols. Terpenes are reportedly more likely than isoprenes to form extremely low volatility organic compounds and hence, contribute to the formation of secondary aerosols. Thus, managing for different tree species has the potential to influence the volume of aerosols and hence global warming (Giffen 2016, memo to WHRC partners [can be provided on request]). BVOCs, along with other sources of aerosols, also contribute to the formation of cloud condensation nuclei that influence cloud formation and perhaps the length of time that clouds remain in the atmosphere. Understanding the role of forests in these processes is among the most challenging of the various influences that forests have on climate. Clouds can both contribute to warming by blocking outgoing radiation and reduce warming by reflecting incoming solar radiation, as discussed in the text boxes associated with Figure 25. The overall effect of clouds is to cool the earth.

6. Oxidation of Methane

Forests, particularly older forests, can reduce methane levels when compared to crops. Methane (CH_4) is a potent greenhouse gas with a Global Warming Potential (GWP) estimated to be 28–36 times that of CO_2 over 100 years. (See: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials). Besides removing methane, forests also release less nitrous oxide (N_2O) than crops. Nitrous Oxide (N_2O) has a GWP 265–298 times that of CO_2 for a 100-year timescale. (See: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials). Thus, keeping forests as forests and managing them for older age classes offers an opportunity to mitigate climate change.

The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years. GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases (e.g., to compile a national GHG inventory), and allows policymakers to compare emissions reduction opportunities across sectors and gases. See: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

Figure 27. Comparison of the effects of forests and crops on two greenhouse gases [7]



CH_4 oxidation (top) and N_2O production (bottom) in annual and perennial cropping systems and unmanaged systems. Annual crops were managed as conventional cropping systems, as no-till systems, as low–chemical input systems, or as organic systems (no fertilizer or manure). Mid-successional systems were either never tilled (NT) or historically tilled (HT) before establishment. All systems were replicated three to four times on the same or similar soil series; fluxes were measured over the 1991–99 period. There are no significant differences ($P > 0.05$) among bars that share the same letter on the basis of analysis of variance. Triangles indicate average fluxes when including the single day of anomalously high fluxes in the no-till and low-input systems in 1999 and 1991, respectively (Robertson, et al. 2000).

Robertson, et al. state that “In contrast to the annual cropping systems, all of the perennial crops and successional communities had a net negative or neutral GWP. The 10-year-old early successional community had the highest mitigation potential (-211 g CO_2 equivalents m^{-2} $year^{-1}$) owing to a high rate of soil C storage, no CO_2-producing agronomic activities, and very low rates of N_2O production. However, these rates of soil C storage did not appear to persist beyond a few

[7] These results need to be confirmed in a New England context.

decades—in our 50--year-old mid-successional sites, soil C storage rates were about 15% of rates in the early successional sites, yielding a net mitigation potential of only -31 g CO_2 equivalents m^{-2} $year^{-1}$. Neither the mid-successional never-tilled sites nor the late successional forests stored detectable amounts of soil C; in both cases, the GWP of N_2O production was largely offset by higher rates of CH_4 oxidation, yielding net GWPs close to zero." They go on to say that "Maximum mitigation is provided by removing land from [agricultural] production. The strong mitigation potential of our early successional system will persist into mid-succession as carbon is also allowed to accumulate in unharvested wood."

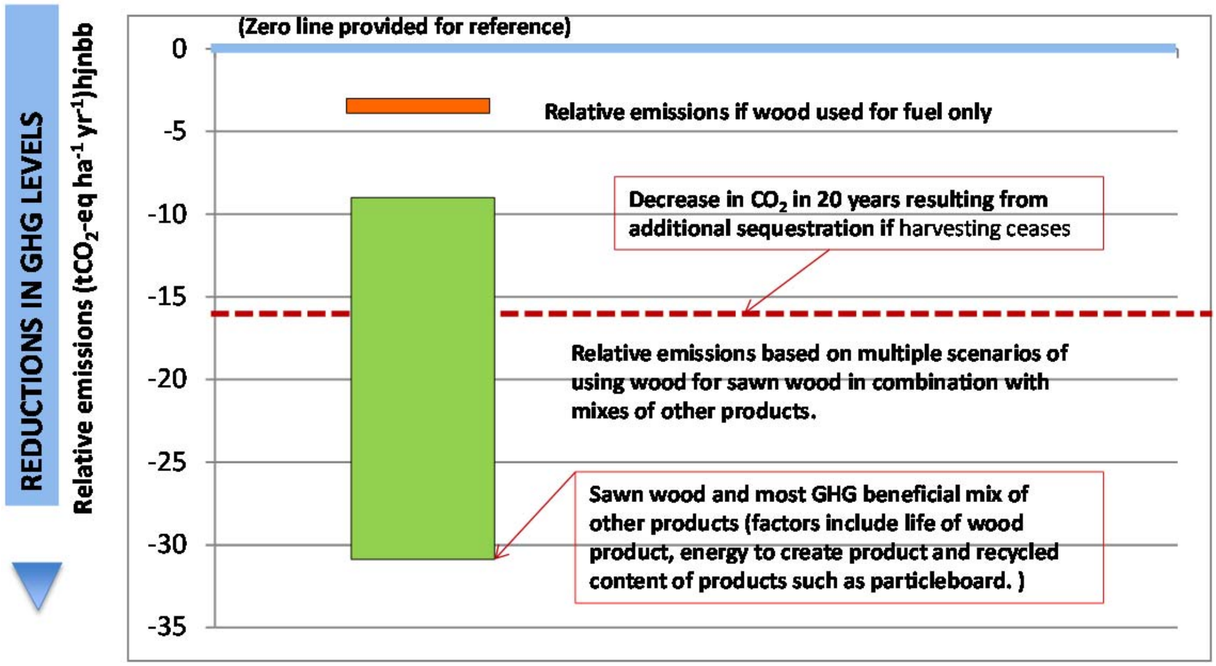
7. Wood Substitution Benefits

a. Construction Materials

Substituting wood for other materials can also reduce emissions. A thorough analysis of the "substitution benefits" of using wood was conducted by Matthews (2014) in the UK. Its essential conclusions for forests with a history of sustained yield management are shown in Figure 28. The take-home message is that the greatest gains for reducing greenhouse gases from these forests over the next few decades can be achieved by:

- Continued active management including sustained yield timber harvests;
- Use of the wood harvested for long-lived wood products; and
- Use of the residues (limbs and tops and manufacturing waste) as fuel.

Figure 28. Relative GHG emissions over 20 years comparing use of wood to use of non-wood substitutes. (Based on UK conifer forests with a history of sustained yield management.)



Simplified by R. Alec Giffen, but based on Figure 5.12 and Table 5.2 from Matthews, et al. (2014).

Matthews, et al. found the greatest GHG benefits (the lowest portion of the green bar) to result from use of harvested wood as follows: sawlogs used for timber; sawlog offcuts and small round wood used for particleboard (also using 75% recycled wood); and bark and 50% of branch wood used for fuel. All results are relative, that is, they are in comparison to the use of non-wood alternatives. If wood is used for the same combination of products but particleboard is manufactured without using recycled wood, the results are somewhat less beneficial. The authors noted that the results for OSB would be approximately the same for particleboard made with 0% recycled wood. Matthews, et al. found that while burning harvested wood for fuel only results in a slight decrease in CO_2 emissions when substitution for fossil fuels is taken into account, the GHG impact is less beneficial than ceasing harvesting (shown as the red dotted line). These results show that **use of wood primarily for long-lived products is far more GHG beneficial than 1) using wood primarily for fuel, or 2) ceasing harvesting and manufacturing products from non-wood alternatives**. (For more on this topic see the separate report, *The Greenhouse Gas Benefits of Substituting Wood for Other Construction Materials in New England*.) http://newenglandforestry.org/wpcontent/uploads/2016/04/9_The_Benefits_of_Substituting_Wood_for_Other_Construction_Materials_0922141.pdf.

This is consistent with the findings of the IPCC which stated:

"*In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fiber, or energy from the forest, will generate the largest sustained mitigation benefit*" (Nabuurs 2007).NEFF has initiated its "Build it with Wood" project to capitalize on this opportunity. Please see https://builditwithwood.org/ for more on this topic.

b. Biomass Fuels

In the long term, assuming that the forest regrows to its initial condition, the CO_2 emitted from burning biomass is recaptured by the forest. Whether or not burning biomass reduces or increases GHG levels depends on the specific sources of biomass (e.g., logging or manufacturing waste vs whole trees), the use of biomass (e.g., heat or combined heat and power vs just electricity) and how long one assumes it will take to decarbonize energy systems.

Burning whole trees that would otherwise be long-lived increases greenhouse gas levels for the near term even if they are from sustainably managed forests. As state earlier, the conclusion as to whether or not whole tree harvesting biomass for fuel is climate beneficial can be different if only impacts on carbon are considered as opposed to including both the influences on carbon and albedo together (Figure 15). Sources that can reduce greenhouse gas levels in the near term, as well as the long term, are: logging slash; manufacturing wood waste; urban wood waste; and trees that would die and decompose anyway (the supply of these is large) as their carbon would end up in the atmosphere in a matter of decades. These fuels could be increased significantly with the right polices, including increased emphasis on the use of wood for construction (as it would increase the volumes of slash and manufacturing waste and might create markets for small/low quality trees). In addition, expanding payments for early commercial thinning could reduce GHG levels by harvesting trees for fuel that would otherwise die anyway. **Biomass heating (and cooling) does offer real opportunities to reduce greenhouse gas levels if pursued using policies based on sound science**.

Figure 29. Biomass fuels can reduce or increase greenhouse gas levels in the near term – it depends on sources, uses and timeframe

Overview of sources and uses of woody biomass in the northeastern US that may be presumed to reduce global warming within 20 to 30 years (Note that the two columns are largely independent of one another; that is, except where specifically noted, a particular source does not need to be used for the use with the corresponding number – so, fuel source #1 could be used for any of the purposes identified and still yield benefits in the short term although pairing fuel source #1 with use #1 would maximize benefits)

Maximum reductions in GHGs	**Sources of Biomass Fuel**	**Use Displaced**	**Maximum reductions in GHGs**
	1) Wood that would otherwise be burned to dispose of it, e.g., wood from land clearing and some qualifying fire hazard reduction operations	1) Heating with oil (includes thermally led CHP that displaces oil)	
	2) Wood from certain biomass plantations	2) Generating electricity with coal	
	3) Wood that would otherwise be left to decompose, e.g., slash from logging operations	3) Heating with natural gas	
	4) Whole tree chips from trees dying from insects or disease, or which will die during stand development, or potentially decadent stands which are replaced with fast growing species	4) Generating electricity with natural gas provided that the biomass fuel is from Source 1 or 2 above	
Lesser reductions in GHGs			**Lesser reductions in GHGs**

©Alec Giffen, Clean Air Task Force

8. Market Factors

Forests, shaped by policies that influence their extent, location and use, can also have an influence on what are called "market factors", which have climate change implications. For example, policies favoring establishing forest plantations on what was previously agricultural land can lead to a shift of agricultural production to other lands (e.g., rainforests in the tropics) with significant negative carbon consequences. This is not idle speculation as European Union policies promoting the use of biofuels have promoted deforestation in the tropics to allow the production of these environmentally "beneficial" fuels, particularly expansion of palm oil plantations.
http://www.ucsusa.org/global_warming/solutions/stop-deforestation/palm-oil-and-forests.html#.V2wAwY-cE5s

> Palm oil is ubiquitous in the global marketplace. It is an ingredient in thousands of everyday products, from baked goods to shampoo. And it is used to fry fast food and to fuel cars and trucks in many places around the world. Unfortunately, because current palm oil production methods often cause the destruction of carbon-rich tropical forests and peatlands, it is a major contributor to global warming. In order to conserve our natural resources, protect biodiversity, and reduce our risk of climate change, we must transform the palm oil industry.
>
> Union of Concerned Scientists Fact Sheet, December 2013

Likewise, it is possible that, while in general keeping New England's forests as forests is climate beneficial, there may be instances where conversion of highly productive soils to agricultural use could yield even greater climate benefits. This issue needs further study. New tools, such as the atmospheric modeling referred to earlier, may prove beneficial in weighing these tradeoffs and allow us to reach well informed decisions.

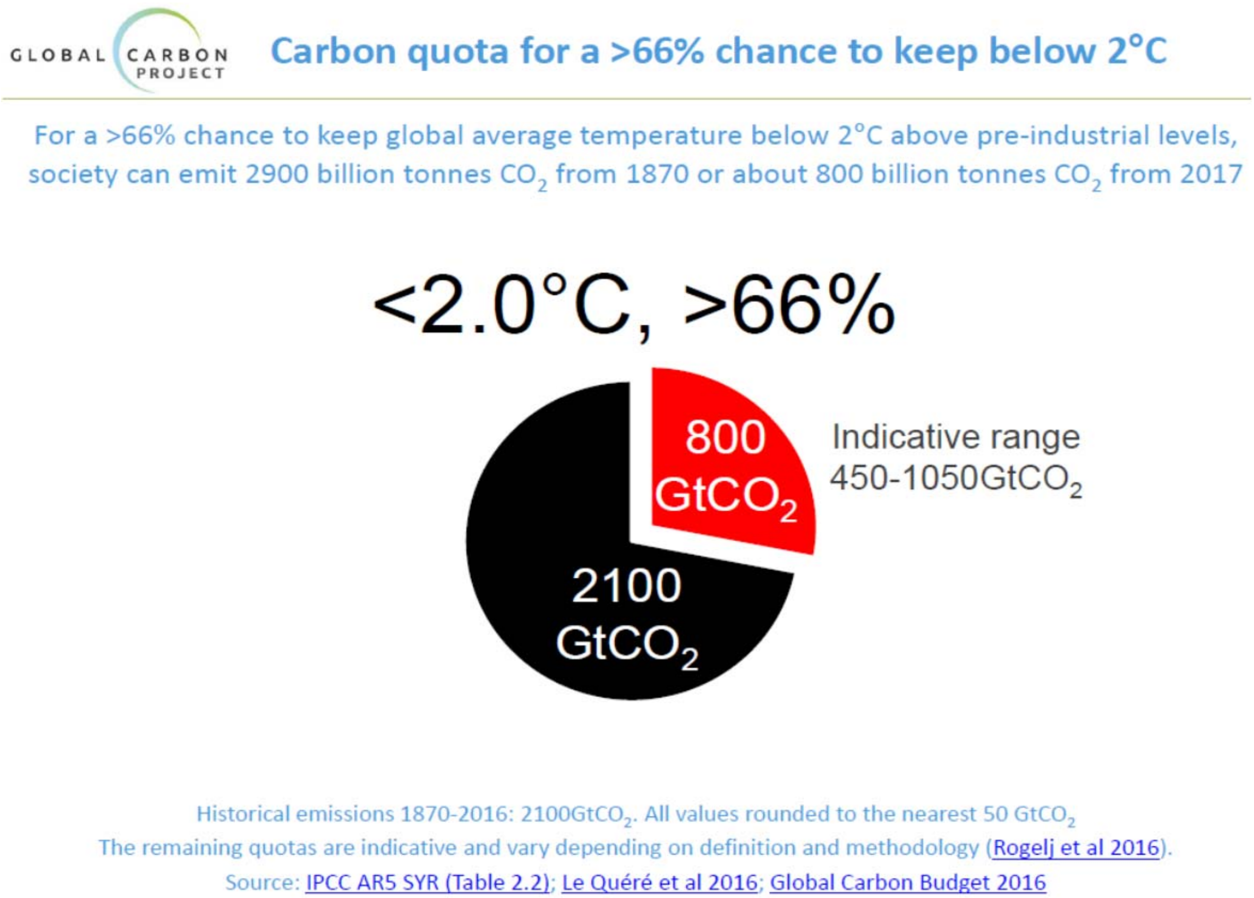
9. Timing – The Importance of Acting Promptly

Time is of the essence in determining not only how to use forests to mitigate climate change but also to limit changes in greenhouse gas levels. The International Panel on Climate Change (IPCC) states in their 2014 report that emissions must be kept within a specific range if we are to avoid the worst effects of climate change; that is, temperature increases beyond 2^{o}C (3.6^{o}F) (goal is to hold the increase in global average temperature below 2°C above pre-industrial levels.)

Human activity through 2016 has already used up more than two-thirds of the CO_2 budget that would limit climate warming to less than two degrees centigrade. This leaves space for less than800 gigatonnes ($GtCO_2$) (1 GtCO2 = 1 billion tons of CO2) of future CO_2 in the atmosphere before climate-forcing emissions must drop to zero from all activities to avoid exceeding this warming limit (see Figures 30 and 31). Current global CO_2 emissions are about 37 $GtCO_2$ per year, so even if we could immediately limit CO_2 emissions to current levels, the remaining global CO_2 budget would be used up within 22 years by 2039.

For more on this topic, see Attachment 1.

Figure 30. Carbon quota for a >66% chance to keep below 2°C (3.6°F)

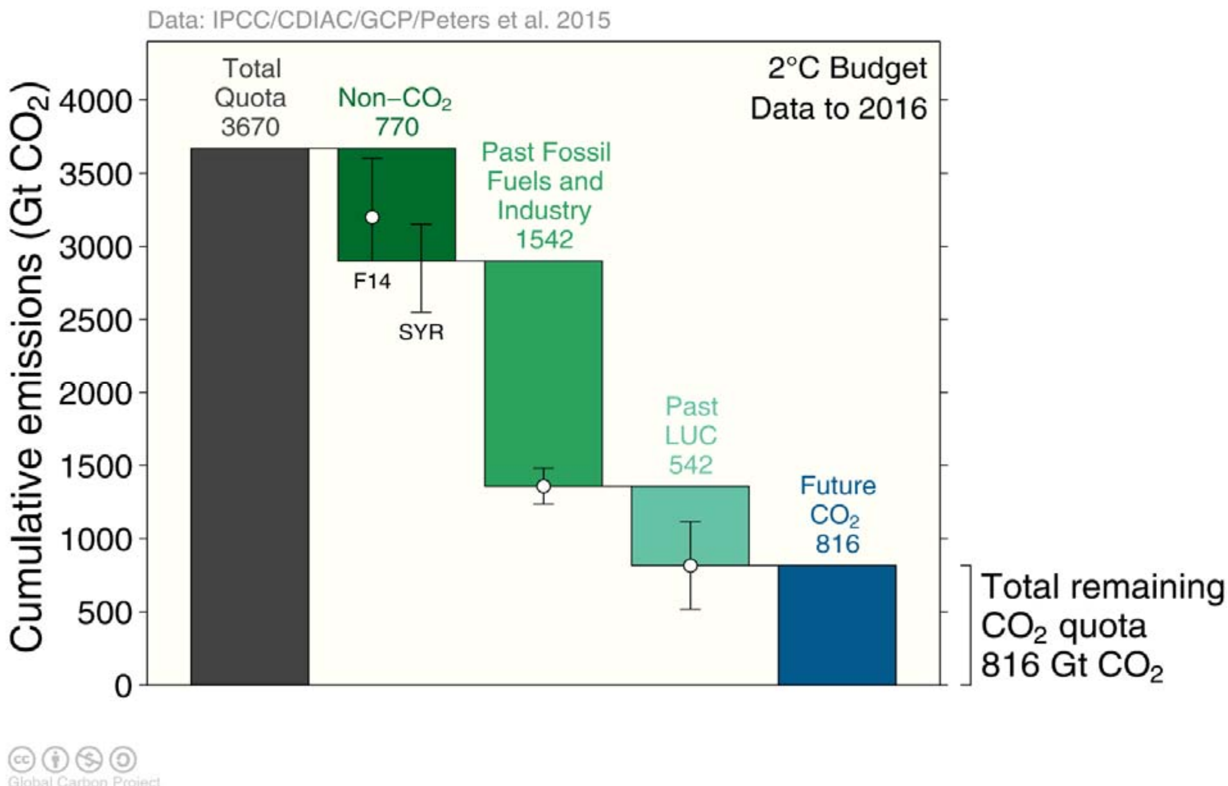


See: http://www.globalcarbonproject.org/carbonbudget/16/files/GCP_CarbonBudget_2016.pdf

> **According to the IPCC, to limiting warming to below 2°C relative to pre-industrial levels *"would require substantial emissions reductions over the next few decades"* (IPCC 2014a).**

Figure 31, which follows, graphically portrays this analysis.

Figure 31. The total remaining emissions from 2017 on to keep global average temperature below 2°C (3.6°F) (800GtCO_2) will be used in around 22 years at current emission rates



Past LUC = Past Land Use Change; Grey -- Total CO_2 (not including other greenhouse gases) quota for 2°C (3.6°F) with 66% chance; Dark Green -- Removed from CO_2 only quota; Blue -- Remaining CO_2 quota. Source: Peters et al. 2015 and Global Carbon Budget 2016. "The remaining quotas are indicative and vary depending on definition and methodology."
For more information on the Global Carbon Project see:
http://www.globalcarbonproject.org/carbonbudget/16/files/GCP_CarbonBudget_2016.pdf

By far the largest driver of climate change is the burning of fossil fuels, but we can take some measures to counter their effects by managing forests and using forest products in ways that help to moderate climatic fluctuations. McAlpine, et al. (2010) explored the various roles that forests can play in this regard and made the case for prompt action to maintain these functions. They contend that unless prompt action is taken, the opportunity to capitalize on the ability of forests to moderate climate can be lost permanently.

Even if we immediately stopped emitting greenhouse gasses the Earth's surface temperature would not react instantaneously. There would be a delayed reaction because a huge amount of thermal energy is stored in the ocean, which has a tremendous heat capacity. Because of this lag, call "thermal inertia", even the 0.6–0.9 degrees of global warming we have observed in the past century is not the full amount of warming we can expect from the greenhouse gases we have already emitted. Even if all emissions were to stop today, the Earth's average surface temperature would climb another 0.6 degrees or so over the next several decades before temperatures stopped rising. (See: https://earthobservatory.nasa.gov/blogs/climateqa/would-gw-stop-with-greenhouse-gases/) The time lag is one reason why there is a risk in waiting to control greenhouse gas emissions until the effects of global warming becomes more severe. If we wait until the impacts of global warming reach an intolerable level to take extreme action we will unfortunately still experience further unavoidable warming and its associated impacts. (See: https://earthobservatory.nasa.gov/blogs/climateqa/would-gw-stop-with-greenhouse-gases/)

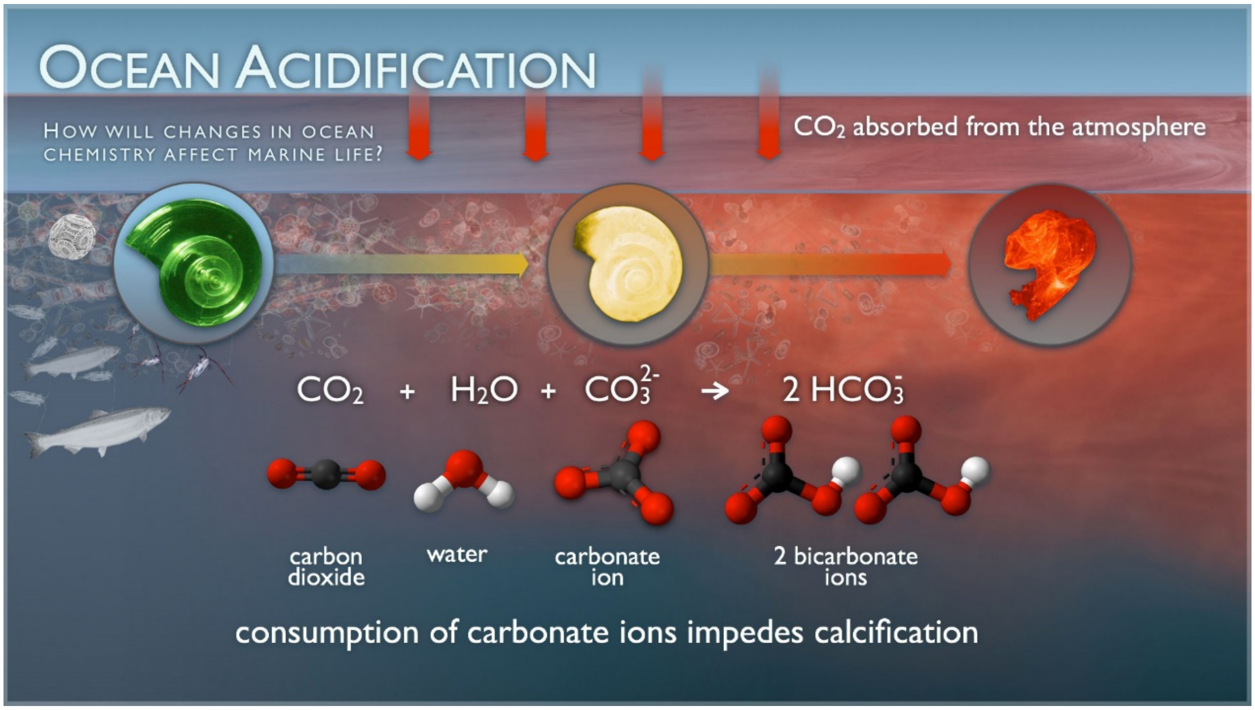
The issue of ***timing*** in reducing GHG emissions is important, not only for atmospheric greenhouse gas levels, but also as shown below for the acidification of ocean waters. Rising carbon dioxide levels in the atmosphere necessarily increase the diffusion of carbon dioxide into the oceans, where the carbon dioxide reacts with water to form carbonic acid, increasing the acidity of the oceans. Depending on the acidity level reached, this could interfere with the formation of shells by marine organisms such as crabs and lobsters, kill coral reefs, and potentially produce large dead zones in the ocean. Dead zones reduce biological uptake of carbon dioxide by plankton and the subsequent sequestration of carbon in deep waters as those plankton die and drift to the bottom. This would exacerbate greenhouse gas levels and accelerate climate change. A report on the effects of acidification on the Southern Ocean predicts that at current rates of emissions problems with certain zooplankton are likely to start occurring in approximately the same time frame (20+ years) as outlined above (McNeil, et al. 2008).

When carbon dioxide (CO_2) is absorbed by seawater, chemical reactions occur that reduce seawater pH, carbonate ion concentration, and saturation states of biologically important calcium carbonate minerals. These chemical reactions are termed "ocean acidification”. Calcium carbonate minerals are the building blocks for the skeletons and shells of many marine organisms. In areas where most life now congregates in the ocean, the seawater is supersaturated with respect to calcium carbonate minerals. This means there are abundant building blocks for calcifying organisms to build their skeletons and shells. However, continued ocean acidification is causing many parts of the ocean to become under saturated with these minerals, which is likely to affect the ability of some organisms to produce and maintain their shells.

Source: NOAA

Figure 32 illustrates how increasing ocean acidification leads to the creation of bicarbonate ions that impede the calcification process of marine life shells. Marine organisms consume calcium carbonate ions through their filtering and feeding activities and use these compounds to form shells. Acidification causes the *consumption* of calcium carbonate through a chemical reaction resulting in the production of bicarbonate ions that are not able to be used by shellfish to form shells. The shell on the left appears normal, while the shell in the middle begins to show the adverse effects of reduced availability of calcium carbonate ions, and the shell on the right exhibits malformation at low calcium carbonate concentrations. These effects have been verified in laboratory experiments.

Figure 32. Potential impacts of ocean acidification on calcification of shells of marine life if current rates of ocean acidification continues to 2100

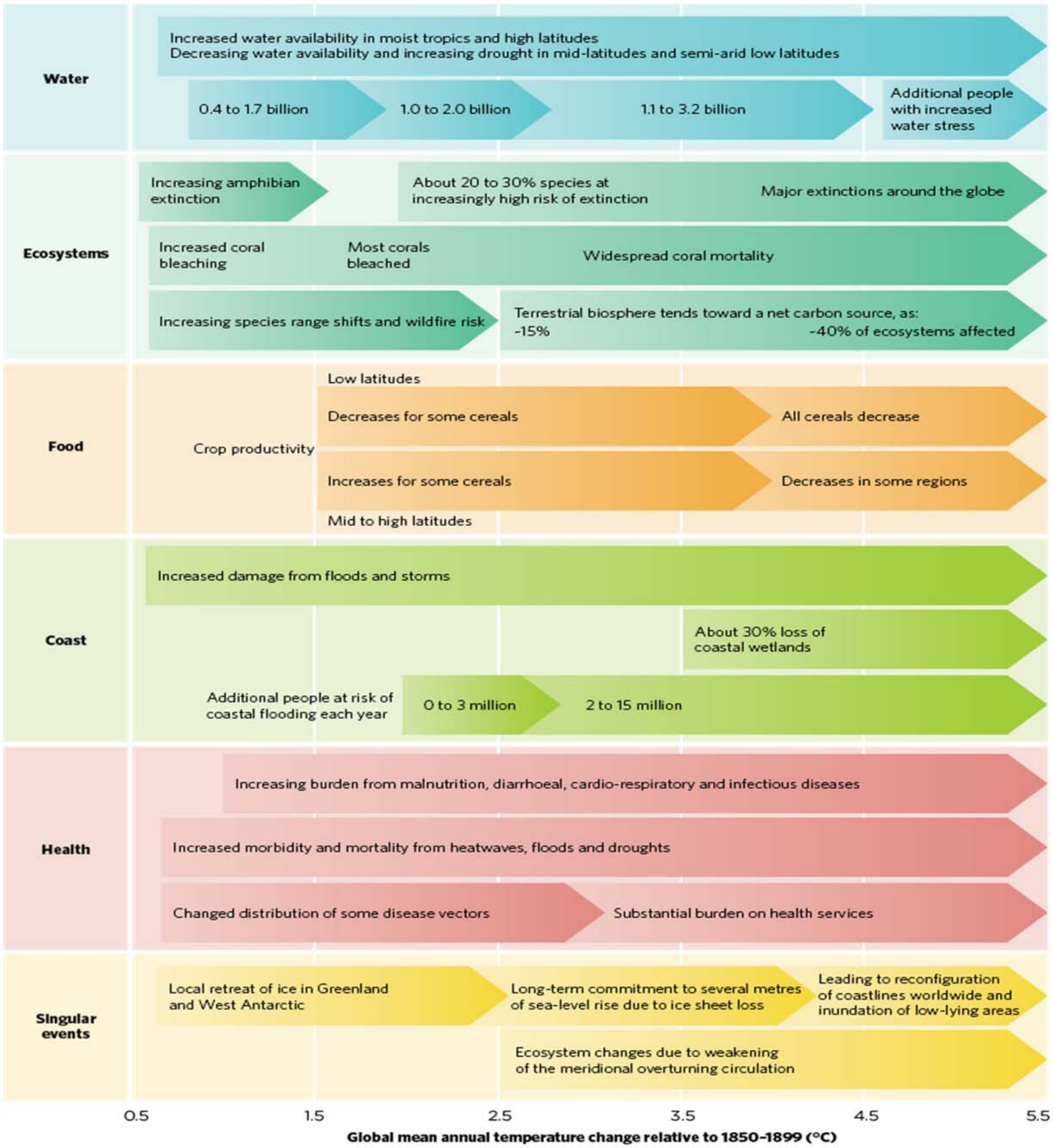


Source: NOAA See: https://www.pmel.noaa.gov/co2/story/Ocean+Acidification

A more acidic environment has a dramatic effect on some calcifying species, including oysters, clams, sea urchins, shallow water corals, deep sea corals and calcareous plankton. When shelled organisms are at risk, the entire food web may also be at risk. Today, more than a billion people worldwide rely on food from the ocean as their primary source of protein. Many jobs and economies in the U.S. and around the world depend on the fish and shellfish in our oceans. (See: https://www.pmel.noaa.gov/co2/story/What+is+Ocean+Acidification%3F).

There will be global impacts from rising temperatures that will become more sever as the temperatures increase during this century. Impacts will affect water, ecosystems, food, health the coast and result in major global events such as retreat of local ice in Greenland and West Antarctica. Figure 33, which follows, shows the global impacts projected from rising temperatures from 0.5°C to 5.5°C in 1°C increments relative to the period 1850 – 1899 (bottom of graphic). Arrows pointing to the right indicate increasing levels of change with increasing temperatures. In the category of 'Food' increasing temperatures might lead to increasing production in mid to high latitudes within the temperature range of 1.5 to 3.5°C increase. However, for all other categories increasing temperatures portend increasing adverse impacts. For ecosystems, including forests, rising temperatures will mean species shifts, increase in wildfires and the terrestrial biosphere will become a net carbon source rather than a sink.

Figure 33. Global impacts projected to result from rising temperatures



Source: Adapted from IPCC 2007b, Table TS.3. All entries of impact are drawn from chapters of the IPCC Fourth Assessment Report, where more detailed information is available.

Finally, while scientists have done their best to predict how the earth's climate system will respond to climate change itself, very considerable uncertainties remain particularly regarding tipping points. Tipping points are when emissions reach a level where positive feedback mechanisms come into play causing warming to accelerate and the Earth's climate system to be thrown into a new and irreversible state. Tipping points can cause abrupt state changes in Earth's climate system although the full consequences may not be realized in the short term.

The realization that tipping points exist and that when we may reach them is unpredictable makes the role of forests in mitigating climate change all the more important.

Lenton, et al. (2007) in their article "Tipping elements in the Earth's climate system" refer to 'tipping points' as 'tipping elements'. They state that "The term 'tipping point' commonly refers to a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system. Here we introduce the term 'tipping element' to describe large-scale components of the Earth system that may pass a tipping point. We critically evaluate potential policy-relevant tipping elements in the climate system under anthropogenic forcing, drawing on the pertinent literature and a recent international workshop to compile a short list, and we assess where their tipping points lie."

They cite the following tipping elements (which are only summarized here) as being policy-relevant:

Artic Sea Ice

As sea-ice melts it exposes a much darker ocean surface which absorbs more radiation– amplifying the warming. For both summer and winter Arctic sea-ice, the area coverage is declining at present with summer sea-ice declining more markedly and the ice has thinned significantly over a large area. Positive ice-albedo feedback (warming) dominates external forcing in causing the thinning and shrinkage since 1988, indicating strong nonlinearity and leading some to suggest that this system may already have passed a tipping point, although others disagree.

Greenland Ice Sheet

Ice-sheet models typically exhibit multiple stable states and nonlinear transitions between them. In some simulations with the Greenland Ice Sheet removed, summer melting prevents its reestablishment, although others disagree. Warming at the periphery lowers ice thickness, increasing surface temperature and causing a positive feedback (warming) that is expected to exhibit a critical threshold beyond which there is ongoing net mass loss and the Greenland Ice Sheet shrinks radically or eventually disappears.

West Antarctic Ice Sheet

Most of the West Antarctic Ice Sheet is grounded below sea level and has the potential to collapse if grounding line retreat triggers a strong positive feedback (warming) whereby ocean water undercuts the ice sheet and triggers further separation from the bedrock. Glaciers that end in the ocean are called Tidewater Glaciers. The point at which these glaciers start to float is the Grounding Line. The location of the grounding line is important, because mass loss from Antarctica is strongly linked to changes in the ice shelves and their grounding lines. The West

Antarctic Ice Sheet collapse may be preceded by the disintegration of ice shelves and the acceleration of ice streams. Ice shelf collapse could be triggered by the intrusion of warming ocean water beneath them or by surface melting.

Atlantic Thermohaline Circulation

The Atlantic Thermohaline Circulation can be regarded as a big overturning of the North Atlantic Ocean from top to bottom. It is driven as the name suggests by both temperature and salinity. In cold regions the highest surface water densities are reached, this causes convective mixing and sinking of deep water, which drives the circulation. Global warming can affect the Atlantic Thermohaline Circulation in two ways -- surface warming and surface freshening, both reducing the density of high-latitude surface waters and thus inhibiting deep water formation and hence circulation. A shutoff in the Atlantic Thermohaline Circulation and the associated North Atlantic Deep Water Formation can occur if sufficient freshwater and/or heat enters the North Atlantic to halt the density-driven North Atlantic Deep Water formation. Deep Water Formation takes place in a few localized areas: the Greenland-Norwegian Sea, the Labrador Sea, the Mediterranean Sea, the Wedell Sea and the Ross Sea. Atlantic Thermohaline Circulation reorganizations played an important part in rapid climate changes recorded in Greenland during the last glacial cycle. Atlantic Thermohaline Circulation collapse is now widely discussed as one of a number of "low probability - high impact" risks associated with global warming. More likely than a breakdown of the Atlantic Thermohaline Circulation, which only occurs in very pessimistic scenarios, is a weakening of the Atlantic Thermohaline Circulation by 20-50%, as simulated by many coupled climate models (see: http://www.pik-potsdam.de/~stefan/thc_fact_sheet.html). A change in the Atlantic Thermohaline Circulation could have dramatic impacts on Europe's climate leading to a cooling.

El Niño–Southern Oscillation (ENSO)

Gradual anthropogenic forcing is expected, on theoretical grounds, to interact with natural modes of climate variability by altering the relative amount of time that the climate system spends in different states. ENSO is the most significant ocean-atmosphere mode and increased ocean heat uptake could cause a shift from present day ENSO variability to greater amplitude. (In response to a warmer stabilized climate, the most realistic models simulate increased El Niño amplitude with no clear change in frequency.) The ENSO is considered to be a potential tipping element in Earth's climate and, under the global warming can enhance or alternate regional climate extreme events. The required warming could occur this century with the transition happening within a millennium, but the existence and location of any threshold is particularly uncertain. Writing in Nature Climate Change thirteen researchers join together to predict the results of more extreme El Niño's. They state that the 1982/83 extreme El Niño featured a pronounced eastward extension of the west Pacific warm pool and development of atmospheric convection, and hence a huge rainfall increase, in the usually cold and dry equatorial eastern Pacific. If this became a more common pattern, then extreme El Nino events could severely disrupted global weather patterns, affecting ecosystems, agriculture, tropical cyclones, drought, bushfires, floods and other extreme weather events worldwide (see: http://www.nature.com/nclimate/journal/v4/n2/full/nclimate2100.html).

Indian Summer Monsoon (ISM)

The land-to-ocean pressure gradient, which drives the monsoon circulation is reinforced by the moisture the monsoon itself carries from the adjacent Indian Ocean (moisture-advection feedback). Consequently, any perturbation that tends to weaken the driving pressure gradient has the potential to destabilize the monsoon circulation. Greenhouse warming that is stronger over land and in the Northern Hemisphere tends to strengthen the monsoon, but increases in planetary albedo over the continent due to aerosol forcing and/or land-use change tend to weaken it. The ISM exhibited rapid changes in variability during the last ice age. Models and conclusions by researchers differ as to the future characteristics of the ISM as a result of global warming.

Amazon Rainforest

A large fraction of precipitation in the Amazon basin is recycled, and, therefore, simulations of Amazon deforestation typically generate 20–30% reductions in precipitation, lengthening of the dry season and increases in summer temperatures that would make it difficult for the forest to reestablish. Dieback of the Amazon rainforest has been predicted to occur under 3–4°C global warming because of a more persistent El Niño state that leads to drying over much of the Amazon basin. Different vegetation models driven with similar climate projections also show Amazon dieback, but some global climate models project smaller reductions (or increases) of precipitation and, therefore, do not produce dieback. However, a regional specific climate model predicts Amazon dieback due to widespread reductions in precipitation and lengthening of the dry season.

Boreal Forest

The boreal system exhibits a complex interplay between tree physiology, permafrost and fire. Under climate change, increased water stress, increased peak summer heat stress causing increased mortality, vulnerability to disease and subsequent fire, as well as decreased reproduction rates could lead to large-scale dieback of the boreal forests. This could result in transitions to open woodlands or grasslands. In interior boreal regions temperate tree species will remain excluded from succession due to frost damage in still very cold winters. Continental steppe grasslands will expand at the expense of boreal forest where soil moisture along the arid timberline ecotone declines further, amplified through concurrent increases in the frequency of fires. Newly unfrozen soils that regionally drain well, and reductions in the amount of snow, also support drying, more fire and hence less biomass. In contrast, increased thaw depth and increased water-use efficiency under elevated CO_2 will tend to increase available soil moisture, decreasing fire frequency and increasing woody biomass. Studies suggest a threshold for boreal forest dieback of 3°C global warming, but limitations in existing models and physiological understanding make this highly uncertain.

Lenton, et al. (2007) did not include as a “tipping element” the impact of increased global temperatures on CO_2 and methane release from the Arctic, so included here in the text box below is an overview from the National Snow and Ice Data Center.

Methane Release from the Arctic

The Arctic takes up more carbon than it releases because plants take up carbon during the growing season, but do not release as much carbon through decay. So, for now the Arctic acts as a carbon sink. But if the Earth continues to warm, and a lot of permafrost thaws out, the Arctic could become an overall source of carbon to the atmosphere, instead of a sink. This is referred to as a "tipping point." A system reaches a tipping point when it switches from a relatively stable state to an unstoppable cycle. In this case, the Arctic would change from a carbon sink to a carbon source. There are two potential sources of methane in the Arctic. The first is called methyl clathrate a form of methane in gas bubbles that are frozen into ice crystals. Melting ice could release these gas bubbles to the atmosphere. The other major source of methane in the Arctic is the organic matter frozen in permafrost. There is a huge amount of carbon stored in permafrost. Right now, the Earth's atmosphere contains about 850 gigatons of carbon. (A gigaton is one billion tons—about the weight of one hundred thousand school buses). We estimate that there are about 1,400 gigatons of carbon frozen in permafrost. So the carbon frozen in permafrost is greater than the amount of carbon that is already in the atmosphere today. That doesn't mean that all of the carbon will decay and end up in the atmosphere. The challenge is to find out how much of the frozen carbon is going to decay, how fast, and from where. As organic matter decays, it's consumed and digested by microbes. If oxygen is available, the microbes make carbon dioxide. Lacking oxygen, they make methane. Most of the places where methane would form are the swamps and wetlands. And there are millions of acres of wetlands in the Arctic. Methane is 20 times more potent as a greenhouse gas than CO_2. If the Arctic permafrost releases more carbon than it absorbs, it would start a cycle where the extra carbon in the atmosphere leads to increased warming. The increased warming means more permafrost thawing and more carbon release.

National Snow and Ice Data Center (See: National Snow and Ice Data Center. *All About Frozen Ground.* http://nsidc.org/frozenground/

Lenton, et al. (2007) also did not include as a "tipping element" the impact of increased global temperatures on release of soil carbon as a result of increasing temperature accelerating soil respiration. Crowther et al. (2016) state that "Given that global average soil surface temperatures are projected to increase by around 2°C over the next 35 years under a business-as-usual emissions scenario, this extrapolation would suggest that warming could drive net loss of approximately 55 + or – 50 PgC from the upper soil horizon." There is still much uncertainty about the fate of soil carbon in a warming climate and it is an area needing further research. But as the authors state "If as expected this carbon entered the atmospheric pool the atmospheric burden of CO_2 would increase by approximately 25 parts per million over this period." This would represent a significant increase in atmospheric carbon leading to further warming (see: www.nature.com/articles/nature20150.epdf).

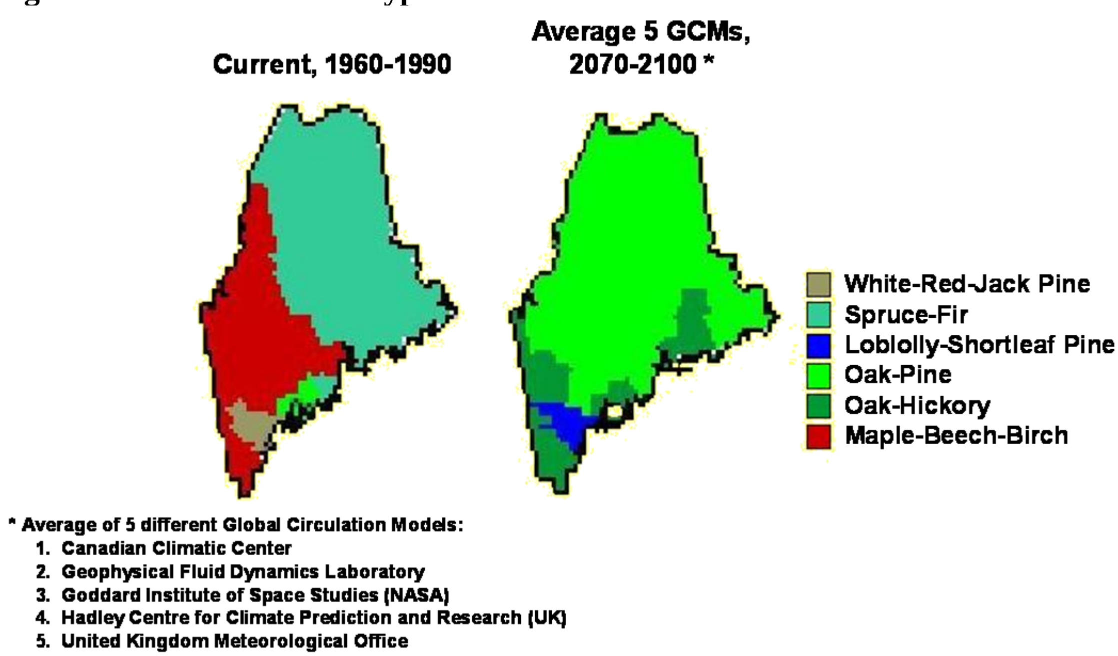
The uncertainties associated with these various 'tipping elements' is due to the complex nature of the Earth's climate system and our still nascent abilities to model it and understand it. Therefore, we should embrace the 'precautionary principle' and take actions necessary to reduce and eventually reverse emissions of greenhouse gases to avoid reaching these points-of-no-return. As this report demonstrates the role of forests in mitigating climate change generally, including avoiding reaching levels that exceed tipping points could be substantial. Therefore we should maximize the role that forests can play to mitigate climate change.

H. Climate Change Effects on Forests

Forests of course will also be affected by climate change (Tang and Beckage 2010). In New England, as elsewhere, climate change will affect the health, mortality and regeneration of tree species differentially. Some species will be better suited to the environmental conditions in a warming world with changing precipitation regimes. Forests will respond as the more resilient tree species fair better, or even thrive under the new conditions, and other less well adapted tree species drop out of the forest over time.

Figure 34 shows how changes in the suitability of climate zones might occur in Maine by the end of the century. These changes in climate zones could result in the replacement over time of the Maple-Beech-Birch type and the Spruce-Fir type with Oak-Pine and Oak-Hickory.[8] The frequency of insect outbreaks, the occurrence of ice storm damage, changes in wildlife populations and other disturbances such as the spread of invasive species will also be affected by climate change and in turn affect the region's forests. These climate-driven changes will interact with other factors influencing forests, such as the spread of urban and suburban development, changes in atmospheric deposition, and importation of non-native forest pests.

Figure 34. Dominant forest types

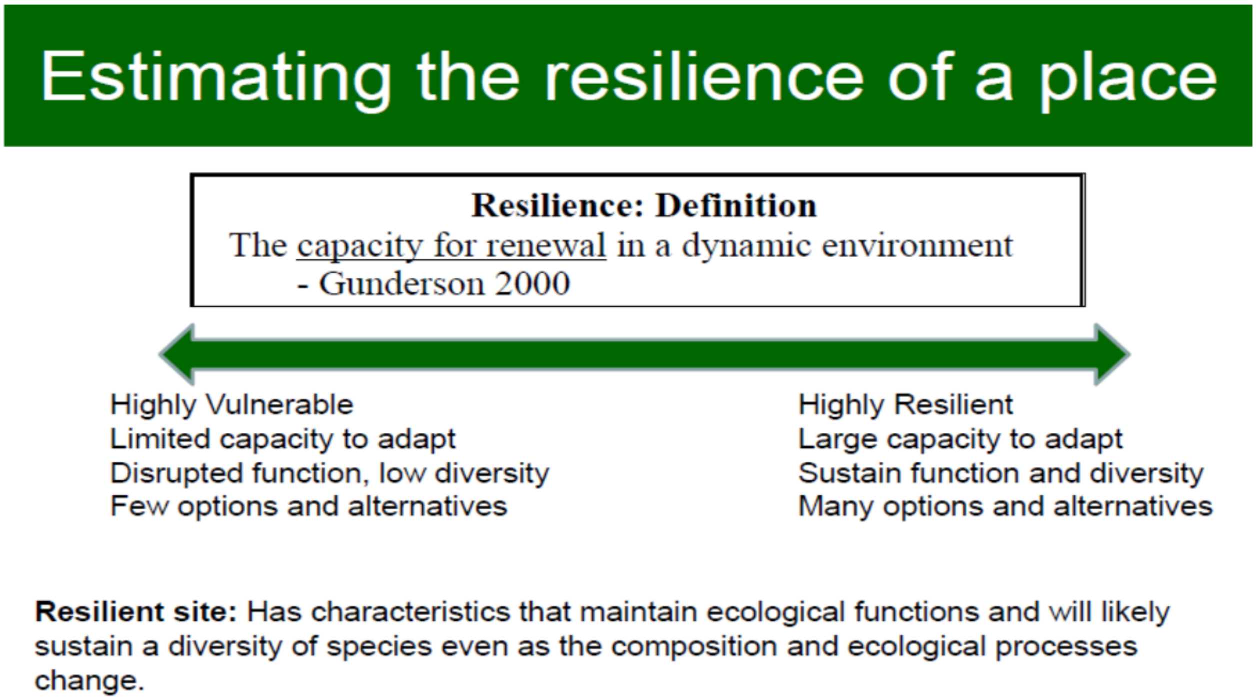


Source: Prasad and Iverson (1999 and ongoing).

[8] Recent work by the USFS "Changing Climate, Changing Forests: The Impacts of Climate Change on Forests of the Northeastern United States and Eastern Canada" available at (https://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs99.pdf) supports the conclusions of this earlier work as does very recent work by Aaron Weiskettel at the University of Maine - Forecasting the Unknown: Potential impacts of climate change on Maine's forest**,** Aaron Weiskittel, Associate Professor of Forest Biometrics and Modeling, Irving Chair of Forest Ecosystem Management.

To maintain existing benefits for mitigating climate change and ameliorating its effects, as well as capitalize on opportunities to enhance these benefits, forests need to be resilient to climate change and be able to adapt to the changes which are coming and have already been made inevitable. Resilience is defined by the IPCC as "the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning" (IPCC 2007a).

Figure 35. Vulnerability and resilience of social or ecological systems

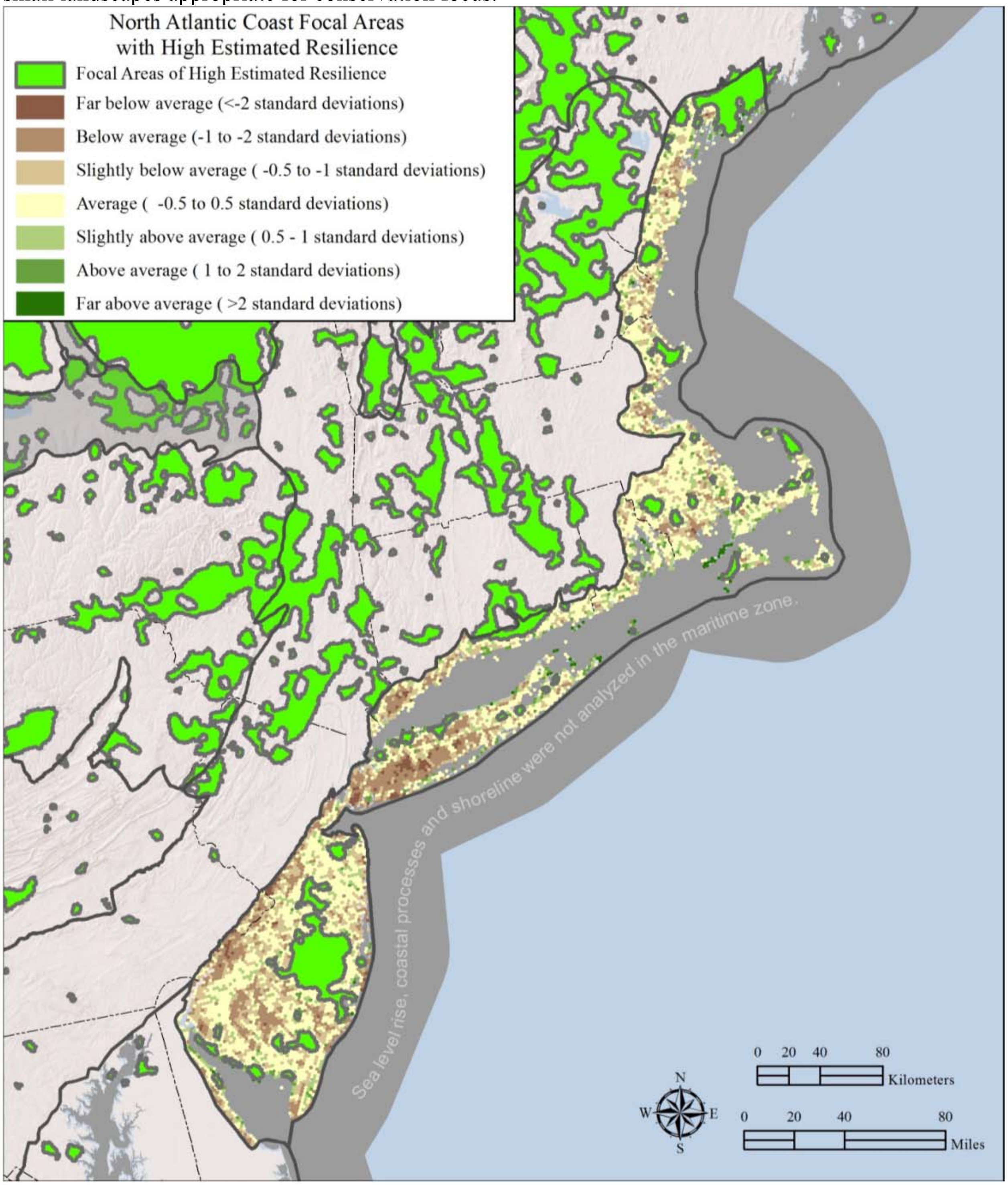


Source: Anderson 2014.

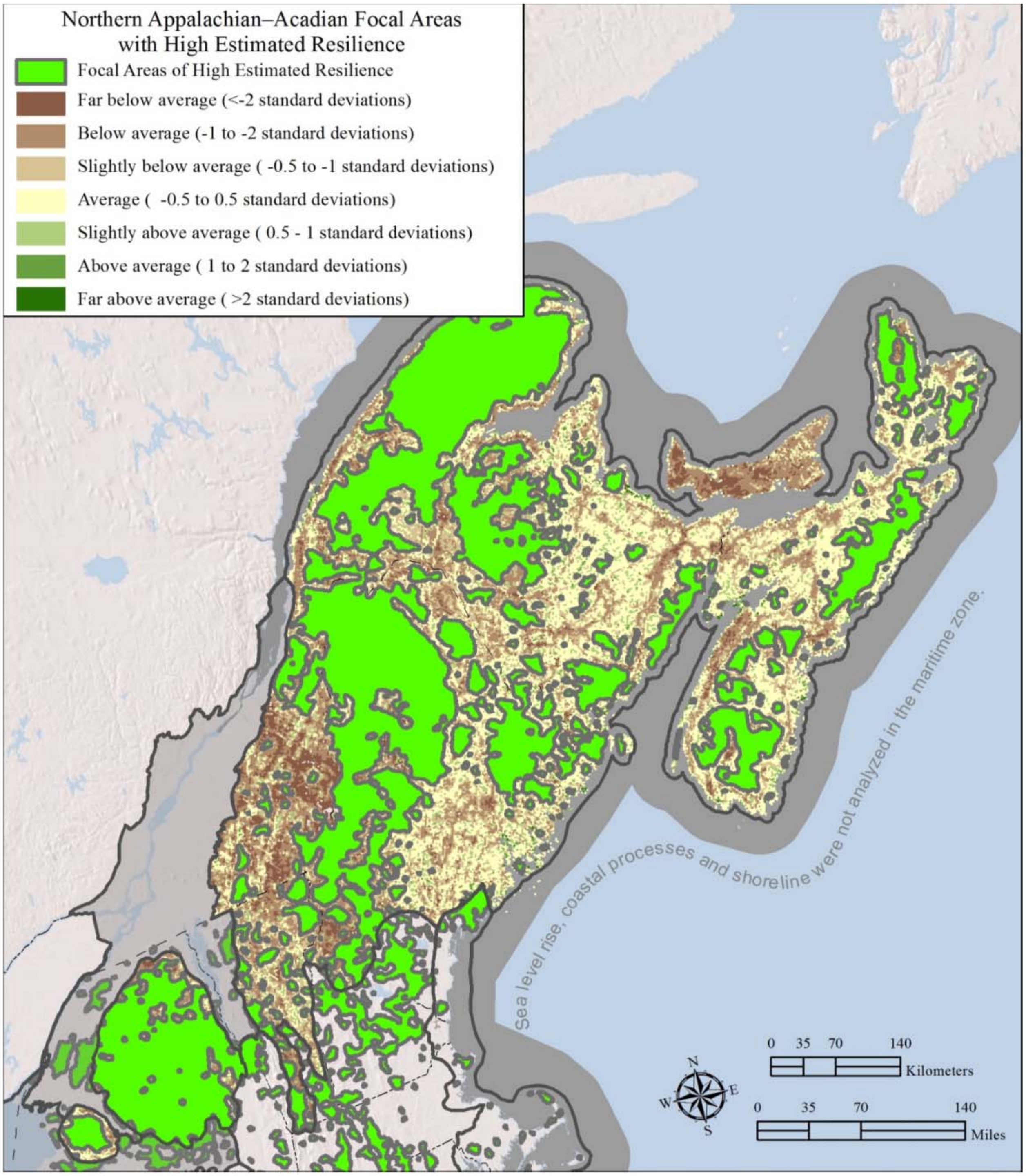
New England's forests vary in their resilience to climate change. For stands to be as resilient as possible, we need to maximize stand vigor to increase the trees' ability to withstand stress. This means controlling insects and diseases, as well as thinning stands to release the most vigorous trees to grow. Resilience is a short term response to climatic change. In the longer term, forests must also adapt to the effects of a changing climate. The Nature Conservancy and others assert that to facilitate forest adaptation to climate, we need to maintain the "stage." That is maintain the physical sites, preferably as diverse as possible in terms of geology, soils, topography, elevation and species composition, where forests can adapt over time.

Figure 36. Focal areas with high estimated resilience within Northeast U.S.

Map 6.24: North Atlantic Coast: Focal Areas with High Estimated Resilience. This map simplifies the estimated resilience map by clustering adjacent areas of high resilience into larger sites and ignoring single small isolated sites. Although the map relinquishes some detail, it is designed to identify large and small landscapes appropriate for conservation focus.



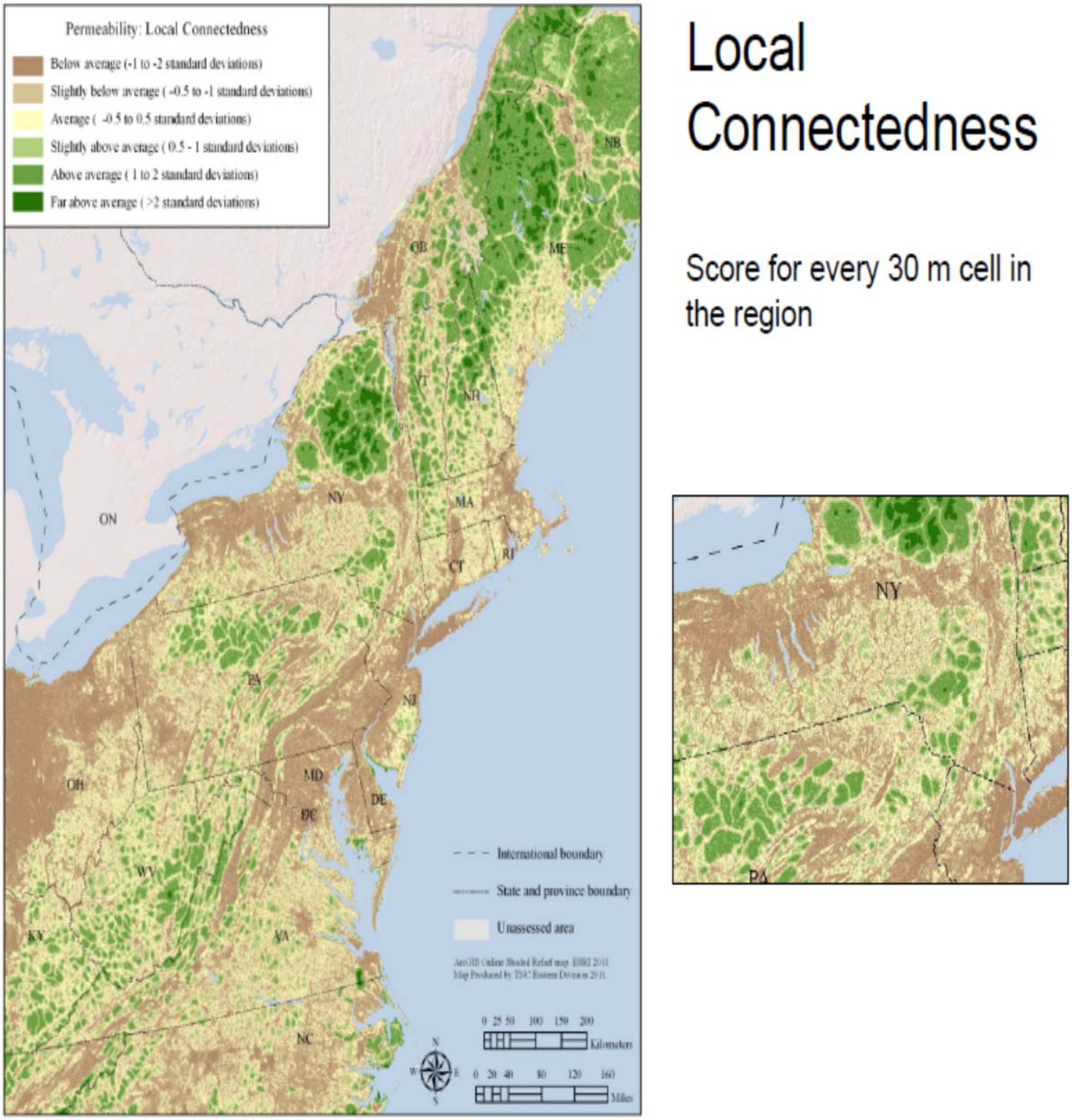
Map 6.29: Northern Appalachian: Focal Areas with High Estimated Resilience. This map simplifies the estimated resilience map by clustering adjacent areas of high resilience into larger sites and ignoring single small isolated sites. Although the map relinquishes some detail, it is designed to identify large and small landscapes appropriate for conservation focus.



Source: Anderson, et al. (2012).

Figure 37. Degree of local connectedness of ecosystems

Note: Brown grading to tan represents below average connectedness; cream is average connectedness; and light green grading to medium green to dark green represents increasing levels of above average connectedness of ecosystems.



Source: Anderson (2014). Identifying and Protecting Resilient Ecosystems: New Directions for Conservation in a Changing World. See: http:conserveonline/ECS/resilientsites1

Maintaining connectivity between forest areas, particularly along north-south axes, is important so that species can migrate “naturally” as climate changes. Such ecological linkages, particularly if similar efforts are undertaken to the south and north of New England, should allow species and ecosystems to adapt over time. As alluded to earlier, it is also desirable that within these corridors as many different physical settings as possible are represented, such that species have the opportunity to utilize different ecological settings even at a specific latitude (Anderson 2010). Considering both resilience as well as connectivity, it is apparent that New England’s and New York’s northern mountain ranges have special value as climate change zones.

In addition to maintaining connectivity, in the interest of promoting resilience and adaptation, it is important to maintain or increase diversity, both within and among species. Within species it is important to maintain genetic diversity that may allow species to effectively adjust to climate change. This can be accomplished by managing for a single species across the full range of habitats it can occupy and a diversity of growth habits.

It is also important to increase diversity by introducing and/or favoring the species likely to be best suited to future climates, which as stated earlier are predicted to be warmer, wetter, more variable, and turbulent with more frequent extreme weather events.

I. The Role of New Englanders and New England Forests in Determining How to Maximize the Benefits of Forests to Mitigate Climate Change

New England with its extensive forests, long history of non-profit advocacy for forests and innovative thinking on forest conservation and management, as well as its outstanding forestry schools and research institutions, is well positioned to lead the way in determining how to best use forests to mitigate climate change, ameliorate its effects, increase forest resilience and facilitate forest adaptation to a changing climate. New England forests could serve as a case study and laboratory for this work with benefits to the region and far beyond. For example, in partnership with the New England Forestry Foundation and the Clean Air Task Force, the Woods Hole Research Center is working to develop the analytical approaches discussed earlier that are intended to evaluate the net effects of several interrelated forest climate influences. As also discussed earlier, this is critical as evaluating the effect of any one or two factors independently of the others can lead to erroneous conclusions.

Research could cover a wide range of other topics as well. A few suggestions are listed below:

- How can we manage New England’s forests to make them more resilient to climate change so that their ability to produce wood and provide other benefits is maintained and or even enhanced in a changing climate?

- How can we facilitate the adaptation of New England forests to potential future climates so that our forests remain productive and can continue to mitigate climate change? It is important that decisions on future management lead to the most “robust” solutions possible. That is, ones which can succeed even if the prediction regarding the climate future of New England proves to be wrong.

- What forest management strategies should be employed to enhance regional cooling, flood control, maintain summer stream flows and serve as refuges from high temperatures?
- What are the best strategies for managing forests and using wood products from New England forests to sequester carbon for the long term?
- In the long term, after we have decarbonized our energy systems, what are the best mechanisms to employ to store the carbon captured by forests for the long term that is decades and even centuries?

Existing tools, such as the latest atmospheric models, may be used to explore some of these questions, and it is likely that new modeling tools will also be needed. This will be a fertile area for research. The New England Forestry Foundation in conjunction with the Woods Hole Research Center and the Clean Air Task Force has established a partnership to tackle these challenging areas of research (for an outline of the research concepts, see Attachments 3 and 4.) The lives, livelihoods and wellbeing of New Englanders could depend on the development of effective strategies to mitigate climate change and ameliorate its effects. This research effort to determine "net effects" outlined earlier should get underway as soon as possible as it will take time to develop the necessary climate research tools and to find the answers to challenging and complex questions about our changing climate. We are fortunate to have the Woods Hole Research Center, a world leader on this topic, and the Clean Air Task Force as partners in this enterprise.

J. Conclusions

Globally, nationally and regionally climate change is already causing changes in temperatures, precipitation, floods and droughts. The National Climate Assessment (2014) foresees these changes continuing and intensifying driven largely by the amount of greenhouse gases emitted into the atmosphere. It is not possible based on current climate change models to say with complete precision when or to what extent specific climate changes will occur at a regional level.

For the Northeast the report has some key messages:

1. "Climate Risks to People - Heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems.
2. Stressed Infrastructure - Infrastructure will be increasingly compromised by climate-related hazards, including sea level rise, coastal flooding and intense precipitation events.
3. Agriculture and Ecosystem Impacts - Agriculture, fisheries, and ecosystems will be increasingly compromised over the next century by climate change impacts including seasonal droughts…, adaptive capacity, which varies throughout the region could be overwhelmed by a changing climate."

Time is of the essence, we must begin acting aggressively now to reduce and limit greenhouse gas levels. The International Panel on Climate Change (IPCC) states in their 2014 report that emissions must be kept within a specific range if we are to avoid the worst effects of climate change; that is, temperature increase must be kept below 2^{o}C (3.6^{o}F) (hold the increase in global average temperature below 2°C above pre-industrial levels.)

Human activity through 2016 has already used up more than two-thirds of the CO_2 budget that would limit climate warming to less than two degrees centigrade. This leaves space for less than 800 $GtCO_2$ in the atmosphere before climate-forcing emissions must drop to zero from all activities to avoid exceeding 2^{o}C (3.6^{o}F). Current global CO_2 emissions are about 37 $GtCO_2$ per year, so even if we could immediately limit CO_2 emissions to current levels, the remaining global CO_2 budget will be used up within 22 years, by 2039.

While it is obvious that New England's forests cannot by themselves fully mitigate global climate change or even ameliorate all of the regional impacts that are likely to occur, they could, along with the region's intellectual capital working on this issue, serve as a site for case studies that enable us to determine:

1. How to maximize the climate benefits of forests (maximize net benefits);
2. How to increase forest resilience; and
3. How to facilitate forest adaptation to species that will be favored by a warming climate.

It is imperative that we get underway with this research soon if we are to lead the way for other regions and initiate policies and practices that will take full advantage of New England's forests to mitigate, prevent and ameliorate climate change.

The lives, livelihoods and wellbeing of New Englanders could depend upon the development of effective strategies to mitigate climate change and ameliorate its effects. It will take time to develop the necessary climate research tools and to employ them to find answers to challenging and complex questions about our changing climate. We are fortunate to have the Woods Hole Research Center, a world leader on this topic, and the Clean Air Task Force as partners in this enterprise.

Actions We Can Take Now!

Finally, despite the need for additional research, there are steps we can take now to capitalize on the opportunities New England's forests offer to: 1) ameliorate and 2) mitigate climate change, as well as 3) facilitate the adaption of forests to future climate conditions, so they can both amelioration and mitigation climate change in the future. That is, because we understand their consequences, we can with confidence take the following actions:

Ameliorate Climate Change

- Increase use of urban trees to shade buildings to reduce ground level air temperatures and thereby reduce emissions associated with air conditioning and block winter winds to reduce emissions from heating.
- Utilize 'green infrastructure', defined as vegetation systems intentionally designed to promote environmental quality, to reduce the intensity of heat islands by providing shade and cooling from evapotranspiration, and increase infiltration of precipitation.
- Maintain and expand urban parks to provide cooling benefits downwind into surrounding residential areas.

Mitigate Climate Change Now

- Keep New England's forests as forests – not only to store carbon but also to reduce emissions of N_2O.
- Utilize management plans developed by professional foresters to ensure that the forestry objectives outlined are realized.
- Restore management for longer rotation ages to increase the oxidation of methane (many actively managed areas are now managed for shorter rotation ages than they were historically).
- Reforest marginal agricultural lands in areas that are not likely to be used for agriculture. (Note: Some of these lands could be used for short rotation production of biomass fuels if demand warrants it).
- Minimize soil disturbance during logging, unless needed for intentional regeneration of desired species.
- Regenerate logged areas as quickly as possible to the desired species.
- Favor tree species best suited to grow valuable products (particularly those suitable for long-lived wood products) under future climatic conditions.
- Employ intensive management practices on the most productive forest lands to increase sustainable production of wood per acre – this will result in storing more carbon on-site and will provide more wood for long-lived purposes.
- Substitute wood in construction for other materials with higher life cycle greenhouse gas emissions.
- Productively use trees that are dead or will die in the next few decades, so that the carbon contained in them can be used in ways that most effectively reduce greenhouse gas emissions.
- Prevent and control wildfires (note that controlled burns may be appropriate to create or maintain certain habitats).
- Use limbs and tops from logging, forest manufacturing waste, and urban wood waste for biomass fuel, favoring heating and combined heat and power over biomass electrical generation.
- Allow forest waste to naturally decompose onsite when it cannot be used for a climate beneficial purpose or when it is needed to maintain desirable site conditions rather than burning onsite (attenuates release of CO_2, increases soil carbon and reduces black carbon emissions).

Facilitate the Adaptation of Forests to Future Climate Conditions (Adaptation is needed to allow forests to both amelioration and mitigation climate change in the future.)

- Thin stands to improve growth on trees targeted for management and to make them more resilient to climate change; and harvest trees that would otherwise die.
- Manage for species that will be favored by a warming climate (e.g., oak, hickory and pine) over much of New England.
- Create a strategically designed system of reserves to maintain the values of older forests and provide ecological benchmarks that can be used to qualify and quantify impacts due to a changing climate.

- Maintain the "connectivity" between forest areas (particularly along high elevation areas and the north/south axis) in the Northern Appalachian/Acadian Forest to allow for species migration over time.

In summary, New England's forests provide options to ameliorate, mitigate and adapt to climate change. They in turn will be strongly influenced by the actions we choose to take. If forests are managed to optimize climate benefits, considering the full range of forest-climate systems interactions without adverse climate impacts (e.g. displacing agriculture to a region where it results in greater radiative forcing), they could contribute to what Garman, et al. (2014) referred to as "climate remediation." This would be an example of employing techniques to improve our circumstances rather than simply avoiding making them worse. This can be thought of as "green" geoengineering that has multiple benefits without the risks that other more extreme geoengineering approaches could entail. This effort should include expanded urban and agroforests, as well as wildland forests.

K. References Cited in this Report

Agostini, A., J. Giuntoli and A. Boulamanit. 2013. Carbon accounting of forest bioenergy: Conclusions and recommendations from a critical literature review. European Commission Joint Research Centre, Institute for Energy, and Transport, Tech. Rep. EUR 25354 EN. Available online at iet.jrc.ec.europa.eu/bf-ca/sites/bfca/files/files/documents/eur25354en_ online-final.pdf; last accessed Oct. 1, 2014.

Akbari, H., M. Pomerantz and H. Taha. 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, 70(3): 295-310.

Alig, R.J., J.D. Kline, and M. Lichtenstein. 2003. Urbanization on the US landscape: Looking ahead in the 21st century. *Landscape and Urban Planning,* 69:219–234.

Anderson R.G., J. G. Canadell, J. T. Randerson, R. B. Jackson, B. A. Hungate, D. D. Baldocchi, G. A. Ban-Weiss, G. B. Bonan, K. Caldeira, L. Cao, N. S. Diffenbaugh, K. R. Gurney, L. M. Kueppers, B. E. Law, S. Luyssaert, and T. L. O'Halloran. 2011. Biophysical considerations in forestry for climate protection. Frontiers in Ecology and the Environment, Volume 9, Issue 3. April 2011. Pages 174–182.

Anderson, M.G., M. Clark, and A. Olivero Sheldon. 2012. Resilient sites for terrestrial conservation in the Northeast and Mid-Atlantic Region. The Nature Conservancy, Eastern Conservation Science. 168 pp.

Anderson (2014). Identifying and Protecting Resilient Ecosystems: New Directions for Conservation in a Changing World. See: http:conserveonline/ECS/resilientsites1

Arnfield, A. J. Two Decades of Urban Climate Research: A Review of Turbulence, Exchanges of Energy and Water and the Urban Heat Island. International Journal of Climatology 23:1–26 (2003).

Birdsey, Richard A. 1992. Carbon storage and accumulation in United States forest ecosystems. Gen. Tech. Rep. WO-59. Washington D.C.: U.S. Department of Agriculture, Forest Service, Washington Office. 51p.

Bonan, G. B. 2008. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. Science, 320: 1444-1449.

Burns, D.A., J. Klaus, and M.R. McHale. 2007. Recent climate trends and implications for the water resources in the Catskill Mountain region, New York, USA. *Journal of Hydrology,* 336:155-170.

Cherubini, F., R.M. Bright, and A. Stromman. 2012. Site-specific global warming potentials of biogenic CO_2 for bioenergy: contributions from carbon fluxes and albedo dynamics. *Environ. Res. Lett.* 7:045902.

Clean Air Task Force. 2014. Promoting forest practices and policies to protect climate: A proposal for research and action – starting in North America. 25 p.

Crowther, T. W., K. E. O. Todd-Brown, C. W. Rowes, W. R. Wieder, J. C. Carey, M. B. Machmuller, B. L. Snoek, S. Fang, G. Zhou, S. D. Alison, J. M. Blair, S. D. Bridgham, A. J. Barton, Y. Carrillo, P. B. Reich, J. S. Clark, A. T. Classen, F. A. Dijkstra, B. Elberling, B. A. Emmett, M. Estiarte, S. D. Frey, J. Guo, J. Harte and L. Jiang. 2016. Quantifying global soil carbon losses in response to warming. Nature 540, 104 – 108 (01 December 2016) doi: 10.1038.

Depietri, Y, F.G. Renaud, and G. Kallis. 2012. Heat waves and floods in urban areas: a policy-oriented review of ecosystem services. *Sustainable Science*, 7:95–107.

Fazio, J. R. 2010. How trees can retain stormwater runoff. *Tree City USA Bulletin* No. 55. Nebraska City: Arbor Day Foundation. 8 pg. http://www.northlandnemo.org/images/800TreeCityUSABulletin_55.pdf (accessed December 8, 2016).

Gálos, B., C. Mátyás, D. Jacob. 2011. Regional characteristics of climate change altering effects of afforestation. *Environment Research Letters*, 6 044010 (9pp).

Garman, D., K. Emanuel, and B. Phillips. 2014. Breaking the climate deadlock. *Issues in Science and Technology,* Summer.

Gifffen et al. 2013. A Distillation of the Many Ways that Forests Influence Climate - Far More than Carbon Sequestration. Unpublished paper available on request.

Giffen, R. A. 2015. Testing the role of alternative forest management and wood use regimes could play in mitigating climate change: A study of the issues in the Acadian Forest Region. Unpub. 28 pp.

Girvetz, E. and C. Zganjar. 2014. Dissecting indices of aridity for assessing the impacts of global climate change. Climatic Change, 126, 469–483, doi:10.1007/s10584-014-1218-9.

Gunderson, L. H. 2000. Ecological Resilience—In Theory and Application. Annual Review of Ecology and Systematics Vol.31:1-595 (Volume publication date November 2000) DOI: 10.1146/annurev.ecolsys.31.1.425

Horton, R., and G. Yohe. 2014. Northeast region. In: U.S. Global Research Program. 2014. 2014 National Climate Assessment. http://nca2014.globalchange.gov/report/regions/northeast (accessed July 15, 2014).

Huntington, T.G. 2003. Climate warming could reduce runoff significantly in New England, USA. *Agricultural and Forest Meteorology*, 117:193-201.

IPCC, 2007a: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC. 2007b. Intergovernmental Panel on Climate Change, Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the IPCC, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (Cambridge, UK: Cambridge University Press, 2007)

IPCC. 2014. Chapter 5. Drivers, trends and mitigation. In: Climate Change 2014: Mitigation of climate change. http://www.ipcc.ch/report/ar5/wg3/ (accessed July 15, 2014).

IPCC. 2014a. Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jaganmohan, M., S. Knapp, C.M. Buchmann, and N. Schwarz. 2016. The bigger, the better? The influence of urban green space design on cooling effects for residential areas. J. Environ. Qual. 45:134–145. doi:10.2134/ jeq2015.01.0062

Kurtén, T., Kulmala, M., Dal Maso, M., Suni, T., Reissell, A., Vehkamäki, H., Hari, P., Laaksonen, A., Viisanen, Y. & Vesala, T. 2003: Estimation of different forest-related contributions to the radiative balance using observations in southern Finland. Boreal Env. Res. 8: 275–285.

Lenton, T., H. Held, E. Kriegler, J. Hall, W. Lucht, S. Rahmstorf and H. J. Schellnhuber. (2007). Tipping elements in the Earth's climate system. Proceedings of the National Academy of Sciences of the United States of America. Vol. 105 no. 6 1786-1793, doi: 10.1073/pnas.0705414105.

Lowenstein, F., and E. Girvetz. 2014. Conservation practices – challenges and opportunities in the face of climate change. Handbook of Global Environmental Pollution. Global Environmental Change. Springer.

Liveslely, S. J., E. G. McPherson, and C. Calfapeltra. (2016). The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat and Pollution Cycles at the Tree, Street and City Scale. J. of Environ. Qual. 45:119-124. doi: 10.2134.

Matthews, R., N. Mortimer, E. Mackie, C. Hatto, A Evans, O. Mwabonje, T. Randle, W. Rolls, M. Sayce, and I. Tubby. 2014. Carbon impacts of using biomass in bioenergy and other sectors: forests. DECC project TRN 242/08/2011 Final report: Parts a and b. Available online atwww.gov.uk/government/uploads/system/uploads/attachment_data/file/282812/DECC_carbon_impacts_final_report30th_January_2014.pdf (accessed February 6, 2015).

McAlpine, C.A., J.G. Ryan, L. Seabrook, S. Thomas, P.J. Dargusch, J.I. Syktus, R.A. Pielke Sr, A.E. Etter, P.M. Fearnside, and W.F. Laurance. 2010. More than CO_2: a broader paradigm for managing climate change and variability to avoid ecosystem collapse. *Current Opinion in Environmental Sustainability*, 2(5–6):334-346.

McMichael, A.J., R E. Woodruff, and S. Hales. 2006. Climate change and human health: Present and future risks. *Lancet*, 367:859–69. www.cyprus-institute.ecoethics.net/PDF/2006-MacMichael-Climate-Human-Health.pdf (Accessed March 31, 2014).

McNeil, B. I., and R. J. Matear. 2008. Southern Ocean acidification: A tipping point at 450-ppm atmospheric CO2. PNAS, 105 (48): 18860-18864.

Melillo, J.M., T.C. Richmond, and G.W. Yohe (eds). 2014: Climate change impacts in the United States: The Third Melillo et al. US Global Change Research Program, 841 pp.

Micales, J. A. and K. E. Skog. (1996). The placement of forest products in landfills serves as a significant carbon sink and its importance in global carbon balance should not be overlooked. International Biodeterioration & Biodegradation Vol. 39, No. 2–3 (1997) 145–158

Nabuurs, G.J., O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, O. Krankina, W.A. Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.J. Sanz Sanchez, X. Zhang, 2007: Forestry. *In* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York: Cambridge University Press.

National Research Council, 2005: Radiative forcing of climate change: Expanding the concept and addressing uncertainties. Committee on Radiative Forcing Effects on Climate Change, Climate Research Committee, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, The National Academies Press, Washington, D.C., 208 pp.

Ollinger, S. V., et al. (2008). Potential effects of climate change and rising CO2 on ecosystem processes in northeastern U.S. forests. Mitig. Adapt. Strategies Global Change, doi:10.1007/s11027-007-9128-z.

Prasad, A.M., and L.R. Iverson. 1999-ongoing. A climate change atlas for 80 forest tree species of the Eastern United States (database). Delaware, OH: USDA Forest Service, Northeastern Research Station.

Robertson, G. P., E. A. Paul, and R. R. Harwood. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. Science, 289(5486):1922-1925.

Rosenzweig, C., W. Solecki, and R. Slosberg. 2006. Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces. Albany, NY: New York State Energy Research and Development Authority. Report 06-06. Running, S.W. 2008. Ecosystem disturbance, carbon and climate. *Science* 321:652-653.

Ruddiman, W.F. 2003. The anthropogenic greenhouse era began thousands of years ago. *Climate Change,* 61:261-193.

Ruddiman, W.F. 2005. How did humans first alter global climate? *Scientific American,* 292(3):46-53.

Ruddiman, W.F. 2013. Earth transformed. W. H. Freeman & Co. 400 pp.

Sugawara, H., S. Shimizu, H. Takahashi, S. Hagiwara, K. Narita, T. Mikami, and

T. Hirano. 2016. Thermal influence of a large green space on a hot urban environment. J. Environ. Qual. 45:125–133. doi:10.2134/jeq2015.01.0049

Seneviratne, S.I., M.G. Donat, B. Mueller, and L.V. Alexander. 2014. No pause in the increase of hot temperature extremes. *Nature Climate Change*, 4:161-163. www.nature.com/nclimate/journal/v4/n3/fig_tab/nclimate2145_F2.html (accessed May 31, 2014)

Shuman, J.K., H.H. Shugart and T.L. O'Halloran. 2011. Sensitivity of Siberian larch forests to climate change *Global Change Biology* (Accepted Article) doi 10.1111/j.1365-2486.2011.02417.x

Sujay, S. S., G. E. Likens, N. A/. Jaworski, M. L. Pace, A. M. Sides, D/ Seekell, K. T. Belt, D. H. Secor and R. L. Wingate. (2010). Rising Stream and River Temperatures in the United States. Front. Ecol. Environ. 2010; 8(9): 461–466, doi:10.1890/090037.

Tang, G., and B. Beckage. 2010. Projecting the distribution of forests in New England in response to climate change. *Diversity and Distributions*, 16:144-158.

USDA, Forest Service, Carbon Storage and Accumulation in United States Forest Ecosystems, August, 1992

U.S. EPA. 2016. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014. Washington, DC: U.S. Environmental Protection Agency. EPA #430-R-16-002. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2014 (accessed April 21, 2017).

Vogel, R.M., C.J. Bell, and N.M. Fennessey. 1997. Climate, streamflow and water supply in the northeastern United States. *Journal of Hydrology*, 198:42-68.

Zhang, P., M.L. Imhoff, L. Bounoua, and R.E. Wolfe. 2012. Exploring the influence of impervious surface density and shape on urban heat islands in the northeast United States using MODIS and Landsat. *Canadian Journal of Remote Sensing*, 38(4):441-451.

Zhao, K., and R.B. Jackson. 2013. Biophysical forcings of land-use changes from potential forestry activities in North America. *Ecological Monographs,* 84(2):329-353.

L. References that Informed the Writing of this Report

Abrahamson, L. P., T. A. Volk, R. F. Kopp, E. H. White, and J. L. Ballard. 2002. Willow bioenergy producer's handbook (revised). Syracuse, NY: State University of New York College of Environmental Science and Forestry.

Abt, R. C., C. S. Galik, and J. D. Henderson. 2010. The near-term market and greenhouse gas implications of forest biomass utilization in the southeastern United States. Duke University.

Akbari, H. 2002. Shade trees reduce building energy use and CO2 emissions from power plants. Environmental Pollution 116: S11-S126.

Akbari, H., and S. Konopacki. 2003. Energy effects of heat-island reduction strategies in Toronto, Canada. Energy, 29: 191-210.

Akbari, H., S. Menon, and A. Rosenfeld. 2009. Global cooling: increasing world-wide urban albedos to offset CO2. Climatic Change, 94: 275-286.

Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen, and N. Meinshausen. 2009a. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature, 458. 1163-1166.

Allen, M., D. Frame, K. Frieler, W. Hare, C. Huntingford, C. Jones, R. Knutti, J. Lowe, M. Meinshausen, N. Meinshausen, and S. Raper. 2009b. The exit strategy. Nature Reports Climate Change, vol. 3.

Anderson, B.T., Hayhoe, K. & Liang, XZ. 2010. Anthropogenic-induced changes in twenty-first century summertime hydroclimatology of the Northeastern US. Climatic Change 99: 403. doi:10.1007/s10584-009-9674-3

Anderson, K., and A. Bows. 2008. Reframing the climate change challenge in light of post-2000 emission trends. Philosophical Transactions of the Royal Society 368: 3863-3882.

Anon. 2010. Comparison of IFPRI/EPA-CARD/CARB biofuel policy analyses. Review of IFPRI EC Report, Agricultural Conservation Economics, Final August 16.

Anon. 2010. Facing the consequences: Global action is not going to stop climate change. The world needs to look harder at how to live with it. The Economist. November 25. http://www.economist.com/node/17572735 (accessed June 1, 2011).

Anon. 2010. Global warming: "Cooling" forests can heat too. ScienceDaily, January 25.

Anon. 2011. A bi-national forest carbon offset standard: Report on development process. DRAFT Report on the NAFCS. January 29.

Anon. 2011. Study finds wood pellet biomass increases greenhouse gases. ClickGreen. March 25.

Anon. N.d. Cool roof. Wikipedia. (Accessed 8/21/11).

Anon. N.d. Forest biomass and air emissions. Face Sheet. Washington State: Department of Natural Resources.

Anon. N.d. Trees and your environment. Website: Clean Air Gardening, Gardening tips. (Accessed 08/20/11).

Anon. N.d. Urban forest. Wikipedia. (Accessed 8/21/11).

Apps, M., T. Karajalainen, G. Marland, and B. Schlamadinger. 1997. Accounting System Considerations: CO2 Emissions from Forests, Forest Products, and Land-Use Change—A Statement from Edmonton. Paris, France: International Energy Agency, Office of Energy Technology, Efficiency and R&D.

Atlantic Consulting. 2009. LPG's carbon footprint relative to other fuels: A scientific review. Switzerland

Baker, D. S. 2011. Woody biomass facts: A look at the myths regarding a sustainable Energy Source. Forest Business Network online. See link (accessed 08/21/11).

Bala, G., K. Caldeira, M. Wickett, T. J. Phillips, D. Lobell, C. Delire, and A. Mirin. 2007. Combined climate and carbon cycle effects of global deforestation, Proceedings of the National Academy of Sciences, 104(16):6550-6555.

Barford, C. C., S. C. Wofsy, M. L. Goulden, J. W. Munger, E. H. Pyle, S. P. Urbanski, L. Hutyra, S. R. Saleska, D. Fitzjarrald and K. Moore. 2001. Factors controlling long-and short-term sequestration of atmospheric CO2 in a mid-latitude forest. Science, 294:1688-1981.

Barth, M., J. McFadden, J. Sun, C. Wiedinmyer, P. Chuang, D. Collins, R. Griffin, M. Hannigan, T. Karl, S.-W. Kim, S. Lasher-Trapp, S. Levis, M. Litvak, N. Mahowald, K. Moore, S. Nandi, E. Nemitz, A. Nenes, M. Potosnak, T. Raymond, J. Smith, C. Still, and C. Stroud. 2005. Coupling between land ecosystems and the atmospheric hydrologic cycle through biogenic aerosol pathways. American Meteorological Society, 86(12):1738-1742.

Bergman, R., M. Peuttmann, and A. Taylor. N.d. Carbon impacts of wood products. Center for Renewable Carbon, University of Tennessee.

Berlik, M. M., D. B. Kittredge* and D. R. Foster. 2002. The illusion of preservation: a global environmental argument for the local production of natural resources. Journal of Biogeography, 29:1557-1568.

Berry, J.E., M.R. Holland, P.R. Watkiss, R. Boyd, et al. 1998. Power Generation and the Environment—A U.K. Perspective. Abingdon, Oxfordshire: AEA Technology.

Biofuelwatch.org. 2011. A critical review of biochar science and policy. Executive Summary. http://www.biofuelwatch.org.uk/2011/a-critical-review-of-biochar-science-and-policy/ (Accessed 02/01/12).

Biomass Energy Resource Center. 2012. Biomass supply and carbon accounting for southeastern forests. 123 pp + app.

Birdsey, R.A., K. Pregitzer, and A. Lucier. 2006. Forest carbon management in the United States: 1600-2100. Journal of Environmental Quality 35:1461-1469.

Bond-Lamberty, B., and A. Thomson. 2010. Temperature-associated increases in the global soil respiration record. Nature, 464: 579-583

Boyle, J.F., M-J. Gaillard, J.O. Kaplan, and J.A. Darling. 2011. Modelling prehistoric land use and carbon budgets: A critical review. *The Holocene*, 21(5):715-722.

Bracmort, K. 2011. Is biopower carbon neutral? CRS Report for Congress, R41603.

Breakthrough Institute. 2011. How efficiency can increase energy consumption. Blog on website (accessed 08/22/11).

Brick, S. 2011. Harnessing the power of biomass residuals: Opportunities and challenges for midwestern renewable energy. Chicago, IL: Chicago Council on Global Affairs.

Buck, M. 2010. Edited summary of the Cancun Climate Change Conference: November 29-December 11, 2010. Summary for the National Association of State Foresters.

Caldeira, K., S. Gibbard, G. Bala, M. E. Wickett, and T. J. Phillips. 2005. Will growing forest make the global warming problem better or worse? Presentation to AGU Fall Meeting, Dec. 7.

California Air Resources Board. 2005. Review of the California ambient air quality standard for ozone. Staff Report. March 11.

California Climate Action Registry. 2008. Urban forest project reporting protocol: Version 1.0. For Board Approval, August 12.

CarbonFix. 2010. Climate forestation projects, version 3.1. http://www.carbonfix.info/chameleon//outbox//public/209/CarbonFix-Standard-v31.pdf

CATF. Letter to Administration Jackson December 1, 2010.

CATF. 2010. Discussion points for BACT GHG meeting with EPA. December 21.

CDIAC. 2011. Trace Gas Emissions. Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center. Retrieved August 1, 2011 from http://cdiac.ornl.gov/by_new/bysubjec.html#trace.

Center for the Study of Carbon Dioxide and Global Change. 2012. Old growth forests of northeast China. http://www.co2science.org/articles/V14/N47/B2.php (accessed 02/01/12).

Charlson, R. J., S. E. Schwartz, J. M. Hales, R. D. Cess, J. A. Coakley,Jr., J. E. Hansen, and D. J. Hoffman. 2002. Climate forcing by anthropogenic aerosols. Science, New Series, 2555(5043):423-430.

Cherubini, F., R.M. Bright, and A. Stromman. 2012a. Site-specific global warming potentials of biogenic CO2 for bioenergy: contributions from carbon fluxes and albedo dynamics. *Environ. Res. Lett.* 7:045902.

Cherubini, F., G. Gues, and A. H. Stromman. 2012b. Application of probability distributions to the modeling of biogenic CO2 fluxes in life cycle assessment. GCB Bioenergy, DOI: 10.1111/j.1757-1707.2011.01156.x

Cherubini, F., G. Peters, T. Berntsen, A. Stromman, and E. Hertwich. 2011. CO2 emissions from biomass combustion for bioenergy: Atmospheric decay and contribution to global warming. GCB Bioenergy (2011), doi: 10.1111/j.1757-1707.2011.01102.x

Ciais, P., M. J. Schelhaas, S. Zaehle, S. L. Piao, A. Cescatti, J. Liski, S. Luyssaert, G. Le-Maire, E.-D. Schulze, O. Bouriad, A. Freibauer, R. Valentini, and G. J. Nabuurs. 2008. Carbon accumulation in European forests. Nat. Geosci. 1, 1.

Clean Air Counts. 2001. Final parkinglot shading, Chicago. See link (Accessed 08/20/11).

Clean Air Task Force, Conservation Law Foundation, Natural Resources Council of Maine, Natural Resources Defense Council, Sierra Club, Southern Environmental Law Center. 2010. Comments on the Environmental Protection Agency's call for information on greenhouse gas emissions associated with bioenergy and other biogenic sources. 75 Fed. Reg. 41,173 (July 15, 2010), EPA-HW-OAR-2010-0560.

Conn, R., and D. Tillman. 2000. Analysis of willow for use as a biomass energy source. Topical Report prepared by the Foster Wheeler Development Corporation.

Cotana, F., F. Rossi, and A. L. Pisello. N.d. Solar radiation management for global warming mitigation. University of Perugia, Italy: CIRIAF, Interuniversity Research Center on Pollution from Physical Agents.

Cover email from Al Steele on Tailoring Rule

Davidson, E. A., M. Keller, H. E. Erickson, L. V. Verchot, and E. Veldkamp. 2000. Testing a conceptual model of soil emissions of nitrous and nitric oxides. BioScience, 50(8):667-680.

Crucifix, M., M-F. Loutre, and A. Berger. 2005. Commentary on "The Antrhopogenic Greenhouse Era Began Thousands of Years Ago." *Climate Change*, 69:419-426.

Davis, S. J., K. Caldeira, and H. D. Matthews. 2010. Future CO2 emissions and climate change from existing energy infrastructure. Science, 329: 1330-1333.

De la Cruz, F.B., and M.A. Barlaz. 2010. Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. Environmental Science & Technology 44 (12):4722-4728.

Delucchi, M. 2011. Beyond life-cycle analysis: Developing a better tool for simulating policy impacts. Ch. 13 in: Ogden, J. and L. Anderson (eds). 2011. Sustainable transportation energy pathways: A research summary for decision makers. Davis, CA: Institute of Transportation Studies, Univ. of Cal-Davis.

Delucchi, M. A. 2006. Lifecycle analyses of biofuels. DRAFT. Davis, CA: Institute of Transportation Studies. 78 pp.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, et al. 2007. Couplings Between Changes in the Climate System and Biogeochemistry. In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller. Cambridge, UK, and New York, NY: Cambridge University Press.

Deru, M., and P. Torcellini. 2007. Source energy and emission factors for energy use in buildings. Golden, CO: National Renewable Energy Laboratory, Tech. Rept. NREL/TP-550-38617.

Dickens, D. 2001. Intensive pine management. University of Georgia: Master Tree Farmer. Various papers.

Dickens, D. 2001. Intensive pine management. University of Georgia: Master Tree Farmer. Various papers.

Diochon, A., L. Kellman, and H. Beltrami. 2009. Looking deeper: An investigation of soil carbon losses following harvesting from a managed northeastern red spruce (picfea rubens Sarg.) forest chronosequence. Forest Ecology and Management, 257:413-420.

Duffy, P. B., R. A. Houghton, and W. Moomaw. 2016. Forest bioenergy worsens climate change. Policy Brief, April. Falmouth, MA: Woods Hole Research Center. 2 p

Doughty, C.E. 2013. Preindustrial human impacts on global and regional environment. *Annu. Rev. Environ. Resour.*, 38:503-27.

Dwivedi, P, R. Bailis R, D. R. Carter, and A. Sharma. 2011. A landscape-based approach for assessing spatiotemporal impacts of forest biomass-based electricity generation on the age structure of surrounding forest plantations in the Southern United States. GCB Bioenergy Glob. Change Biol. Bioenergy.

Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, D. Arvizu, T. Bruckner, J. Christensen, J.-M. Devernay, A. Faaij, M. Fischedick, B. Goldstein, G. Hansen, J. Huckerby, A. Jäger-Waldau, S. Kadner, D. Kammen, V. Krey, A. Kumar, A. Lewis, O. Lucon, P. Matschoss, L. Maurice, C. Mitchell, W. Moomaw, J. Moreira, A. Nadai, L.J. Nilsson, J. Nyboer, A. Rahman, J. Sathaye, J. Sawin, R. Schaeffer, T. Schei, S. Schlömer, R. Sims, A. Verbruggen, C. von Stechow, K. Urama, R. Wiser, F. Yamba, T. Zwickel. 2011. Summary for policy makers. In: Edenhofer, O. R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. v. Stechow (eds). IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge: Cambridge University Press.

Edwards, L. n.d. "Tipping Point" keyword search in Larry's climate library.

Edwards, L. n.d. 4 degrees and beyond conference - partial bibliography (Edwards). Implications of a global climate change of 4+ degrees for people, ecosystems and the earth-system. International Climate Conference 28-30 September 2009, Oxford, UK.

Ehrhardt-Martinez, K., and J. A. Laitner. 2010. Rebound, technology and people: Mitigating the rebound effect with energy-resource management and people-centered initiatives. ACEEE Summer Study on Energy Efficiency in Buildings, 7:76-91.

Eisentraut, A. 2010. Sustainable production of second-generation biofuels: Potential and perspectives in major economies and developing countries. Paris, France: International Energy Agency. 221 pp.

Elsayed, M. A., R. Matthews, and N. D. Mortimer. 2003. Carbon and energy balances for a range of biofuels options. Sheffield Hallam University Project # B/B6/00784/REP URN 03/836.

Elvingson, P., and C. Ågren. 2004. Ground-level ozone. Chapter 7. In: Air and the Environment. See: http://www.airclim.org/airAndEnvironment/AE_foreword.htm.

Email fr J. Feddema re Effect of land cover changes on global warming. March 14, 2012.

Email fr J. Lewis forwarding T. Searchinger thoughts on timing. March 20, 2012.

Emission factors & AP 42, Compilation of air pollutant emission factors. AP 42, Fifth Edition. US EPA, Technology Transfer Network.

Environment Northeast. 2010. Forest future: The role forests can play in addressing climate and promoting sustainable economies. Rockport, ME: Environment Northeast. 22 pp.

EPA flags uncertainties in draft study of biofuels' environmental impacts. February 3, 2011. News article.

EUROPA. 2010. Results of the emission inventory EDGAR v4.1 of July 2010. http://edgar.jrc.ec.europa.eu/background.php (accessed 04/20/12).

Evans, A. M. 2008. Synthesis of knowledge from woody biomass removal case studies. Forest guild.

Evans, A. M. and M. J. Ducey. 2010. Carbon accounting and management of lying dead wood.

Extance, A. 2011. Climate benefit from trees depends on location. https://simpleclimate.wordpress.com/2011/11/19/climate-benefit-from-trees-depends-on-location/ (accessed 02/01/12).

Fact sheet for PEW Environmental Group: Biomass generation. December 2010. 3 pp.

"Fahey, T. J., P. B. Woodbury, J. J. Battles, C. L. Goodale, S. P. Hamburg, S. V. Ollinger, and C W. Woodall. 2009. Forest carbon storage: ecology, management, and policy. Frontiers in Ecology and the Environment 8: 245–252. doi:http://dx.doi.org/10.1890/080169.

Fargione, J., Hill, J., Tilman, D., Polasky, S. & Hawthorne, P. 2008. Land clearing and the biofuel carbon debt. Science 319, 1235 1238.

Feddema, J. J., K. W. Oleson, G. B. Bonan, L. O. Mearns, L. W. Buja, G. A. Meehl, and W. M. Washington. 2005. The importance of land-cover change in simulating future climates. Science, 310:1674–78.

Fedorov A.V., P.S. Dekens, M. McCarthy, A.C. Ravelo, P.B. deMenocal, M. Barreiro, R.C. Pacanowski, and S.G. Philander. 2006. The Pliocene paradox: Mechanisms for a permanent El Niño. Science 312(5779):1485-1489.

Fehrs, J. E. 1999. Secondary mill residues and urban wood waste quantities in the United States. Washington, DC: Northeast Regional Biomass Program.

Foley, J. A., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, N. D. Mueller, C. O'Connell, D. K. Ray, P. C. West, C. Balzer, E. M. Bennett, S. R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockstrom, J. Sheehan, S. Siebert, D. Tilman, and D. P. M. Zaks. 2011. Solutions for a cultivated planet, Nature, 478(7369):337-342.

Forest carbon accounting in products -- A proposed methodology. 3rd Draft, December. (w/cover email from Chaisson, Clean Air Task Force).

Forestry Commission England. N.d. A wood fuel strategy for England. Www.forestry.gov.uk/england.

Foster, D. R., and D. A. Orwig. 2006. Preemptive and salvage harvesting of New England forests: When doing nothing is a viable alternative. Conservation Biology, 20(4): 959-970.

Gaffin, S., C. Rosenzweig, L. Parshall, D. Beattie, R. Berghage, G. O'Keefe, and D. Braman. 2005. Energy balance modeling applied to a comparison of white and green roof cooling efficiency. In: Third Annual Greening Rooftops for Sustainable Communities Conference, Awards, and Trade Show, Washington, D.C.

Galik, C. S., and R. C. Abt. 2012. The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass. Nicholas Institute for Environmental Policy Solutions, Working Paper NI WP 12-02.

Galloway, J. N. 1998. The global nitrogen cycle: Changes and consequences. Environmental Pollution, 102, S1:15–24.

Galloway, J. N., J. D. Aber, J. W. Erisman, S. P. Seitzinger, R. W. Howarth, E. B. Cowling, and B. J. Cosby. 2003. The nitrogen cascade. BioScience 53:341–56.

Galveston-Houston Association for Smog Prevention. 1999. Trees and our air: The role of trees and other vegetation in Houston-Area air pollution. See link (accessed 08/21/11)

Geiger, J.R. 2006. Trees - The Air Pollution Solution. USDA Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research.

Gibbard, S., K. Caldeira, G. Bala, T. J. Phillips, and M. Wickett. 2005. Climate effects of global land cover change. Geophysical Research Letters, 32, L23705.

Gill, S. E., J. F. Handley, A. R. Ennos, and S. Pauleit. 2007. Adapting cities for climate change: The role of the green infrastructure. Built Environment, 33(1): 115-133.

Gillett, N. P., V. K. Arora, K. Zickfield, S. J. Marshall, and W. J. Merryfield. 2011. Ongoing climate change following a complete cessation of carbon dioxide emissions. Nature Geoscience, 4: 83-87.

Gillis, J. 2011. 2010 carbon dioxide output shows biggest jump ever. http://www.nytimes.com/2011/12/05/science/earth/record-jump-in-emissions-in-2010-study-finds.html?_r=2 (accessed 01/27/12).

Girvetz and Zganjar. 2014. Dissecting indices of aridity for assessing the impacts of global climate change. Climatic Change (2014) 126:469–483 DOI 10.1007/s10584-014-1218-9.

Goodale, C. L., K. Lajtha, K. J. Nadelhoffer, E. W. Boyer, and N. A. Jaworski. 2002. Forest nitrogen sinks in large eastern U.S. watersheds: Estimates from forest inventory and an ecosystem model. Biogeochemistry, 57/58:239-266.

Gower, S.T., A. McKeon-Ruediger, A. Reitter, M. Bradley, D.J. Refkin, T. Rollefson, F.J. Souba Jr., A. Taup, L. Embury-Williams, S. Schavone, J. Weinbauer, A.C. Janetos and R. Jarvis. 2006. Following the paper trail: The impact of magazine and dimensional lumber production on greenhouse gas emissions: A case study.

Grahan, R. T., A. E. Harvey, T. B. Jain, and J. R. Tonn. 1999. The effects of thinning and similar stand treatments on fire behavior in Western forests. Portland, OR: USDA Forest Service, Pacific Northwest Research Station, Gen. Tech. Rep. PNW-GTR-463. 27 pp.

Grant FNE09-673 The effect of biochar applications on soil fertility and crop production on a small vegetable farm in the Northeast US.

Grimmond, S. 2007. Urbanization and global environmental change: local effects of urban warming. Royal Geographical Society, Cities and Global Environmental Change, 83-88.

Harmon, M. E., Ferrell, W. K. & Franklin, J. F. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247, 699 702.

Head, H. 2008. Net energy study: summary. Presented at the PFI Annual Conference, July.

Heimlich. R. E. 2010. Resources for cellulosic ethanol production in the United States: A review.

Heller, M.C., G.A. Keoleian, and T.A. Volk. 2003. Life cycle assessment of a willow bioenergy cropping system. Biomass and Bioenergy 25 (2):147-165.

Heller, M.C., G.A. Keoleian, M.K. Mann, and T.A. Volk. 2004. Life cycle energy and environmental benefits of generating electricity from willow biomass. Renewable Energy 29 (7):1023-1042.

Hoffert, M. L. 2010. Farewell to fossil fuels? Science, 329: 1292-1294.

Hong, B. D., and E. R. Slatick. 1994. Carbon dioxide emission factors for coal. Energy Information Administration, Quarterly Coal Report. DOE/EIA-0121(94Q1), pp. 1-8.

Hoover, C., and S. Stout. 2007. The carbon consequences of thinning techniques: stand structure makes a difference. Journal of Forestry 105, 266-270.

Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds). 1996. Climate change 1995: The science of climate change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: University Press.

Howarth, R. W., R. Santoro, and A. Ingraffea. 2010. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change, 2011; DOI: 10.1007/s10584-011-0061-5.

Hudiburg, T.W., B.E. Law, C. Wirth, S. Luyssaert. 2011. Regional carbon dioxide implications of forest bioenergy production. Nature Climate Change 1(7), 23-Oct-2011. doi: 10.1038/nclimate1264.

Hunsberger, R. 2008. Biomass heating roundtable system components. See p. 41 for Emissions comparison slide.

Hurteau, M. D. & North, M. 2010. Carbon recovery rates following different wildfire risk mitigation treatments. Forest Ecol. Manag. 260, 930 937.

Ingerson, A. 2011. Carbon storage potential of harvested wood: summary and policy implications. Mitig. Adapt. Strateg. Glob. Change, 16:307-323.

Intergovernmental Panel on Climate Change. 2001. Climate change 2001: Summary for policy makers. http://www.grida.no/climate/ipcc_tar/vol4/english/pdf/spm.pdf. (accessed 04/20/12).

Introduction to iCans for Educators. Website (accessed 8/21/11).

IPCC. 1996. Climate Change 1995, The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), UNEP and WMO (World Meteorological Organization, Cambridge University Press,

IPCC. 2006a. Volume 2: Energy. In 2006 IPCC Guidelines for National Greenhouse Gas Inventories, edited by L. B. H.S. Eggleston, K. Miwa, T. Ngara and K. Tanabe. Kanagawa, Japan: National Greenhouse Gas Inventory Programme, Intergovernmental Panel on Climate Change, IGES.

IPCC. 2006b. Volume 4: Agriculture, Forestry and Other Land Use. In 2006 IPCC Guidelines for National Greenhouse Gas Inventories, edited by L. B. H.S. Eggleston, K. Miwa, T. Ngara and K. Tanabe. Kanagawa, Japan: National Greenhouse Gas Inventory Programme, Intergovernmental Panel on Climate Change, IGES.

IPCC. 2006c. Volume 5: Waste. In 2006 IPCC Guidelines for National Greenhouse Gas Inventories, edited by L. B. H.S. Eggleston, K. Miwa, T. Ngara and K. Tanabe. Kanagawa, Japan: National Greenhouse Gas Inventory Programme, Intergovernmental Panel on Climate Change, IGES.

IPCC. 2011. FAQs—Frequently Asked Questions. Intergovernmental Panel on Climate Change.

Jacobson, M. Z., and M. A. Delucchi. 2009. A plan to power 100 percent of the planet with renewables. Scientific American. http://www.scientificamerican.com/article.cfm?id=a-path-to-sustainable-energy-by-2030 (accessed 03/31/12).

Jansson, C., S.D. Wullschleger, U. C. Kalluri, and G. A. Tuskan. 2010. Phytosequestration: Carbon biosequestration by plants and the prospects of genetic engineering. BioScience, 60(9): 685-696.

Jenkins, J., T. Nordhaus, and M. Shellenberger. 2011. Energy emergence: Rebound & backfire as emergent phenomena. Breakthrough.

Jenkins, J., T. Nordhaus, and M. Shellenberger. 2011. Energy emergence: Rebound & backfire as emergent phenomena. Breakthrough. (Powerpoint).

Jenkinson, D. W. 2001. The impact of humans on the nitrogen cycle, with focus on temperate arable agriculture. Plant and Soil, 228:3–15.

Jones, G., D. Loeffler, D. Clkin, and W. Chung. 2010. Forest treatment residues for thermal energy compared with disposal by onsite burning: Emissions and Energy return. Biomass and Bioenergy, 34:737-746.

Josep G. Canadell, J. G., C. Le Que´ re´ , M. R. Raupach, C. B. Field, E. T. Buitenhuis, P. Ciais, T. J. Conway, N. P. Gillett, R. A. Houghton, and G. Marland. 2007. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. PNAS, 104(47): 18866-18870.

Keoleian, G., and T. Volk. 2005. Renewable energy from willow biomass crops: life cycle energy, environmental and economic performance. Critical Reviews in Plant Sciences 24 (5-6):385-406.

Kesselmeier, J., and M. Staudt. 1999. Biogenic volatile organic compounds (VOC): An overview on emission, physiology and ecology. Journal of Atmospheric Chemistry, 33:23-88.

Kopp, R. E., R. Shwom, G. Wagner and J. Yuan. 2016. Tipping elements and climate-economic shocks: Pathways toward integrated assessment. Earth's Future DOI: 10.1002/2016EF000326.

Kuhns, M. 2008. Landscape trees and global warming. Utah State University Forestry Extension, Home Farm and Community Trees. See link (accessed link 8/21/11).

Kulkarni, M. 2010. Annotated Bibliography of papers relevant to the climate effects of using wood for fuel. Clean Air Task Force. 10 pp.

Kulkarni, M. 2011. Methane and nitrogen emissions from forest soils. Notes.

Kulkarni, M. V., P. M. Grofman, and J. B. Yavitt. 2008. Solving the global nitrogen problem: It's a gas! Frontiers in Ecology and the Environment, 6(4):199-206.

Law, B. E. and M. E. Harmon. 2011. Forest sector carbon management, measurement and verification, and discussion of policy related to climate change. Carbon Management, 2(1): 73-84.

Lee, X., M. L. Goulden, D. Y. Hollinger, A. Barr, T. A. Black, G. Bohrer, R. Bracho, B. Drake, A. Goldstein, L. Gu, G. Katul, T. Kolb, B. E. Law, H. Margolis, T. Meyers, R. Monson, W. Munger, R. Oren, K. T. Paw U, A. D. Richardson, H. P. Schmid, R. Staebler, S. Wofsy, and L. Zhao. 2011. Observed increase in local cooling effect of deforestation at higher latitudes. Nature, 479(7373):384-387.

Letter from Western Governors' Association to Carol Browner, Climate Change and Energy Advisor to the President, August 10, 2010.

Letter from Gina McCarthy to Martella, et al. re petition to EPA.

Letter from Lisa Jackson to Honorable Stabenow re letter on CO2 emissions.

Letter to Washington State Legislature, February 2, 2011.

Lewis, S. L., G. Lopez-Gonzalex, B. Sonke, K. Affum-Baffo, T. R. Baker. 2009. `. Nature 457, 1003-1006.

Lippke, B., E. Oneil, R. Harrison, K. Skog, L. Gustavsson, and R. Sathre. 2011. Life cycle impacts of forest management and wood utilization on carbon mitigation: Knowns and unknowns. Carbon Management, 2(3): 303-333.

Lippke, pers.comm.

Lobell, D. B., G. Bala, and P. B. Duffy. 2006. Biogeophysical impacts of cropland management changes on climate. Geophysical Research Letters 33:L06708.

Lustgarten, A. 2011. Climate benefits of natural gas may be overstated. http://www.propublica.org/article/natural-gas-and-coal-pollution-gap-in-doubt (Accessed June 1, 2011.

Luyssaert, S., E.D. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B. E. Law, P. Ciais, and J. Grace. 2008. Old-growth forests as global carbon sinks. Nature, 455:213-215.

Malmsheimer, R. W., J. L. Bowyer, J. S. Fried, E. Gee, R. L. Izlar, R. A. Miner, Munn, E. Oneil, and W. C. Stewart. 2011. Managing Forests because Carbon Matters: Integrating Energy, Products, and Land Management Policy. Journal of Forestry, 109(7S).

Mann, M.K., and P.L. Spath. 1997. Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System. Golden, CO: National Renewable Energy Laboratory. NREL/TP--430-23076.

Marland G., R. A. Pielke, Sr., M. Apps, R. Avissar, R. A. Betts, K. J. Davis, P. C. Frumhoff, S. T. Jackson, L. Joyce, P. Kauppi, J. Katzenberger, K. G. MacDicken, R. Neilson, J. O. Niles, D. D. S. Niyogi, R. J. Norby, N. Pena, N. Sampson, and Y. Xue. 2003. The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. Climate Policy, 3:149-157.

Maron, D. F. 2010. FORESTS: A man who doesn't want his work to go up in smoke. E&E.

Maron, D. F. 2010. Regulation: Western governors push exception for biomass burning. August 11.

Mason, C. L., R. Gustafson, J. Calhoun, B. R. Lippke, and N. Raffaeli. 2009. Wood to energy in Washington: Imperatives, opportunities, and obstacles to progress. Report to the Washington State Legislature. Seattle, WA: Univ. of Washington, College of Forest Resources.

Massachusetts Forest Watch. N.d. Wood-fueled biomass power plants and co2 emissions. See link: http://www.maforests.org/Chris-Matera-Biomass%20Carbon%20Emissions.pdf

McGuire, B., T. McCoy, J. Christie and Jon Kusler. ?. Reducing global warming and promoting fish and wildlife: Findings and recommendations for biologicl carbon storage and sequestering. Association of Fish & Wildlife Agencies and Association of State Wetland Managers. 14 pp.

McKechnie, J., S. Colombo, J. Cheng, W. Mabee, H. L. MacLean. 2011. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. Environmental Science & Technology. Accepted November 17, 2010.

McMahon, S. M., G. G. Parker, and D. R. Miller. 2010. Evidence for a recent increase in forest growth. Proceedings National Academy of Science, 107(8): 3611–3615.

McPherson, E. G., and R. A. Rowntree. 1993. Energy conservation potential of urban tree planting. Journal of Arboriculture, 19(6): 321-331.

McPherson, E. G., J. R. Simpson, P. J. Peper, and E. Aguaron. 2008. Urban forestry and climate change. Albany, CA: USDA Forest Service, Pacific Southwest Research Station.

Melville, K. 2002. Trees may contribute to ozone problem. http://www.scienceagogo.com/?s=Trees+may+contribute+to+ozone+problem&submit=Search. Accessed 3/2/17

Micales, J. A., and K. E. Skog. 1997. The decomposition of forest products in landfills. International Biodeterioration and Biodegradation, 39(2-3): 145-158.

Mikaloff Fletcher, S.E., P.P. Tans, L.M. Bruhwiler, J.B. Miller, et al. 2004b. CH4 sources estimated from atmospheric observations of CH4 and its 13C/12C isotopic ratios: 2. Inverse modeling of CH4 fluxes from geographical regions. Global Biogeochemical Cycles 18.

Milford, J. 2007. Atmospheric aerosols from biogenic hydrocarbon oxidation. Presentation to Atmospheric Science Progress Review Meeting, June 21-22.

Mitchell, S.R., M.E. Harmon, and K.E.B. O'Connell. 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecological Applications 19 (3):643-655.

Morris, G. 2008. Bioenergy and greenhouse gases. Prepared fro the U.S. Forest Service. Berkeley, CA: Pacific Institute. 50 pp.

Morrison, P. H., J. W. Karl, L. Swope, K. Harma, T. Allen, P. Becwar, and B. Sabold. 2000. Assessment of summer 2000 wildfires: Landscape history, current condition and ownership. Winthrop, WA: Pacific Biodiversity Institute. 75 pp.

Mosier, A. R., M. A. Bleken, P. Chaiwanakupt, E. C. Ellis, J. R. Freney, R. B. Howarth, P. A. Matson, K. Minami, R. Naylor, K. N. Weeks, and Z-L Zhu. 2002. Policy implications of human-accelerated nitrogen cycling. Biogeochemistry, 57/58:477–516.

Murray, B.C., B.A. McCarl, and H.-C. Lee. 2004. Estimating leakage from forest carbon sequestration programs. Land Economics 80 (1):109-124.

Muzika, R. M., and A. M. Liebhold. 2000. A critique of silvicultural approaches to managing defoliating insects in North America. Review Paper. Agricultural and Forest Entomology, 2:97-105.

Myhrvold, N. P., and K. Caldeira. 2012. Greenhouse gases, climate change and the transition from caol to low-carbon electricity. Environmental Research Letters, 7: 014019.

Naiman, R. J., P. A. Bisson, R. G. Lee, and M. G. Turner. 1997. Approaches to management at the watershed scale. Pages 239-253 In: Kohm, K. A. and J. F. Franklin (eds). Creating a Forestry for the 21st Century: the Science of Ecosystem Management. Washington, DC: Island Press.

Nasa. N.d. The role of O3 in climate forcing and feedback. http://tes.jpl.nasa.gov/mission/climateO3/ (accessed 02/01/12).

Nationalatlas.gov. 2011. Forest resources of United States. http://www.nationalatlas.gov/articles/biology/a_forest.html (accessed 04/20/12)

NaturalGas.org. See Link: http://www.naturalgas.org/

Nave, L. E., E. D. Vance, C. W. Swanston, and P. S. Curtis. 2009. Impacts of elevated N inputs on north temperate forest soil C storage, C/N, and net N-mineralization. Geoderma, 153: 231-240.

Nave, L. E., E. D. Vance, C. W. Swanston, and P. S. Curtis. 2010. Harvest impacts on soil carbon storage in temperate soils. Forest Ecology and Management, 259: 857-866.

Neurath, R., and A. Friedland. 2011. Carbon loss in mineral soil horizons: The effects of 120 years of forest harvesting in New England. Presentation to Woody Biomass Energy Research Symposium for the Northern Forest. April 28.

New England Biochar. See Link: http://newenglandbiochar.org/ (accessed 3/2/17).

Norby, R. J., E. H. DeLucia, B. Gielen, C. Calfapietra, C. P. Giardina, J. S. King, J. Ledford, H. R. McCarthy, D. J. P. Moore, R. Ceulemans, P. De Angelis, A. C. Finzi, D. F. Karnosky, M. E. Kubiske, M. L. Lukac, K. S. Pregitzer, G. E. Scarascia-Mugnozza, W. H. Schlesinger, and R. Orenh. 2005. Forest response to elevated CO2 is conserved across a broad range of productivity. Proc Natl Acad Sci U S A. 2005 December 13; 102(50): 18052–18056.

Notaro, M., S. Vavrus, and Z. Liu. 2007. Global vegetation and climate change due to future increases in CO2 as projected by a fully coupled model with dynamic vegetation. Journal of Climate, 20:70–90.

Notes from discussions with DEP on landfill emissions (Alec Giffen handwritten notes).

Nowak, D. J. 2000. The interactions between urban forests and global climate change. In: Abdollahi, K., Z. H. Ning, and V. A. Appeaning (eds.). Global Climate Change and the Urban Forest. Baton Rouge, LA: GCRCC and Franklin Press. pp. 31-44.

Nowak, D. J., and D. E. Crane. 2001. Carbon storage and sequestration by urban trees in the USA. Environmental Pollution 116: 381-389.

Nunery, J. S., and W. S. Keeton. 2010. Forest carbon storage in the northeastern United States: Net effects of harvesting. Forest Ecology and Management 259:1363–1375.

Oneil, E., B. Lippke, and J. B. McCarter. 2011. Life cycle carbon tracking for the working forests of I'm British Columbia: Carbon pool interactions from forests, to building products, and displacement of fossil emissions. A report prepared for the British Columbia Forest Sector Climate Action Steering Committee by CORRIM, Seattle, WA, 73 p.

Oneil, E.E., and B. Lippke. 2010. Integrating products, emission offsets, and wildfire into carbon assessments of Inland Northwest forests. Wood Fiber Sci. 42:144-164.

Pacala, S.W., G.C. Hurtt, R.A. Houghton, R.A. Birdsey, L. Heath, E.T. Sundquist, R.F. Stallard, D. Baker, P. Peylin, P. Moorcroft, J. Caspersen, E. Shevliakova, M.E. Harmon, S.-M. Fan, J.L. Sarmiento, C. Goodale, C.B. Field, M. Gloor and D. Schimel. 2001. Consistent Land- and Atmosphere-Based U.S. Carbon Sink Estimates. Science 292 (5525): 2316-2320.

Pacaldo, R. S., T. A. Wolk, L. P. Abrahamson, and R. D. Briggs. 2011. Above- and below-ground biomass and soil organic carbon inventories of willow biomass crops across a 19-year chronosequence. Presentation for the Woody Biomass Energy Research Symposium, April 28-30.

Page, S.E., F. Siegert, J. O. Rieley, H-D. V. Boehn, A. Jaya and S. Limin. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature, 420: 61-65.

Pan, Y., R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A. Shvidenko, S. L. Lewis, J. G. Canadell, P. Ciais, R. B. Jackson, S. Pacala, A. D. McGuire, S. Piao, A. Rautiainen, S. Sitch, D. Hayes. 2011. A Large and Persistent Carbon Sink in the World's Forests. Science. DOI: 10.1126/science.1201609

Pan, Y., R. Birdsey, J. Hom, K. McCullough. 2009. Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of U.S. Mid-Atlantic temperate forests. For. Ecol. and Manage. 259, 151.

Paul, K., T. Booth, A. Elliott, T. Jovanovic, P. Polglase, and M. Kirschbaum. 2003. Life cycle assessment of greenhouse gas emissions from domestic woodheating. CSIRO Forestry and Forest Products.

Pearce, F. 2011. Can 'climate-smart' agriculture help both Africa and the Planet? http://e360.yale.edu/feature/after_durban_can_climate_smart_farming_help_africa_and_the_planet/2477/ (accessed 01/27/12).

Peckham, S.D., and S.T. Gower. 2011. Simulated long-term effects of harvest and biomass residue removal on soil carbon and nitrogen content and productivity for two Upper Great Lakes forest ecosystems. GCB Bioenergy 3 (2):135-147.

Piety, C. 2007. Appendix G-13: The relationship between urban tree cover and ground level ozone, Cecil County, Maryland. Appendix G-13, In: Maryland Department of the Environment. 8-Hour Ozone State Implementation Plan and Base Year Inventory: SIP Revision 07-05.

Plevin, R. 2010. Bioenergy accounting review. August 31. 15 pp.

Plevin. N.d. The GHG benefits of bioenergy are uncertain. 11 pp.

Pollet, J., and P. N. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal of Wildland Fire 11:1–10.

Powell, A. 2011. Growing strong: Still-thriving forests buffer effects of climate change. Harvard Science, Nov. 10. http://news.harvard.edu/gazette/story/2011/11/growing-strong/ (accessed 01/27/12).

Princeton Geoengineering. 2011. Technological limitations. Geoengineering in approach to climate change. Princeton University. Was an online document, but has been removed.

Pyke, C. R. and S. J. Andelman. 2007. Land use and land cover tools for climate adaptation. Climatic Change, 80:239–51.

Ralloff, J. 2011. Study recalibrates trees' carbon uptake. ScienceNews, Oct. 11. http://www.sciencenews.org/view/generic/id/334948/title/Study_recalibrates_trees_carbon_uptake_ (accessed 02/05/12)

Raloff, J. 2011. Urban smog control: A new role for trees? Science News website (accessed 08/21/11).

Ramanathan, V., and Y. Feng. 2008. Air pollution, greenhouse gases and climate change: Global and regional perspectives. Atmospheric Environment, 43:37-50.

Randerson, J., J. Canadel, and R. Jackson. 2007. Linking carbon storage in terrestrial ecosystems with other climate forcing agents: A synthesis allowing for effective carbon dioxide stabilization policies. 9 pp.

Reay, D. S., F. Dentener, P. Smith, J. Grace and R. A. Feely. 2008. Global nitrogen deposition and carbon sinks. Nature Geoscience, 1: 430-437.

Rebound effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency. Abstract. Clean Air Conservancy website (accessed 8/23/11)

Reese, A. 2011. Wallow fire 'a high-speed locomotive,' but restoration projects help apply brakes. Forest Business Network online. See link (accessed 08/21/11).

Regulation of fuels and fuel additives: changes to renewable fuel standard program, 75 Fed. Reg. 14,670 (Mar. 26, 2010). EPA Docket No. EPA-HQ-OAR-2005-0161.

Repo, A., M. Tuomi, and J. Liski. 2010. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. GCB Bioenergy, doi: 10.111/j.1757-1707.2010.01065.

Ritter, M. A., K. Skog and R. Bergman. n.d. Science supporting the economic and environmental benefits of using wood and wood products in green building construction

Rose, S. 2011. Biomass supply for power & environmental implications. Presentation for EPRI Global Climate Change Research Seminar, Washington, DC, May 25.

Rotenberg, E., and D. Yakir. 2010. Contribution of semi-arid forests to the climate system. Science, 327: 451-454.

Ruddiman, W.F. 2013. Earth transformed. W. H. Freeman & Co. 400 pp.

Ruddiman, W.F. and E.C. Ellis. 2009. Effect of per-capita land use changes on Holocene forest clearance and CO_2 emissions. *Quarternary Science Reviews*, 28:3011-3015.

Running, S. W. 2008. Ecosystem disturbance, carbon and climate. Science, 321: 652-653.

Sathre, R., and J. O'Connor. 2010. Meta-analysis of grenhouse gas displacement factors of wood product substitution. Environmental Science & Policy, 13(2): 104-114

Sathre, R., and L. Gustavsson. 2011. Time-dependent climate benefits of using forest residues to substitute fossil fuels. Biomass and Bioenergy, 35:2506-2516.

School of Fisheries & Ocean Sciences. 2009. Ocean acidification in Alaska: New findings show increased ocean acidification in Alaska waters. August 11.

ScienceDaily. 2009. Potential to amass more carbon in eastern North American forests. http://www.sciencedaily.com/releases/2009/04/090406192333.htm (accessed 02/01/12).

Searchinger, T. 2010. Bioenergy: The need for additional carbon. Presentation to CEQ, July 6.

Searchinger, T. 2011a. Global consequences of the bioenergy accounting error. Forthcoming in Inderwildi O. (ed), Energy Transport & the Environment (Spring, London in press).

Searchinger, T. 2011b. Quick fix to the food crisis. June 16.

Searchinger, T. 2012. Some comments on draft report of Science Advisory Panel on Biogenic Emissions.

Searchinger, T. D. 2009. Biofuels and the need for additional carbon. Environmental Research Letters, 5: 024007.

Shuman, J.K., H.H. Shugart and T.L. O'Halloran. 2011. Sensitivity of Siberian larch forests to climate change *Global Change Biology* (Accepted Article) doi 10.1111/j.1365-2486.2011.02417.x

Simpson, I. J., F. S, Rowland, S. Meinardi, and D. R. Blake. 2006. Influence of biomass burning during recent fluctuations in the slow growth of global tropospheric methane. Geophysical Research Letters, 33: L22808, doi: 10.1029/2006GL027330.

Simpson, J. R. 2002. Improved estimates of tree-shade effects on residential energy use. Energy and Buildings, 34: 1067-1076.

Sitch, S., P. M. Cox, W. J. Collins and C. Huntingford. 2007. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. Nature, 448(16): 791-794.

Skog, K.E., and G. Nicholson. 2000. Carbon Sequestration in Wood and Paper Products. In The Impact of Climate Change on America's Forests: a Technical Document Supporting the 2000 USDA Forest Service RPA Assessment, edited by L. A. Joyce and R. Birdsey. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Slosberg, R., C. Rosenzweig, and W. Solecki. 2006. New York City Regional Heat Island Initiative: Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces (Final Report 06□06). Albany, NY: New York State Energy and Research Development Authority.

Smith, W.B., P.D. Miles, C.H. Perry, and S.A. Pugh. 2009. Forest Resources of the United States, 2007. Washington, DC: U.S. Department of Agriculture, Forest Service. General Technical Report WO-78.

Society of American Foresters. 2011. Managing forests because carbon matters: Integrating energy, products, and land management policy. *Journal of Forestry* supplement, 109(7S).

Solid Waste Association of North America. 2002. Successional approaches to recycling urban wood waste. Gen. Tech. Rep. FPL-GTR-133. Madison, WI: USDA Forest Service, Forest Products Lab. 20 pp.

Solomon S., D. Qin, M. Manning, Z. Chen, A. Marquis, K. B. Averyt , M. Tignor, and H. L. Miller (eds). 2007. IPCC Climate Change. The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Solomon S., D. Qin, M. Manning, Z. Chen, A. Marquis, K. B. Averyt , M. Tignor, and H. L. Miller (eds). 2007. IPCC Climate Change. The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H. L. Miller (eds). N.d. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein. 2009. Irreversible climate change due to carbon dioxide emissions. PNAS, 106(6): 1704-1709.

Solomon, S., J. S. Daniel, T. J. Sanford, D. M. Murphy, G.-K. Plattner, R. Knutti, and P. Friedlingstein. 2010. Persistence of climate changes due to a range of greenhouse gases. PNAS Early Edition, www.pnas.org/cgi/doi/10.1073/pnas.1006282107.

Soule, P.T. and Knapp, P.A. 2006. Radial growth rate increases in naturally-occurring ponderosa pine trees: a late 20th century CO_2 fertilization effect? New Phytologist 171: 379-390.

Southern Environmental Law Center. 2010. Letter to EPA Docket Center, RE: Call for information: Information on greenhouse gas emissions associated with bioenergy and other biogenic sources, 75 Fed. Reg. 41173 (July 15, 2010)

Spath, P.L., and M.K. Mann. 2004. Biomass Power and Conventional Fossil Systems with and without CO2 Sequestration—Comparing the Energy Balance, Greenhouse Gas Emissions and Economics. Golden, CO: National Renewable Energy Laboratory.

Spitzley, D., and G.A. Keoleian. 2005. Life Cycle Environmental and Economic Assessment of Willow Biomass Electricity: A Comparison with Other Renewable and Non-Renewable Sources. Ann Arbor, MI: University of Michigan, Center for Sustainable Systems. Report CSS04-05R

Spracklen, D. V., B. Bonn, and K. S. Carslaw. 2008. Boreal forests, aerosols and the impacts on clouds and climate. Philosophical Transactions of the Royal Society A. Published online.

Stein, S. M., R. E. McRoberts, R. J. Alig, M. D. Nelson, D. M. Theobald, M. Eley, M. Dechter, and M. Carr. 2005. Forests on the edge: housing development on America's private forests. Gen. Tech. Rep. PNW-GTR-636. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Stone, C., A. Hudak, and P. Morgan. 2000. Forest harvest can increase subsequent forest fire severity. USDA Forest Service, Gen. Tech. Rep. PSW-GTR-xxx.

Stop Spewing Carbon website.

Stowe, N. 2011. The future of biopower in the US: Draft working paper. Environment and Energy Study Institute. Feb 16, 2011.

Stuart, J. S. 2001. A Near-Earth Asteroid Population Estimate from the LINEAR Survey. Science 23 Nov: 1691-1693.

Sunderland, F. 2011. Biofuels: the biggest driver of land-grabbing deals. http://www.thegreencarwebsite.co.uk/blog/index.php/2011/12/19/biofuels-the-biggest-driver-of-land-grabbing-deals/ (accessed 02/01/12).

Kaushal, Sujay S., G. E. Likens, N. A. Jaworski, M. L. Pace, A. M. Sides, D. Seekell, K. T. Belt, D. H. Secor, and R. L. Wingate. 2010. Rising stream and river temperatures in the United States. Front Ecol Environ 2010; 8(9): 461–466, doi:10.1890/090037 (published online 23 Mar 2010).

Swackhamer, D. L., and M. Khanna. 2012. Letter to Administrator Jackson, SAB review of EPA's accounting framework for biogenic CO2 emissions from stationary sources. March 9.

Taha, H., 2013. "Meteorological, emissions, and air-quality modeling of heat-island mitigation: Recent findings for California, U.S.A.". *International Journal of Low Carbon Technologies*, doi: 10.1093/ijlct/ctt010

Taha, H., 2012. "The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas". *Solar Energy*, doi:10.1016/j.solener.2012.09.014.

Taha, H., Sailor, D. 2010. "Evaluating the effects of radiative forcing feedback in modeling urban ozone air quality in Portland, Oregon: Two-way coupled MM5 - CMAQ simulations". *Boundary-Layer Meteorology*, Volume 137, No. 2, (2010), pp. 291-305-- doi:10.1007/s10546-010-9533-9.

Taha, H., 2008. "Meso-urban meteorological and photochemical modeling of heat island mitigation". *Atmospheric Environment*, Vol. 42, No. 38 (December 2008), pp. 8795 – 8809 - doi:10.1016/j.atmosenv.2008.06.036.

Taha, H. 2008. "Episodic performance and sensitivity of the urbanized MM5 (uMM5) to perturbations in surface properties in Houston TX". *Boundary-Layer Meteorology* -- Volume 127, No. 2 (May 2008), pp. 193-218. doi:10.1007/s10546-007-9258-6.

Taha, H., Konopacki, S., Akbari, H. 1998. "Impacts of lowered urban air temperatures on precursor emission and ozone air quality". *Journal of the Air & Waste Management Association*, Vol. 48 (1998), pp. 860-865.

Taha, H. 1996. "Modeling the Impacts of Increased Urban Vegetation on the Ozone Air Quality in the South Coast Air Basin". *Atmospheric Environment*, Vol. 30, No. 20 (1996), pp. 3423-3430.

Taylor, P. 2011. Wildfire prevention less costly than treatment, experts say. Forest Business Network online. See link (accessed 08/21/11)

Ter-Mikaelian, M.T., S.J. Colombo, and J. Chen. 2015. The Burning Question: Does Forest Bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions about Forest Carbon Accounting. *J. For.* 113(1):57-68.

Thompson, J. R., D. R. Foster, R. Scheller, and D. Kittredge. 2011. The influence of land use and climate change on forest biomass and composition in Massachusetts, USA. Ecological Application, forthcoming.

Tierney, J. 2011. When energy efficiency sullies the environment. New York Times reprints. March 7.

Tsao, J. Y., H. D. Saunders, J. R. Creighton, M. E. Coltrin, and J. A. Simmons. 2010. Journal of Physics D: Applied Physics, 43(35).

Tunved, P. H.-C. Hansson, V.-M. Kerminen, J. Ström, M. Dal Maso, H. Lihavainen, Y. Viisanen, P. P. Aalto, M. Komppula, and M. Kulmala. 2006. High natural aerosol loading over boreal forests. Science, 312(5771): 261-263.

Turner, II, B. L., E. F. Lambin, and A. Reenberg. 2007. The emergence of land change science for global environmental change and sustainability. Proceedings of the National Academy of Sciences, 104(52): 20666-20671.

UN FAO. 2005. Extent of forest resources. Ch. 2 in Global Forest Resource Assessment 2005. http://www.fao.org/forestry/fra/fra2005/en/ (accessed 04/20/12).

UN FAO. 2010. Global Forest Resource Assessment 2010. http://www.fao.org/forestry/fra/fra2010/en/

UN-Energy. 2007. Sustainable bioenergy: A framework for decision makers. Research papers.

Urban Heat Island Mitigation website.

Urban Wood Waste (Alec Giffen handwritten notes)

US Department of Energy. 2011. U.S. billion-ton update: Biomass supply for a bioenergy and bioproducts industry. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. 227p.

US EPA. 2005. Greenhouse gas mitigation potential in U.S. Forestry and Agriculture. Washington, DC. EPA 430-R-05-006.

US EPA. 2007. Greenhouse gas impacts of expanded renewable and alternative fuels use. Office of Transportation and Air Quality. EPA 420-F-07-035. 3 pp.

US EPA. 2009. Municipal Solid Waste Generation, Recycling, and Disposal in the United States. Washington, DC: United States Environmental Protection Agency (EPA).

US EPA. 2010. Identification of Non-Hazardous Materials That Are Solid Waste. Supporting material for Resource Conservation and Recovery Act (RCRA) final rule.

US EPA. 2010. Methane and Nitrous Oxide Emissions from Natural Sources. Washington, DC: U.S. Environmental Protection Agency (EPA). EPA 430-R-10-001.

US EPA. 2010. Renewable Fuel Standard2 Program (RFS2) Regulatory Impact Analysis. Washington, DC: U.S. Environmental Protection Agency (EPA).

US EPA. 2011. Accounting framework for biogenic CO2 emissions from stationary sources. Washington, DC.

US EPA. 2012a. Climate change - greenhouse gas emissions. Website. http://www.epa.gov/climatechange/emissions/globalghg.html (accessed 04/20/12).

US EPA. 2011. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. Washington, DC: U.S. Environmental Protection Agency (EPA). USEPA #430-R-11-005.

US EPA. 2012b. 2012 U.S. greenhouse gas inventory report. Website. http://www.epa.gov/climatechange/emissions/usinventoryreport.html. (accessed 04/20/12).

USDA Economic Research Service. 2012. Major land uses. http://www.ers.usda.gov/data/majorlanduses/ (see esp. Summary Table 2). (accessed 05/15/12).

USDA Forest Service, Center for Urban Forest Research. 2008. Urban forests and climate change: Project reporting protocol.

USDA Forest Service. 2008. DRAFT National Report on Sustainable Forests - 2010. http://www.fs.fed.us/research/sustain/ (Accessed February 17, 2011).

USDA Forest Service, Northern Research Station. 2017. Carbon Sequestration.

USFS. 2011. Forest Service report documents environmental benefits of wood as a green building material. News Release No. 0426.11. Sept. 29.

U.S. Global Change Research Program. 2014. National Climate Assessment. www.globalchange.gov (Accessed July10, 2014).

Van Loo, S., and J. Koppejan. 2008. The Handbook of Biomass Combustion and Co-firing. London, UK: Earthscan.

VanEgeran, J. 2010. Wood chips may pose problems when Charter Street plan converts to biomass. Capital Times, August 9.

Vitousek, P. M., J. D. Aber, R. W. Howarth, G. E. Likens, P. A. Matson, D. W. Schindler, W. H. Schlesinger, and D. G. Tilman. 1997. Technical report: Human alteration of the global nitrogen cycle: Sources and consequences. Ecological Applications, 7:737–50.

Walker, S. 2011. Projecting the wood biomass industry. RISI. http://www.risiinfo.com/technologyarchives/environment/Projecting-the-wood-biomass-industry.html (accessed 02/01/12).

Walker, T., P. Cardellichio, A. Colnes, J. Gunn, B. Kittler, B. Perschel, C. Recchia, and D. Saah. 2010. Biomass and carbon policy study. Brunswick, ME: Manomet Center for Conservation Sciences. http://www.manomet.org/sites/manomet.org/files/Manomet_Biomass_Report_Full_LoRez.pdf (accessed February 28, 2008).

Wear, D.N., and B.C. Murray. 2001. A Tale of Two Birds: Spotted Owls, Trade Hawks, and their Impacts on U.S. Softwood Markets. Research Triangle Park, NC: Environmental and Natural Resource Economics Program, Research Triangle Institute. Working Paper.

Wear, D. N., and B. C. Murray. 2004. Federal timber restrictions, interregional spillovers, and the impact on U.S. softwood markets. Journal of Environmental Economics and Management, 47(2):307-330.

Weisser, D. N.d. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies.

Whitehead, D. 2011. Forests as carbon sinks -- benefits and consequences. Tree Physiology, 31:893-902.

Wilson, W. 2011. Constructed climates: A primer on urban environments. Section 4.3 Tree Pollution. In: Chicago: University of Chicago Press. 288 pp.

Wood: The most natural resource website (accessed 9/1/11).

World Resources Institute. 2005. http://www.wri.org/chart/world-greenhouse-gas-emissions-2005 (accessed 05/02/12).

Wynn, G. 2011. EU biofuels industry in denial over CO2 error. http://www.reuters.com/article/2011/11/14/climate-biomass-idUSL5E7MB3BL20111114 (accessed 01/27/12).

Zanchi, G., N. Pena and N. Bird. 2011. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel GCB Bioenergy, doi: 10.1111/j.1757-1707.2011.01149.x.

Zhu, Z. (ed), B. Bergamaschi, R. Bernknopf, D. Clow, D. Dye, S. Faulkner, W. Forney, R. Gleason, T. Hawbaker, J. Liu, S. Liu, S. Prisley, B. Reed, M. Reeves, M. Rollins, B. Sleeter, T. Sohl, S. Stackpoole, S. Stehman, R. Striegl, A. Wein, and Z. Zhu. 2010. A method for assessing carbon stocks, carbon sequestration, and greenhouse-gas fluxes in ecosystems of the United States under present conditions and future scenarios: U.S. Geological Survey Scientific Investigations Report 2010-5233. 188 pp.

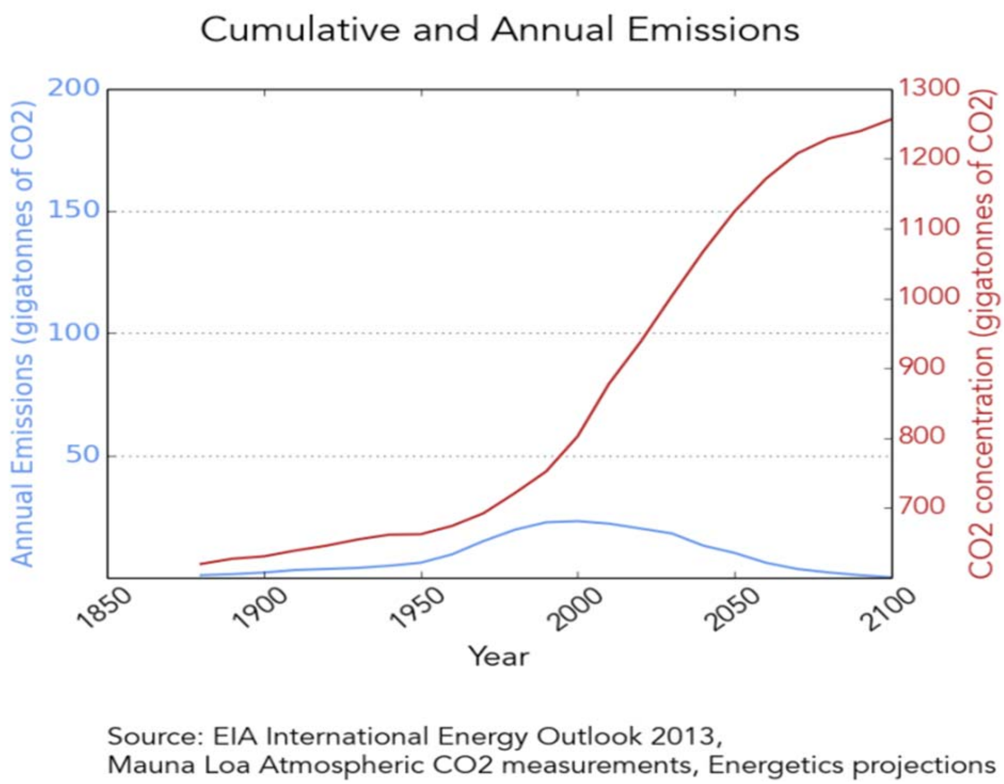
Zhu, Zhiliang, and Stackpoole, Sarah, 2011, Assessing carbon stocks, carbon sequestration, and greenhouse-gas fluxes in ecosystems of the United States under present conditions and future scenarios: U.S. Geological Survey Fact Sheet 2011-3007, 2 p.

Zhu, Zhiliang, ed., Bergamaschi, Brian, Bernknopf, Richard, Clow, David, Dye, Dennis, Faulkner, Stephen, Forney, William, Gleason, Robert, Hawbaker, Todd, Liu, Jinxun, Liu, Shuguang, Prisley, Stephen, Reed, Bradley, Reeves, Matthew, Rollins, Matthew, Sleeter, Benjamin, Sohl, Terry, Stackpoole, Sarah, Stehman, Stephen, Striegl, Robert, Wein, Anne, and Zhu, Zhiliang, 2010, A method for assessing carbon stocks, carbon sequestration, and greenhouse-gas fluxes in ecosystems of the United States under present conditions and future scenarios: U.S. Geological Survey Scientific Investigations Report 2010–5233.

M. Attachments

1. How Much Headroom in the Atmosphere for Future CO_2?

How much "space" is available in the atmosphere for future carbon emissions? Given CO_2's long residence time in the atmosphere (a significant portion of carbon emitted today will remain in the atmosphere for millennia), the CO_2 that is being emitted is for all practical purposes permanently there, increasing atmospheric burden. While uncertainty exists about the precise temperature response created by doubling the pre-industrial concentration of CO_2, numerous analyses indicate that the likelihood of severe consequences increases significantly if warming exceeds two degrees centigrade. Reductions in emissions do not remove any existing carbon dioxide from the atmosphere. Partial reductions in emissions combined with steep increases in overall energy use will still result in significant additions of carbon to the atmosphere.

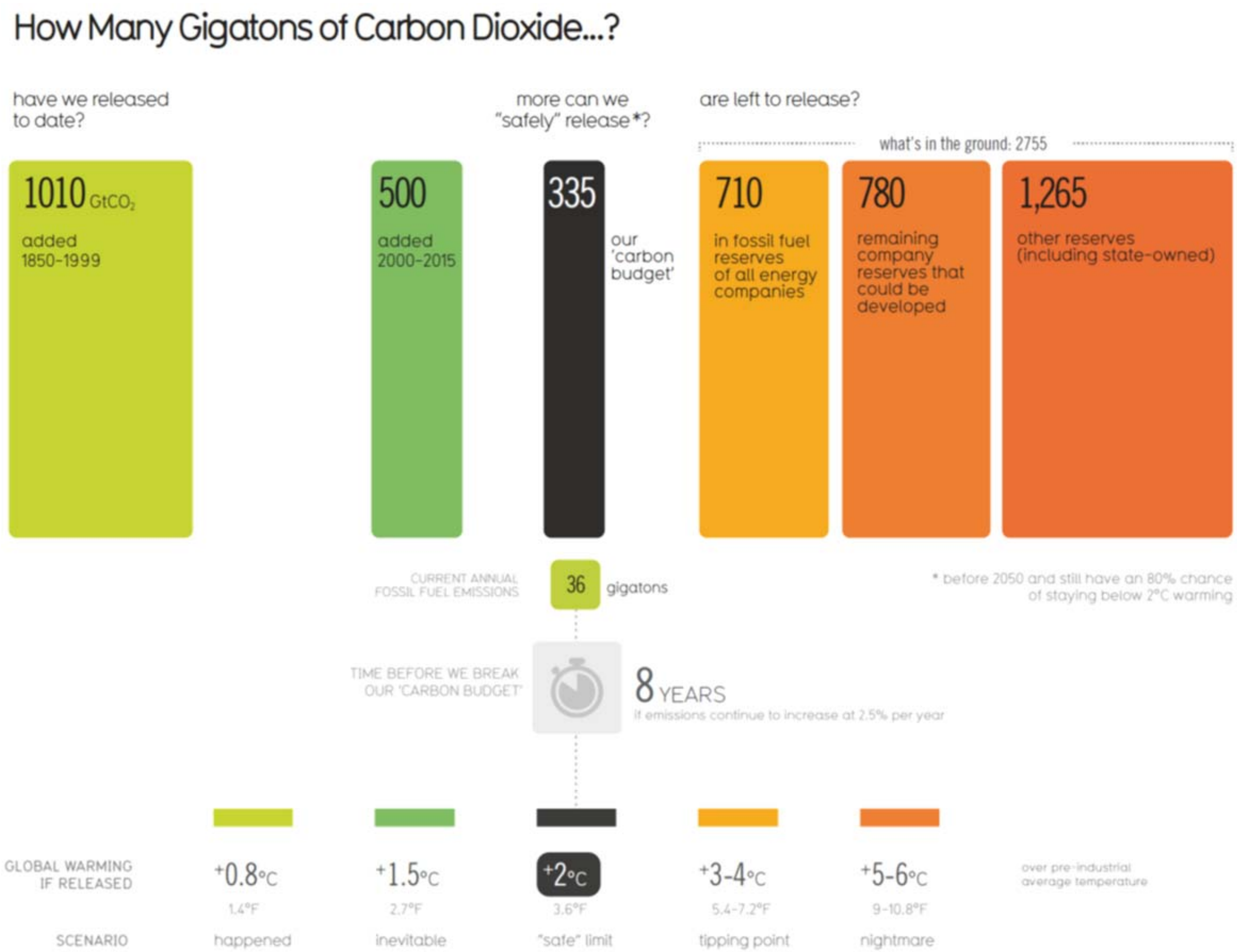


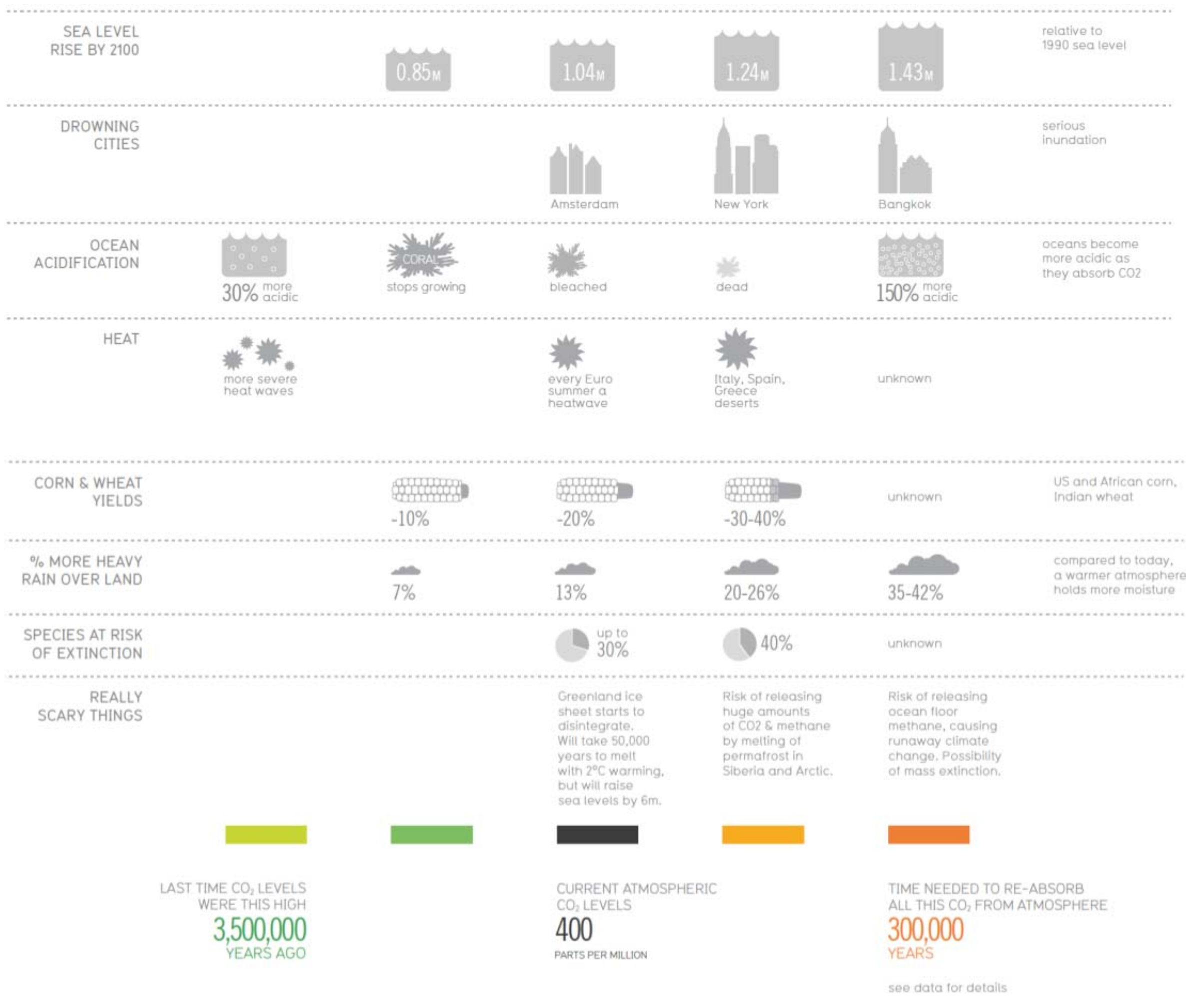
Human activity through 2016 has already used up about two-thirds of the CO_2 budget that would limit climate warming to less than two degrees centigrade. This leaves space for less than ~890 gigatonnes of future CO_2 ($GtCO_2$) in the atmosphere before climate-forcing emissions must drop to zero from all activities to avoid exceeding this warming limit.[9] (See Figure. 27 in this report). Current global CO_2

[9] *IPCC AR-5 Working Group I Summary for Policy Makers*, on page 27 at last bullet point. This remaining CO2 budget of ~890 GtCO2 assumes a >66% probability of constraining incremental warming from anthropogenic GHG emissions to less than 2 degrees C. This figure is calculated using AR-5's estimated remaining CO2 budget through 2011 of ~1890 GtCO2 when accounting for non-CO2 forcers and is then adjusted for estimated 2012 plus 2013 global CO2 emissions of about 72 GtCO2, as sourced from http://co2now.org for 2012 and http://cdiac.ornl.gov/GCP/carbonbudget/2013/ for 2013.

emissions are about 37 $GtCO_2$ per year, so even if we could immediately limit CO_2 emissions to current levels, *the remaining global CO_2 budget would be used up within ~24 years - by 2038.*

There is debate about how much headroom in the atmosphere is left for additional CO2. The diagram below estimates that there is only 335 GtCO2 left of headroom, and with current estimated annual fossil fuel emissions of 36 GtCO2 it will take 8 years to reach the limit of the carbon budget if emissions continue to rise at 2.5% per year. Whether it takes only 8 years or 24 years to use up the remaining global CO2 budget, there is little doubt that global climate change is real, we are continuing to impact the climate with greenhouse gas emissions and it is urgent that we take steps to dramatically curb greenhouse gases.





Note: Our emissions data is expressed in gigatons of carbon dioxide (GtCO2), so values are 3.664 times larger than the same amount of emissions expressed in gigatons of carbon (GtC).

Data based on emissions from fossil fuel burning only – see data sheet for emissions including land use changes.

All data & workings: **http://bit.ly/CO2Gigatons2016**

Concept & Design: David McCandless // v2.2 // Feb 2016
Lead Research: Miriam Quick
Additional Research: Ella Hollowood // Additional design: Kathryn Ariel Kay, Paulo Estriga, Fabio Bergmaschi

InformationisBeautiful.net

Sources: Carbon Tracker Initiative, International Energy Agency (IEA), IPCC 2014 & 2007, CDIAC, Global Carbon Project
NASA, National Oceanic and Atmospheric Administration (NOAA), National Research Council,
Potsdam Institute for Climate Impact Research, World Bank, European Commission Joint Research Centre, our own calcs

2. Input on the Potential Role of Regional Modeling in Determining Net Effects of Forest Management and Wood Use

CLEAN AIR TASK FORCE

Feb. 2, 2013 draft[10]

Questions and Answers on the Modeling the Clean Air Task Force Proposes as Part of its Forests & Climate Systems Program

Note: There are 8 questions and answers to the modeling discussion. Only 2 are shown here to give a sense of the potential models offer for understanding how forests and wood use affect the climate. If you would like to access the whole document, please click the hyperlink here.

Q1: Why is mathematical modeling of forest influences on climate important?

A1: Forests influence climate in many ways. Forests not only store and sequester carbon, but also affect cloudiness and precipitation, humidity, soil moisture, surface and air temperature, air pollutant emissions, deposition of particulates and gases, atmospheric reactions, pollutant transport, reflectance and transfer of solar radiation and heat, wind speed and air turbulence. The complex interactions among these factors affect the earth's energy and water balance, and therefore the local, regional, and global climates. As such, understanding the relationship between forests and climate involves:

- Atmospheric physics (near-ground, tropospheric, and stratospheric);
- Atmospheric chemistry and transport of pollutants near the ground and aloft;
- Meteorology (short term variations, weather);
- Climatology (long-term climate);
- Biology and biogeochemistry; and
- Radiative fluxes (incoming light absorbed as heat, re-radiation to atmosphere as heat) and radiative forcing (atmospheric heating due to greenhouse gases)

The relationships among these processes and their effects are complex, non-linear and involve multiple two-way feedbacks. These relationships are too complicated to reduce to simple understandings, approximations, or "rules of thumb". It is now possible, however, to analyze their effects and interrelationships through highly sophisticated mathematical modeling, using multi-scale and multi-dimensional atmospheric models.

[10] This document was created with substantial input from Haider Taha, Principal, Altostratus.

Q2: How does "multi-scale and multi-dimensional atmospheric modeling" work?

A2: With the advent of powerful, fast computers, it became possible to perform the very large number of calculations necessary to evaluate multiple processes, effects, and their interactions in the atmosphere and on land, in soils, and waterbodies. The modeling community (including industry, academia, and national/federal organizations) have worked for decades to integrate known dynamics, physics, chemistry, and related processes in the atmosphere and simulate conditions or scenarios to be studied. Compared to only a few years ago, the models can now much more accurately and reliably forecast the weather and air quality and provide answers to "if-then" questions and scenarios, including, in this case, changes in forest cover, vegetation species, agricultural and forest practices, harvesting, and so on.

Inputs of relevant data (such as topography, type of land-cover, urban surface geometry, emissions of heat and air pollutants and meteorological conditions) are fed into mathematical models for analysis. For example, ever more sophisticated weather research and forecasting models can ingest comprehensive input from current conditions, process it using sophisticated mathematical parameterizations that analyze the interplay of atmospheric physics, dynamics, and chemistry to forecast weather conditions with a high degree of detail.

The modeling community has also developed modeling systems that "couple" (link) weather forecasting models with emissions and air-chemistry models that can for example, predict when a set of weather circumstances or future climate will result in higher ground-level ozone levels in a particular geographic area. Such linked modeling systems can also determine how evapotranspirative cooling and shading by tree canopies can reduce surface and air temperatures and quantify the resulting reductions in air-conditioning cooling demand and associated emissions from power plants. The models can also address other phenomena such as information about heat island effects, air pollution concentrations and transport, and other information of importance to public health, energy demand, and air quality.

Different models are used for different scales. These include, for example:

- Local-scale models (also called "fine scale", "micro-scale", or "urban scale" models) with ability to evaluate input data and atmospheric changes in areas of tens to hundreds of meters

- Regional-scale models (also called "mesoscale" or "meso-urban" models), with ability to evaluate input data and atmospheric changes in areas of one to tens of kilometers)

- Global-scale models (also known as "Atmosphere-Ocean General Circulation Models) that can evaluate atmospheric conditions at resolutions of 100 to 200 km. These models are used to evaluate the continental and global climate effects of interactions of surface and atmospheric conditions, changes in the oceans circulations, and air chemistry on and over large areas and land masses, but cannot be utilized to evaluate conditions and changes at the mesoscale or fine scale without being “downscaled.” In such cases, the global-scale models “drive” the regional-scale models which, in turn, “drive” the local-scale simulations.

Even within the same model, i.e., global, regional, or local, it is possible, and frequently desirable, to use a “nested-grid” approach, where fine scale modeling is used to evaluate conditions and possible changes in a specific, fine-resolution, well-defined area, and regional scale models are used to analyzing the impacts on the broader surrounding region, allowing for linkage of information between the fine scale and mesoscale models. For example, fine scale modeling can evaluate the role of expanded tree cover in shading and evapotranspiration from soils and trees (themselves interrelated), leading to reduced air temperature, which in turn reduces emissions and ozone formation. Modeling of the surrounding region will both provide input in to the fine scale analysis (how regional influences and weather patterns influence conditions in the “fine scale” area) and will incorporate output from the fine scale model (how the effects of expanded tree cover are likely to affect air quality and meteorological conditions in the larger, surrounding area).

3. DRAFT: Developing a First Approximation of Management Guidelines Aimed at Maximizing Climate Mitigation from the Acadian Forest

Work proposed by The Woods Hole Research Center, the New England Forestry Foundation and the Clean Air Task Force (the Partners)

Introduction/Summary

Scientific studies have shown that forest, including those managed for multiple uses (the focus of this proposal and called wildland forests herein), as well as urban, and agroforests, can influence regional and global climate in a number of important ways. While most of the analyses of the potential of forests to mitigate climate change have focused on onsite carbon sequestration, other forest influences (e.g., albedo) are known to be more important in some circumstances. The impact of forests on cloudiness, not only as a result of evapotranspiration, but also their contribution to the formation of cloud condensation nuclei may prove to be one of their most significant impacts (clouds are responsible for reducing global warming by 20-30 w/m2 while anthropogenic CO_2 is responsible for increases of approximately 1.5 w/m2). Further, the use of wood in construction can both store carbon and reduce the emissions by replacing other more energy intensive building materials (for more information on this topic see these charts simplified from Matthews, et al. (2014) and Oliver, et al. (2015).

Therefore, the challenge we face in using forests most appropriately to mitigate climate change is to accurately assess the interactions among forest influences and maximize the benefits of forest management's "net effects." Answering the question of which forest management regime, in specific forest regions, will maximize net benefits, will ultimately require sophisticated modeling of atmospheric chemistry, physics and meteorology at fine, meso and global scales. However, the partners in this work believe we know enough now to propose some common sense steps to advance the use of the Acadian Forest to mitigate climate change while more refined answers are pursued.

As a first step in determining how should we be managing the forests to maximize climate benefits, WHRC, NEFF and CATF propose to convene a small group of scientists with expertise in the relevant subject areas (carbon sequestration of course, but also albedo, forest management, BVOCS, cloud formation, methane and forest interactions, atmospheric modelers, etc.) to gestalt a first approximation of guidelines for managing of the Acadian Forest – a forest ecosystem that the partners know a good deal about. Work in advance of convening such a group would include identifying the disciplines to be represented (initial thoughts are presented below), identifying specific individuals to represent them, preparing the panelists for the task at hand (e.g., providing background info) and of course arranging all the logistics. Two meetings of such a group would likely be most productive. The first would be to share perspectives, discuss potential interactions, identify other potential participants and additional background work that is needed, etc. The second meeting would be to develop a first draft of the management guidelines. This first draft could then be refined via email and then circulated for broader review. The draft could then serve as the basis for a Journal article.

Such a project has the advantages of:

1) Enabling us to quickly answer the question of what we know with confidence about how to manage the Acadian Forest to benefit climate mitigation

2) Jump starting people's thinking on this topic (for both the Acadian and other forest regions)

3) Being modest in cost

4) Enhancing the prospects for funding the more comprehensive and refined work needed to not only fill in gaps in our current understanding but also refine our understanding of interactions among influences to more accurately assess the "net effects" of forest management on climate (for more on this larger study, please see the full proposal here).

The Work Needed

Task 1. Preparation for the first meeting involves:

- Summarizing our collective (CATF, NEFF, WHRC) understanding of the issues and assumptions – drawing from or using the materials already prepared (e.g., matrix on influences, how forests fit into climate mitigation strategies, etc.)
- Identifying the most important influences (on a preliminary basis) – see initial thoughts as reflected below by areas of expertise proposed to be invited and "Influences of Forests on Climate" for a comprehensive list of the potential choices
- Making arrangements with participants
- Arranging logistics of meeting place, meals, accommodations, etc.
- Finalizing the draft agenda
- Circulating summaries of our collective understandings, statement of purpose and agenda to participants and invite comments
- Refining the above based on comments received

Task 2. Holding the first meeting involves:

- Establishing (with input from the participants) the purpose of the meeting – to share perspectives on how to approach the issue (e.g., relative importance of various forest influences), to identify the most relevant research already available, determining whether all the needed areas of expertise are represented, identifying other individuals (if any) who should be invited to participate, etc.
- Inviting the following disciplines and people to participate:
    - Acadian Forest Management – Bob Seymour and Brian Roth
    - Likely influences of climate change on the Acadian Forest – Aaron Weiskittel

    - BVOCs (production and impacts) – David Nowak (on production of BVOCs) and an expert on BVOCs climate effects
    - Albedo – Crystal Schaff
    - Forest influences on methane and N2O – Ivan Fernandez
    - Substitution benefits – Chad Oliver
    - Land cover influences on climate – Rob Jackson from Stanford and Phil Duffy
    - Impacts on harvesting on soil C – Linda Heath
    - Evapotranspiration – an expert (e.g., a researcher from the University of Arizona?)
    - Re-radiation of heat absorbed – an expert
    - Interactions among factors – Gordon Bonan and Haider Taha

    (Total of 16 people) (Plus partners staff, potential funders and policy makers?)

- Determining steps in the process and hence refining the agenda. Preliminary thoughts regarding the agenda include:
    - Welcome / purpose of the meeting – NEFF, CATF, WHRC
        - Explanation of the purpose of the meeting and proposed process
    - Self-introductions and explanation of expertise and perspectives by each participant
    - Questions about purpose and process – with refinements made as needed
    - Discussion of how each of the forest influences on climate could be effected by management of the Acadian Forest – each participant to explain their understanding of impacts for their area of expertise and potential interactions with other influences
    - Discussion of preliminary identification of most important influences to evaluate as part of this process – with refinements made as needed
    - Discussion of the most effective and efficient process for developing draft guidelines for climate beneficial management of the Acadian Forest
    - Identification of next steps including but not limited to additional areas of expertise which should be represented (if any) and persons to invite to participate, additional information and analyses needed, agenda for next meeting, etc.
- Facilitating the meeting
- Recording key points in the discussion, as well as follow-up and action needed

Task 3. Following up to first meeting involves:

- Circulating notes from first meeting
- Collecting the additional information requested
- Extending invitations to other experts (if needed)

Task 4. Planning for the second meeting involves:

- Making arrangements with participants
- Arranging Logistics
- Finalizing the draft agenda
- Preparing participants, e.g., prompting them to think about scenarios likely to mitigate or exacerbate climate change

Task 5. Holding the second meeting involves:

- Reviewing the purposes of the meeting
- Introducing new participants (if any)
- Reviewing and deliberating on the results of the first meeting including the effects of forest management on climate influences
- Identifying management scenarios likely to mitigate (or conversely exacerbate) climate change when considering what are considered to be the most important forest influences on climate (e.g., scenarios would consider the implications of managing for softwoods vs. hardwoods [or vice versa] emphasis on silvicultural system X vs. alternatives and emphasizing using wood for Y versus alternatives – in addition, these scenarios should consider enhancing resilience and adaptation as part of mitigating climate change)
- Identifying any additional information or analyses needed
- Recording key points in discussion, as well as follow-up and actions needed

Task 6. Following up on second meeting involves:

- Drafting notes on key points, information requests and action items
- Following up on additional information and analyses requested and circulating results
- Drafting a report on what we know now about how to manage the Acadian Forest to maximize climate mitigation
- Circulating a draft report to participants and requesting comments
- Refining the draft

Task 7. Releasing the report inviting comments from others outside this process and preparing a journal article

Task 8. Reporting to funders

Budget

Task 1	Preparation for the first meeting (a major part of this is preparing summaries of what is known and assumptions acceptable to the partners) (note some differences of opinion are believed to exist on these topics)	$10,000	
Task 2	Holding the first meeting	$5,000	*
Task 3	Following up to first meeting (this could be more if extensive analyses are requested)	$5,000	
Task 4	Planning for the second meeting	$5,000	
Task 5	Holding the second meeting	$5,000	*
Task 6	Following up on the second meeting	$10,000	**
Task 7	Releasing the report inviting comments and preparing a journal article	$5,000	
Task 8	Reporting to funders	$2,000	
	TOTAL	**$47,000**	***

* Plus travel expenses for participants.
** This could be more if extensive analyses are requested.
*** Plus travel expenses and honorarium for participants if needed.

Note – Most of this would go for the project leader's time and someone to assist with compiling and summarizing research, and handling logistics, etc.

4. DRAFT: Beyond Carbon: Understanding the Impacts of Forest Management and Wood Use Scenarios on Climate Change

Woods Hole Research Center, New England Forestry Foundation, and Clean Air Task Force

Overview

Most assessments of impacts of forests and deforestation on climate have focused on changes in the amount of carbon dioxide that forests absorb from the atmosphere, and generally neglect the numerous other ways in which forests influence radiative forcing and climate. Because the relationship between forests and climate change goes beyond carbon storage, we have only a rudimentary understanding of how different forest management approaches, and the related issue of the changes in the volume and nature of forest products which result, affect climate. This project will characterize some of those factors—such as changes in albedo, surface roughness, evapotranspiration and the emissions of biogenic aerosols—and incorporate them into climate analyses of two distinct forest systems that are subjected to a range of hypothetical management scenarios. From this exercise, we expect to learn how to enhance the value of forests in mitigating climate change through changes in their management and the use of wood products.

While the potential for climate benefits is, we believe, significant, it may be even more important to understand forest-climate interactions to avoid unintended consequences which could prove very detrimental.

Besides looking more completely at the science of how forest affect climate, this project will also demonstrate the potential for forest management to benefit climate while at the same time producing income and furthering other societal goals. Consideration of the real-world context will be essential if forest management is going to contribute significantly to mitigation of global climate change. Here we will analyze not only the full climate impacts of forests, but also the life-cycle greenhouse gas emissions of wood-use scenarios.

Problem Statement

According to the Intergovernmental Panel on Climate Change, the goal of keeping global temperature increases to 2^{o}C or less requires that we limit total anthropogenic carbon emissions (over all time) to about 1000 gigatons. We have already emitted more than half of this amount, and are on pace to push past that limit within a few decades.

Most climate mitigation planning efforts assume that forests will play an important role. This assumption is mainly based on our understanding of carbon dynamics. Pan, et al. (2011) found that from 1990-2007 on average forests worldwide sequestered 1.1 $\pm$ 0.8 petagrams of carbon per year (a petagram is one trillion kilograms). However, this far less than their potential as this figure is reduced by 1.3 $\pm$ 0.7 Pg per year as a result of tropical deforestation. Thus, by increasing the first number and decreasing the second, forests can sequester more of the CO_2 we emit. Further, when wood is used in place of other construction materials, it effectively sequesters carbon over long time scales and avoids the carbon emissions associated with other materials. For example, Roger Sathre estimated by averaging the results of 21 studies that over the long term, every cubic meter of wood used in place of other materials reduces CO_2 emissions by 1.9 tons (Sathre and O'Connor 2010). The impacts of substituting long lived wood products for other materials which result in greater emissions is particularly important.

While important, the focus on carbon dynamics overlooks the other ways in which forests influence climate change. The size and type of the earth's forest cover affects albedo (the proportion of sunlight that is reflected, rather than absorbed, when it hits earth) and surface roughness (which impacts the transport of heat and moisture). The existence of forests also increases evaporation, and different kinds of forests emit different biogenic compounds—both of these factors influence cloud formation.

These non-CO_2, forest-related climate influences have not generally been adequately understood to date. But their impact on climate change—and thus their importance to climate mitigation strategies—is potentially significant. Caldeira *et al*. (2005) found that the benefits of tree plantations depend on resulting changes in albedo, not just the rate of carbon sequestration. Rotenberg and Yakir (2010) showed that the loss of some semi-arid forests has slowed global warming, because the increase in albedo and the re-radiation of heat from the cleared land trumped the cooling benefit associated with the preexisting forests' carbon sequestration rate. Further, Kurten *et al*. (2003) determined that the climate impact of forests' production of biogenic aerosols may be on same order of magnitude as carbon sequestration (in addition to contributing to cloud formation, some aerosols reflect solar radiation directly).

Moreover, we know that the opportunities to use forests as a carbon pump—and to prime that pump by encouraging the use of certain forest products and discouraging the use of others—are significant. For example, Matthews, et al. (2014) compared the lifecycle carbon emissions from wood versus alternative materials and found that the increased use of wood, particularly in long-lived products, has clear climate benefits even in the near term. Bio-energy with carbon sequestration also offers opportunities if it can be done in a way that is cost competitive.

Furthermore, forests are affected by changing climatic conditions, witness the fact that forests in parts of the western US and Canada have become net carbon sources rather than sinks. These potential impacts must also be accounted for when examining the full range of climate-forest interactions.

Altogether there are more than a dozen ways that forests affect climate change aside from their effect on atmospheric CO_2 loading, but these non-CO_2 impacts are often not considered, and in some cases are not treated in regional or global climate models. As a result, the individual and collective impact of those factors is poorly understood and largely absent from key technical analyses and policy discussions concerning climate change mitigation. The lack of analysis about the non-CO_2 impacts associated with different forest management regimes also means that our ability to maximize the climate benefits that forests can provide is badly handicapped.

As alluded to earlier, while we believe that the upside potential to improve on climate change mitigation is large, the downside potential of mismanaging forests is also great – perhaps even greater. This seems particularly likely in light of the fact that most analyses of global climate change simply assume that forests outside the tropics will continue to provide the full suite of climate benefits that they do now. However, such an outcome is far from guaranteed. Even in the case of just carbon, some forest regions have gone from being carbon sinks to sources; while in other areas – although net sequestration continues – forests, and hence carbon stocks, are diminishing. Further, forest management practices are changing in ways that modify other forest climate influences, e.g., reduced albedo as a result of changes in cutting practices.

Proposed Solution: Two Case Studies

The project proposed by the Woods Hole Research Center, New England Forestry Foundation, and Clean Air Task Force would improve our understanding of forests' influences on climate, beyond (but including) CO_2, by characterizing some of these factors and incorporating them into climate analyses. Using state-of-the-art earth system models and the best information available on the parameters involved, we propose to elucidate the net impact of these "biophysical effects" in two model ecosystems: the semi-arid pinyon pine/juniper forest type of United States Southwest and the temperate broadleaf and mixed New England-Acadian forest of the United States and Canada. Both model ecosystems are significant components of total global carbon uptake. Semi-arid regions have been recently highlighted as key drivers of terrestrial uptake variability. More generally, our knowledge of biophysical effects in temperate systems is poorly constrained

In addition to its other benefits, the project would provide practical guidance in how to manage forests to achieve climate and other goals. We feel that case studies like those proposed may be/are probably the only practical way to develop a useful understanding of the complexity of forest management net impacts on climate.

These two case studies were chosen because they are very different forest types, but both are expected to show how changes in forest management and wood use can mitigate climate change and conversely management that could exacerbate it. The Acadian Forest (an area where NEFF has particular expertise) has an active forest products industry and hence active forest management, while the pinyon pine/juniper forest lacks both.

This analysis would significantly improve our understanding of the relative importance of various forest influences on climate and how various forest management approaches in two highly distinct forests influence climate change.

In light of the fact that maximizing in forest carbon density does NOT maximize the net climate benefits of forest systems, and that the "best solution" considers the radiative forcing associated with structure/morphology, not just the carbon in forests, key outputs from the two case studies will include:

- What types of forest management in each forest type will benefit or conversely adversely affect climate mitigation efforts
- How could increasing the volume of wood produced and changing its use contribute to mitigating climate change

These results could also prove helpful in thinking about how management to mitigate climate change relates to management to increase forest resilience and adaptation.

Project Partners

Woods Hole Research Center is an independent research and policy institute that advances understanding of climate change science and brings that understanding into the formulation of climate policy at all levels. For two years running, the WHRC has been named the world's #1 climate change think tank by the International Center for Climate Governance.

New England Forestry Foundation. NEFF, a non-profit organization, works to conserve forest land in New England (NEFF holds over 1 million acres of easements and owns and actively manages another 25,000 acres), and to improve forest management for the full range of public values (wildlife habitat, clean water, climate change, etc.)

Clean Air Task Force. CATF, a nonprofit environmental organization, works to help safeguard against the worst impacts of climate change by catalyzing the rapid global development and deployment of low carbon energy and other climate-protecting technologies through research and analysis, public advocacy leadership, and partnership with the private sector.

Budget

A two-year budget of $700,000 would allow the project partners to analyze the CO_2 and selected non-CO_2 climate impacts associated with various management regimes for the Acadian forest and pinyon pine forests. The primary costs would be the full-time salary for a post-doctoral student and project direction and support by select staff at WHRC, NEFF, and CATF.

References

Caldeira, K., S. Gibbard, G. Bala, M. E. Wickett, and T. J. Phillips. 2005. Will growing forest make the global warming problem better or worse? Pres. to AGU Fall Meeting, Dec. 7.

Kurtén, T., M. Kulmala, M. Dal Maso, T. Suni, A. Reissell, H. Vehkamäki, P. Hari, A. Laaksonen, Y. Viisanen, and T. Vesala. 2003. Estimation of different forest-related contributions to the balance using observations in southern Finland. Boreal Environment Research, 8:275–285.

Matthews, R., N. Mortimer, E. Mackie, C. Hatto, A Evans, O. Mwabonje, T. Randle, W. Rolls, M. Sayce, and I. Tubby. 2014. Carbon impacts of using biomass in bioenergy and other sectors: forests. DECC project TRN 242/08/2011 Final report: Parts a and b. www.gov.uk/government/uploads/system/uploads/attachment_data/file/282812/DECC_carbon_impacts_final_report30th_January_2014.pdf (accessed February 6, 2015).

Pan, Y., R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A. Shvidenko, S. L. Lewis, J. G. Canadell, P. Ciais, R. B. Jackson, S. Pacala, A. D. McGuire, S. Piao, A. Rautiainen, S. Sitch, D. Hayes. 2011. A Large and Persistent Carbon Sink in the World's Forests. Science. DOI: 10.1126/science.1201609

Rotenberg, E., and D. Yakir. 2010. Contribution of semi-arid forests to the climate system. Science 22: 451-454.

Sathre, R., and J. O'Connor. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environmental Science & Policy, 13(2): 104-114