Carbon & Climate-Smart Forestry: Forest protection and management options for climate mitigation

Sara Kuebbing
Director of Research
Yale Applied Science Synthesis Program
Disclaimer: Carbon should probably not be the primary reason to manage forests.
Carbon & Climate-Smart Forestry: Forest protection and management options for climate mitigation

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Overview

1) Why “carbon forestry” is the new hot topic in climate mitigation

2) Why carbon, forestry, and climate are deeply entwined
   [or, an Overview of Forest Carbon Cycling]

3) Carbon & Climate-Smart Forestry: some numbers
Why “carbon forestry” is the new hot topic
We have 1.8 billion billion metric tons of Carbon on Earth

Source: C.A. Suarez, M. Edmonds and A.P. Jones/Elements 2019
https://synthesis.yale.edu
Carbon flows between the atmosphere, ecosystems, and the earth’s crust.

Global Carbon Cycle

- Atmosphere: 750
- Surface Ocean: 7,250
- Intermediate and Deep Ocean: 37,750 Pg
- Fossil Fuels: 5,000 - 10,000 Pg
- Soils: 1,500 Pg
- Earth's Crust: 100,000,000 Pg
- Plants: 560 Pg

Legend:
- Units: Petagrams (Pg) = 10^15 gC
- Pools: Pg
- Fluxes: Pg/year

Copyright 2010 GLOBE Carbon Cycle Project, a collaborative project between the University of New Hampshire, Charles University and the GLOBE Program Office.

Humans have increased the total amount of atmospheric carbon by burning fossil fuels
1950’s: first scientific evidence of irreversible atmospheric change

1980’s: Vocal, global concern about fossil fuel emissions

“Humanity is conducting an unintended, uncontrolled, globally pervasive experiment whose ultimate consequences could be second only to a global nuclear war.”

World Conference on the Changing Atmosphere: Toronto, June 1988
Limiting warming to **1.5°C** and **2°C** involves rapid, deep and in most cases immediate greenhouse gas emission reductions.

Net zero CO₂ and net zero GHG emissions can be achieved through strong reductions across all sectors. Implemented policies result in projected emissions that lead to warming of 1.5°C, with a range of 2.2°C to 3.5°C (medium confidence).
“All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 GtCO2 over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (high confidence).”
Where can we put all this atmospheric CO$_2$?

[= climate mitigation]
Where can we put all this atmospheric CO$_2$?

Global Carbon Cycle

Direct Air Capture (DAC) technology

DAC uses electricity and heat to filter carbon dioxide (CO$_2$) from the ambient air for utilization or for permanent storage deep underground. DAC and storage (DACS) results in the net removal of CO$_2$ from the atmosphere.
Where can we put all this atmospheric CO$_2$?

Photo by [Josh Berendes](https://unsplash.com) on Unsplash
Global Carbon Cycle

Where can we put all this atmospheric CO$_2$?

BrineStans @ Wikimedia Commons
National and international discussions are considering ‘forest carbon management’ as a pillar of climate mitigation

“Rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep and sustained emissions reductions and secure a liveable and sustainable future for all. **These system transitions involve a significant upscaling of a wide portfolio of mitigation and adaptation options.** Feasible, effective, and low-cost options for mitigation and adaptation are already available, with differences across systems and regions. (high confidence)”
Gosh – I wish we didn’t have to have these conversations…

“If we (very) aggressively cut greenhouse gas emissions over the next decades, we can obviate the need for large-scale carbon dioxide removal altogether.”
Relative to other carbon dioxide removal strategies, forest carbon removal is cheap, but limited

Relative to other carbon dioxide removal strategies, forest carbon removal is cheap, but limited

There are strong and divergent opinions about the role of forests for climate mitigation.
Disclaimer: Carbon should probably not be the primary reason to manage forests.
When carbon is viewed as the primary reason to think about forests . . .

it’s easy to conclude that there is no hope and that we should not expend resources on forest management.
Why carbon, forests, and climate are deeply entwined.

[or, an overview of forest carbon cycling]
Forests are highly-evolved, sophisticated ‘direct air capture’ facilities
Forests are highly-evolved, sophisticated ‘direct air capture’ facilities
Forest vegetation removes carbon dioxide from the atmosphere using 100% renewable solar energy.
Forests transfer carbon from plant tissues into soils
Here in the United States, we estimate that forests currently store 58.32 billion tonnes of carbon
Forest ecosystems are **dynamic** carbon storage facilities.
Regardless of whether forests are part of the "carbon dioxide removal" portfolio – forest carbon is a huge part of the carbon budget!
Historically, forests are a net carbon sink each year

\[ \text{CO}_2 \text{ removal} > \text{CO}_2 \text{ emissions} \]
Historically, forests are a net carbon sink each year

[CO$_2$ removal > CO$_2$ emissions]
In 2021, US forest captured ~ 593 MMT CO$_2$e
Forests emit carbon dioxide when they are disturbed or converted to other land uses.
Forests emit carbon dioxide when they are converted to other land uses

https://www.epa.gov/ghgreporting

Historical annual carbon emissions from forest conversion range from 22-125 MMT CO$_2$ per year

<table>
<thead>
<tr>
<th>Source</th>
<th>Area (Mha per year)</th>
<th>Forest Emissions (MMT CO$_2$ per year)</th>
<th>Key Regions of Opportunity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harris et al. 2016</td>
<td>0.1</td>
<td>22 ± 3.67</td>
<td>Pacific Northwest, eastern urban population centers</td>
</tr>
<tr>
<td>US EPA 2021</td>
<td>--</td>
<td>125.3 in 2021</td>
<td>---</td>
</tr>
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Forests emit carbon dioxide when they are disturbed
Wildfire in the US is leading cause of current forest fire emissions, with ~ 120 MMT of forest CO$_2$e per year (2016-2020)
Wildfire in the US is leading cause of current forest fire emissions, with ~ 120 MMT of forest CO$_2$e per year (2016-2020).


https://www.epa.gov/ghgreporting
Tree mortality from hurricanes emit an average of 18 - 66 MMT of forest CO₂ per year

Table 1 | Ten most destructive hurricane events with dates and categories at landfalling. Numbers in parentheses show minimum and maximum range

<table>
<thead>
<tr>
<th>Name</th>
<th>Landfalling Date</th>
<th>Category at Landfalling*</th>
<th>Biomass mortality (TgC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camille</td>
<td>8/15/1969</td>
<td>5</td>
<td>59.49 [41.42 ~ 77.58]</td>
</tr>
<tr>
<td>Donna</td>
<td>9/10/1960</td>
<td>4</td>
<td>51.48 [35.80 ~ 67.16]</td>
</tr>
<tr>
<td>Hazel</td>
<td>10/15/1954</td>
<td>4</td>
<td>47.39 [32.27 ~ 62.51]</td>
</tr>
<tr>
<td>Okeechobee</td>
<td>9/17/1928</td>
<td>4</td>
<td>41.22 [28.78 ~ 53.69]</td>
</tr>
<tr>
<td>Elena</td>
<td>9/1/1985</td>
<td>3</td>
<td>38.42 [26.98 ~ 49.86]</td>
</tr>
<tr>
<td>Katrina</td>
<td>8/29/2005</td>
<td>3</td>
<td>36.03 [27.75 ~ 46.29]</td>
</tr>
<tr>
<td>Gracie</td>
<td>9/29/1989</td>
<td>3</td>
<td>33.85 [23.47 ~ 44.21]</td>
</tr>
<tr>
<td>Diana</td>
<td>9/13/1984</td>
<td>3</td>
<td>33.43 [23.18 ~ 43.68]</td>
</tr>
<tr>
<td>Hugo</td>
<td>9/22/1989</td>
<td>4</td>
<td>30.47 [20.91 ~ 40.05]</td>
</tr>
<tr>
<td>Frederic</td>
<td>9/13/1979</td>
<td>3</td>
<td>30.4 [21.22 ~ 39.58]</td>
</tr>
</tbody>
</table>

*based on Saffir-Simpson scale.
Tree mortality from hurricanes on the rise?

Continental United States Hurricane Impacts/Landfalls
1851-2022
(Revised in April 2023 to add in the 2022 season)

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>States Affected and Category by States</th>
<th>Highest Saffir-Simpson U.S. Category</th>
<th>Central Pressure (mb)</th>
<th>Max Wind (kt)</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>None</td>
<td></td>
<td>0</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>2011</td>
<td>Aug NC, 1</td>
<td></td>
<td>1</td>
<td>952</td>
<td>75</td>
<td>Irene</td>
</tr>
<tr>
<td>2012</td>
<td>Aug LA, 1</td>
<td></td>
<td>1</td>
<td>966</td>
<td>70</td>
<td>Isaac</td>
</tr>
<tr>
<td>2012</td>
<td>Oct * NY, 1</td>
<td></td>
<td>1</td>
<td>942</td>
<td>65</td>
<td>Sandy</td>
</tr>
<tr>
<td>2013</td>
<td>None</td>
<td></td>
<td>0</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>2014</td>
<td>Jul NC, 2</td>
<td></td>
<td>2</td>
<td>973</td>
<td>85</td>
<td>Arthur</td>
</tr>
<tr>
<td>2015</td>
<td>None</td>
<td></td>
<td>0</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>2016</td>
<td>Sep FL, NW1</td>
<td></td>
<td>1</td>
<td>981</td>
<td>70</td>
<td>Hermine</td>
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<tr>
<td>2016</td>
<td>Oct * FL, NE2; GA, 1; SC, 1; NC, 1</td>
<td></td>
<td>2</td>
<td>963</td>
<td>85</td>
<td>Matthew</td>
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<tr>
<td>2017</td>
<td>Aug TX, C4</td>
<td></td>
<td>4</td>
<td>937</td>
<td>115</td>
<td>Harvey</td>
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<tr>
<td>2017</td>
<td>Sep FL, SW4, SE 1</td>
<td></td>
<td>4</td>
<td>931</td>
<td>115</td>
<td>Irma</td>
</tr>
<tr>
<td>2017</td>
<td>Oct LA, 1, MS 1</td>
<td></td>
<td>1</td>
<td>983</td>
<td>65</td>
<td>Nate</td>
</tr>
<tr>
<td>2018</td>
<td>Sep NC, 1</td>
<td></td>
<td>1</td>
<td>956</td>
<td>80</td>
<td>Florence</td>
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<tr>
<td>2018</td>
<td>Oct FL, NW5; 1-GA, 2</td>
<td></td>
<td>1</td>
<td>919</td>
<td>140</td>
<td>Michael</td>
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<tr>
<td>2019</td>
<td>Jul LA, 1</td>
<td></td>
<td>1</td>
<td>993</td>
<td>65</td>
<td>Barry</td>
</tr>
<tr>
<td>2019</td>
<td>Sep NC, 2</td>
<td></td>
<td>2</td>
<td>956</td>
<td>85</td>
<td>Dorian</td>
</tr>
<tr>
<td>2020</td>
<td>Jul TX, S1</td>
<td></td>
<td>1</td>
<td>973</td>
<td>80</td>
<td>Hanna</td>
</tr>
<tr>
<td>2020</td>
<td>Aug NC, 1; SC, 1</td>
<td></td>
<td>1</td>
<td>986</td>
<td>80</td>
<td>Isaías</td>
</tr>
<tr>
<td>2020</td>
<td>Aug LA, 4; TX, N1</td>
<td></td>
<td>4</td>
<td>939</td>
<td>130</td>
<td>Laura</td>
</tr>
<tr>
<td>2020</td>
<td>Sep AL, 2; FL, NW2</td>
<td></td>
<td>2</td>
<td>965</td>
<td>95</td>
<td>Sally</td>
</tr>
<tr>
<td>2020</td>
<td>Oct LA, 2</td>
<td></td>
<td>2</td>
<td>970</td>
<td>85</td>
<td>Delta</td>
</tr>
<tr>
<td>2020</td>
<td>Oct LA, 3; MS, 2; 1-AL, 1</td>
<td></td>
<td>3</td>
<td>970</td>
<td>100</td>
<td>Zeta</td>
</tr>
<tr>
<td>2021</td>
<td>Aug LA, 4</td>
<td></td>
<td>4</td>
<td>931</td>
<td>130</td>
<td>Ida</td>
</tr>
<tr>
<td>2021</td>
<td>Sep TX, N1</td>
<td></td>
<td>1</td>
<td>991</td>
<td>65</td>
<td>Nicholas</td>
</tr>
<tr>
<td>2022</td>
<td>Sep FL, SW4; 1-FL, SE1; FL, NE1; SC, 1</td>
<td></td>
<td>4</td>
<td>941</td>
<td>130</td>
<td>Ian</td>
</tr>
</tbody>
</table>
Tree mortality from forest pests and pathogens emit an average of 12.8 to 20.3 MMT of forest CO$_2$ per year


Forests emit carbon dioxide when they are disturbed.

Unplanned disturbances
Forests emit carbon dioxide when they are disturbed

Ducey 2023


Percent annual forest area harvested
But timber harvesting is estimated to be a net carbon sink because estimated annual carbon storage in wood products (446 MMT CO$_2$e) is greater than harvesting emissions (341 MMT CO$_2$e).
Carbon & Climate-Smart Forestry
"... the concept of “Climate Smart Forestry” (CSF) which we see as a more specific (climate-oriented) form of the Sustainable Forest Management paradigm. The idea behind CSF is that it considers the whole value chain from forest to wood products and energy, and illustrates that a wide range of measures can be applied to provide positive incentives for more firmly integrating climate objectives into the forest and forest sector framework. CSF is more than just storing carbon in forest ecosystems; it builds upon three main objectives:

(i) reducing and/or removing greenhouse gas emissions;
(ii) adapting and building forest resilience to climate change; and
(iii) sustainably increasing forest productivity and incomes. “
Forestry for reducing or removing greenhouse gas emission
Forests are highly-evolved, sophisticated ‘direct air capture’ facilities
Forestry for reducing or removing greenhouse gas emission

1. Increase the total amount of forestland
2. Increase forest carbon dioxide removal efficiency
3. Increase durability of forest carbon storage
Increase the total area of forest

Reforestation & Afforestation

Avoiding deforestation

NLCD 2016 Landcover

Key to Land Cover Types
- Open Water
- Perennial Ice and Snow
- Developed, Open Space
- Developed, Low Intensity
- Developed, Medium Intensity
- Developed, High Intensity
- Barren Land
- Deciduous Forest
- Evergreen Forest
- Mixed Forest
- Dwarf/Scrub
- Shrub/Scrub
- Grassland/Herbaceous
- Sedge/Herbaceous
- Moss
- Pasture/Hay
- Cultivated Crops
- Woody Wetlands
- Emergent Herbaceous Wetlands

NLCD 2016 Land Cover for the conterminous United States represented as 16 land cover classes.
Increase the total area of forest

Reforestation & Afforestation

Avoiding deforestation

Building new direct air capture facilities

Decommissioning existing direct air capture facilities
Planting trees is highly likely to increase total forestland carbon storage for the United States.

<table>
<thead>
<tr>
<th>Study</th>
<th>Reforestation &amp; Afforestation Considerations</th>
<th>Area (Mha)</th>
<th>Mitigation Potential (MMT CO₂ per year)</th>
<th>Cost</th>
<th>Key Regions of Opportunity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cook-Patton et al. 2020</td>
<td>Restoring tree cover in former forestland</td>
<td>51.6</td>
<td>314.2</td>
<td>~ 50% at &lt; $20 tCO₂ -1</td>
<td>Southeast</td>
</tr>
<tr>
<td>Fargione et al. 2018</td>
<td>Reforesting former forestland that is not currently wetland, active cropland, or livestock pastureland.</td>
<td>62.9</td>
<td>306.6</td>
<td>~ 80% &lt; $50 USD Mg CO₂e-1</td>
<td>Northeast and south central</td>
</tr>
<tr>
<td>Haight et al. 2020</td>
<td>Incentivizing private landowners in the eastern US to plant trees and planting trees in federal forests in the west.</td>
<td>15.1</td>
<td>107</td>
<td>6.5 Billion</td>
<td>South</td>
</tr>
<tr>
<td>Wear and Coulston 2015</td>
<td>Incentivizing private landowners in the eastern US to retire croplands and plant trees and planting trees in federal forests in the west.</td>
<td>7.73</td>
<td>27.6</td>
<td>--</td>
<td>South and Pacific Northwest</td>
</tr>
<tr>
<td>Zhang et al. 2023</td>
<td>Planting pine trees in the southeastern United States for pineland restoration</td>
<td>2.1</td>
<td>71.14</td>
<td>$1.22 per tonne</td>
<td>Southeast</td>
</tr>
</tbody>
</table>
Future projections estimate that avoiding forest conversion could protect ~39 MMT CO$_2$e

<table>
<thead>
<tr>
<th>Source</th>
<th>Forest C Protection (MMT CO$_2$ per year)</th>
<th>Key Regions of Opportunity</th>
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<tr>
<td>Fargione et al. 2018</td>
<td>38</td>
<td>Southern, Pacific Northwest</td>
</tr>
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<td>Haight et al. 2020</td>
<td>39</td>
<td>Rocky Mountains</td>
</tr>
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Forestry for reducing or removing greenhouse gas emission

1. Increase the total amount of forest

2. Increase forest carbon dioxide removal efficiency
In 2021, US forest captured ~ 593 MMT CO$_2$e
Increase forest carbon dioxide removal efficiency

Increasing # trees (stocking density) within existing forestlands

“Improved Forest Management” to promote tree health

Increasing the number of fans and filters at an existing DAC facilities

Maintenance of broken fans and filters
Understocked US timberlands sequester 20% less carbon dioxide and store 30% less carbon in trees than fully stocked forests.
Fully stocking understocked timberland could increase forest CO$_2$ removals by 20% (187.7 ± 9.1 MMT CO$_2$) per year.

Domke et al. 2020, Proceedings of the National Academy of Science, DOI 10.1073/pnas.2010840117
What is IFM?

TABLE 4 Definition of improved forest management proposed by this synthesis

<table>
<thead>
<tr>
<th>Proposed definition</th>
<th>Silvicultural management practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved forest management (IFM)</td>
<td>Extended rotations</td>
</tr>
<tr>
<td>IFM encompasses a range of silvicultural management actions that incorporate above-</td>
<td>Thinning for stand improvement and fuel management</td>
</tr>
<tr>
<td>and below-ground biomass C components, as well soil C stocks.</td>
<td>Promoting uneven-aged forest management (including partial harvesting)</td>
</tr>
<tr>
<td></td>
<td>Facilitating stand re-establishment/regeneration and seedling survival</td>
</tr>
<tr>
<td></td>
<td>Avoiding logging damage to remaining trees</td>
</tr>
<tr>
<td></td>
<td>Species selection: retaining native species, and if possible, diversifying species in stand</td>
</tr>
<tr>
<td></td>
<td>Minimizing soil disturbance and extensive soil damage: compaction, mixing and displacement</td>
</tr>
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<td></td>
<td>Retain coarse woody debris (stumps, downed trees, snags) in a stand</td>
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"Improved Forest Management"

What is IFM?

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</table>

Extended rotations of private, commercial forestland estimated to avoid 267 MMT forest CO₂ emissions per year


Zuckerman 2021, *Northwest Natural Resource Group*
Limited empirical or modeling work on the direct effects of IFM on forest carbon stocks and sequestration at regional or national scales
Ecological theory and local studies support IFM as a tool

Reduced-Impact Logging as a Carbon-Offset Method

Conservation Biology
Volume 7, No. 4, December 1993
Ecological theory and local studies support IFM as a tool

Avoiding soil disturbance

A new study finds that the period of frozen ground has declined by an average of two or three weeks since 1948. Logging trucks have a harder time accessing forests with wet, unfrozen soil – and can leave their marks along the way.

Photo: Wisconsin DNR

https://news.wisc.edu/muddy-forests-shorter-winters-present-challenges-for-loggers/
Forestry for reducing or removing greenhouse gas emission

1. Increase the total amount of forest
2. Increase forest carbon dioxide removal efficiency
3. Increase durability of forest carbon storage
Forests emit carbon dioxide when they are disturbed.

Unplanned disturbances

Planned disturbances
Forests emit carbon dioxide when they are disturbed.

Unplanned disturbances = Less direct control
- Impossible to predict over space and time;
- impact of disturbance on forest varies locally;

Planned disturbances = More control
Unplanned disturbances are projected to increase with increasing atmospheric CO$_2$
Forests are part of our carbon accounting budget – whether we choose to manage or not.

ALL climate mitigation facilities can be disturbed by hurricanes and wildfires

Weather tracker: Hurricane Idalia leaves trail of damage in Florida
Matt Williams for MetDesk

Category 3 storm causes extensive flooding in south-east US, while heavy rain and winds also hit France and Italy

In case of hurricane, apply Enphase, tighten bolts and mind your wind codes!

FEMA’s recommendations for solar system hurricane preparedness focused on structural engineering, installation competence, plus simply tightening the bolts regularly, along with microinverters to mitigate individual panel damage.

November 29, 2021 JON FITZGERALD WOLBER

Kilo Fire. Photo credit, Los Angeles County Fire Department.
ALL carbon storage facilities can be ‘leaky’
Increase durability of forest carbon

- Increase forest resilience to unplanned disturbances
- Increase infrastructure resilience to unplanned disturbances
- Increase climate benefits harvested wood products
- ?
‘Improved forest management’ practices likely to increase forest resilience, but empirical data is local and limited.

**TABLE 4** Definition of improved forest management proposed by this synthesis

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<td>Retain coarse woody debris (stumps, downed trees, snags) in a stand</td>
</tr>
</tbody>
</table>

But data is coming...
Managing for forest resilience to wildfire and pests and pathogens

Increase forest resilience to unplanned disturbances
Thinning overstocked forests can reduce wildfire impact

WILDFIRE RESILIENCE INSURANCE:
Quantifying the Risk Reduction of Ecological Forestry with Insurance

Summary of Insights

UNMANAGED FOREST  Fire in an unmanaged ponderosa pine forest (where fires have been repeatedly suppressed): Overcrowding can make the forest less healthy and resilient. When such a forest burns, the fire can extend into the crowns, killing large swaths of trees. © Erica Sloniker / TNC

MANAGED FOREST  Fire in a managed ponderosa pine forest (using controlled burns with or without mechanical thinning): A fire burns low through the understory, maintaining gaps between some trees that help prevent future large crown fires. © Erica Sloniker / TNC

Increase forest resilience to unplanned disturbances

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But because we do not know when or where fire will occur, fire resilience treatments may opt to prioritize human and ecological communities...not carbon.
Protecting forests from introduced pests and pathogens: the old

Laurel wilt disease, Georgia © Kevin Potter
Balsalm Wooly Adelgid, Tennessee © Kevin Potter
Mountain Pine Beetle, Colorado © Wikimedia
Protecting forests from introduced pests and pathogens: the NEW

Aukema et al. 2010, BioScience, DOI 10.1525/bio.2010.60.11.5
We need more robust policies to prevent accidental introduction of forest pests

Scientists’ warning on invasive alien species

Petr Pyšek1,2,3*, Philip E. Hulme4, Dan Simberloff5, Sven Bacher6, Tim M. Blackburn7,8,3, James T. Carlton9, Wayne Dawson10, Franz Essl11,3, Llewellyn C. Foxcroft11,12,4, Piero Genovesi13,3, Jonathan M. Jeschke14,15,16, Ingolf Kühn17,18,19, Andrew M. Liebhold20,21, Nicholas E. Mandrak22, Laura A. Meyerson23, Aníbal Pauchard24,25, Jan Pergl1, Helen E. Roy26, Hanno Seebens27, Mark van Kleunen28,29, Montserrat Vila30,31, Michael J. Wingfield32, and David M. Richardson3

Aukema et al. 2010, BioScience, DOI 10.1525/bio.2010.60.11.5
Wood products may have additional climate benefits through energy & product substitution

Planned disturbances
Wood products may have additional climate benefits through energy & product substitution.
Innovative, commercial pine planting could mitigate ~ 3-4 billion metric tonnes CO$_2$e over 100 years
Conclusions

1) Land managers and policy makers are actively discussing “Carbon forestry” for climate mitigation

2) Carbon, forestry, and climate are deeply entwined and whether we chose to act or not – forest carbon is part of the globe’s carbon budget.

3) There are a host of Climate-Smart Forestry practices that hold promise for climate adaptation and mitigation
Disclaimer: Carbon should probably not be the primary reason to manage forests.
Sara Kuebbing
Director of Research
Yale Applied Science Synthesis Program

sara.kuebbing@yale.edu