# The Global Forest Carbon Budget: Inventory and Modeling


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**AGU Fall Meeting 2014**

B54C "Global Forest Dynamics and Interactions with a Changing Climate"

19 December 2014

ORNL is managed by UT-Battelle
for the US Department of Energy

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# **Model and Inventory Perspectives on the Role of Forests in the Global Carbon Cycle:** Results from the Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP)

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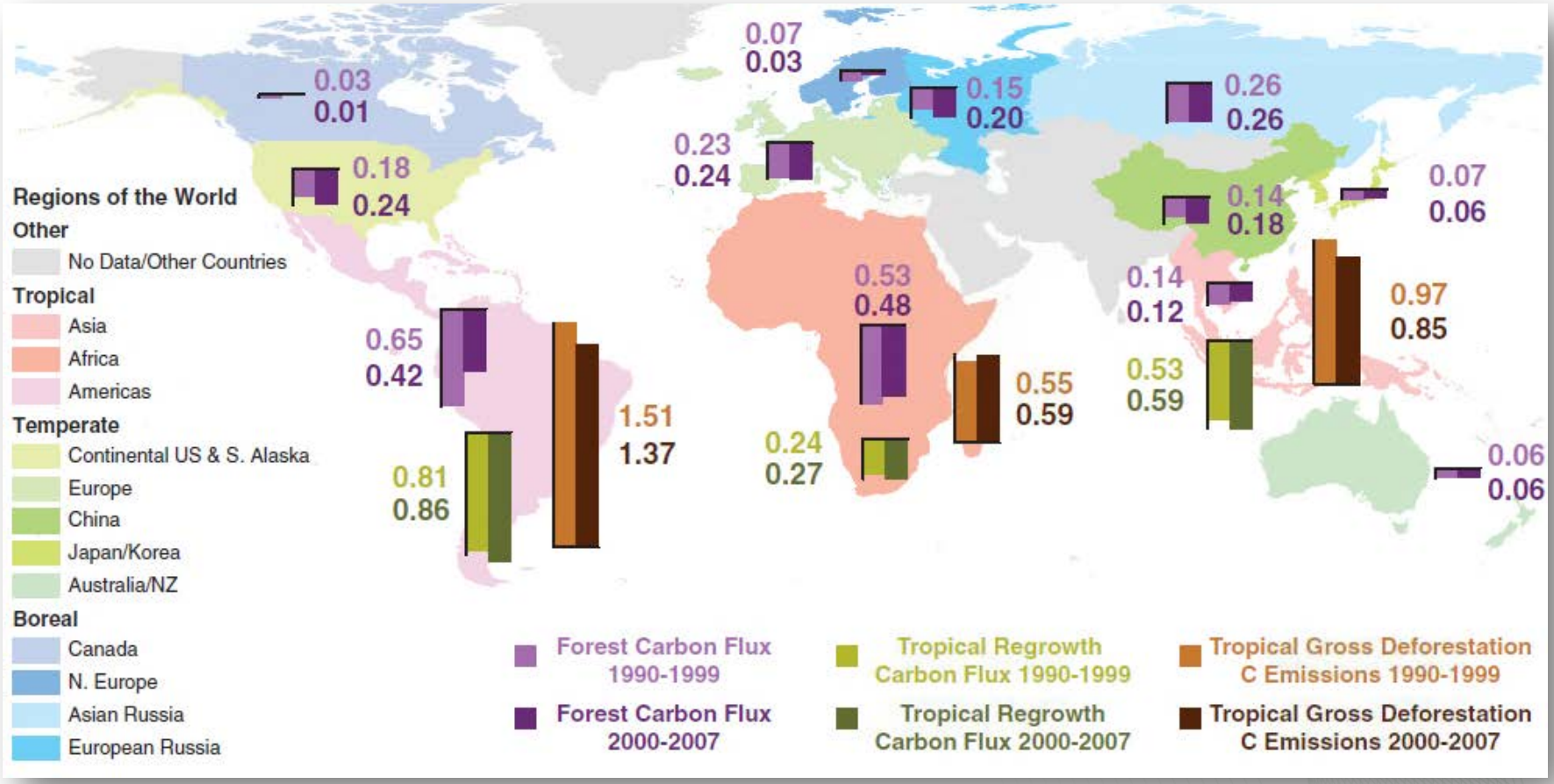
# A Large and Persistent Carbon Sink in the World's Forests

Yude Pan *et al.*

*Science* **333**, 988 (2011);
DOI: 10.1126/science.1201609



# The Role of Forests in the Global C Budget

**Table 3.** The global carbon budget for two time periods (Pg C year$^{-1}$). There are different arrangements to account for elements of the global C budget (see also table S6). Here, the accounting was based on global C sources and sinks. The terrestrial sink was the residual derived from constraints of two major anthropogenic sources and the sinks in the atmosphere and oceans. We used the C sink in global established forests as a proxy for the terrestrial sink.

| Sources and sinks | 1990–1999 | 2000–2007 |
|---|---|---|
| | *Sources (C emissions)* | |
| Fossil fuel and cement* | 6.5 ± 0.4 | 7.6 ± 0.4 |
| Land-use change† | 1.5 ± 0.7 | 1.1 ± 0.7 |
| Total sources | 8.0 ± 0.8 | 8.7 ± 0.8 |
| | *Sinks (C uptake)* | |
| Atmosphere† | 3.2 ± 0.1 | 4.1 ± 0.1 |
| Ocean‡ | 2.2 ± 0.4 | 2.3 ± 0.4 |
| Terrestrial (established forests)§ | 2.5 ± 0.4 | 2.3 ± 0.5 |
| Total sinks | 7.9 ± 0.6 | 8.7 ± 0.7 |
| Global residuals‖ | 0.1 ± 1.0 | 0.0 ± 1.0 |

38%

30%

Pan et al. 2011 *Science*

# The Role of Forests in the Global C Budget

## Persistent uptake / increasing sinks?

- Fertilization from increasing atmospheric $CO_2$ and N deposition
- Favorable climate conditions
- Longer growing seasons
- Vegetation dynamics / plant migration
- Forest management, carbon storage

## Weakening sinks / increasing sources?

- Atmospheric pollution
- Unfavorable climate conditions
- Disturbances (fire, insects, disease, storms, etc.)
- Deforestation / land use change
- Logging, resource extraction, degradation

# Diagnosis, Attribution & Prediction

Strengths & weaknesses of alternative approaches

(Hayes et al. 2012 *GCB*)

**Table 5** A comparison of the strengths and weaknesses of alternative NEE scaling approaches (inventory-based, AIMs and TBMs)

| | Inventory-based | Atmospheric inversion models (AIMs) | Terrestrial biosphere models (TBMs) |
|---|---|---|---|
| Strengths | 1) Employs a large number of repeated biomass measurements<br>2) Allows estimation of product-related C sources | 1) assimilates measurements of atmospheric $CO_2$ concentration<br>2) Employs atmospheric mass balance | 1) Processes are represented so attribution is possible<br>2) Sensitive to interannual variation in climate<br>3) Many opportunities for validation |
| Weaknesses | 1) Not all C pools are measured<br>2) Possible undersampling<br>3) Limited attribution ability<br>4) Missing NEE of unmanaged ecosystems<br>5) Poorly resolved temporally | 1) Transport model uncertainty<br>2) Limited number of $CO_2$ measurements<br>3) Low spatial resolution<br>4) Limited attribution ability | 1) Many inputs, each with their own uncertainty<br>2) Many parameters, each with their own uncertainty<br>3) Spatial resolution may not resolve management scale disturbances |

# Multi-scale Synthesis & Terrestrial Model Intercomparison Project (MSTMIP)

- Over 19 different institutions
- Over 20 different models
  - ~6 dynamic vegetation models
  - ~9 models have prognostic fire
  - ~2 data assimilation models
- Most models participated in NACP site and/or regional interim synthesis activities

| | | | |
|---|---|---|---|
| VEGAS | DLEM | CLM-VIC | ISAM |
| SIPNET | PRIPLEX-GHG | LPJ-wsl | Ecosys |
| MC1 | CLASS-CTEM-N+ | GEMS | ORCHIDEE |
| SiB | SiB-CASA | TEM | CLM-CN |
| Biome-BGC | IRC | ED | GTEC |

*+ multiple models out of JPL*

Huntzinger et al. 2013 *GMD*

# MSTMIP Formal Simulation Protocol

| Order | Domain | Code | Climate | LULUC | Atm. $CO_2$ | Nitrogen |
|---|---|---|---|---|---|---|
| 1 | Global  | RG1 | Constant | Constant | Constant | Constant |
| 2 | | SG1 | CRU+NCEP | | | |
| 3 | | SG2 | | Hurtt et al. | | |
| 4 | | SG3 | | | Observed | |
| 5 | | BG1 | | | | Observed |
| 6 | North Amer.  | RR1 | Constant | Constant | Constant | Constant |
| 7 | | SR1 | NARR | | | |
| 8 | | SR2 | | Hurtt et al. | Observed | |
| 9 | | SR3 | | | | |
| 10 | | BR1 | | | | Observed |

Huntzinger et al. 2013 *GMD;* Wei et al., 2013 *ORNL DAAC*

# **Methods:** Model estimates vs. Inventory

## Summary & Analysis

- Carbon stock change in vegetation & soils (wood products N/A)
- Annual averages per decade: 1980s, 1990s, 2000s
- Time-varying forest mask of 0.5° grid cells as "inventory region" for model estimates
- Forest area divided into biome + country / region for 21 reporting units
- Uncertainty in model estimates calculated as 1 σ around the mean of model results across the ensemble

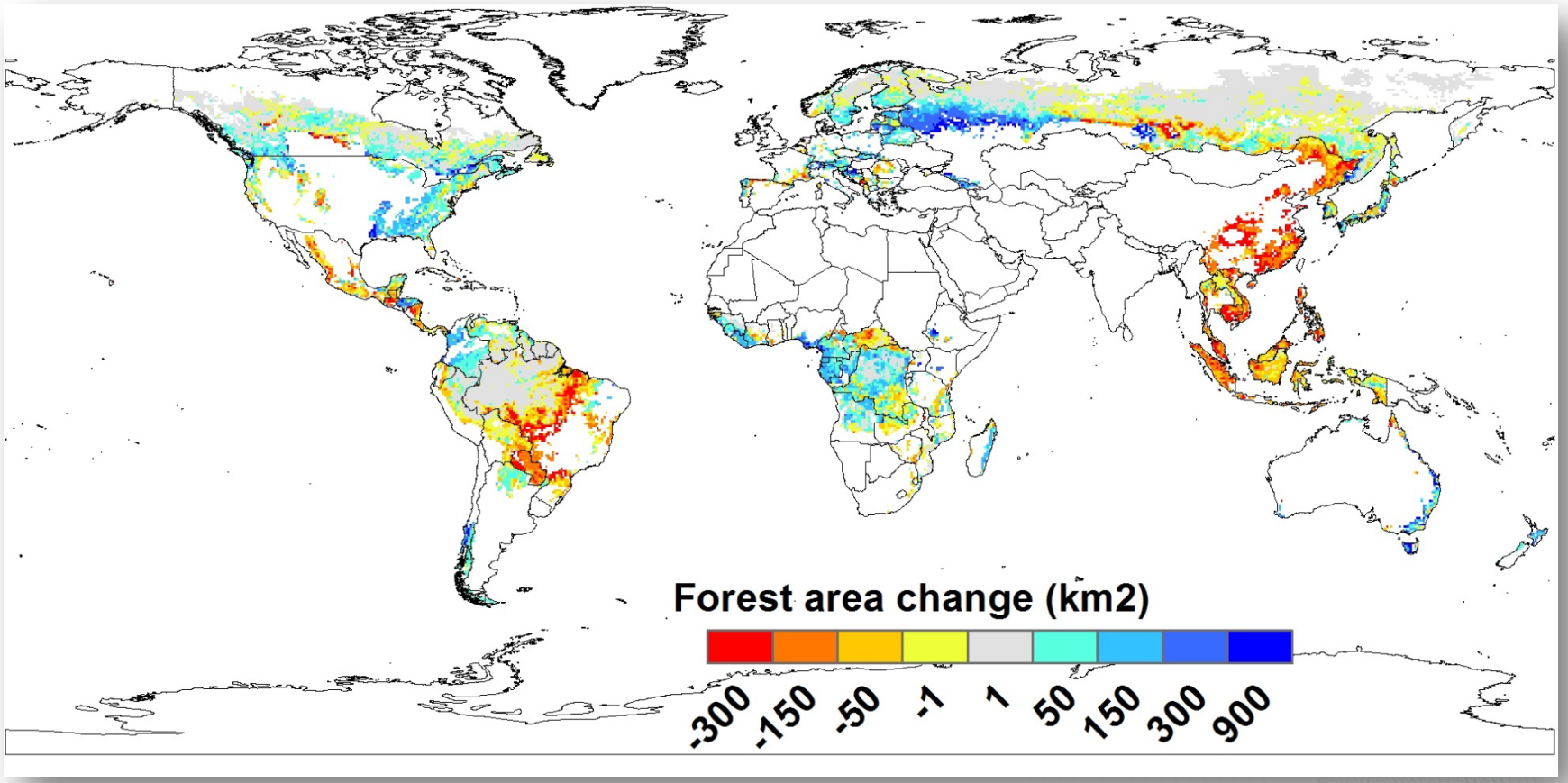
Table 2. Estimated annual change in C stock (Tg C year$^{-1}$) by biomes by country or region for the time periods of 1990 to 1999 and 2000 to 2007. Estimates include C stock changes on "forest land remaining forest land" and "new forest land" (afforested land). The uncertainty calculation refers to the supporting online material. ND, data not available; [1], litter is included in soils.

| Biome and country/region | 1990–1999 | | | | | | | | 2000–2007 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Biomass | Dead wood | Litter | Soil | Harvested wood product | Total stock change | Uncertainty (±) | Stock change per area (Mg C ha$^{-1}$ year$^{-1}$) | Biomass | Dead wood | Litter | Soil | Harvested wood product | Total stock change | Uncertainty (±) | Stock change per area (Mg C ha$^{-1}$ year$^{-1}$) |
| | (Tg C year$^{-1}$) | | | | | | | | (Tg C year$^{-1}$) | | | | | | | |
| *Boreal** | | | | | | | | | | | | | | | | |
| Asian Russia | 61 | 66 | 63 | 45 | 19 | 255 | 64 | 0.39 | 69 | 97 | 43 | 42 | 13 | 264 | 66 | 0.39 |
| European Russia | 37 | 10 | 22 | 36 | 41 | 146 | 37 | 0.93 | 84 | 19 | 35 | 35 | 26 | 199 | 50 | 1.21 |
| Canada | 6 | –24 | 14 | 6 | 23 | 26 | 7 | 0.11 | –53 | 16 | 19 | 7 | 21 | 10 | 3 | 0.04 |
| European boreal† | 13 | 0 | 3 | 38 | 11 | 65 | 16 | 1.12 | 21 | 0 | 4 | –10 | 13 | 27 | 7 | 0.45 |
| Subtotal | 117 | 53 | 103 | 125 | 94 | 493 | 76 | 0.45 | 120 | 132 | 101 | 74 | 73 | 499 | 83 | 0.44 |
| *Temperate** | | | | | | | | | | | | | | | | |
| United States‡ | 118 | 6 | 13 | 9 | 33 | 179 | 34 | 0.72 | 147 | 9 | 18 | 37 | 28 | 239 | 45 | 0.94 |
| Europe | 117 | 2 | 8 | 81 | 24 | 232 | 58 | 1.71 | 137 | 2 | 9 | 65 | 27 | 239 | 60 | 1.68 |
| China | 60 | 22 | 15 | 31 | 7 | 135 | 34 | 0.96 | 115 | 24 | 8 | 28 | 7 | 182 | 45 | 1.22 |
| Japan | 24 | 9 | ND | 19 | 2 | 54 | 14 | 2.28 | 23 | 5 | ND | 8 | 2 | 37 | 9 | 1.59 |
| South Korea | 6 | 2 | ND | 5 | 0 | 14 | 4 | 2.14 | 12 | 2 | ND | 4 | 0 | 18 | 5 | 2.86 |
| Australia | 17 | ND | 10 | 15 | 8 | 50 | 13 | 0.33 | 17 | ND | 10 | 14 | 10 | 51 | 13 | 0.34 |
| New Zealand | 1 | 0 | 0 | 1 | 5 | 7 | 2 | 0.91 | 1 | 0 | 0 | 1 | 6 | 9 | 2 | 1.05 |
| Other countries | 1 | ND | ND | ND | 0 | 1 | 1 | 0.07 | 2 | 0 | 0 | 0 | 0 | 3 | 2 | 0.18 |
| Subtotal | 345 | 42 | 46 | 160 | 80 | 673 | 78 | 0.91 | 454 | 42 | 45 | 156 | 80 | 777 | 89 | 1.03 |
| *Tropical intact* | | | | | | | | | | | | | | | | |
| Asia | 125 | 13 | 2 | ND | 5 | 144 | 38 | 0.88 | 100 | 10 | 2 | ND | 6 | 117 | 30 | 0.90 |
| Africa | 469 | 48 | 7 | ND | 9 | 532 | 302 | 0.94 | 425 | 43 | 6 | ND | 8 | 482 | 274 | 0.94 |
| Americas | 573 | 48 | 9 | ND | 22 | 652 | 166 | 0.77 | 345 | 45 | 5 | ND | 23 | 418 | 386 | 0.53 |
| Subtotal | 1167 | 109 | 17 | ND | 35 | 1328 | 347 | 0.84 | 870 | 98 | 13 | ND | 36 | 1017 | 474 | 0.71 |
| Global subtotal§ | 1630 | 204 | 166 | 286 | 209 | 2494 | 363 | 0.73 | 1444 | 273 | 158 | 230 | 189 | 2294 | 489 | 0.69 |
| *Tropical regrowth* | | | | | | | | | | | | | | | | |
| Asia | 498 | ND | [1] | 27 | ND | 526 | 263 | 3.52 | 564 | ND | [1] | 30 | ND | 593 | 297 | 3.53 |
| Africa | 169 | ND | [1] | 73 | ND | 242 | 121 | 1.48 | 188 | ND | [1] | 83 | ND | 271 | 135 | 1.47 |
| Americas | 694 | ND | [1] | 113 | ND | 807 | 403 | 4.67 | 745 | ND | [1] | 113 | ND | 858 | 429 | 4.56 |
| Subtotal | 1361 | ND | [1] | 213 | ND | 1574 | 496 | 3.24 | 1497 | ND | [1] | 226 | ND | 1723 | 539 | 3.19 |
| *All tropics‖* | | | | | | | | | | | | | | | | |
| Asia | 623 | 13 | 2 | 27 | 5 | 670 | 266 | 2.14 | 664 | 10 | 2 | 30 | 6 | 711 | 298 | 2.38 |
| Africa | 638 | 48 | 7 | 73 | 9 | 774 | 325 | 1.06 | 613 | 43 | 6 | 83 | 8 | 753 | 305 | 1.08 |
| Americas | 1267 | 48 | 9 | 113 | 22 | 1458 | 436 | 1.42 | 1090 | 45 | 5 | 113 | 23 | 1276 | 577 | 1.30 |
| Subtotal | 2529 | 109 | 17 | 213 | 35 | 2903 | 605 | 1.40 | 2367 | 98 | 13 | 226 | 36 | 2740 | 718 | 1.38 |
| Global total¶ | 2991 | 204 | 166 | 498 | 209 | 4068 | 615 | 1.04 | 2941 | 273 | 158 | 456 | 189 | 4017 | 728 | 1.04 |

Pan et al. 2011 *Science*

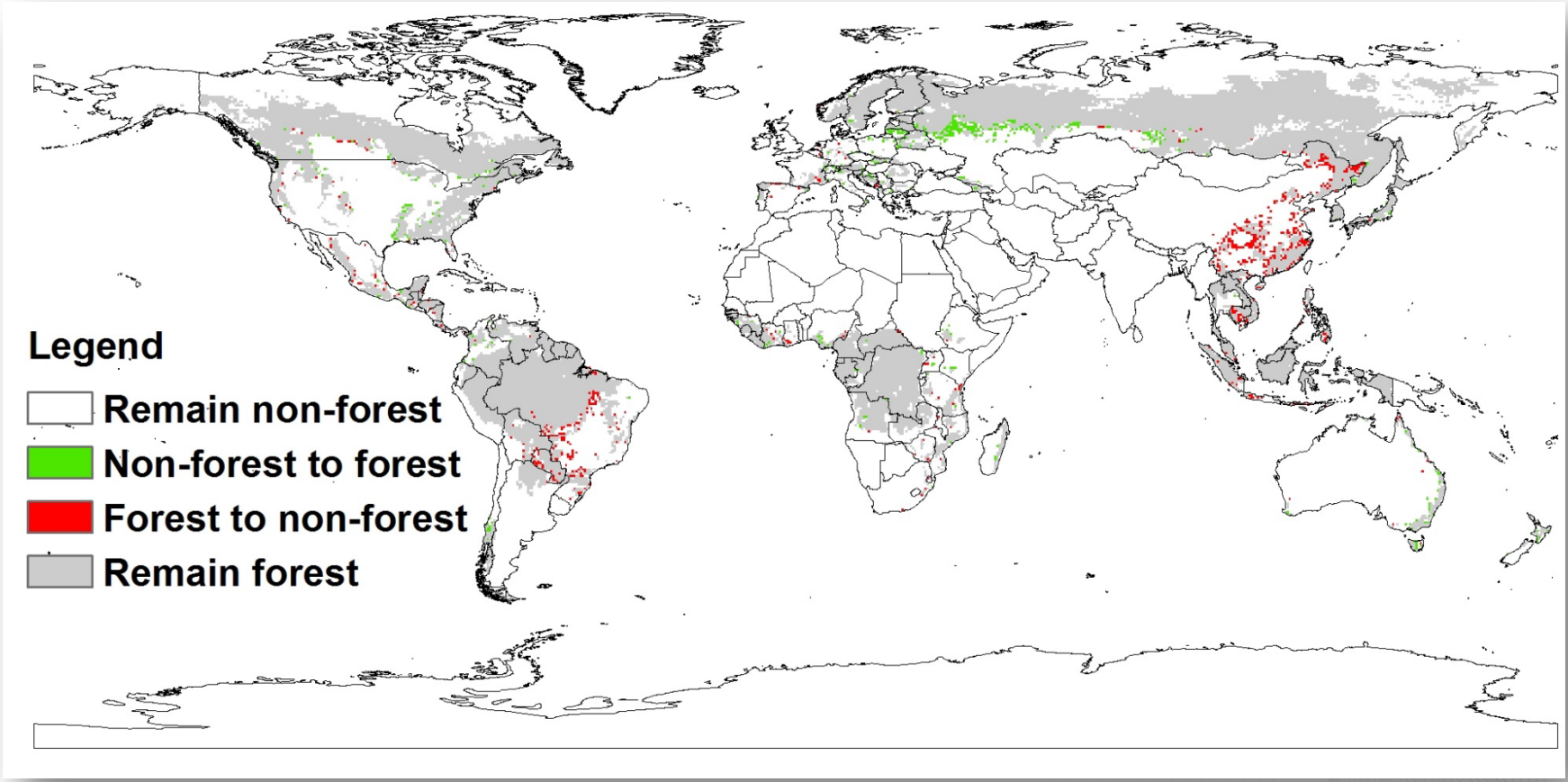
# **Methods:** Model estimates vs. Inventory

## Change in forest **AREA**, 1980 – 2010



# **Methods:** Model estimates vs. Inventory

## Change in forest **MASK**, 1980 – 2010



**Carbon sinks and sources in the world's forests:** comparing national / regional inventory estimates of total carbon stock change (PgC $yr^{-1}$) for the 1990's and 2000's against the mean and standard deviation of estimates from the MsTMIP ensemble.

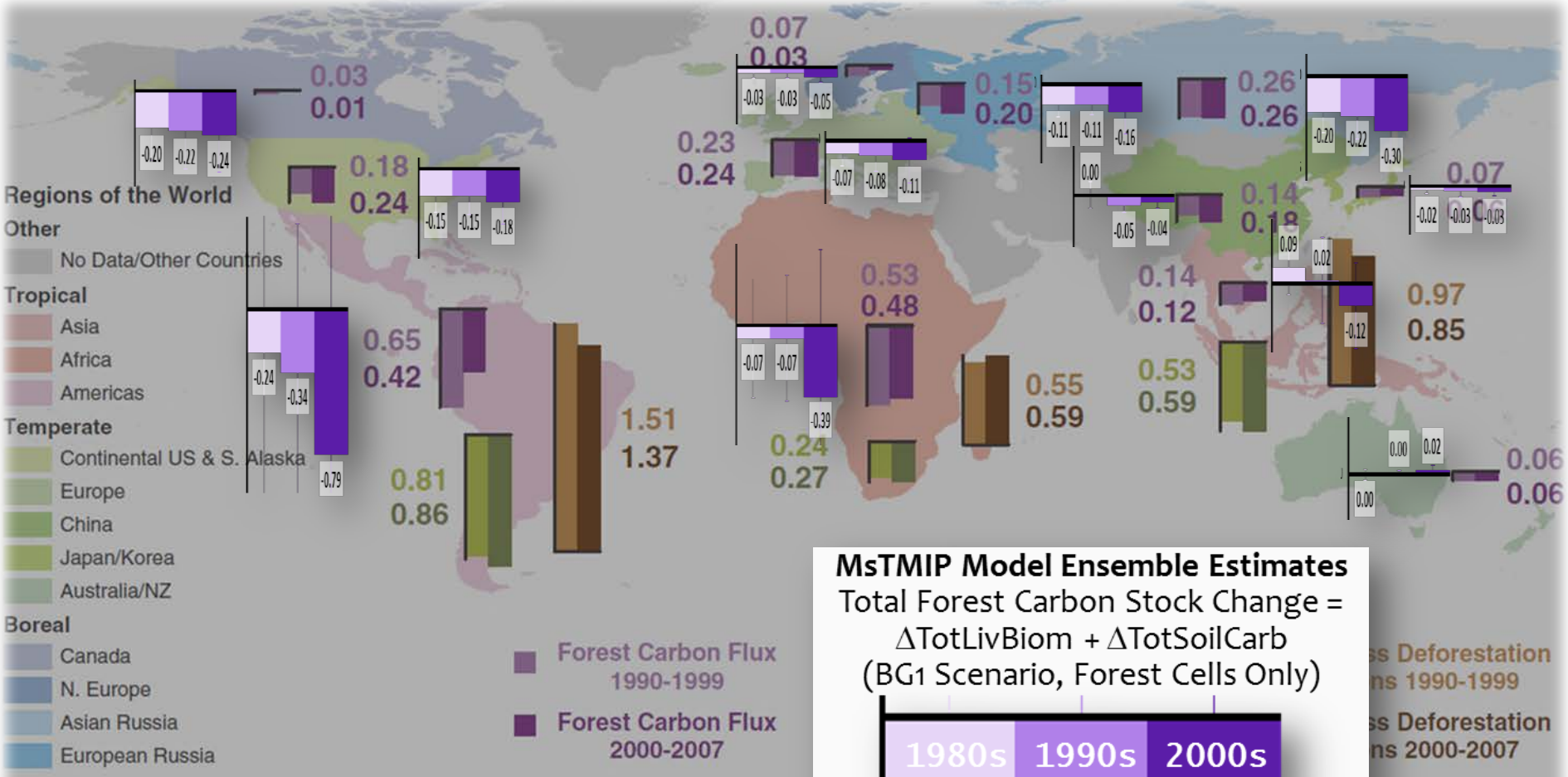



**Fig. 1.** Carbon sinks and sources (Pg C $year^{-1}$) in the world's forests. Colored bars in the down-facing direction represent C sinks, whereas bars in the upward-facing direction represent C sources. Light and dark purple, global ... forests); light and dark green, tropical regrowth forests after anthropogenic disturbances; and light and dark brown, tropical gross deforestation emissions.

# MsTMIP vs. Forest Carbon Inventory:

**Δ Total C (PgC $yr^{-1}$):** model ensemble estimates (highlighted in blue) compared with inventory estimates (gray text)

* Both the model and inventory estimates combine all tropical forest estimates (= intact + regrowth + deforestation)

| Carbon sink and source in biomes | 1990–1999 | 2000–2007 | 1990–2007 |
|---|---|---|---|
| Boreal forest | 0.50 +/- 0.08 | 0.50 +/- 0.08 | 0.50 +/- 0.08 |
| | 0.58 +/- 0.38 | 0.75 +/- 0.51 | 0.66 +/- 0.44 |
| Temperate forest | 0.67 +/- 0.08 | 0.78 +/- 0.09 | 0.72 +/- 0.08 |
| | 0.31 +/- 0.21 | 0.34 +/- 0.24 | 0.33 +/- 0.22 |
| Tropical forest* | -0.13 +/- 1.05 | -0.08 +/- 1.17 | -0.11 +/- 1.11 |
| | 0.40 +/- 1.30 | 1.29 +/- 2.61 | 0.85 +/- 1.90 |
| **Global net forest sink#** | 1.04 +/- 1.21 | 1.20 +/- 1.34 | 1.11 +/- 1.27 |
| | 1.27 +/- 1.74 | 2.33 +/- 3.00 | 1.84 +/- 2.47 |

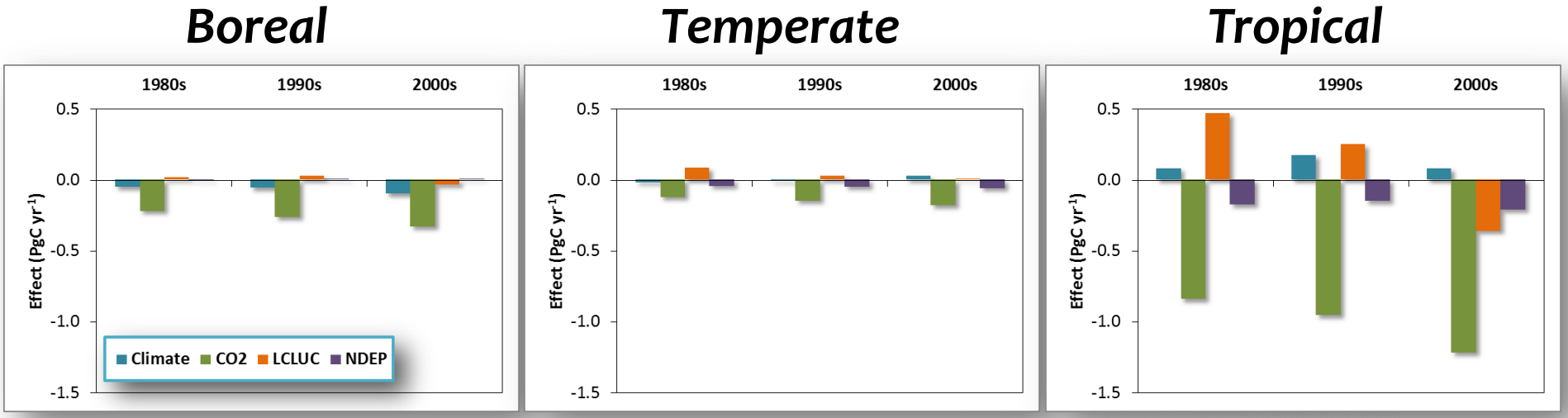
# MsTMIP vs. Forest Carbon Inventory:

**Δ Total C (PgC yr$^{-1}$):** model ensemble estimates (highlighted in blue) compared with inventory estimates (gray text)

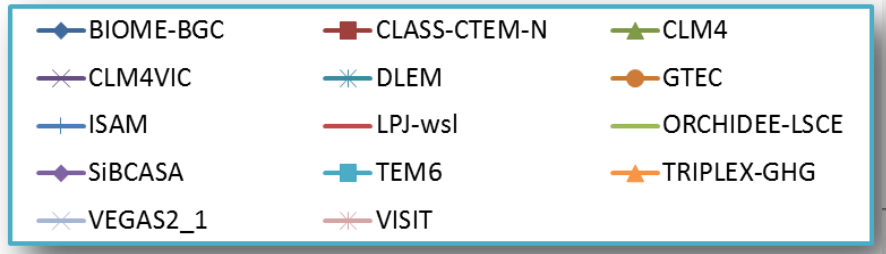
| Biome and country / region | 2000-2007 | | | | |
|---|---|---|---|---|---|
| | Biomass | Dead organic matter | Harvested wood product | Total stock change | Uncertainty (+/-) |
| | ( Tg C year $^{-1}$) | | | | |
| Asian Russia | 69 | 182 | 13 | 264 | 66 |
| | 344 | -43 | ? | 304 | 196 |
| European Russia | 84 | 89 | 26 | 199 | 50 |
| | 163 | -17 | ? | 156 | 110 |
| Canada | –53 | 42 | 21 | 10 | 3 |
| | 256 | -28 | ? | 237 | 198 |
| UnitedStates‡ | 147 | 64 | 28 | 239 | 45 |
| | 184 | -15 | ? | 180 | 120 |
| Europe | 137 | 76 | 27 | 239 | 60 |
| | 103 | -7 | ? | 109 | 122 |
| China | 115 | 60 | 7 | 182 | 45 |
| | 43 | -11 | ? | 39 | 29 |

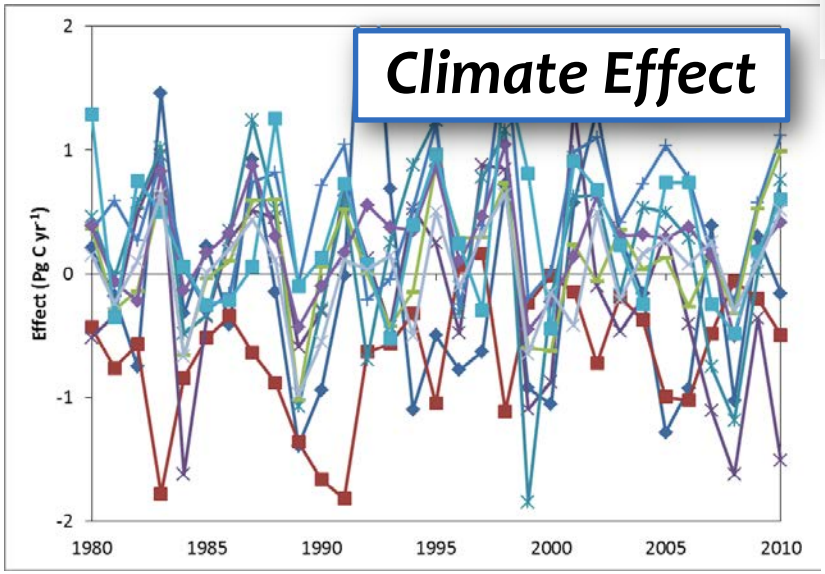
# Driver Effects

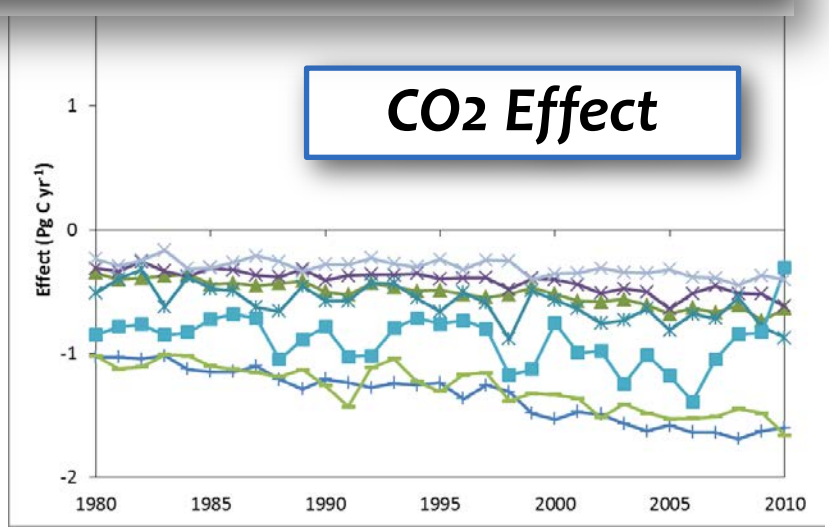
- Effect of Climate, CO2, Land use change, and N deposition on model estimates of Δ Total Forest Carbon (Pg C $yr^{-1}$) per decade

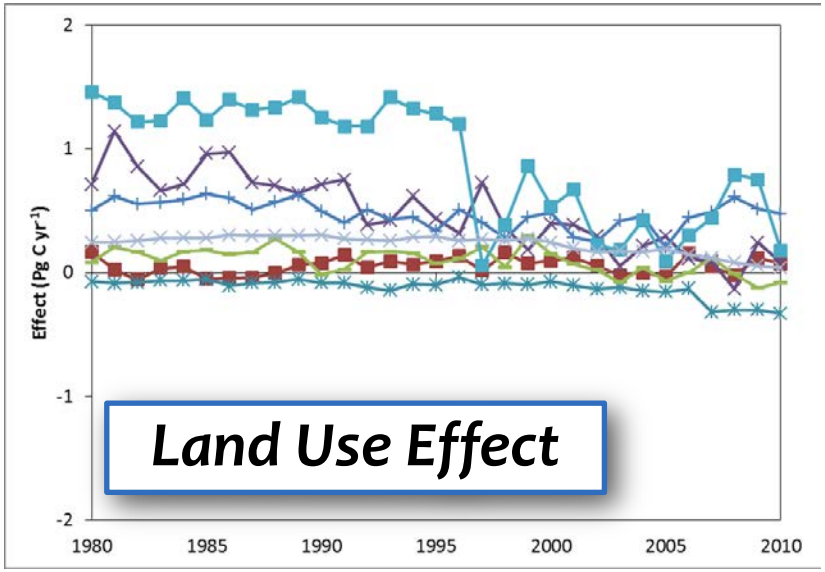


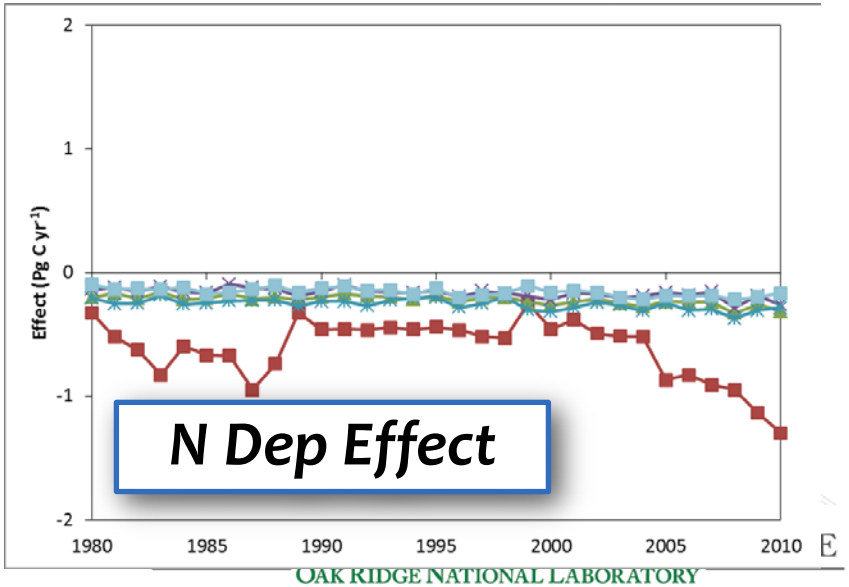
# Model Sensitivity



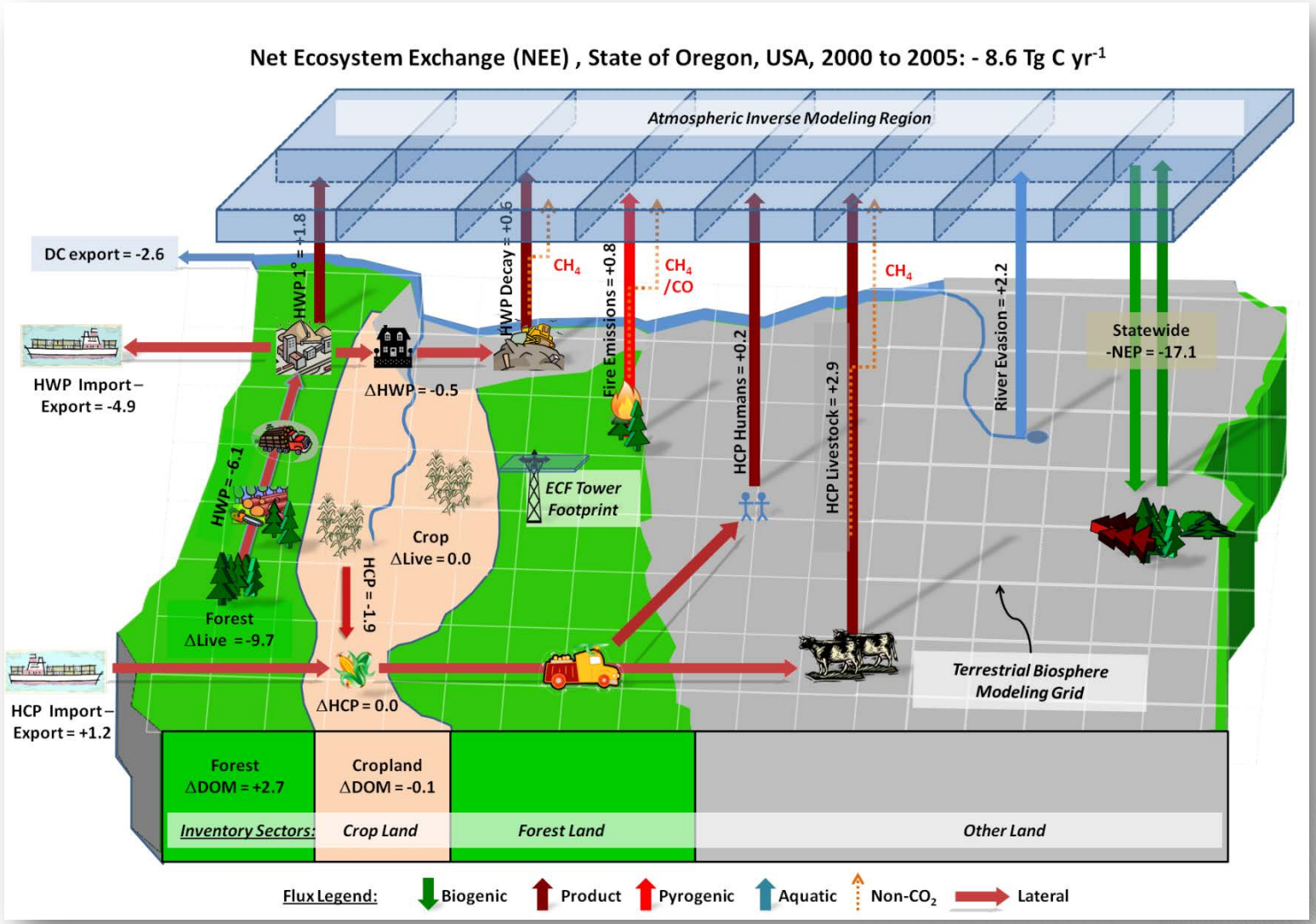



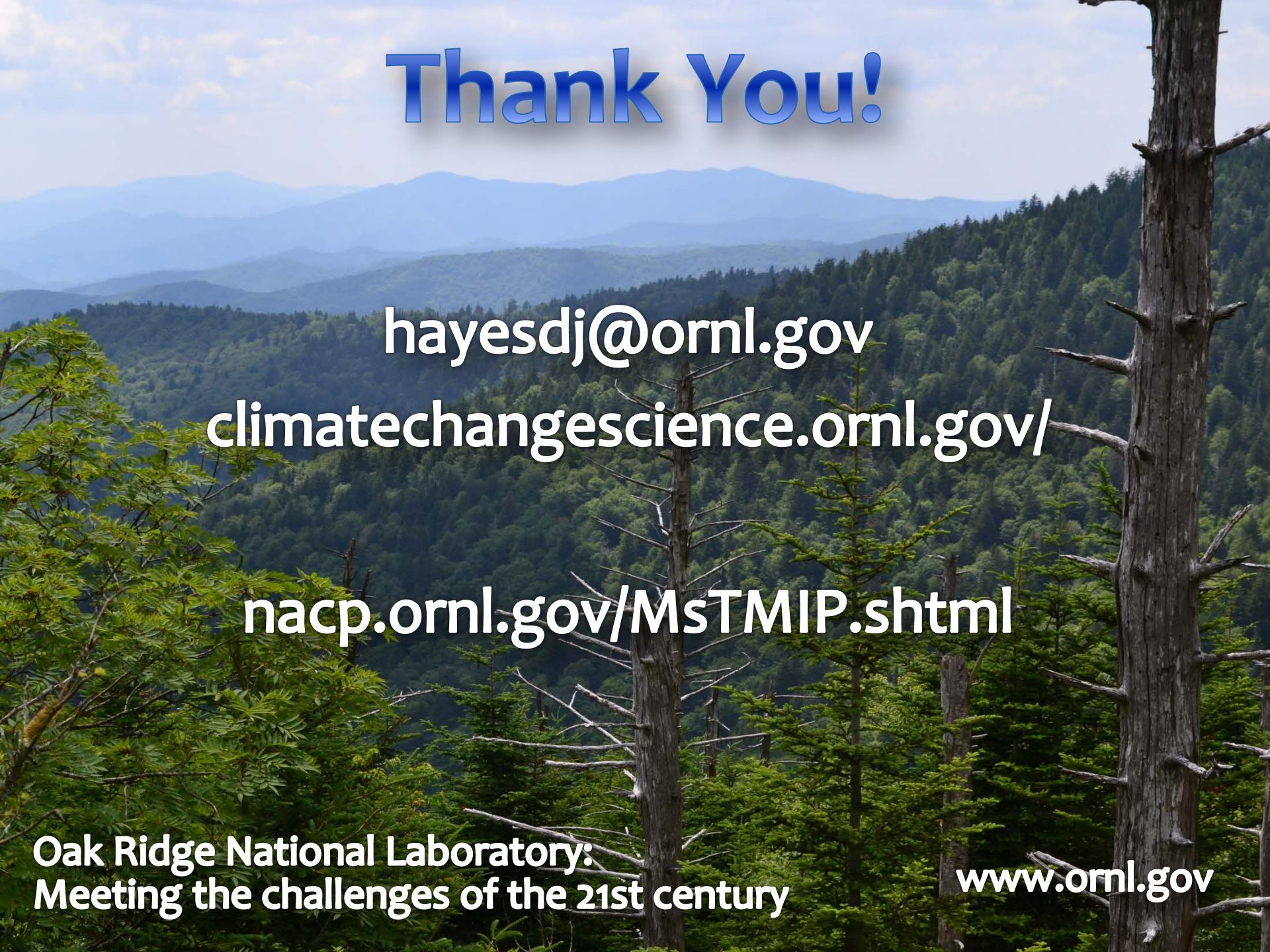



# Challenges and Opportunities




Hayes and Turner, 2012 *Eos Trans. AGU*


Thank You!
hayesdj@ornl.gov
climatechangescience.ornl.gov/
nacp.ornl.gov/MsTMIP.shtml
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