Climate impacts of historical deforestation in New England, USA using a WRF multi-physics ensemble

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Peak Deforestation in Mid-1800s
East Boston, c. 1855
Southworth and Hawes, daguerreotype
Completion of the Great Northern Railway, 1893
Forest History Society
“Instead of putting the results of all the computations in a table, with figures giving a deceptive appearance of greater accuracy than can be claimed for them, they are represented graphically by curves in the accompanying diagram, one for each state. Horizontal distances represent time and vertical distances the percentage of the total area supposed to be wooded at any time.”

Figure 1. Historical changes in forest cover show that reforestation of abandoned farmland from the mid-19th through the late 20th century has provided a second chance to determine the fate of the region’s forests. Recent trends show the loss of forest throughout the region.

Harper, 1918
Baldwin, 1942
Foster et al. 2008
Instead of putting the results of all the computations in a table, with figures giving a deceptive appearance of greater accuracy than can be claimed for them, they are represented graphically by curves in the accompanying diagram, one for each state. Horizontal distances represent time and vertical distances the percentage of the total area supposed to be wooded at any time.

**Figure 1.** Historical changes in forest cover show that reforestation of abandoned farmland from the mid-19th through the late 20th century has provided a second chance to determine the fate of the region’s forests. Recent trends show the loss of forest throughout the region.

- Harper, 1918
- Baldwin, 1942
- Foster et al. 2008
8. Marsh Self-Binder drawn by oxen, Dalrymple Farm, Red River Valley, D.T., 1877. Regarded as the mechanized wonders of the day, the bonanza farms used the latest available agricultural implements that cut the amount of manpower needed during plowing, seeding, and harvest. The move toward mechanization, including the use of the revolutionary self-binder, came rapidly in frontier areas where seasoned agricultural help was often scarce and large acreages demanded a large labor force.
Global Land Cover Change

Crop and Pasture Fraction Difference: 1992-1870

1-2° C cooler during snow season (Betts 2001)

1-2° C warmer during snow season?

Figure from Pitman et al. (2009). Land cover map constructed using data from Ramankutty and Foley (1999) and Goldewijk et al (2001).
Biophysical Processes

• Evapotranspiration
• Albedo
• Surface roughness
Biophysical Processes

- Evapotranspiration
- Albedo
- Surface roughness
Biophysical Processes

- Albedo = $SW_{up}/SW_{down}$

Snow-Covered Field 0.85

Cooler open lands due to increased shortwave being reflected when snow is present.
Biophysical Processes

• Albedo = $SW_{up}/SW_{down}$

Snow Covered Forest 0.25

Warmer forests due to decreased shortwave being reflected.
Biophysical Processes

- Albedo
- Surface roughness

Warmer forests at night from enhanced mixing and higher turbulence at night over rough canopies.
Biophysical Processes

- Albedo
- Surface roughness

Warmer over open land during the day from suppressed mixing; rough forest canopies dissipate sensible heat more efficiently.
Albedo & surface roughness effects are of opposite sign. Which dominates in temperate winter?
Diurnal Temperature Differences: Forest - Pasture

Warmer at night over canopy compared to adjacent pasture site.

Durham, NH
Diurnal Temperature Differences: Pasture – Forest

... Warmer nighttime canopy temps associated with low wind speeds. Evidence of surface roughness effect?
Weather, Research, and Forecasting (WRF) Model V3.5.1 to evaluate mid-1800’s climate responses to deforestation

• How well do WRF configurations simulate extremes in cold season (Dec-Mar) climate in New England?

• Do climate responses to deforestation vary with WRF model configuration?

• What are the dominant biophysical processes controlling climate responses to deforestation?
Modeling Approach

- Simulate climatic extremes
- Develop mid-1800s deforested land cover scenario
- Use a multi-physics ensemble to evaluate response to land cover change
Climate Extremes

(1) Cold, Snowy: Dec 2008 through March 2009
(2) Warm, Dry: Dec 2011 through March 2012 (proxy for future climate)

<table>
<thead>
<tr>
<th>State</th>
<th>Temperature Departure (°C)</th>
<th>% Precip of normal</th>
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<tbody>
<tr>
<td></td>
<td>Cold, Snowy (2008/09)</td>
<td>Warm, Dry (2011/12)</td>
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<tr>
<td>Connecticut</td>
<td>-0.6</td>
<td>+2.9</td>
</tr>
<tr>
<td>Maine</td>
<td>-1.4</td>
<td>+2.6</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>-0.5</td>
<td>+2.7</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>-0.7</td>
<td>+2.8</td>
</tr>
<tr>
<td>Rhode Island</td>
<td>-0.9</td>
<td>+2.2</td>
</tr>
<tr>
<td>Vermont</td>
<td>-0.6</td>
<td>+2.7</td>
</tr>
</tbody>
</table>

- ERA-Interim initial conditions, lateral boundaries, and sea surface temperature (6h)
- 4-month cold season (Dec-Mar) simulations, 1 month spin-up
Area with at least 30 days of snow cover 1960-1990

Hayhoe et al. 2007
Area with at least 30 days of snow cover 2070-2100 (High Emissions)

Hayhoe et al. 2007
NOHRSC Snow Depth

(a) 2008/2009
(b) 2011/2012

NOHRSC Snow Depth (cm)
Modeling Domains, one-way nests
Land Cover Scenarios

Mid 1800s

Decid. Broadleaf
Mixed Forest
Evergreen Needleleaf

Urban & Built-Up
Crop/Grass
Dry Crop & Pasture

Present-Day
WRF Multi-Physics Ensemble

Three land surface models
Two longwave/shortwave (LW/SW) schemes
Two microphysics schemes
12 ensemble members

• Yonsei University Planetary Boundary Layer scheme
• Kain-Fritsch cumulus scheme (domain 1 and 2 only)

Why Use a Multi-Physics Ensemble?
Characterize uncertainty in land cover response related to physics parameterizations.
Land Surface Models: WRF/NOAH-MP

- Semi-tile subgrid scheme:
- Longwave (L), Latent heat (LE), Sensible heat (H), Ground heat (G) fluxes for veg and bare portions
- Shortwave fluxes entire grid cell w/ gap probabilities as function of SZA and 3D structure of canopy
- Single layer canopy
- Three-layer snowpack
- Four-layer soil column

Niu et al. 2011
Land Surface Models: WRF/NOAH-MP

<table>
<thead>
<tr>
<th>Feature</th>
<th>Combinations</th>
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<tbody>
<tr>
<td>Leaf Area Index</td>
<td>4</td>
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<tr>
<td>Turbulent transfer</td>
<td>2</td>
</tr>
<tr>
<td>Soil moisture stress factor</td>
<td>3</td>
</tr>
<tr>
<td>Canopy stomatal resistance</td>
<td>2</td>
</tr>
<tr>
<td>Snow surface albedo</td>
<td>2</td>
</tr>
<tr>
<td>Frozen soil permeability</td>
<td>2</td>
</tr>
<tr>
<td>Supercooled liquid water</td>
<td>2</td>
</tr>
<tr>
<td>Radiation transfer</td>
<td>3</td>
</tr>
<tr>
<td>Precipitation partitioning</td>
<td>2</td>
</tr>
<tr>
<td>Runoff and ground water</td>
<td>4</td>
</tr>
</tbody>
</table>

9,216 Combinations

418 billion WRF/NOAH-MP
Land Surface Models: WRF/NOAH-MP

Leaf Area Index
Turbulent transfer
Soil moisture stress factor
Canopy stomatal resistance
Snow surface albedo
Frozen soil permeability
Supercooled liquid water
Radiation transfer
Precipitation partitioning
Runoff and ground water

Prescribed by veg. type
Original Noah
Original Noah
Ball-Berry
BATS & CLASS
Linear, more permeable
No iteration
Modified two-stream
Snow when T<0C
Original Noah

http://www.iges.org/lsm/Yang_S2_LSM.pdf

Niu et al. 2011
Noah MP Albedo Options

Biosphere-Atmosphere Transfer Scheme (BATS)
Direct and diffuse radiation over visible and near-infrared wave bands, accounting for fresh snow albedo, variations in snow age, solar zenith angle, grain size growth, and impurities (more CLM-like)

Canadian LAnd Surface Scheme (CLASS)
Accounts for fresh snow albedo and decrease in albedo with snow age.
Land Surface models: WRF/CLM4.0

- Called as a sub-routine in WRF
- Five sub-grid land cover types (glacier, lake, wetland, urban, vegetated)
- Vegetated subgrid includes up to 16 Plant Functional Types
- USGS 24-class land cover translated into 5 sub-grid land cover types and/or PFTs
- Single layer canopy
- Five-layer snowpack
- Ten-layer soil column

Jin et al. 2010
Lu and Kueppers, 2012
Oleson et al., 2010
Longwave/Shortwave Schemes:

(1) RRTM/Goddard
   - Rapid Radiative Transfer Model Longwave:
     • $\text{CO}_2 = 379$ ppm
     • $\text{N}_2\text{O} = 319$ ppb
     • $\text{CH}_4 = 1774$ ppb

(2) CAM/CAM V5.1
   - CAM Longwave:
     • $\text{CO}_2 = \text{annual values}$
     • $\text{N}_2\text{O} = 311$ ppb
     • $\text{CH}_4 = 1714$ ppb
Microphysics

(1) WRF Single-Moment 6-class (WSM6)
   - Hong and Lim, 2004
   - Mixing ratios of water vapor, cloud water, cloud ice, snow, rain, and graupel
   - Spherical snow with constant bulk density
   - Exponential shape for snow size distribution

(2) Thompson et al. 2008 (Thompson 08)
   - cloud water, cloud ice, snow, rain, and graupel
   - Non-spherical snow
   - Sum of exponential and gamma snow size distributions
## WRF Multi-Physics Ensemble

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Land Surface Model</th>
<th>Longwave/Shortwave</th>
<th>Microphysics</th>
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<tr>
<td>1</td>
<td>CLM</td>
<td>RRTM/Goddard</td>
<td>WSM6</td>
</tr>
<tr>
<td>2</td>
<td>NoahMP1 (BATS albedo)</td>
<td>RRTM/Goddard</td>
<td>WSM6</td>
</tr>
<tr>
<td>3</td>
<td>NoahMP2 (CLASS albedo)</td>
<td>RRTM/Goddard</td>
<td>WSM6</td>
</tr>
<tr>
<td>4</td>
<td>CLM</td>
<td>CAM/CAM</td>
<td>WSM6</td>
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<tr>
<td>5</td>
<td>NoahMP1</td>
<td>CAM/CAM</td>
<td>WSM6</td>
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<td>6</td>
<td>NoahMP2</td>
<td>CAM/CAM</td>
<td>WSM6</td>
</tr>
<tr>
<td>7</td>
<td>CLM</td>
<td>RRTM/Goddard</td>
<td>Thompson 2008</td>
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<tr>
<td>8</td>
<td>NoahMP1</td>
<td>RRTM/Goddard</td>
<td>Thompson 2008</td>
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<tr>
<td>9</td>
<td>NoahMP2</td>
<td>RRTM/Goddard</td>
<td>Thompson 2008</td>
</tr>
<tr>
<td>10</td>
<td>CLM</td>
<td>CAM/CAM</td>
<td>Thompson 2008</td>
</tr>
<tr>
<td>11</td>
<td>NoahMP1</td>
<td>CAM/CAM</td>
<td>Thompson 2008</td>
</tr>
<tr>
<td>12</td>
<td>NoahMP2</td>
<td>CAM/CAM</td>
<td>Thompson 2008</td>
</tr>
</tbody>
</table>

*YSU PBL in all simulations
**Kain-Fritsch Cumulus in domain 1 and 2
Model Validation, WRF minus PRISM

Land Surface Models

CLM  NoahMPI  NoahMP2
Model Validation, WRF minus PRISM

Longwave/Shortwave

- RRTM/Goddard
- CAM/CAM
- RRTM/Goddard
- CAM/CAM
Cold, Snowy

(a) CLM  NoahMP1  NoahMP2

WSM6

Thompson

Warm, Dry

(b) CLM  NoahMP1  NoahMP2

RRTM/ Goddard

CAM/ CAM

RRTM/ Goddard

CAM/ CAM

T2max

WRF minus PRISM T2max (°C)

42
T2max

Cold, Snowy

(a) CLM
NoahMP1
NoahMP2

WSM6

Clay

(b) CLM
NoahMP1
NoahMP2

RRTM/Goddard

CAM/CAM

Warm, Dry

WRF minus PRISM T2max (°C)

-8  -6  -4  -2  0  2  4  6  8
**T2max**

**Cold, Snowy**

(a) CLM  NoahMPI1  NoahMPI2

(b) CLM  NoahMPI1  NoahMPI2

**Warm, Dry**

WSM6

CAM/CAM

RRTM/Goddard

CAM/CAM

RRTM/Goddard

Thompson

CAM/CAM

Legend:

-8 -6 -4 -2 0 2 4 6 8

WRF minus PRISM T2max (°C)

44
Cold, Snowy

(a) CLM  NoahMP1  NoahMP2

WSM6

Thompson

T2min

(b) CLM  NoahMP1  NoahMP2

RRTM/ Goddard

CAM/ CAM

Warm, Dry

RRTM/ Goddard

CAM/ CAM
WRF/CLM4.0 generally better …
Precip. Cold, Snowy

CLM NoahMP1 NoahMP2

WSM6

Thompson

Precip. Warm, Dry

CLM NoahMP1 NoahMP2

RRTM/Goddard

CAM/CAM

RRTM/Goddard

CAM/CAM
Hard to say any are “better”

Thompson 2008 microphysics with CAM best of the worst?
Snow Depth

Cold, Snowy

CLM
NoahMP1
NoahMP2

RRTM/Goddard

CAM/CAM

WSM6

Warm, Dry

Deeper Snowpack

CAM/CAM Radiation
NoahMP

Thompson

RRTM/Goddard

CAM/CAM

WRF DJFM SNOWH (cm)

0 30 60 90 120 150
Snow Depth

Cold, Snowy

WSM6

NoahMP1

CLM

NoahMP2

RRTM/Goddard

CAM/CAM Radiation

NoahMP

Warm, Dry

Deeper Snowpack:

WSM6

CAM/CAM

RRTM/Goddard

Shallower Snowpack:

Thompson

RRTM/Goddard

CLM

CAM/CAM
Albedo vs. Snow Depth

Vertical fraction of vegetation covered by snow:

**CLM:** $f_{\text{snow}} = \min(z_{\text{snow}}, z_c) / z_c$, $z_c = 20 \text{ cm}$

**Noah-MP:** $h_{\text{snow,c}} = h_{\nu,t} \cdot e^{-h_{\text{snow}}/0.1}$

CoCoRAHS Data: Burakowski et al., 2013, *Hydrological Processes*
WRF and MODIS albedo

(a) Snow-Covered

All Sky Albedo

Crop/Grass  Decid. Brdlf  Mixed Forest  Evergreen Needle

MCD43A3 BRDF/Albedo v5

Schaaf et al. (2002) MCD43A3 BRDF/Albedo v5
Hyperspectral Imagery and MODIS

MODIS cropland grid cells often contain darker surfaces such as trees, buildings, and roads that produce negative albedo bias.

Burakowski et al., 2013, Remote Sensing of Environment
WRF and MODIS albedo

(a) Snow-Covered

- **Crop/Grass**
- **Decid. Brdlf**
- **Mixed Forest**
- **Evergreen Needle**

*MODIS, CLM, NoahMPI, NoahMP2*

Schaaf et al. (2002) MCD43A3 BRDF/Albedo v5
WRF and MODIS albedo

(b) Snow-Free

All Sky Albedo

Crop/Grass | Decid. Brdlf | Mixed Forest | Evergreen Needle

MODIS | CLM | NoahMPI1 | NoahMP2

Schaaf et al. (2002) MCD43A3 BRDF/Albedo v5
How well do WRF configurations simulate extremes in cold season climate?

- WRF/CLM4.0 reasonably simulates Tmax and Tmin
- WRF/Noah-MP warm bias (+5 to +8K) in Tmax
- All configurations fail to capture precipitation
- Snow-covered deciduous broadleaf albedo overestimated in all models
- Snow-covered evergreen needleleaf albedo underestimated in WRF/NoahMP
Climate responses to deforestation

All results are Present-Day minus Mid-1800s Deforested

Expect to see:

• Warmer T2max over forest (albedo effect)
• Warmer T2min over forest (surface roughness)
Land Cover Scenarios

Mid 1800s

Present-Day

Decid. Broadleaf
Mixed Forest
Evergreen Needleleaf
Urban & Built-Up
Crop/Grass
Dry Crop & Pasture
T2max

Cold, Snowy

CLM
NoahMP1
NoahMP2

Warm, Dry

CLM
NoahMP1
NoahMP2

WSM6

Thompson

RRTM/Goddard

CAM/CAM

RRTM/Goddard

CAM/CAM

Present-Day Minus Deforested T2max (°C)

62
T2max

Cold, Snowy

CLM
NoahMP1
NoahMP2

WSM6

Thompson

Warm, Dry

CLM
NoahMP1
NoahMP2

RRTM/
Goddard

CAM/
CAM

RRTM/
Goddard

CAM/
CAM

Present-Day Minus Deforested T2max (°C)
Albedo

Cold, Snowy

CLM  NoahMP1  NoahMP2
WSM6

RRTM/Goddard

CAM/CAM

Warm, Dry

CLM  NoahMP1  NoahMP2

RRTM/Goddard

CAM/CAM

Thompson

Present-Day Minus Deforested Albedo
T2min

Cold, Snowy

CLM  NoahMP1  NoahMP2

RRTM/ Goddard

CAM/ CAM

Warm, Dry

CLM  NoahMP1  NoahMP2

RRTM/ Goddard

CAM/ CAM

WSM6

Thompson

Present-Day Minus Deforested T2min (°C)
Dominant Biophysical Processes

Daytime
- **Albedo**: warmer forests due to increase in SW absorbed by vegetation (albedo)
- **Surface Roughness**: cooler forests due to more efficient dissipation of sensible heat & warmer open land due to suppressed mixing

Nighttime
- **Surface Roughness**: warmer forests due to enhanced mixing, drawing warmer air from aloft during stable conditions
Diurnal change in surface energy fluxes: Evergreen Needleleaf minus Grass/Crop

Larger increase in shortwave absorbed by vegetation (SW Veg) in Noah-MP compared to CLM.
Diurnal change in surface energy fluxes: Evergreen Needleleaf minus Grass/Crop

Larger increase in ground heat flux in 2011/2012 with low snow cover. Ground heat flux negative at night (soil cooling).
Increase in SW absorbed by vegetation in all LSMs. Decrease in SW absorbed by ground in CLM. Increase in NoahMP.
Increase in SWV absorbed by vegetation in all LSMs. Decrease in SW absorbed by ground in CLM. *Increase* in NoahMP.
Responses to Reforestation

(a) T2max

(b) T2min

Temperature Difference (°C)

Decid. Broadleaf  Mixed Forest  Evergreen Needleleaf

Cold, Snowy

Warm, Dry

Decid. Broadleaf  Mixed Forest  Evergreen Needleleaf
Summary

• How well do WRF configurations simulate extremes in cold season (Dec-Mar) climate in New England?
  – Choice of land surface model influences of T2max
  – Choice of longwave radiation scheme influences T2min
  – WRF/CLM generally better at simulating temperature extremes
  – Precipitation not simulated well by any physics configuration tested here
  – Snow-covered albedo of deciduous broadleaf forest overestimated relative to MODIS by all model configurations
  – Snow-covered albedo of evergreen needleleaf underestimated relative to MODIS by all model configurations
Summary

Do climate responses to reforestation vary with WRF model configuration?

- $T_{2\text{max}}$ warms in all physics configurations (albedo)
- $T_{2\text{min}}$ response is uncertain; multi-physics ensemble spans both cooling and warming responses.
- Unclear why the model does not consistently simulate the observed warming at night (e.g., $T_{2\text{min}}$) driven by changes in surface roughness over forest compared to open land.
Future Work

Summer biophysical impacts of land cover change
Future Work

Summer biophysical impacts of land cover change

Where are New England Forests headed?
Future Work

Summer biophysical impacts of land cover change

Where are New England Forests headed?

And for that matter, climate?
Questions?