Land cover and land use change as climate forcing: from historical conjecture to modern theories

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Human activities (agriculture, deforestation, urbanization) and their effects on climate, water resources, and biogeochemical cycles

What is our collective future?

Can we manage the Earth system, especially its ecosystems, to create a sustainable future?
Loss of tree cover and increase in cropland
- Farm abandonment and reforestation in eastern U.S. and Europe
- Extensive wood harvest

Historical LULCC in CLM4
A long-standing interest

The European tradition
Theophrastus (circa 300 BC)
Pliny the Elder (circa 1st century AD)

The American tradition
- Christopher Columbus, 1494
- Constantin-François Volney, 1803: “very perceptible partial changes in the climate...as the land was cleared”
- Alexander von Humboldt, 1807: “The statements so frequently advanced...are now generally discredited”
- Samuel Aughey, 1880: cultivation of the Great Plains increases rainfall, “rain follows the plow”
- U.S. Congress, 1873: legislation to promote afforestation to increase rainfall
Ecosystems and climate policy

Introduction

These comments are tongue-in-cheek and do not advocate a particular position.

Boreal forest - menace to society - no need to promote conservation

Temperate forest - reforestation and afforestation

Tropical rainforest - planetary savior - promote avoided deforestation, reforestation, or afforestation

Biofuel plantations to lower albedo and reduce atmospheric CO₂
Multiple biogeophysical and biogeochemical influences of ecosystems
**Prevaling paradigm**
The dominant competing signals from historical deforestation are an increase in surface albedo countered by carbon emission to the atmosphere.

**Biogeophysical**
Weak global cooling (−0.03 °C)

**Biogeochemical**
Strong warming (0.16–0.18 °C)

**Net**
Warming (0.13–0.15 °C)

Change in annual surface temperature from anthropogenic LULCC over the 20th century

The LUCID intercomparison study

Multi-model ensemble of global land use climate forcing (1992-1870)

Seven climate models of varying complexity with imposed land cover change (1992-1870)


Experiments
- 4 experiments, 5-member ensembles each
- 30-year simulations
- Total of 20 simulations and 600 model years

<table>
<thead>
<tr>
<th>Case</th>
<th>Land cover</th>
<th>CO₂</th>
<th>SST &amp; SIC</th>
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<tbody>
<tr>
<td>PDv</td>
<td>1870</td>
<td>375 ppm</td>
<td>1972-2001</td>
</tr>
<tr>
<td>PI</td>
<td>1870</td>
<td>280 ppm</td>
<td>1871-1900</td>
</tr>
<tr>
<td>PIV</td>
<td>1992</td>
<td>280 ppm</td>
<td>1871-1900</td>
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</tbody>
</table>
Change in JJA near-surface air temperature (°C) resulting from land cover change (PD - PDv)

**Key points:**
The LULCC forcing is regional
Differences among models matter

Pitman, de Noblet-Ducoudré, et al. (2009)
GRL, 36, doi:10.1029/2009GL039076
Latent heat flux

Change in JJA latent heat flux (W m$^{-2}$) resulting from land cover change (PD - PDv)

Key points:
The LULCC forcing is regional
Differences among models matter

Pitman, de Noblet-Ducoudré, et al. (2009)
GRL, 36, doi:10.1029/2009GL039076
Land cover change offsets greenhouse gas warming

**CCSM Models**
- **Atmosphere** - CAM3.5
- **Land** - CLM3.5 + new datasets for present-day vegetation + grass optical properties
- **Ocean** - Prescribed SSTs and sea ice
Climate change attribution

Multi-model ensemble of the simulated changes between the pre-industrial time period and present-day

North America

Eurasia

\[ CO_2 + SST + SIC \] forcing leads to warming

\[ LULCC \] leads to cooling

Key points:
The LULCC forcing is counter to greenhouse warming

The LULCC forcing has large inter-model spread, especially JJA

The bottom and top of the box are the 25th and 75th percentile, and the horizontal line within each box is the 50th percentile (the median). The whiskers (straight lines) indicate the ensemble maximum and minimum values.
**Community Earth System Model CMIP5 simulations**

Full transient (all forcings)  
Land cover change only

Historical changes in annual surface albedo and temperature (1850 to 2005)

Key points:  
LULCC forcing is counter to all forcing  
LULCC forcing is regional, all forcing is global

Peter Lawrence et al. (2012) J. Clim., in press
Opposing trends in vegetation

Historical changes in annual leaf area index (1850 to 2005)

Single forcing simulation
Land cover change only

Loss of leaf area, except where reforestation

All forcing simulation
CO₂
Climate
Nitrogen deposition
Land cover change

Increase in leaf area, except where agricultural expansion

Peter Lawrence et al. (2012) J. Clim., in press
21st century land use & land cover change

Description

- **RCP 2.6** - Largest increase in crops. Forest area declines.
- **RCP 4.5** - Largest decrease in crop. Expansion of forest areas for carbon storage.
- **RCP 6.0** - Medium cropland increase. Forest area remains constant.
- **RCP 8.5** - Medium increases in cropland. Largest decline in forest area. Biofuels included in wood harvest.

Peter Lawrence et al. (2012) J. Clim., in press
21st century forests

Change in tree cover (percent of grid cell) over the 21st century

(c) RCP 2.6 IMAGE (2100-2006) Tree PFTs

(e) RCP 4.5 MiniCAM (2100-2006) Tree PFTs

(g) RCP 6.0 AIM (2100-2006) Tree PFTs

(i) RCP 8.5 MESSAGE (2100-2006) Tree PFTs
Change in crop cover (percent of grid cell) over the 21st century
Simulations with CLM/CESM are consistent with the estimated land use flux over the historical period.

Simulations with CLM/CESM are consistent with the estimated wood harvest flux over the historical period and the RCPs.

Peter Lawrence et al. (2012) J. Clim., in press
Land use choices matter

**Ecosystem carbon (excluding product pools)**

**RCP 4.5**: reforestation drives carbon gain

**RCP 8.5**: deforestation and wood harvest drive carbon loss

Peter Lawrence et al. (2012) J. Clim., in press
Surface albedo

Maximum snow-covered albedo

LULCC effects
- Vegetation masking of snow
- High albedo of crops

Monthly surface albedo (MODIS) by land cover type in NE US

Higher summer albedo

Forest masking

Colorado Rocky Mountains


Surface albedo: present day – potential vegetation

**CLM3.5**

- **DJF**: Current - Potential
- **JJA**: Current - Potential

**MODIS**

- **DJF**: Current - Potential
- **JJA**: Current - Potential

Units are $\Delta$albedo $\times$ 100

Peter Lawrence, unpublished
Prevailing model paradigm

**Crops & grasses**
Low latent heat flux because of:
- Low roughness
- Shallow roots decrease soil water availability

**Trees**
High latent heat flux because of:
- High roughness
- Deep roots allow increased soil water availability

*Tropical forest* - cooling from higher surface albedo of cropland and pastureland is offset by warming associated with reduced evapotranspiration

*Temperate forest* - higher albedo leads to cooling, but changes in evapotranspiration can either enhance or mitigate this cooling

Forest evapotranspiration cools climate locally

**Annual mean temperature change**

<table>
<thead>
<tr>
<th></th>
<th>OF to PP</th>
<th>OF to HW</th>
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<tbody>
<tr>
<td><strong>Albedo</strong></td>
<td>+0.9°C</td>
<td>+0.7°C</td>
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<tr>
<td><strong>Ecophysiology and aerodynamics</strong></td>
<td>-2.9°C</td>
<td>-2.1°C</td>
</tr>
</tbody>
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**Forest**
- Lower albedo (+)
- Greater leaf area index, aerodynamic conductance, and latent heat flux (-)
Energy exchanges at the peak of the July 2006 heatwave for neighboring flux towers over forest and grassland. c, Grillenburg and Tharandt (distance 4 km). The solid lines indicate HWD values; the dashed lines indicate the baseline conditions in a normal year. Black: net radiation ($R_n$), blue: latent heat flux ($\lambda ET$), red: sensible heat flux ($H$).

Watershed deforestation studies

Hubbard Brook Experimental Forest

\[ P - E = R \]

Deforestation decreases evapotranspiration (E) and increases runoff (R)
Conclusions

**Broad conclusions**
- LULCC matters at the regional scale and so must be included in detection & attribution studies
- The choices we make in LULCC will likely influence future climate
- Differences among models matter and so we must devise appropriate model tests

**Biogeochemistry**
- Land use flux is important, especially the wood harvest flux

**Biogeophysics**
- Higher albedo of croplands & grasslands cools climate
- Less certainty about role of evapotranspiration
- Implementation of land cover change (spatial extent, crop parameterization) matters

**Climate biases matter**
- Vegetation masking of snow albedo is less important when snow cover is biased low
- Evapotranspiration feedbacks depend on the precipitation biases
- The regionality of LULCC challenges models in their climate simulation