Land management for carbon and climate mitigation under RCP 8.5 using the Community Earth System Model 1.0 and 2.0

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CMIP5 Land Cover Change Attribution

1. The Coupled Model Intercomparison Project phase 5 - CMIP5 prescribed Land Cover Change and Wood Harvest as a major climate forcing for both historical and future RCP Climate Model simulations.
CMIP5 Land Cover Change Attribution

1. The Coupled Model Intercomparison Project phase 5 - CMIP5 prescribed Land Cover Change and Wood Harvest as a major climate forcing for both historical and future RCP Climate Model simulations.
1. To investigate the effectiveness of Land based Carbon Dioxide Remove (CDR) through Afforestation or the carbon cost associated with widescale crop biofuel production we performed a range of CESM 1.0 simulations with maximum afforestation and crop expansion under future climate and CO$_2$.

2. Land Cover/Use Change fluxes are complicated as they combine fluxes from direct actions as well as indirect fluxes that may have occurred in the absence of human actions.

3. Direct fluxes include those from:
   - Clearing of natural land for agriculture or biofuel production
   - Wood harvest of trees for wood products or biofuel
   - Uptake of carbon through afforestation on unforested land

4. Indirect fluxes include:
   - The loss of carbon that would have been taken up through changes in atmospheric CO$_2$ and climate in deforested areas
   - Changes in uptake of carbon in young forests after wood harvest
**CMIP5 Land Cover Change Attribution – Exp. Design**

<table>
<thead>
<tr>
<th>Simulations</th>
<th>Land Cover</th>
<th>Wood Harvest</th>
<th>Other Forcings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Historical Control</td>
<td>Transient</td>
<td>Transient</td>
<td>Full Transient</td>
</tr>
<tr>
<td>2 Historical No Land Cover Change</td>
<td>Constant 1850</td>
<td>No Wood Harvest</td>
<td>Full Transient</td>
</tr>
<tr>
<td>3 RCP 8.5 Control</td>
<td>Transient</td>
<td>Transient</td>
<td>Full Transient</td>
</tr>
<tr>
<td>4 RCP 8.5 No Land Cover Change</td>
<td>Constant 2005</td>
<td>1995 – 2005 average wood harvest</td>
<td>Full Transient</td>
</tr>
<tr>
<td>5 RCP 8.5 Maximum Afforestation</td>
<td>Transient Afforestation 2005 Crop Area</td>
<td>1995 – 2005 average wood harvest</td>
<td>Full Transient</td>
</tr>
<tr>
<td>6 RCP 8.5 Crop Expansion</td>
<td>Transient Crop Increase</td>
<td>1995 – 2005 average wood harvest</td>
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</tbody>
</table>

*All simulations were performed as ensembles of 3 fully coupled CESM 1.0 simulations following the CMIP5 protocol with the only difference the prescription of Land Use Land Cover Change*

** The RCP 8.5 simulations were also done under RCP 4.5 to investigate the role of CO₂ and Climate on these results
CMIP5 Land Cover Change – Total Ecosystem Carbon

Global Total Ecosystem Carbon (PgC)

Historical
Historical No LCC
RCP 8.5
RCP 8.5 No LCC

-61.2 PgC
-49.0 PgC
+68.4 PgC
+119.8 PgC

(a) RCP 8.5 No LCC 2095 - 2010 Total Ecosys C gC/m2
(b) RCP 8.5 - No LCC (2095) Total Ecosys C gC/m2
CMIP5 Land Cover Change – Total Ecosystem Carbon

Global Total Ecosystem Carbon (PgC)

Ecosys Carbon | Transient LCC | No LCC | Net LCC Em | CMIP5 FF Em
--- | --- | --- | --- | ---
Historical | -61.2 PgC | +68.4 PgC | 129.6 PgC | 313.8 PgC
RCP 8.5 | -49.0 PgC | +119.8 PgC | 168.8 PgC | 1925.0 PgC
Extending Land Cover Change

1. Given that the CMIP5 Land Cover Change had big impacts on the Carbon Cycle we extended these experiments to assess a “maximum plausible” afforestation and crop expansion

3. Afforestation starts in 2015 and replaces non tree vegetation with trees in climatically suitable areas while maintaining current day crops (Tree PFTs + 22.5 million km^2)

4. Crop expansion starts in 2015 and increases cropping area in climatically suitable areas with proximity to existing crops (CLM4 Crop PFT + 22.5 million km^2)

5. Both simulations maintain current day wood harvest areas

6. Simulations are ensembles of 3x RCP 8.5 with the new Afforestation and Crop Expansion LULCC compared to RCP 8.5 and No Land Cover Change under the same transient RCP 8.5 forcing
Crop Expansion and Afforestation Land Cover Change

Global Tree PFT area

Historical

RCP 4.5

RCP 8.5

+2.75 m km²

-3.5 m km²

1850 1900 1950 2000 2050 2100

Global Tree PFT area

Historical

RCP Afforestation

RCP Crop Expansion

+ 22.4 m km²

(2x GCAM 4.5)

-11.9 m km²

1850 1900 1950 2000 2050 2100
Crop Expansion and Afforestation Land Cover Change

Global Crop PFT area

- Historical
- RCP 4.5
- RCP 8.5

Area Million km²

+2.7 m km²

-3.8 m km²

1850 1875 1900 1925 1950 1975 2000 2025 2050 2075 2100

Global Crop PFT area

- Historical
- RCP Afforestation
- RCP Crop Expansion

+22.5 m km²

1850 1875 1900 1925 1950 1975 2000 2025 2050 2075 2100
Crop Expansion and Afforestation Land Cover Change
Maximum Land Cover Change – Total Ecosystem Carbon

Global Ecosystem Carbon RCP 8.5

- Historical
- RCP 8.5
- Hist No LCC
- RCP 8.5 No LCC
- RCP 8.5 Crop Exp
- RCP 8.5 Afforest

- +349 PgC
- +119.8 PgC
- -49.0 PgC
- -61.2 PgC
- -109.6 PgC

Afforestation RCP 8.5 - No LCC (2090) Total Ecosystem Carbon

Crop Exp RCP 8.5 - No LCC (2090) Total Ecosystem Carbon

Map of global ecosystems with color coding for net changes in carbon.
Maximum Land Cover Change – Total Ecosystem Carbon

<table>
<thead>
<tr>
<th>Ecosys Carbon</th>
<th>Transient LCC</th>
<th>No LCC</th>
<th>Net LCC Em</th>
<th>CMIP5 FF Em</th>
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<tr>
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<td>168.8 PgC</td>
<td>1925.0 PgC</td>
</tr>
<tr>
<td>RCP 8.5 Aff.</td>
<td>+349.0 PgC</td>
<td></td>
<td>-229.5 PgC</td>
<td></td>
</tr>
<tr>
<td>RCP 8.5 Crop</td>
<td>-109.6 PgC</td>
<td></td>
<td>229.4 PgC</td>
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<td>-61.2 PgC</td>
<td>+68.4 PgC</td>
<td>129.6 PgC</td>
<td>313.8 PgC</td>
</tr>
<tr>
<td>RCP 4.5</td>
<td>+62.8 PgC</td>
<td>+68.6 PgC</td>
<td>5.8 PgC</td>
<td>791.5 PgC</td>
</tr>
<tr>
<td>RCP 4.5 Aff.</td>
<td>+276.4 PgC</td>
<td></td>
<td>-207.8 PgC</td>
<td></td>
</tr>
<tr>
<td>RCP 4.5 Crop</td>
<td>-144.5 PgC</td>
<td></td>
<td>213.1 PgC</td>
<td></td>
</tr>
<tr>
<td>RCP 8.5 Aff.</td>
<td>+349.0 PgC</td>
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Maximum Land Cover Change – Conclusions

1. Maximum Afforestation could offset 26% off RCP 4.5 Fossil Fuel Emission and 12% of RCP 8.5 Fossil Fuel Emissions

2. The Carbon Cycle response to Afforestation under RCP 8.5 was around 10% larger than the same experiment in RCP 4.5

3. Maximum Crop expansion in CESM 1.0 has a similar increase in RCP Emissions as the decrease from Afforestation. This would have to be offset by biofuel production.

4. As part of the Societal Dimension Working Group we have a project to repeat these experiments in CESM 2.0 with CLM5.

5. The CLM5 Crop simulations will allow us to better assess the biofuel production capacity of the crop expansion experiments for guidance on the carbon trade off in terms of natural ecosystem carbon losses
CMIP5 Land Cover Change – Land Surface Temperature

**Global Land Surface Air Temperature**

- Historical
- RCP 4.5
- RCP 8.5
- Hist No LCC
- RCP 4.5 No LCC
- RCP 8.5 No LCC

**Global Land Air Temperature Difference**

- Historical
- RCP 4.5
- RCP 8.5

Temperature changes over time are depicted, with historical data showing a baseline, and future scenarios (RCP 4.5, RCP 8.5) projected to 2100, illustrating potential temperature increases.
Land Cover Change – Other Carbon Pools

Global Leaf Carbon RCP 8.5

Global Soil Carbon RCP 8.5
Land Cover Change – Other Carbon Pools

Global Net Primary Productivity RCP 8.5

Global Fire RCP 8.5
Land Cover Change – Land Use and Land Sink

Global Cumulative Land Use Flux RCP 8.5

- Historical
- RCP 8.5
- Hist No LCC
- RCP 8.5 No LCC
- RCP 8.5 Crop Exp
- RCP 8.5 Afforest

Global Cumulative Land Sink RCP 8.5

- Historical
- RCP 8.5
- Hist No LCC
- RCP 8.5 No LCC
- RCP 8.5 Crop Exp
- RCP 8.5 Afforest
Land Cover Change – Biogeophysics Temperature

Global Land Air Temperature Difference RCP 8.5

- Historical
- Crop Exp
- Afforest

Global Land Air Temperature Difference RCP 4.5

- Historical
- Crop Exp
- Afforest
Land Cover Change – Biogeophysics Temperature
Land Cover Change – Biogeophysics Temperature
Land Cover Change – Biogeophysics Albedo Latent
Land Cover Change – Biogeophysics Albedo
Land Cover Change – Biogeophysics Latent Heat Flux

Aforest RCP 4.5 - No LCC (2081 - 2100) Change in Latent Heat Flux (W/m²)

Crop Exp RCP 4.5 - No LCC (2081 - 2100) Change in Latent Heat Flux (W/m²)
3. Temperature responses were larger under RCP 4.5 than RCP 8.5 with both were driven primarily by Albedo changes with Latent Heat change complex and impacted by Precipitation feedbacks.
Land Cover Change Impacts - Conclusions.

1. Maximum reasonable Afforestation and Crop Expansion experiments in CLM 4 – CAM 4 had strong robust impacts on both the Carbon Cycle and surface Climate

2. The Carbon Cycle response under RCP 8.5 was around 10% larger than the same experiment in RCP 4.5