The carbon costs of tropical deforestation through changes on regional climate

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Climate & land-use change are two main risks to tropical ecosystems

An essential task in biogeochemistry:
Quantify ecosystem response & ecosystem feedback to carbon cycle

(Davidson et al. 2012, Nature)
This gamma is driven by CO$_2$-induced climate change, however, other climate change is driven by deforestation. Question: Does climate change associated with land-use change yield a larger or smaller gamma?
Complex pathway of land use change in the climate-carbon feedback

(Harris et al. 2021, Nat Clim Chang)
Tropical deforestation

CMIP6-LUMIP, CMIP6-piControl simulations

Deforestation impacts (DEF minus CTL)

Observational spatial sensitivity

Waveform-based ESA-CCI aboveground biomass

Observational climate products (TRMM rainfall, CRU air temperature)

Additional experiments using CESM2 for tropics only
Idealized deforestation causes local warming & decrease in rainfall

Tree cover fraction
Amazon: $-44.7 \pm 6.0 \%$,
Congo: $-38.7 \pm 8.8 \%$,
TropAsia: $-31.2 \pm 8.9 \%$

Annual rainfall
Amazon: $-150 \pm 105 \text{ mm yr}^{-1}$ (-6.7%)
Congo: $-41 \pm 56 \text{ mm yr}^{-1}$ (-2.7%)
TropAsia: $-38 \pm 58 \text{ mm yr}^{-1}$ (-1.3%)

Annual temperature
Amazon: $0.5 \pm 0.5 \degree \text{C}$
Congo: $0.1 \pm 0.5 \degree \text{C}$
TropAsia: $-0.1 \pm 0.2 \degree \text{C}$
Revisit the observational spatial climate sensitivity of vegetation carbon

AGB: aboveground biomass

<table>
<thead>
<tr>
<th></th>
<th>AGB</th>
<th>Rainfall coefficient</th>
<th>Temperature coefficient</th>
<th>$R^2$</th>
<th>$\frac{\partial AGB}{\partial \text{Rainfall}}$</th>
<th>$\frac{\partial AGB}{\partial \text{Temperature}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations*</td>
<td>3.4</td>
<td>-0.32</td>
<td>0.49</td>
<td>8.2%</td>
<td>/100mm yr$^{-1}$</td>
<td>-0.8% /°C</td>
</tr>
<tr>
<td>CMIP6 piControl</td>
<td>1.6</td>
<td>-0.02</td>
<td>0.60</td>
<td>6.9%</td>
<td>/100mm yr$^{-1}$</td>
<td>-0.09% /°C</td>
</tr>
</tbody>
</table>

*Equation: Aboveground biomass (AGB) = a*Rainfall + b*Temperature + ε. The units are mm yr$^{-1}$ and °C, and Mg C ha$^{-1}$. Sensitivity is computed as the relative value of the coefficients a and b to the observed/simulated AGB.

CMIP6 has lower rainfall sensitivity due to a lower magnitude of AGB
<table>
<thead>
<tr>
<th>Region</th>
<th>Biophysical property changes</th>
<th>Climate impacts on vegetation carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon</td>
<td>-150 mm yr(^{-1}), +0.5°C</td>
<td>-6.7 Mg C ha(^{-1}) (6.8%)</td>
</tr>
<tr>
<td>Congo</td>
<td>-41 mm yr(^{-1}), +0.1°C</td>
<td>-3.1 Mg C ha(^{-1}) (4.1%)</td>
</tr>
<tr>
<td>TropAsia</td>
<td>-38 mm yr(^{-1}), -0.1°C</td>
<td>-0.2 Mg C ha(^{-1}) (0.3%)</td>
</tr>
</tbody>
</table>
Implication: Deforestation-driven climate change yields a larger climate-carbon cycle feedback

- **CO₂-driven climate-carbon cycle feedback**
  \[
  \gamma_{CO2} = \frac{\Delta C_{veg_{COU}} - \Delta C_{veg_{BGC}}}{\Delta T_{COU}}
  \]

- **Deforestation-driven climate-carbon cycle feedback**
  \[
  \gamma_{deforestation} = \frac{\Delta C_{veg_{def\_biophys}}}{\Delta T_{def\_biophys}}
  \]
Take home message:

In the Amazon, deforestation-driven climate change causes intact forests to lose an additional 6.8% of their biomass as a consequence of decreasing rainfall.

Carbon credits for avoided deforestation should be larger to account for positive forest effects on regional climate.

Land use effects on precipitation would amplify the climate-carbon cycle feedback in the tropics.

Thanks for your listening and particular thanks to the NCAR team for early discussions and help on computing on Cheyenne.
Temperature

[Image of maps and graphs showing the impact of tropical deforestation and global deforestation on temperature changes, with correlation coefficients and RMSE values.]
<table>
<thead>
<tr>
<th>Model (AGB=)</th>
<th>a</th>
<th>b</th>
<th>R²</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a \cdot \text{MAP} + b \cdot \text{MAT} + \varepsilon$</td>
<td>0.034</td>
<td>-0.316</td>
<td>0.49</td>
<td>32.1</td>
</tr>
<tr>
<td>$a \cdot \text{MAP} + b \cdot \text{Tamp} + \varepsilon$</td>
<td>0.026</td>
<td>-1.148</td>
<td>0.26</td>
<td>40.4</td>
</tr>
<tr>
<td>$a \cdot \text{MAP} + b \cdot \text{MAXT} + \varepsilon$</td>
<td>0.030</td>
<td>-0.280</td>
<td>0.60</td>
<td>29.8</td>
</tr>
<tr>
<td>$a \cdot \text{MAP} + b \cdot \text{VPD} + \varepsilon$</td>
<td>0.026</td>
<td>-0.676</td>
<td>0.25</td>
<td>40.5</td>
</tr>
<tr>
<td>$a \cdot \text{Pamp} + b \cdot \text{MAT} + \varepsilon$</td>
<td>0.136</td>
<td>0.105</td>
<td>0.19</td>
<td>40.3</td>
</tr>
<tr>
<td>$a \cdot \text{Pamp} + b \cdot \text{Tamp} + \varepsilon$</td>
<td>0.210</td>
<td>-3.707</td>
<td>0.12</td>
<td>44.1</td>
</tr>
<tr>
<td>$a \cdot \text{Pamp} + b \cdot \text{MAXT} + \varepsilon$</td>
<td>0.106</td>
<td>0.427</td>
<td>0.01</td>
<td>46.7</td>
</tr>
<tr>
<td>$a \cdot \text{Pamp} + b \cdot \text{VPD} + \varepsilon$</td>
<td>0.193</td>
<td>-1.469</td>
<td>0.00</td>
<td>46.9</td>
</tr>
<tr>
<td>$a \cdot \text{PRD} + b \cdot \text{MAT} + \varepsilon$</td>
<td>0.510</td>
<td>0.888</td>
<td>0.39</td>
<td>34.8</td>
</tr>
<tr>
<td>$a \cdot \text{PRD} + b \cdot \text{Tamp} + \varepsilon$</td>
<td>0.395</td>
<td>1.173</td>
<td>0.06</td>
<td>45.6</td>
</tr>
<tr>
<td>$a \cdot \text{PRD} + b \cdot \text{MAXT} + \varepsilon$</td>
<td>0.393</td>
<td>0.637</td>
<td>0.57</td>
<td>30.9</td>
</tr>
</tbody>
</table>

- **Key role of rainfall**
- **High linear correlation among water stress factors or among the energy stress factors**

**Water stress factors:**
- MAP: mean annual precipitation (mm yr⁻¹)
- Pamp: intraannual amplitude of precipitation (mm month⁻¹)
- PRD: precipitation during the driest season (mm month⁻¹)

**Heat stress factors:**
- MAT: mean annual air temperature (°C)
- Tamp: intraannual amplitude of air temperature (°C)
- MAXT: mean annual maximum air temperature (°C)
- VPD: vapor pressure deficit (hPa)
Correction on the AGB using observational AGB-tree cover relationship

- Amazon: 22 Mg C ha\(^{-1}\) / 10%
- Congo: 19 Mg C ha\(^{-1}\) / 10%
- TropAsia: 20 Mg C ha\(^{-1}\) / 10%
- Tropics: 21 Mg C ha\(^{-1}\) / 10%

MODIS VCF

ESA-CCI
AGB