Terrestrial Ecosystem Forcings and Feedbacks in the Climate System

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Anthropogenic land cover change

Land cover change occurs from human uses of land

- Agroecosystems
  - Albedo
  - Bowen ratio
  - Infiltration/runoff
  - Soil water holding capacity
  - Atmospheric CO₂
  - Nitrogen cycle
  - Dust
Natural vegetation dynamics

Upland boreal forest succession, Fairbanks, Alaska

Land cover change occurs from natural ecological processes

**Vegetation dynamics**
- Albedo
- Bowen ratio
- Infiltration/runoff
- Soil water holding capacity
- Atmospheric CO$_2$
- Nitrogen cycle
- Dust

Van Cleve & Viereck (1981) in *Forest Succession: Concepts and Application*, West et al., Eds., 185-211
Tree-covered land has a lower albedo during winter than other snow-covered land.
Annual mean surface albedo change caused by anthropogenic vegetation changes

Table 1. Black-Sky Snow Free Surface Albedo Values for Various Land Cover Types According to the IGBP Vegetation Classes Given for 4 Months as 4 Years Mean

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>February</th>
<th>May</th>
<th>August</th>
<th>November</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evergreen needleleaf (1)</td>
<td>0.096</td>
<td>0.090</td>
<td>0.096</td>
<td>0.092</td>
</tr>
<tr>
<td>Evergreen broadleaf in Amazonas (2)</td>
<td>0.122</td>
<td>0.119</td>
<td>0.124</td>
<td>0.127</td>
</tr>
<tr>
<td>Evergreen broadleaf excluding Amazonas (2)</td>
<td>0.121</td>
<td>0.116</td>
<td>0.118</td>
<td>0.127</td>
</tr>
<tr>
<td>Deciduous needleleaf (3)</td>
<td>0.103</td>
<td>0.095</td>
<td>0.110</td>
<td>0.103</td>
</tr>
<tr>
<td>Deciduous broadleaf (4)</td>
<td>0.116</td>
<td>0.127</td>
<td>0.140</td>
<td>0.119</td>
</tr>
<tr>
<td>Mixed forest (5)</td>
<td>0.096</td>
<td>0.101</td>
<td>0.119</td>
<td>0.100</td>
</tr>
<tr>
<td>Open shrubland 35S–65N (7)</td>
<td>0.220</td>
<td>0.219</td>
<td>0.209</td>
<td>0.217</td>
</tr>
<tr>
<td>Open shrubland Australia (7)</td>
<td>0.177</td>
<td>0.177</td>
<td>0.177</td>
<td>0.173</td>
</tr>
<tr>
<td>Open shrubland other (7)</td>
<td>0.137</td>
<td>0.126</td>
<td>0.141</td>
<td>0.129</td>
</tr>
<tr>
<td>Woody savanna (8)</td>
<td>0.106</td>
<td>0.117</td>
<td>0.110</td>
<td>0.112</td>
</tr>
<tr>
<td>Savanna (9)</td>
<td>0.140</td>
<td>0.141</td>
<td>0.142</td>
<td>0.133</td>
</tr>
<tr>
<td>Gravel (10)</td>
<td>0.185</td>
<td>0.165</td>
<td>0.165</td>
<td>0.178</td>
</tr>
<tr>
<td>Gravel Hunasia (12)</td>
<td>0.144</td>
<td>0.140</td>
<td>0.150</td>
<td>0.139</td>
</tr>
<tr>
<td>Gravel East Asia, India (12)</td>
<td>0.162</td>
<td>0.161</td>
<td>0.151</td>
<td>0.156</td>
</tr>
<tr>
<td>Gravel other (12)</td>
<td>0.162</td>
<td>0.151</td>
<td>0.165</td>
<td>0.159</td>
</tr>
<tr>
<td>Barren in Saharan and the Arabian desert (16)</td>
<td>0.365</td>
<td>0.356</td>
<td>0.353</td>
<td>0.365</td>
</tr>
<tr>
<td>Barren in Asia (16)</td>
<td>0.222</td>
<td>0.229</td>
<td>0.232</td>
<td>0.228</td>
</tr>
<tr>
<td>Barren excluding Saharan, the Arabian desert and Asia (16)</td>
<td>0.208</td>
<td>0.213</td>
<td>0.175</td>
<td>0.215</td>
</tr>
</tbody>
</table>

*Data in the analysis are based on high quality and snow free quality assurance flag.

Surface energy fluxes

Observations taken in nearby forest and pasture sites in Amazonia during the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS)

Observations taken during the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) show similar results

Global NPP on land decreased during El Niño events with corresponding increases in atmospheric CO\textsubscript{2} growth rate.

The period 1991-1993, following the eruption of Mount Pinatubo, is an exception to the general relationship between ENSO and NPP.

Deforestation is a carbon source

Idealized changes in ecosystem carbon pools (top) and resulting carbon flux (bottom) due to harvest and regrowth in a temperate forest. 10 Mg ha\(^{-1}\) = 1 kg m\(^{-2}\)

Synthesis results from 12 FACE studies in forest, grassland, desert, and agricultural ecosystems exposed to CO₂ concentrations of 475-600 ppm. Data are the mean response (circles) and 95% confidence intervals (bars) for all species and by plant functional type for light-saturated leaf photosynthetic rate ($A_{sat}$) and stomatal conductance ($g_s$).

Photosynthesis increases and stomatal conductance decreases with higher atmospheric CO₂.

**Community Land Model**

- Land model for Community Climate System Model
- Developed by the CCSM Land Model Working Group in partnership with university and government laboratory collaborators

Energy fluxes: radiative transfer; turbulent fluxes (sensible, latent heat); heat storage in soil; snow melt

Hydrologic cycle: interception of water by leaves; infiltration and runoff; snow accumulation and melt; multi-layer soil water; partitioning of latent heat into evaporation of intercepted water, soil evaporation, and transpiration

Bonan et al. (2002) J Climate 15:3123-3149
Oleson et al. (2004) NCAR/TN-461+STR
Dickinson et al. (2006) J Climate 19:2302-2324
Community Land Model

Carbon cycle and dynamic vegetation

Ecosystem carbon balance

Leaf phenology

Vegetation dynamics

Tropical deforestation

Settlement and deforestation surrounding Rio Branco, Brazil (10°S, 68°W) in the Brazilian state of Acre, near the border with Bolivia. The large image covers an area of 333 km x 333 km.

Numerous climate model studies find a warmer, drier tropical climate following deforestation.
U.S. deforestation

Cropland (percent of grid cell)

Broadleaf deciduous tree (percent of grid cell)
Summer Surface Air Temperature Difference (Present Day - Natural Vegetation)

Four paired climate simulations with CAM2 using two land surface models
- NCAR LSM
- CLM2
and two surface datasets
- Biome dataset without subgrid heterogeneity
- Dataset of plant functional types with subgrid heterogeneity

Conclusion
Magnitude of cooling associated with croplands is sensitive to surface datasets and model physics

CO₂ fertilization and stomatal conductance

Amazonian evergreen forest, diurnal cycle January

CO₂ fertilization (RP, RPV) reduces canopy conductance and increases temperature compared with radiative CO₂ (R)

Global climate:
- Reduced conductance
- Reduced evaporation
- Reduced precipitation
- Warmer temperature

Bounoua et al. (1999) J Climate 12:309-324
Climate of the 20\textsuperscript{th} century

What are the causes of this observed climate change?
20th century climate forcings

The combination of natural and anthropogenic forcings can match the observed temperature record.

What is the vegetation forcing of climate over this period?

Meehl et al. (2004) J Climate 17:3721-3727
Climate of the 21st century

**Climate forcings**
- Greenhouse gases
- Ozone
- Solar variability
- Sulfate aerosols
- Volcanic aerosols
- Black carbon aerosols

What is the vegetation forcing of climate?

Meehl et al. (2006) J Climate 19:2597-2616
Historical land use forcing of climate

Many studies have examined the global climate forcing due to historical changes in land cover. The emerging consensus is that land cover change in middle latitudes has cooled the Northern Hemisphere (primarily because of higher surface albedo).

Comparison of 6 earth system models of intermediate complexity forced with historical land cover change, 1000-1992...

Northern Hemisphere annual mean temperature decreases by 0.19 to 0.36 °C relative to the pre-industrial era

Brovkin et al. (2006) Climate Dynamics 26:587-600
Historical land use forcing of climate

Brovkin et al. (2006) Climate Dynamics 26:587-600
Future land cover change as a climate forcing

Future IPCC SRES Land Cover Scenarios for NCAR LSM/PCM

a) Present day land cover

b) B1 2050 land cover
d) A2 2050 land cover
c) B1 2100 land cover
e) A2 2100 and cover

- **A2** - Widespread agricultural expansion with most land suitable for agriculture used for farming by 2100 to support a large global population
- **B1** - Loss of farmland and net reforestation due to declining global population and farm abandonment in the latter part of the century

Feddema et al. (2005) Science 310:1674-1678
Future land cover change as a climate forcing

PCM/NCAR LSM transient climate simulations with changing land cover. Figures show the effect of land cover on temperature:

\[(\text{SRES land cover + SRES atmospheric forcing}) - \text{SRES atmospheric forcing}\]

Feddema et al. (2005) Science 310:1674-1678
U.S. deforestation warms climate

**Land cover**

- **1700**
  - Forest
  - Grassland
  - Woodland
  - Semi-desert
  - Desert

- **1910**
  - Cropland
  - Grassland
  - Woodland

- **1990**
  - Cropland
  - Woodland
  - Needleleaf evergreen tree
  - Broadleaf deciduous tree

**July temperature difference**

- **1910 - 1700**
  - Forest → cropland in east
  - Grass → cropland in central US

- **1990 - 1910**
  - Reforestation in east
  - Greater cropland in central US

**GRASS with LEAF-2**

- Grass → crop: Increased ET
- Forest → crop: Increased albedo, reduced z₀, reduced ET (rooting depth)

Winter wheat warms temperature


MM5 with LSX
A broad diversity of crops worldwide

Carbon cycle feedback

Transient simulations 1860-2100 with a carbon cycle, forced with anthropogenic CO₂ emissions
Two simulations to isolate the carbon cycle feedback:
• Coupled carbon cycle-climate simulation (with carbon cycle-climate feedback)
• Carbon cycle-climate simulation but no effect of CO₂ on climate (no carbon cycle-climate feedback)

Without climate change (i.e., without carbon cycle-climate feedback), CO₂ fertilization of plant growth increases carbon uptake by the terrestrial biosphere throughout the 20th and 21st centuries. In the fully coupled model, climate change decreases the terrestrial carbon sink, and the biosphere becomes a source of carbon by the middle of the 21st century.

Cox et al. (2004) Theoretical Applied Climatol. 78:137-156
Experimental protocol
Eleven climate models of varying complexity with active carbon cycle

Transient climate simulations through 2100 forced with historical fossil fuel emissions and IPCC SRES A2 emissions

Vegetation forcings of climate
• Direct biogeochemical effect (atmos. CO₂)
• Indirect biogeophysical effect (stomata, leaf area, biogeography)

Results
Models have large uncertainty in simulated atmospheric CO₂ at 2100 (range is from 730 ppm to 1020 ppm)
C4MIP - Climate and carbon cycle

Large uncertainty in terrestrial fluxes at year 2100

- 1 model simulates a 6 Pg C/yr source of carbon from land
- 1 model simulates a 11 Pg C/yr terrestrial carbon sink
- majority of models simulate a modest carbon sink

Relatively less uncertainty in ocean fluxes

All models simulate carbon uptake ranging from 4-10 Pg C/yr at year 2100

Friedlingstein et al. (2006) J Climate 19:3337-3353
Effect of climate change on carbon cycle

Climate-carbon cycle feedback
- All models have a positive climate-carbon cycle feedback
- The difference between fully coupled carbon cycle climate simulations and uncoupled simulations ($CO_2$ has no radiative effect) ranges from 20 ppm to 200 ppm

Distribution at 2100 of cumulative anthropogenic carbon emissions
The amount of carbon stored in the atmosphere increases in each model compared with the comparable simulation without climate-carbon cycle feedback, while the land carbon storage decreases.

Friedlingstein et al. (2006) J Climate 19:3337-3353
Fraction of cumulative anthropogenic CO$_2$ emission in air, ocean, and land up to 2000 (open symbols) and to 2100 (closed symbols) for eleven carbon cycle climate model simulations.

All models show that the efficiency of the carbon cycle to store anthropogenic CO$_2$ in ocean and land decreases in the future.

Biogeophysical vs. biogeochemical interactions

Historical land cover change

Biogeophysical cooling

Biogeochemical warming

Biogeophysical cooling offsets biogeochemical warming

Future land cover change

A2 - Widespread agricultural expansion with most land suitable for agriculture used for farming by 2100 to support a large global population.

B1 - Loss of farmland and net reforestation due to declining global population and farm abandonment in the latter part of the century.
Biogeophysical
A2 - cooling with widespread cropland
B1 - warming with temperate reforestation

Biogeochemical
A2 - large warming; widespread deforestation
B1 - weak warming; less tropical deforestation, temperate reforestation

Net effect similar
A2 - BGC warming offsets BGP cooling
B1 - moderate BGP warming augments weak BGC warming
Permissible anthropogenic CO\textsubscript{2} emissions to achieve a targeted atmospheric CO\textsubscript{2} are derived from specified atmospheric CO\textsubscript{2} concentration and simulated land and ocean carbon fluxes.

The positive carbon cycle-climate feedback reduces the ability of the biosphere to store anthropogenic carbon emissions and necessitates reductions in emissions to achieve stabilization goals.

The CO\textsubscript{2} fertilization effect is particularly important as this increases the terrestrial carbon sink and allows high anthropogenic emissions.
Reforestation might be chosen as an option for the enhancement of terrestrial carbon sequestration or biofuel plantations as a substitute for fossil fuels.
Carbon plantations and biofuel plantations reduce atmospheric $CO_2$, leading to cooling.

Carbon plantations have lower albedo than biofuels, leading to warming.

Colonial Americans and forests

Thomas Cole – “View from Mount Holyoke, Northampton, Massachusetts, after a Thunderstorm (The Oxbow)”, 1836

Conveys the views Americans at that time felt toward forests. The forest on the left is threatening. The farmland on the right is serene.

Forest - dark, sinister, forbidding, lacking order, threat to survival
Ecology or climatology

**Climatic Interpretation**

Lamb (1977) *Climate: Present, Past and Future. Volume 2, Climatic History and the Future*

- Painted in the winter of 1565
- Records Bruegel’s impression of severe winter
- Start of a long interest in Dutch winter landscapes that coincided with an extended period of colder than usual winters

Lamb (1995) *Climate, History and the Modern World*

**Ecological Interpretation**

Forman & Godron (1986) *Landscape Ecology*

- Defines ecological concept of a landscape
- Heterogeneity of landscape elements
- Spatial scale
- Movement across the landscape