Biosphere–atmosphere interactions in Earth system models

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NCAR models circa 1993

- Prescribed soil wetness and snow depth
- Prescribed surface albedos
- No plant canopies (no leaves or stomata)
Advent of land surface models

Simple Biosphere Model (SiB) (Sellers et al. 1986, 1996)
Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1986, 1993)

Diffusive fluxes as controlled by plant canopies:
- Radiative transfer
- Turbulent energy fluxes
- Stomata
- Hydrology
- Momentum transfer
Biogeochemical perspective

Evolution of carbon sinks in a changing climate

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Fung et al. (2005) PNAS, 102, 11201-11206

First coupled carbon cycle-climate model at NCAR using CASA‘ adaptation of CASA biogeochemical model

- Simple 12-pool model

Earth system models use mathematical formulas to simulate the **physical**, **chemical**, and **biological** processes that drive Earth’s atmosphere, hydrosphere, biosphere, and geosphere.

A typical Earth system model consists of coupled models of the **atmosphere**, **ocean**, **sea ice**, **land**, and **glaciers**.

Land is represented by its **ecosystems**, **watersheds**, **people**, and **socioeconomic** drivers of environmental change.

The model provides a comprehensive understanding of the processes by which people and ecosystems **affect**, **adapt to**, and **mitigate** global environmental change.
Earth system models

What are the consequences of alternative socioeconomic pathways?

Scientific discovery
Identify ecological processes that determine climate

Advance theory
Test generality of ecological theories at the macroscale
Earth system models

Prominent terrestrial feedbacks
- Snow cover and climate
- Soil moisture-evapotranspiration-precipitation
- Land use & land cover change
- Carbon cycle
- Reactive nitrogen
- Chemistry-climate (BVOCs, O\textsubscript{3}, CH\textsubscript{4}, aerosols)
- Biomass burning

The Anthropocene

Human activities (energy use, 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?

Human domination of Earth system

World: Total Population

Ecosystems and climate

Multiple processes at many timescales

Near-instantaneous (30-min) coupling with atmosphere (energy, water, chemical constituents)

Long-term dynamical processes that control these fluxes in a changing environment (disturbance, land use, succession)

The Community Land Model

Fluxes of energy, water, CO₂, CH₄, BVOCs, and Nr and the processes that control these fluxes in a changing environment


CLM5 documentation: cesm.ucar.edu/models/cesm2/land

**Spatial scale**
1.25° longitude × 0.9375° latitude (288 × 192 grid), ~100 km × 100 km

**Temporal scale**
- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century (disturbance, land use, succession)
- Paleoclimate (biogeography)

**Surface energy fluxes**
- Direct solar
- Diffuse solar
- Reflected solar
- Absorbed solar
- Emitted longwave
- Latent heat flux
- Sensible heat flux
- Momentum flux
- Wind speed

**Hydrology**
- Precipitation
- Transpiration
- Throughfall
- Sublimation
- Evaporation
- Infiltration
- Surface runoff

**Biogeochemistry**
- Photosynthesis
- BVOCs
- Autotrophic respiration
- Heterotrophic respiration
- N dep
- N fixation
- N mineralization
- N uptake

**Landscape dynamics**
- Glacier
- Wetland
- Urban
- Runoff
- River discharge
- Land Use Change
- Competition
- Disturbance
- Vegetation Dynamics
- Growth
Biogeophysical processes

Trees have a low albedo

NSF/NCAR C-130 aircraft above a patchwork of agricultural land during a research flight over Colorado and northern Mexico


Colorado Rocky Mountains
Biogeophysical processes

Trees are tall (aerodynamically rough)

Cowling Arboretum, Carleton College

Biogeophysical processes

Soil moisture and evapotranspiration

2012 drought, Waterloo, NE (Nati Harnik, AP)

Land-atmosphere coupling

Hydrometeorological coupling at short timescales (sub-seasonal to seasonal); e.g. soil moisture and atmospheric predictability

Historical land use & land cover change, 1850-2005

Change in tree and crop cover (percent of grid cell)

Historical land use & land-cover change
- Loss of tree cover and increase in cropland
- Farm abandonment and reforestation in eastern U.S. and Europe

Lawrence et al. (2012) J. Clim., 25, 3071-95
Forests influences on global climate

What happens when forests are replaced with grassland?

Net response (annual mean)

Albedo-only

Higher albedo = cooling

Evapotranspiration-only

Surface roughness-only

Reduced evapotranspiration = warming

Reduced surface roughness = warming

Annual mean surface temperature change (°C)

Historical land use & land cover change

Warming from sensible and latent heat fluxes

Radiative cooling

Model variability

15 CMIP5 models: Change in JJA temperature (°C) with 20th century land-cover change

- Atmosphere model
- Land model
- How land cover change is implemented
Observationally based analyses

Radiative forcing
- Change in surface albedo and carbon storage with disturbance
  Randerson et al. (2006) *Science*, 314, 1130-32

Climate regulation value
- Evaporative cooling is a positive climate service
- Surface warming from low albedo is a negative climate service
- Biogeochemical processes; e.g., carbon storage is a positive climate service

Flux tower analyses
- Change in surface temperature for paired sites
  Lee et al. (2011) *Nature*, 479, 384-87

MODIS surface temperature, albedo and evapotranspiration

How do these analyses constrain models?
Twenty-first century land-cover change

Change in tree cover (percent of grid cell)

RCP4.5

Mitigation - afforestation to enhance the terrestrial carbon sink

RCP8.5

Business as usual - continued deforestation

Percent of grid cell

Lawrence et al. (2012) J. Clim., 25, 3071-95
Land management

Forest management

Agricultural management

Cumulative percent of grid cell harvested

Crop selection
Irrigation
Fertilizer use
Tillage

8 crop functional types:
Maize (temperate, tropical)
Soybean (temperate, tropical)
Spring wheat
Sugarcane
Cotton
Rice

Lawrence et al. (2012) J. Clim., 25, 3071-95
Lombardozi et al. (2019) JGR: Biogeosci., submitted
Carbon cycle

The global carbon cycle

Atmospheric CO$_2$ has increased over the industrial era as the balance of:

- Fossil fuel emissions
- Land-use and land-cover change emissions
- Terrestrial and oceanic sinks

How will the global carbon cycle change in the future?

Will the terrestrial biosphere continue to be a carbon sink?

Land use emissions

Global flux of carbon from land use and land cover change 1850-2015

Biogeophysics and biogeochemistry

- **Biogeophysical**
- **Biogeochemical**
- **Net**

**Historical land use & land-cover change**

- Biogeophysical processes decrease annual mean temperature (albedo)
- Deforestation releases carbon (warms temperature)
- Biogeochemical warming exceeds biogeophysical cooling

**Prevailing paradigm**

The dominant competing signals from historical deforestation are an increase in surface albedo countered by carbon emission to the atmosphere

Uncertainty in land carbon uptake due to differences among models is considerably larger than the spread across scenarios.
Sources of uncertainty

- Internal variability
- Model structure
- Scenarios

Hawkins & Sutton (2009) BAMS, 90, 1095-1107

CMIP5 model uncertainty

Weighting models does not substantially reduce uncertainty

Nitrogen addition alters the composition and chemistry of the atmosphere, and changes the radiative forcing. The net radiative forcing varies regionally.
Chemistry – climate interactions

- Loss of forests and increase in croplands reduces global BVOC emissions
- Decreases ozone, CH$_4$, and secondary organic aerosols
- Net radiative forcing is $-0.11$ W m$^{-2}$

Global climate effects of historical cropland expansion


Biomass burning and dust

Dust plume off Africa

Atmospheric radiation
Atmospheric chemistry
Surface albedo


Terrestrial ecosystems and geoengineering

Green solutions to mitigate climate change

Solar Radiation Management

Stratospheric aerosols

Increase cloud albedo

Carbon dioxide removal

- Increase surface albedo
- Leaf reflectance of crops
- White roofs in cities
- Biofuels & crop management
- Biochar
- Afforestation & reforestation
- Carbon capture
- Geological storage
- Ocean fertilization

Areas of the world that are presently occupied by cropland but which could potentially support forests were allowed to be afforested.

Biogeophysical warming is prominent in northern high latitudes, where the warming from the lower albedo is important and initiates loss of sea ice.

Afforestation increases the land carbon uptake over the twenty-first century and reduces atmospheric CO₂ compared with the control simulation.

Net radiative forcing

Consequences of boreal afforestation

Swann et al. (2010) *PNAS*, 107, 1295-1300


Spracklen et al. (2008) *Phil. Tran. R. Soc. A*, 366, 4613-26

Bonan et al. (1992) *Nature*, 359, 716-718

But can (should) forests be managed for climate services?

**Trade-offs in using European forests to meet climate objectives**

Sebastiaan Lyssarts	extsuperscript{1,2,4}, Guillaume Marie	extsuperscript{1}, Aude Valade	extsuperscript{3,5}, Yi-Ying Chen	extsuperscript{2,6}, Sylvester Njakou Djomo	extsuperscript{4}, James Ryder	extsuperscript{2,7}, Juliane Otto	extsuperscript{7,8}, Kim Nauits	extsuperscript{2,9}, Anne Sofie Lansen	extsuperscript{2}, Josefine Ghattas	extsuperscript{3} & Matthew J. McGrath	extsuperscript{2}


**Natural climate solutions for the United States**


Harvard Forest (Rose Abramoff)

**The forest question**

*Trees are supposed to slow global warming, but growing evidence suggests they might not always be climate saviours.*

Earth system prediction

- Land as a source of atmospheric predictability
  - Soil moisture
  - Snow
  - Vegetation state (leaf area)

(NAS, 2016)
Earth system change

... or predictability of land state and fluxes

Drought, wildfires, floods, tree mortality, vegetation greening, habitat loss, infectious disease
The various models used for climate projections, mitigation, and impacts (VIA) overlap in scope and would benefit from a broad perspective of Earth system prediction.

Earth system prediction

Time of emergence of forced signal in land carbon uptake (RCP8.5)

Lombardozzi et al. (2014) *Nature Climate Change*, 4, 796-800
Increasing model complexity

Breadth and complexity of land surface models as documented by NCAR technical notes

Do more complexity and more authentic process parameterizations provide a better model?

Many paths to reduce model uncertainty

**Model intercomparisons (MIPs)**
CMIP6: carbon cycle, land use, land-atmosphere coupling, ...  
Range of plausible outcomes, but more models ≠ better results

**Model benchmarking**
Comprehensive model evaluation against observations

**Real-world experiments and models**
FACE, N addition

**Model-data fusion**
Data assimilation, parameter estimation

“Discover” critical missing process
Add another process that is ecologically important but poorly known at the global scale.  
Tune a key parameter to get a good simulation.

**Model intracomparison**
Focus on model structural uncertainty to identify processes contributing to uncertainty

**Model hierarchy**
CLM5; process models (multilayer canopy, MIMICS); simple models (Marysa Lägue)

**Model deconstruction**
Take apart into sub-components to expose biases, flaws, or inconsistencies
Modeling caveats

CLM is just a starting point for the science. It is not the science itself

- Easy to run the model and get an answer
- Much harder to understand why you got that answer
- Just because a process is in the model does not mean it is correct
- CLM is a very complex, multidisciplinary model that requires a broad perspective of the Earth system