Modelling dynamic vegetation within the Earth System models

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Climate system

After John Osborn, NOAA
Interactions between the land surface and the atmosphere that have direct impacts on the physical climate system.

(A) Surface radiation budget. (B) Effect of heat fluxes on the atmosphere.

Sellers et al., Science, 1997
Atmospheric gas composition

Biogeochemical effects
Changes in ecosystems affect sources and sinks of:
- Greenhouse gases
- Aerosols
- Other gases (e.g. oxygen)

Biogeophysical effects
Changes in ecosystems affect:
- Heat fluxes
- Water fluxes
- Wind (direction and magnitude)

Terrestrial ecosystems

after Foley et al. (2003)
Climatic control of terrestrial vegetation

Purves et al., Life: The Science of biology
Köppen climate zones

- Af (tropical rainforest climate)
- Am (monsoon variety of Af)
- Aw (tropical savannah climate)
- BS (steppe climate)
- BW (desert climate)
- Cf (mild humid climate with no dry season)
- Cs (mild humid climate with a dry summer)
- Cw (mild humid climate with a dry winter)
- Dw (snowy-forest climate with a dry winter)
- Df (snowy-forest climate with a moist winter)
- E (polar ice climate)
- F (highland climate)
Vegetation models

• Biogeography models (climate-vegetation classifications)
  – classifications by Köppen, Holdridge
  – plant functional type (PFT) concept: species are lumped into several PFTs, such as evergreen needleleaf trees (BIOME1)
  – Biogeography + carbon cycle models (BIOME4)

• Dynamic Global Vegetation Models (DGVMs)
  – Fractional land cover representation (plant functional type)
  – Temporal dynamics
  – Disturbances as driving forcing of vegetation succession (explicitly or implicitly)
DGVM

Vegetation cover: models vs present-day reconstruction

JSBACH
Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg

AOGCM
ECHAM5/MPIOM

vertical structure

vertical atmosphere column

Ocean
MPIOM

horizontal dynamics

Atmosphere

vertical dynamics

communication interface

land surface processes
**Modules of JSBACH**

**Dynamic land biosphere**

- **Stomata Model:** BETHY
  - Transpiration (CO$_2$-sensitive stomatal cond.)
  - Photosynthesis: Carbon assimilation (NPP)

- **Phenology model:** (LoGro-P)
  - dynamic Leaf Area Index (LAI)

- **Albedo model:**
  - visible and NIR surface albedo

- **Dynamic land cover:**
  - tiling land approach; 8 PFTs
  - veget dynamics based on NPP and climate
  - anthropogenic land cover change

**Carbon Flow Model:** Cbalance

- heterotrophic (soil) respiration
- net CO$_2$-exchange with atmosphere (NEP)
- Carbon accounting for plants and soil (C-pools)

**Soil model:** ECHAM5-scheme:

- surface/soil hydrology
- energy balance
- mosaic approach for surface properties
Simple model for dynamic vegetation: concept

**Tiling of land surface**

| Land area excluded from vegetation dynamics (e.g. crops & pastures, glaciers) |
| Slow variable: Desert or bare ground, $B_g$ |
| Fast variable: Bare soil, $B_s$ |

**ECHAM land grid cell**

ODE for FPC (fractional projected cover) solved daily:

$$\frac{dFPC_i}{dt} = EST(FPC_i) - MORT(FPC_i) - FPC_i^{burnt} - FPC_i^{damaged}$$

Bare soil fraction is diagnostic:

$$B_s = 1 - \left( \sum_{\text{grassPFT}} FPC_i + \sum_{\text{woodyPFT}} FPC_i \right)$$
Model equations

FPC dynamical equation solved daily:

\[
\frac{dFPC_i}{dt} = EST(FPC_i) - MORT(FPC_i) - FPC_i^{\text{burnt}} - FPC_i^{\text{damaged}}
\]

Mortality:
\[
MORT(FPC_i) = \frac{FPC_i}{\tau_{\text{mort}}}
\]

Establishment:
\[
EST(FPC_i) = \frac{NPP^{\text{rel}}_i}{\tau_{\text{PFT}_i}}
\]

Relative NPP advantage:
\[
NPP^{\text{rel}}_i = \frac{(NPP_i)^a \cdot FPC_i}{\sum_{\text{woody PFT}} (NPP_k)^a \cdot FPC_k}
\]

FPC fraction burnt:
\[
FPC_i^{\text{burnt}} = \frac{FPC_i}{\tau_{\text{burnt}}}
\]

\[
\tau_{\text{burnt}} = \begin{cases} 
\tau_i^\text{max}, & \text{if } q \geq q_{\text{crit}} \\
\tau_i^\text{max} (1 + k_p \frac{q - q_{\text{crit}}}{q_{\text{crit}}}), & \text{if } q < q_{\text{crit}} 
\end{cases}
\]

Desert fraction:
\[
B_g = ave_{20yr} \left( \max(0, 1 - \sum_{\text{all PFT}} FPC_i (1 - e^{-0.5 \cdot LAI_i})) \right)
\]
Model topology

Carbon dynamics is done by JSBACH carbon cycle module

FPC dynamics is simulated by dynamic veget module

\[
\begin{align*}
\frac{dB_i}{dt} &= GPP_i - R_{a,i} - \frac{B_i}{\tau_i} - D_i \\
\frac{dFPC_i}{dt} &= EST_i(...) - MORT_i(...) 
\end{align*}
\]
Wildfire disturbance

Coupled model ECHAM5-MPIOM-JSBACH

SPITFIRE model (Thonicke et al., submitted)
Tree fraction

- Observed, MODIS data (Hansen et al., 2006)
- Interactive ECHAM5-MPIOM-JSBACH

Brovkin et al., GRL, 2009
Desert/bare ground fraction

Observed, MODIS data (Hansen et al., 2006)

Interactive ECHAM5-MPIOM-JSBACH
Climate-vegetation feedbacks: interactive loop

Vegetation cover
Temperature, precipitation
Albedo, transpiration, runoff, surface roughness
Atmosphere/ocean
Climate response to global forest or grass cover

Brovkin et al., GRL, 2009
Temperature changes (°C) relative to CTRL simulation

FOREST world

GRASSLAND world

Winter (DJF)

Summer (JJA)

Brovkin et al., GRL, 2009
Projected changes in boreal forest cover in the Hadley Centre model

**Figure 3 | Dynamic and equilibrium boreal forest extent throughout the simulations.** The solid line shows the fractional tree cover (represented as fractional land coverage of both broadleaf and needleleaf trees in the region 45°–80° N) as it evolves dynamically through the SRES A2 simulation and the dashed line shows the committed state corresponding to each year.

*Jones et al., Nature Geoscience, 2009*
Perspective on vegetation modelling

• Going beyond PFT concept
  – Increased representativeness of species, modelling on the patches level (e.g. LPJ-GUESS)
  – Flexible reclassification of PFTs for paleo-applications
  – Direct modelling of climate-relevant plant traits (albedo) response to climate change without PFT step

• Better representation of spatial and temporal heterogeneity of vegetation cover & climate variability
  – Accounting for formation of vegetation patterns
  – Rainfall intermittency in drylands
  – Disturbances regimes
TERRABITES – new European biospheric network (COST Action ES0805)

The main objective of the Action is a cross-disciplinary assessment of our current understanding of the terrestrial biosphere from an Earth system perspective to improve the reliability of future Earth system projections in coupled climate-biosphere simulations.

Bringing together biospheric modellers, ecologists, and data gathering community

4 working groups:
- WG 1: Modeling plant functioning
- WG 2: Modeling carbon and nutrient cycling
- WG 3: Modeling plant ecology
- WG 4: Modeling human land use

Chair of Action MC: Christian Reick, MPI for Meteorology (Hamburg)

Action duration: June 2009 – June 2013

Participants: 14 COST countries; 4 non-COST countries & institutions
  Russian participants invited: Leonid Golubyatnikov (IAP), Dmitry Luri (IG)

Open Symposium: 9-11 February 2010, Hamburg

www.terrabites.net (not yet available!)