Climate-vegetation interactions: Part I

Victor Brovkin

Max-Planck-Institut für Meteorologie
KlimaCampus, Hamburg
Outline

- Land surface physics
- Ecology
- Carbon cycle

*Will be addressed in more details in lectures of Martin Claussen (end of November)*
Guiding question

What is the role of land surface / terrestrial biosphere in the Earth System dynamics?
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

Climate
Land surface albedo, March 2003

Source: MODIS satellite platform (Schaaf et al., 2002)
Land surface albedo, July 2003

Source: MODIS satellite platform (Schaaf et al., 2002)
Tundra

Taiga
Surface radiation budget

\[ R_n = S(1 - \alpha) + L_w - \varepsilon \sigma T_s^4 \]

where \( R_n \) is the net radiation, \( S \) is the insolation, \( \alpha \) is the surface albedo, \( L_w \) is the downward long-wave flux, \( \varepsilon \) is the surface emissivity (>1.0), \( \sigma \) is the Stefan-Boltzmann constant, and \( T_s \) is the land surface temperature.

\[ R_n = G + H + \lambda E \]

where \( G \) is the ground heat flux, \( H \) is the sensible heat flux, \( E \) is the evapotranspiration rate, and \( \lambda \) is the latent heat of vaporization.

Sellers et al., Science, 1997
Figure 2.11: Global mean energy budget under present-day climate conditions. Numbers state magnitudes of the individual energy fluxes in W m\(^{-2}\), adjusted within their uncertainty ranges to close the energy budgets. Numbers in parentheses attached to the energy fluxes cover the range of values in line with observational constraints. (Adapted from Wild et al, 2013.)
1st generation of land surface models (1980s): no vegetation canopy

$$H = \frac{T_s - T_r}{r_a} \rho c_p$$

$$\lambda E = \beta \left[ \frac{e^*(T_s) - e_r}{r_s} \right] \frac{\rho c_p}{\gamma}$$

where $T_r$ is the air temperature within the lowest layer of the atmospheric model, $r_a$ is the aerodynamic resistance between the surface and the lowest layer of the atmosphere, $\rho$ and $c_p$ are the density and specific heat of air, $\beta$ is the moisture availability function ($0 \leq \beta \leq 1$), $e^*(T_s)$ is the saturated vapor pressure at surface temperature $T_s$, $e_r$ is the vapor pressure within the lowest layer of the atmospheric model, and $\gamma$ is the psychrometric constant.

Sellers et al., Science, 1997
Stomata cells

Stoma in a tomato leaf

http://remf.dartmouth.edu/images/botanicalLeafSEM/source/16.html
PAR – photosynthetically active radiation
**2nd generation of land surface models (early 1990s): vegetation canopy**

\[ g_s = g_s(PAR)[f(\delta e)f(T)f(\Psi_1)] \]

where \( g_s(PAR) \) is the PAR-regulated (unstressed) value of leaf conductance and \( f(\delta e), f(T), \) and \( f(\Psi_1) \) are the environmental stress factors that account for the effects of vapor pressure deficit \( \delta e \), temperature \( T \), and leaf water potential \( \Psi_1 \), respectively.

\[ \lambda E = \beta \left[ \frac{e^*(T_s) - e_r}{r_a + r_c} \right] \frac{\rho c_p}{\gamma} \]
3rd generation of land surface models (late 1990s): vegetation canopy + photosynthesis

\[ c_i, c_s, c_a, c_r - \text{CO}_2 \text{ concentration inside leaf, in the leaf surface layer, the canopy layer, and the atmosphere, respectively;} \]

\[ A_c - \text{canopy CO}_2 \text{ assimilation,} \]

\[ R_D - \text{leaf respiration,} \]

\[ R_{\text{soil}} - \text{soil respiration;} \]

\[ r_c - \text{canopy resistance;} \]

\[ r_b - \text{leaf boundary resistance} \]
Difference between land surface types

- **Deeper soil**
- Potential range in fractional cover not achieved because temperature varies little
- Most roots in surface layer

- Large seasonal range in fractional cover

- Many stems and dead matter
- Large fractional cover

- Small fractional cover
- Few roots in lower layer

- Most roots in lower layer
- Small stomatal resistance

- **Short Grass**
- **Tundra**
- **Irrigated Crop**
- **Tropical Forest**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Short grass</th>
<th>Tropical tree</th>
<th>Land Cover/Vegetation Type*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1  2</td>
<td>3  4</td>
<td>5  6</td>
</tr>
<tr>
<td></td>
<td>7  8</td>
<td>9  10</td>
<td>11 12</td>
</tr>
<tr>
<td></td>
<td>13 14</td>
<td>15 16</td>
<td>17 18</td>
</tr>
<tr>
<td>a) Maximum fractional vegetation cover</td>
<td>0.85 0.80 0.80 0.80</td>
<td>0.80 0.80 0.80 0.90</td>
<td>0.80 0.80 0.0 0.0 0.80 0.0 0.80 0.0 0.0 0.80 0.80 0.80</td>
</tr>
<tr>
<td>b) Difference between maximum fractional vegetation cover and cover at temperature of 269 K</td>
<td>0.6 0.1 0.1</td>
<td>0.3 0.3 0.5 0.3</td>
<td>0.0 0.2 0.6 0.1 0.1 0.4 0.0</td>
</tr>
<tr>
<td>c) Roughness length (m)</td>
<td>0.06 0.02 1.0</td>
<td>1.0 0.8 2.0</td>
<td>0.1 0.05 0.04 0.06 0.1 0.01 0.03</td>
</tr>
<tr>
<td>d) Depth of the rooting zone soil layer (m)**</td>
<td>1.0 1.0 1.5</td>
<td>1.5 2.0 1.5</td>
<td>1.0 1.0 1.0 1.0 1.0 1.0 1.0</td>
</tr>
<tr>
<td>e) Depth of the upper soil layer (m)**</td>
<td>0.1 0.1 0.1</td>
<td>0.1 0.1 0.1</td>
<td>0.1 0.1 0.1 0.1 0.1 0.1 0.1</td>
</tr>
<tr>
<td>f) Fraction of water extracted by upper layer roots (saturated)</td>
<td>0.3 0.8 0.67</td>
<td>0.67 0.5 0.8</td>
<td>0.8 0.8 0.9 0.9 0.3 0.8 0.5</td>
</tr>
<tr>
<td>g) Vegetation albedo for wavelengths &lt;0.7 μm</td>
<td>0.10 0.10 0.05</td>
<td>0.05 0.08 0.04</td>
<td>0.08 0.20 0.10 0.08 0.17 0.80</td>
</tr>
<tr>
<td>h) Vegetation albedo for wavelengths &gt;0.7 μm</td>
<td>0.30 0.30 0.23</td>
<td>0.23 0.28 0.20</td>
<td>0.30 0.30 0.30 0.28 0.34 0.60</td>
</tr>
<tr>
<td>i) Minimum stomatal resistance (s m^{-1})</td>
<td>120 200 200</td>
<td>200 200 200</td>
<td>150 200 200 200 200 200 200 200 200 200 200 200 200 200</td>
</tr>
<tr>
<td>j) Maximum LAI</td>
<td>6 2 6 6 6 6 6 6 0 6 6 6 6 0</td>
<td>6 0 0 6 6 6 6 6 6</td>
<td></td>
</tr>
<tr>
<td>k) Minimum LAI</td>
<td>0.5 0.5 5.0</td>
<td>1.0 1.0 5.0</td>
<td>0.5 0.5 0.5 0.5 0.5 0.5 0.0</td>
</tr>
<tr>
<td>l) Stem &amp; dead matter area index</td>
<td>0.5 1.0 2.0</td>
<td>2.0 2.0 2.0</td>
<td>2.0 2.0 2.0 2.0 2.0 2.0 2.0</td>
</tr>
<tr>
<td>m) Inverse square root of leaf dimension (m^{-1/2})</td>
<td>10 5 5 5 5 5 5 5 5 5 5 5 5 5 5</td>
<td>5 5 5 5 5 5 5 5</td>
<td></td>
</tr>
<tr>
<td>n) Light sensitivity factor (m^{2} W^{-1})</td>
<td>0.02 0.02 0.06</td>
<td>0.06 0.06 0.06</td>
<td>0.06 0.02 0.02 0.02 0.02 0.02 0.02 0.02</td>
</tr>
</tbody>
</table>

1 Crop mixed farming
2 Short grass
3 Evergreen needleleaf tree
4 Deciduous needleleaf tree
5 Deciduous broadleaf tree
6 Evergreen broadleaf tree
7 Tall grass
8 Desert
9 Tundra
10 Irrigated crop
11 Semidesert
12 Ice cap/glacier
13 Bog or marsh
14 Inland water
15 Ocean
16 Evergreen shrub
17 Deciduous shrub
18 Mixed Woodland
Moisture recycling over land: 2/3 of rainfall is evaporated or transpired

Units: Thousand cubic km for storage, and thousand cubic km/yr for exchanges
Moisture recycling

Precipitation

↑

↓

Soil moisture

More than half of the solar energy absorbed by land surfaces is currently used to evaporate water.
An absence of vegetation reduces evapotranspiration, increases runoff

Hadley Centre model, R. Betts

House et al., Millennium Ecosystem Assessment, 2006
ECOLOGY
Climatic control of terrestrial vegetation

Diagram showing the relationship between mean annual temperature and mean annual precipitation, illustrating the distribution of different vegetation types across various climatic zones.
Holdridge’s Life Zone model

Holdridge, Science, 1947
Biome shifts in global warming scenario

- Poleward shifts of boreal and temperate forests
- Expansion of steppe, dry woodland and desert

Emanuel et al., Climatic Change, 1995
## BIOME model

**Derivation of bioclimatic indices from interpolated climatic data in the BIOME model**

<table>
<thead>
<tr>
<th>Tolerance/requirement</th>
<th>Ecophysiological mechanism</th>
<th>Bioclimatic index</th>
<th>Climatic variable (monthly means)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold tolerance</td>
<td>Killing temperature during coldest period of the year</td>
<td>$T_{\text{min}}$ (temperature of the coldest month, lower limit)</td>
<td>Temperature</td>
</tr>
<tr>
<td>Chilling requirement</td>
<td>Winter chilling period required for budburst of woody plants</td>
<td>$T_{\text{min}}$ (temperature of the coldest month, upper limit)</td>
<td>Temperature</td>
</tr>
<tr>
<td>Heat requirement</td>
<td>Annual growth respiration requirement</td>
<td>GDD (growing degree days above 0 °C and 5 °C)</td>
<td>Temperature</td>
</tr>
<tr>
<td>Moisture requirement</td>
<td>Soil moisture availability</td>
<td>AET/PET (annual actual evapotranspiration/annual potential evapotranspiration)</td>
<td>Temperature, precipitation, cloudiness</td>
</tr>
</tbody>
</table>

*Source: Prentice et al., 1992.*
## BIOME model

Environmental constraints for each PFT in the BIOME model

<table>
<thead>
<tr>
<th>PFT</th>
<th>$T_{\text{min}}$</th>
<th>$T_{\text{max}}$</th>
<th>GDD$_0$</th>
<th>GDD$_5$</th>
<th>AET/PET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>min</td>
<td>min</td>
</tr>
<tr>
<td>Trees</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropical evergreen</td>
<td>15.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropical raingreen</td>
<td>15.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm temperate evergreen</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperate summergreen</td>
<td>−15.0</td>
<td>15.5</td>
<td></td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>Cool temperate conifer</td>
<td>−19.0</td>
<td>5.0</td>
<td></td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Boreal evergreen conifer</td>
<td>−35.0</td>
<td>−2.0</td>
<td></td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Boreal summergreen</td>
<td>5.0</td>
<td></td>
<td></td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Non-trees</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sclerophyll/succulent</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm grass/shrub</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cool grass/shrub</td>
<td></td>
<td></td>
<td></td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Cold grass/shrub</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Hot desert shrub</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold desert shrub</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No plants</td>
<td>(Dummy type)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: Prentice et al., 1992.*
Global vegetation according to the BIOME model

Prentice et al., Journal of Biogeography, 1992
Vegetation transition along ecoclines

Increasing aridity from mesophytic (moist) forest in the Appalachian Mountains westward to desert in the United States.

Increasing aridity from rain forest to desert in South America.

An elevation gradient in South America from tropical rain forest to the alpine zone.

A temperature gradient from tropical forest to the arctic tundra.

Whittaker, Communities and ecosystems, 1975
Vegetation Description

**Discrete**

Each cell is covered by the only vegetation (land cover) type

- Forest
- Grassland

**Continuous**

Each cell is covered by a mixture of simple vegetation (land cover) types

- 80% trees: 20% grass
- 30% trees: 70% grass

Analytic theory:
- Discrete Automata
- Dynamical System

**BIOME-type equilibrium model**

**Dynamic Global Vegetation Model**
Modular structure of a generic dynamic global vegetation model (DGVM)
Vegetation cover: data versus DGVM

Cramer et al., GCB, 2001
Fire-vegetation feedback

- Possible mechanism: Feedback between fire and vegetation can stabilize a forest and a grassland state.

**Forest:**
- Tree cover: high
- Few fires
- Coarse fuel
- Humid, cool microclimate

**Grassland:**
- Tree cover: low
- Frequent fires
- Fine fuel
- Hot, dry, windy microclimate
MPI-ESM: model of vegetation dynamics

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

FPC – fractional projection cover of \(i\)-th plant functional type (PFT)
PFT dynamics in phase space

\[
\begin{aligned}
\frac{dC_i}{dt} &= GPP_i - R_a - \frac{C_i}{\tau_i} - D_i \\
\frac{dFPC_i}{dt} &= EST_i(...) - MORT_i(...) \\
\end{aligned}
\]

Carbon dynamics

Dynamics of PFT fraction (FPC – fractional projection cover)

Brovkin et al., GRL, 2009
Evaluation of vegetation dynamics in MPI-ESM

Tree

Bare Ground

MODIS data

MPI-ESM: CMIP5 run

Brovkin et al., JAMES, 2013
**Fire-vegetation feedback**

- With SPITFIRE global tree covered area depends on initialization
- Simulation without fire converges
- Multiple stable states are caused by fire
- Alternative stable states occur in regions with difference in fire disturbance
- Regions in Asia were not subject of previous studies
What are changes in natural vegetation cover in the future?
CMIP5 simulations for IPCC AR5
(Climate Model Intercomparison Project 5)

- Representative concentration pathways (RCPs): world development scenarios for 21st century prepared by 4 integrated assessment groups

- ca. 20 climate modelling groups participate in CMIP5 including

<table>
<thead>
<tr>
<th>Institution</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPI for Meteorology</td>
<td>MPI-ESM</td>
</tr>
<tr>
<td>Hadley Center</td>
<td>HadGEM-ES</td>
</tr>
<tr>
<td>JAMSTEC, Japan</td>
<td>MIROC</td>
</tr>
</tbody>
</table>
Climate change in MPI-ESM, 2100-2005

Changes in annual temperature:

- RCP2.6
  - Temperature changes:
    - C:
      - Min: -10°C
      - Max: 0°C

- RCP8.5
  - Temperature changes:
    - C:
      - Min: -1°C
      - Max: 10°C

Changes in annual precipitation:

- RCP2.6
  - Precipitation changes:
    - mm/yr:
      - Min: -1000 mm/yr
      - Max: 1000 mm/yr

- RCP8.5
  - Precipitation changes:
    - mm/yr:
      - Min: -1000 mm/yr
      - Max: 1000 mm/yr
MPI-ESM RCP8.5

Color = Carbon Mass - Difference to 1850 - 1899
Height = Tree Cover Fraction

20 kg/m^2

1850

(c) DKRZ / MPI-M
Change in woody fraction

Change in carbon storage, kgC/m²

2300 - 2100

Average of HadGEM2-ES and MPI-ESM

RCP2.6

RCP8.5
CARBON CYCLE
The land biosphere in the global carbon cycle

Atmosphere: ~590 PgC (passive)
Ocean: ~40000 PgC
Land: ~4500 PgC

Land is the 2nd most important carbon reservoir, reacts much faster than the ocean
The land carbon cycle

- Plant C uptake: Photosynthesis
- Storage of C in plant tissues
- Excess C released in autotrophic respiration
- Transfer of C to soil through litterfall and root exudates
- Soil C release to atmosphere through heterotrophic respiration

Bonan, 2008
Fate of Anthropogenic CO$_2$ Emissions (2007-2016)

9.4 GtC/yr, 88%

1.3 GtC/yr, 12%

4.7 GtC/yr
47%

3.1 GtC/yr
30%

2.4 GtC/yr
23%

Budget Imbalance: 0.5 GtC/yr (6%)

Source: CDIAC; NOAA-ESRL; Houghton and Nassikas 2017; Hansis et al 2015; Le Quéré et al 2017; Global Carbon Budget 2017
Human perturbation: 580 PgC, 1870-2016

Total estimated sources do not match total estimated sinks. This imbalance reflects the gap in our understanding.
Photosynthesis: $C_3$ vs $C_4$ plants

$C_3$-type photosynthesis: ca. 85%
Most of trees; all plants in cold environment

$C_4$-type photosynthesis: ca. 15%
Corn, sugar cane, some plants in warm/dry environment

$C_4$ plants keep part of CO$_2$ released during autotrophic respiration within the leaf
Effect of elevated CO₂ on evapotranspiration and productivity

If \( c_s \) (CO₂ concentration) increases, \( A_n \) can increase as well. This is so-called CO₂ fertilization or increased water-use efficiency (physiological effect of CO₂).
Effect of elevated CO$_2$ on evapotranspiration and productivity

FACE (Free Air CO$_2$ Enrichment Experiments)

Long et al., Science, 2006
Effect of elevated CO$_2$ on evapotranspiration and productivity

Greater canopy temperatures under elevated [CO$_2$] result from lower stomatal conductance, reducing latent heat loss by evapotranspiration and leading to lower crop water use.
Land uptake response to CO$_2$ emissions: greening Earth

- Land is greening, partly due to the CO$_2$ fertilization effect
- Greening is counteracted by increased respiration
- With stabilized CO$_2$ concentration, land uptake will cease soon

Relative GSSNDVI Decadal Trend (%), 2000-2015
Myneni et al., pers. comm.
34% of the vegetated areas show greening (5% browning)

Average global LAI trend is 2.3% per decade, adding 318,000 km² (ca. land area of Germany) every year

Clustered in seven regions across six continents—most notably in China and India

Chen et al., 2019
Drivers of Earth‘s greening

Attribution of greening trend to several forcings:
• CO$_2$ fertilization (global, Zhu et al, 2016);
• Climate change (e.g. Arctic, Sahel);
• Land use
Autotrophic respiration

\[ R_{\text{leaf}} = r \cdot \frac{C_{\text{leaf}}}{c_n_{\text{leaf}}} \phi \cdot g(T) \]

\[ R_{\text{sapwood}} = r \cdot \frac{C_{\text{sapwood}}}{c_n_{\text{sapwood}}} g(T) \]

\[ R_{\text{root}} = r \cdot \frac{C_{\text{root}}}{c_n_{\text{fineroot}}} \phi \cdot g(T_{\text{soil}}) \]

where

- \( r \) – tissue respiration at reference temperature;
- \( g(T) \) – respiration dependence on temperature;
- \( \phi \) – phenology index (0<\( \phi \)<1);
- \( C_i \) – biomass of given component;
- \( c_n \) – C:N ratio of given component
Soil carbon dynamics

\[
\frac{dC_i}{dt} = F_i - k_i(T)C_i
\]

\[
k_i(T) = k_{\text{ref}} Q_{10}^{(T-T_{\text{ref}})/10}
\]

where \( C_i \) is soil carbon content (kg C/m\(^2\)) of the compartment \( i \),
\( F_i \) is a net carbon flux to the compartment \( i \) (litter input),
\( k_i(T) \) is decomposition rate at the given soil temperature \( T \),
\( k_{\text{ref}} \) is a decomposition rate at reference temperature (usually 10° C),
\( Q_{10} \) is a sensitivity of decomposition rate to temperature change (~2).
Biospheric CO₂ fluxes by a high resolution model

Net Ecosystem Exchange, time 2003-07-02 01:00:00

Photosynthesis production during daytime (blue) is compensated by nightly ecosystem respiration (red)

[Max-Planck-Institut für Meteorologie]

[Pillai et al., ACP 2010]
CO$_2$ anomalies in high resolution model

Fossil fuel emissions and nightly respiration (red) mask out the daytime carbon uptake by land ecosystems (blue)

[C Pillai et al., ACP 2010]
Counteracting effects of CO\textsubscript{2} and temperature on land carbon uptake

\[ \Delta \text{NPP} \sim \text{NPP}_{\text{ref}} \cdot \beta \cdot \ln(\text{CO}_2) \]

\[ R_h \sim B \cdot Q_{10}^{(T/T_{\text{ref}}-1)} \]
C uptake in CMIP5 models

Cumulative ocean carbon uptake

Cumulative land carbon uptake

Jones et al., 2013
C uptake in CMIP5 models

Jones et al., 2013
Permafrost carbon: > 1,000 GtC not accounted in CMIP models!

Tarnocai et al., Glob. Biogeochem. Cycles, 2009
Summary

• Ecology provides a good qualitative basis for modelling of competition of plants
• A set of DGVMs and ESMs simulates vegetation dynamics in response to climate and CO\textsubscript{2} changes
• For future emission scenarios, ESMs project
  – a shift of boreal forests to the north
  – a reduction of Amazon forest
  – changes in drylands are not certain
• Different vegetation states for the same climate are possible in reality, but not necessarily in the models