Climate-Vegetation Feedbacks

a) Regional scale: Coupling self-organising systems
b) How to use climate models for paleo reconstructions (Brian Dermody)
c) Continental scale
Climate-Biosphere Feedbacks

Positive feedbacks:
- transpiration-precipitation fb
- albedo feedbacks
Difficult to disentangle various effects

Ek & Holtslag, 2004
• Several orders of magnitude between atmospheric processes and pattern processes!

• Focus on local-scale feedbacks
a. Simple coupling of climate to vegetation
Precipitation feedback on macro-scale

\[ F_{out} = F_{in} + (ET - P)_L \]

\[ F_{in} = w_u = \text{advected moisture} \]

Assuming total mixing and based on water balance:

\[ P = P_l + P_a = P_a (1 + \frac{ET.L}{2w_u}) \]

Recycling ratio (Budyko, 1974)

\[ \beta = \frac{P_l}{P} = \frac{ET.L}{(ET.L + 2w_u)} \]

Entekhabi et al. (1992), Dekker et al. 2007
Pattern model: Infiltration feedback

- **Plants**
  - Uptake
  - Losses (e.g. grazing)

- **Surface water**
  - Rainfall
  - Infiltration

- **Soil water**
3. Coupling

\[ P = P_t + P_a = P_a(1 + \text{ET} \cdot L/2wu) \]

\[ \frac{\partial O(\tilde{x}, t)}{\partial t} = \text{[rainfall]} - \text{[infiltration]} \pm \text{[overland flow]} \]

\[ \frac{\partial W(\tilde{x}, t)}{\partial t} = \text{[infiltration]} - \text{[uptake]} - \text{[evaporation]} \pm \text{[water movement]} \]
### Type of Models

<table>
<thead>
<tr>
<th>Name</th>
<th>Mod</th>
<th>IMod</th>
<th>PMod</th>
<th>IPMod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prec. fb</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Infiltr. fb</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
How realistic?

- No radiation feedback
- Precipitation as annual mean
- No radiation balance in ecological model

→ Coupling Atmospheric boundary layer to the vegetation pattern model
→ close radiation balance: adding sensible/latent heat
Modelling rainfall in time

Ecology:

Actual:

- Daily variability (Intermittency)
- Seasonal variability
- Interannual variability
Model structure

Free atmospheric profile of q, θ

Mean ABL state (here: h, q, θ)

ET as f(W, P, q, θ)

Rainfall R

Soil state (biomass P, moisture W)

R = f(h, LCL)

drainage
• Build up of boundary layer during day
• During monsoon: land doesn’t effect the atmosphere (atmosphere already wet, so it will rain)
• During dry periods: the extra moisture from land is to low to rain out
• In between might be important: increase of growing season

Konings et al. 2010
Two types of feedbacks

SW Radiation

Diagram with arrows indicating feedbacks between variables such as P, α, Rn, H, LE, ABL, and R.
Model Output Analysis

How do you analyze lots of maps? Shannon Entropy,
Response to droughts

- $n_{t_0} = 0.8$
- $n_{t_0} = 0.85$
- $n_{t_0} = 0.95$
- $n_{t_0} = 1$

**Biomass entropy H**

**Mean biomass [kg m$^{-2}$]**

Time [years]
Response to droughts

\( \eta_{sc} = 0.8 \)
\( \eta_{sc} = 0.85 \)
\( \eta_{sc} = 0.95 \)
\( \eta_{sc} = 1 \)

Konings, et al. 2011, under review JGR
Is the effect of feedbacks on patterns meaningful
YES, speed up of desertification
Strong effect of positive feedbacks
Conclusions

Small-scale ecological processes change climate-vegetation feedbacks and in turn change the climate in semi-arid systems.

How to incorporate these non-linear processes in earth system models.
c. GLOBAL SCALE
Positive feedback -> Multiple Steady States

Reported for instance:
- Sahel-Sahara (Brovkin et al): green to desert Sahara, decrease in Monsoon strength
- Amazone (Oyama and Nobre): due to deforestation, decreased rainfall

Questions:
Do we have MSS in current climate?
How sensitive are these MSS to perturbation?
Global Earth-System Model (Planet Simulator PlaSim):

- Ocean dynamic
- Ice dynamics
- Land dynamics (vegetation, soil)
- Atmosphere model (10 horizontal layers)

→ All submodels are connected via interactions and feedbacks

EXPERIMENTS

- Constant SST (sea surface temperature) climatology, constant ice, constant CO₂
- Only atmosphere-land are fully coupled
Dynamic vegetation model

- Only light/water limited primary production
- \( \text{NPP} = f(T, \text{Prec}, \text{RH}) \)
- Calculate the minimum NPP
- Calculate carbon \( \frac{\partial C_{\text{veg}}}{\partial t} = \text{NPP} - \text{RES} - \text{LIT} \)
- Derive LAI, albedo, roughness length
Can we find Climate-Biosphere Feedbacks? If positive then bistability

Kleidon et al.
Run the model to Steady State

Clear Multiple Steady States
Phase-plain:

For the D-run:
Large effect of the recycling feedback

For the G-run:
Only small global mean effect
For the D-run:
Much more variation in global mean temp

For the G-run:
No effect on global mean temp
How stable are the steady states?

Perturb the system
Biomass (kg C/m²)

Simulation time (year)

Stability analyses

Perturbations G+

D-
**D- and G+ Perturbations**

- **Global Perturbation:**
  - D-; every cell -1 kg C/m²
  - G+; every cell +1 kg C/m²

- back to D and G equilibrium for Biomass, Precipitation and Temperature
Biomass (kg C/m²)

Simulation time (year)
D+ and G- Perturbations

- Global Perturbation:
  - D+; every cell +1 kg C/m²
  - G-; every cell -2 kg C/m²

![Graph showing biomass over simulation time with D+ and G- perturbations]
Large $D^{++}$ and $G^{--}$ Perturbations Between steady states $D$ and $G$

- Global Perturbation:

- Biomass, precip and T all new stable global states
• At global scale: Many multiple steady states in climate and land possible

• How do we need to initialize the land for climate runs?

• Why do we have MSS?
Biomass-Precip anomaly:
- clear positive trend
  pos FB works

Biomass-Temp anomaly:
- Low latitudes, negative trend, cooling ET
- High latitudes, positive trend, albedo

![Graphs showing relationship between biomass anomaly (kgC/m²) and Prec anomaly (m/y) and Temp anomaly (K)](attachment:image.png)
How to calculate stability per cell?

\[ S_i = \frac{B_i - Bo_i}{P} \]

5 different options

- **Si > 1**
  - Pos FB

- **0 < Si < 1**
  - weak NF

- **Si < 0**
  - Due to global circulation processes

- **Si = 1, Neutral**

- **Si = 0**
  - Strong NF
Positive perturbations:

(a) Land cover distribution

Global circ processes
Neg FB  Pos FB
Negative perturbations:

(b) Global circ processes

Neg FB

Pos FB
Pos Per | Neg Per | More pos FB from D to G
---|---|---
S>1: | 21% | 10% | More pos FB from D to G
0<S<1 | 30% | 32% |
 n.s. | 12% | 18% | Equal influences of glob circ proc
S<0 | 37% | 40% | Equal influences of glob circ proc
Conclusions

1. Different initializations of vegetation influence climate
2. Multiple equilibria are possible due to: different strengths, history and interplay of feedbacks at disparate scales