Earth System Models and their Ecological Ambitions

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Overview

- What is Ecosystem Demography?
- Science Applications with ED
  - “Taking off the training wheels”
  - Drought trade-off study
- What is FATES? Future progress on ED
Fundamental ecological system

Recruitment

Growth
Competition
Co-existence
Exclusion

Mortality
‘Gap’ Models
(e.g. SORTIE, LPJ-GUESS, SEIB, aDGVM)

**PROS**

- Individual Based
- 3D light environment
- Simulates: competition, recruitment, disturbance

**CONS**

- Stochastic processes...
- Computationally intensive
- Long timesteps
- Inappropriate for climate simulations?
‘Area-based’ Models
(e.g. CLM, TRIFFID, LPJ, IBIS - models used in IPCC assessments)

**PROS**
- Deterministic
- Computationally efficient
- Default in ESM’s

**CONS**
- 1 ‘average tree’ per plant type
- No height structure.
- No light competition
Ecosystem Demography Model (ED)
Moorcroft, Hurtt and Pacala. 2001

- ‘Cohorts’ of trees:
  - grouped according to:
    - Plant type
    - Height
    - Successional stage
‘Cohort-based’ Models as intermediate solutions
Discretization of the land surface

Plant functional type based structure

- NL tree
- BL tree
- Bare Gd
- C3
- C4
- Shrub

‘Time since disturbance’ based structure

- 60 y.o.
- 30 y.o.
- 90 y.o.
- 15 y.o.
- 1 y.o.
- 5 y.o.

Resolves variation along successional axis
Merits of ED approach

- Efficient simulations of ecological dynamics
- Spatial heterogeneity in light environment:
  - Possibility of co-existence along successional gradient
- Link to observations of forest demography
- Simulate impact of disturbance (fire, landuse, mortality).
How does this actually work?
Norman Radiation Scheme as applied to a mixed PFT canopy in CLM(ED)
Norman Radiation Scheme as applied to a mixed PFT canopy in CLM(ED)
Norman Radiation Scheme as applied to a mixed PFT canopy in CLM(ED)
Leaf/Storage balance allocation scheme

- Rauto
- GPP
- NPP
- Reproduction
- Growth
- Live Tissue Turnover
- Storage
- Tissue allocation follows allometry trajectory

Tmax.a  NPP-Tmax.a
Seed Bank model based on TREEMIG: Lischke et al. 1998, 2006 etc. Collaboration with WSL Zurich
CLM4.5 fire: Li et al. 2012

SPITFIRE: Thonicke et al. 2010

-Collaboration with Allan Spessa (Open Univ.) and Mathew Forest (Goethe Univ. Frankfurt)
-Agricultural, land use and peat fires and ignitions need to interface with the Li & Levis CLM4.5 fire model.
- Numerous modifications required to SPITFIRE implemented to allow size-structured fire impacts
Taking off the training wheels: the properties of a dynamic vegetation model without climate envelopes

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WHAT TRAINING WHEELS?

Paradigm:
In Earth System Models, vegetation climate limits are a function of simple climate variables, defined from current distributions.

Climate envelope parameterization from Lund-Potsdam-Jena (LPJ) DGVM (vegetation cannot survive outside limits)

Used in:
- ORCHIDEE (IPSL)
- CTEM (CanESM)
- SEIB (MIROC-ESM)
- CLM-DV (CESM)

<table>
<thead>
<tr>
<th>Plant Functional Type</th>
<th>Temp coldest month</th>
<th>Temp hottest month</th>
<th>Growing Degree Days</th>
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<tr>
<td>Tropical broad-leaved evergreen</td>
<td>15.5</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Tropical broad-leaved rainforest</td>
<td>15.5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Temperate needle-leaved evergreen</td>
<td>–2.0</td>
<td>22.0</td>
<td>900</td>
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<tr>
<td>Temperate broad-leaved evergreen</td>
<td>3.0</td>
<td>18.8</td>
<td>1200</td>
</tr>
<tr>
<td>Temperate broad-leaved summergreen</td>
<td>–17.0</td>
<td>15.5</td>
<td>1200</td>
</tr>
<tr>
<td>Boreal needle-leaved evergreen</td>
<td>–32.5</td>
<td>–2.0</td>
<td>600</td>
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<tr>
<td>Boreal needle-leaved summergreen</td>
<td>–</td>
<td>–2.0</td>
<td>350</td>
</tr>
<tr>
<td>Boreal broad-leaved summergreen</td>
<td>–</td>
<td>–2.0</td>
<td>350</td>
</tr>
<tr>
<td>Temperate herbaceous (TeH)</td>
<td>–</td>
<td>15.5</td>
<td>–</td>
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<tr>
<td>Tropical herbaceous (TrH)</td>
<td>15.5</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Sitch et al. 2003
Problem of extrapolation

Vegetation climate limits might change as CO2 increases

Not clear what to do in no-analogue climates.
HOW TO PROCEED?

The Ecosystem Demography model* we have integrated into the Community Land Model - CLM4.5(ED):

• Has no climatic envelopes

• Can be parameterized directly from plant trait data

• Predicts plant distribution as an outcome of performance

• We can in theory use CLM(ED) for testing hypotheses of vegetation distribution.

*Moorcroft et al. 2001; Fisher et al. 2010; Fisher et al. GMDD 2015
What can we observe about vegetation distribution?

Fraction of evergreen vegetation

AVHRR Vegetation Continuous Fields. De Fries et al. 2000
(One) Hypothesis: The relative carbon economy of deciduous vs. evergreen habits can predict biome boundaries.
“The major task for the developer of the kind of DGVM we are proposing is to conceptualize and parameterize life-history tradeoffs.”
Question: Does how you sample the trait space matter?

Leaf Cost

Leaf Lifespan
CONTROL

Fraction of evergreen vegetation

Answer: Yes!
Control + Alloc

Total Leaf Area Index

Obs
**Leaf Maintenance Respiration**

**CLM4.5 (Ryan et al., 1991)**

\[ \text{lmr}_{\text{top,25}} = N_{\text{area}} \cdot b_{\text{resp}} \]

\[= 0.257 \text{ gC gN}^{-1} \text{ s}^{-1}\]

**CLM4.5(ED) (Atkin et al., 2015)**

- For BDT
  \[ \log_{10}(\text{lmr}_{\text{top,25,BDT}}) = \log_{10}(N_{\text{area}}) \cdot 1.134 - 0.300 \]

- And for NET
  \[ \log_{10}(\text{lmr}_{\text{top,25,NET}}) = \log_{10}(N_{\text{area}}) \cdot 1.005 - 0.346 \]

\[\approx 0.536 \text{ gC gN}^{-1} \text{ s}^{-1}\]

\[\approx 0.452 \text{ gC gN}^{-1} \text{ s}^{-1}\]
**CONTROL**

Obs

**RYAN ET AL, 1991**

**Total Leaf Area Index**

![Heatmap images](image)
Fraction of evergreen vegetation
LEAF TURNOVER VS. TEMPERATURE

Is leaf lifespan dictated by construction cost, or the environment?
ROOT TURNOVER VS. TEMPERATURE

\[ \log_{10}(\text{Imr}_{\text{top},25,\text{BDT}}) = \log_{10}(N_{\text{area}}) \cdot 1.134 - 0.300 \]

\[ \log_{10}(\text{Imr}_{\text{top},25,\text{NET}}) = \log_{10}(N_{\text{area}}) \cdot 1.005 - 0.346 \]

(Data extracted from)
Gill & Jackson 2000
Fraction of evergreen vegetation

Fisher et al. GMDD 2015
Conclusions #1

- Carbon economy of leaf habit can, in some cases, predict dec-evg biome boundaries.

- How we use plant trait data matters for vegetation dynamics predictions.

- Naïve use of plant trait databases does not necessarily lead to skillful prediction.

- Parametric and structural ensembles are both informative for understanding cause & effect in model predictions.
“Models are poorly skilled at simulating tropical drought experiments”

Is this because they don’t have a diversity of hydraulic function?

Powell et al. 2013
“The major task for the developer of the kind of DGVM we are proposing is to conceptualize and parameterize life-history tradeoffs.”
Can we observe diversity in hydraulic function?

Example from Bolivia

Markestieijn et al. 2011
Hacke et al. 2001

Conifers + Angiosperms

Markesteijn et al. 2011

Bolivia

Blackman et al. 2010

Tasmania

Cochard et al. 2007

Poplar + Willow
What is the cost of drought tolerance?
What is the cost of drought tolerance?
What is the cost of drought tolerance?
What is the cost of drought tolerance?

#1: Expensive to tolerate drought

#1: Cheap to tolerate drought
Cheapest wood can tolerate -1.0MPa drought

-0.6MPa
-0.8MPa
-1.1MPa
-1.3MPa
-1.7MPa
-2.0MPa
-2.3MPa
-2.8MPa
-3.7MPa
-4.7MPa

Expensive to be drought tolerant

Ecosystem vulnerable to climatic change

#1: Fraction of biomass in each plant type. Numbers correspond to soil water potential at stomatal closure.
- Cheapest wood can tolerate -1.0 MPa drought
- Cheap to be drought tolerant
- Ecosystem more resilient to climatic change

#2: Fraction of biomass in each plant type. Numbers correspond to soil water potential at stomatal closure.
Conclusions II

• Earth System Models are moving towards ‘trait filtering’ schemes.

• Cost-benefit trade-offs are the ‘raw material’ of trait filtering models, but are typically poorly quantified.

• This development presents a huge opportunity for quantitative hypothesis testing of biome boundaries.

• Understanding the quantitative costs and benefits of alternative life history strategies is important!
$100M 10 year project
NGEE-tropics mode scaling plan
Land Surface Model (CLM, ALM)

- Hydrology
- Soil evaporation
- VOC’s
- Lake model
- Snow model
- Urban model
- Land Ice
- Subgrid structure
- Atmospheric Coupling
- Soil Thermal Processes
- Crop model
- Irrigation

Vegetation structure (patch, cohort)
Allocation, growth, reproduction, mortality, canopy organization, fire

Vegetation physiology (cohort, leaf layer)
Radiation transfer, photosynthesis, evapotranspiration, respiration, interception

ED module
mortality, turnover, seed flux
establishment

Seeds, Litter (patch, size class, PFT)
Fragmentation, fire spread, seed recruitment

Soil Biochemistry (depth, chemistry)
Nitrogen fixation, denitrification, SOM decay, vertical transport, nutrient competition

Interface Layer

Soil water + temperature [CO2], P, humidity, wind, temperature, incoming radiation
intercepted water, land use, soil type & depth

LH, SH, albedo
Root water extraction, LAI, height, bare ground frac, GPP, Rauto,

Nutrient inputs, dust, drydep

Nutrient Leaching, Gaseous N loss, Rnet
Plan for FATES in CLM5

FATES will be a ‘dynamically linked’ library, so that updates to FATES can be made independent of releases of CLM.

The INTERFACE code will likely remain constant.

If you plan on using FATES, please contact me (rfisher@ucar.edu) or Charlie (cdkoven@lbl.gov) to check in on the latest science updates.