Community tools for predictive ecosystem assembly

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With thanks to
Charlie Koven, Ryan Knox, Lara Kueppers, Chonggang Xu
Dave Lawrence, Gordon Bonan & many others

“What you would do now if you could start over developing an Earth System Model and would have complete freedom in doing so?”

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2. Why would one want to start over again?

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To make some sort of data-driven machine-learning land surface scheme?

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Not sure I know of any theory sufficiently revolutionary to justify starting -again-, yet…

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What is the problem we are trying to address?

Models are too complicated?

Models are too slow?

Models are not enough like the real world?

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What is the problem we are trying to address?

Models are too complicated?

We can build hierarchical complexity into ESMs. (see Abby & Charlie's talks)

Models are too slow?

We haven't even really started proper code optimization, in most cases.

Models are not enough like the real world?

Improving this is "business as usual"

1. I don't think we should start again…
2. Why would one want to start over again?
3. If not start again, then what should we do?
4. What business do I have being un-cynical about the status quo?

- Building open community tools **can and will** accelerate progress on all fronts

- Given appropriate funding, **emerging data products** will massively improve model constraints, if compare to equivalent processes in models

- Usage of modern **data-model integration** packages (ILAMB, PECAN. etc.) will accelerate model improvement process.

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3. If not start again, then what should we do?
4. What business do I have being un-cynical about the status quo?
5. Still, there are some things that would help accelerate progress

Some cultural shifts that might help

1. **Stop it with the "first to add/change a thing" papers**: Editors should mandate sober analysis of new components, discussion of uncertainties in structure & parameters, limitations, etc.

2. **Give less weight to the concept of "the model":** Single sets of structure and parameters that happen to give OK results are not magic. Consideration of model uncertainty and ensemble simulations should be mandatory

3. **Land surface models aren't just accessories to the atmosphere, they are the only way we can understand impacts on people and ecosystems:** We need to make that clearer, to funding agencies in particular.

Understanding model components

Initial parameter sensitivity analysis in CLM5

http://www.cesm.ucar.edu/models/cesm2.0/land/

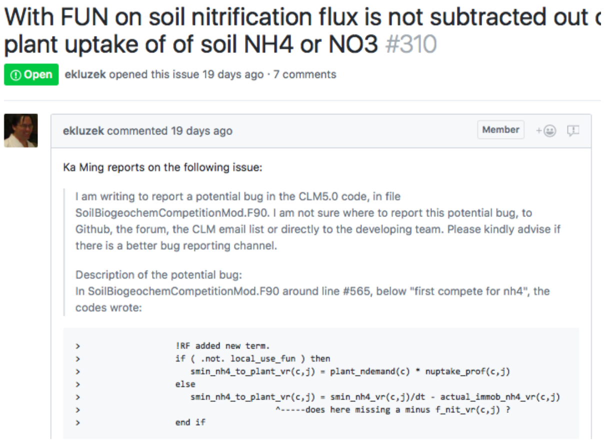
The CLM is now available publically at
https://github.com/ESCOMP/ctsm

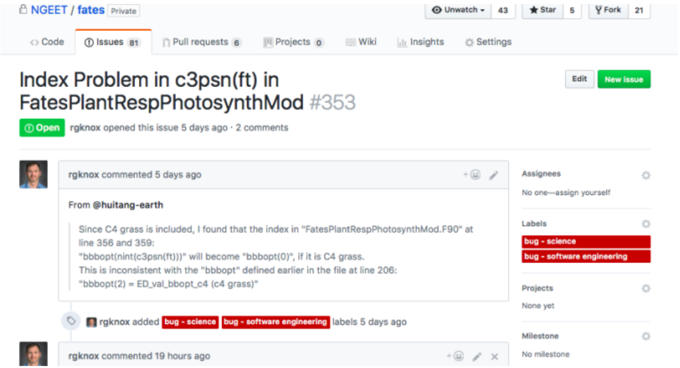
+More eyes on code is always better

+Better coordination of development

+Forum for collaboration: questions can be directed to whole community

-This requires
Solid funding for maintenance of system
Development of community ethical guidelines (no scooping, etc.)

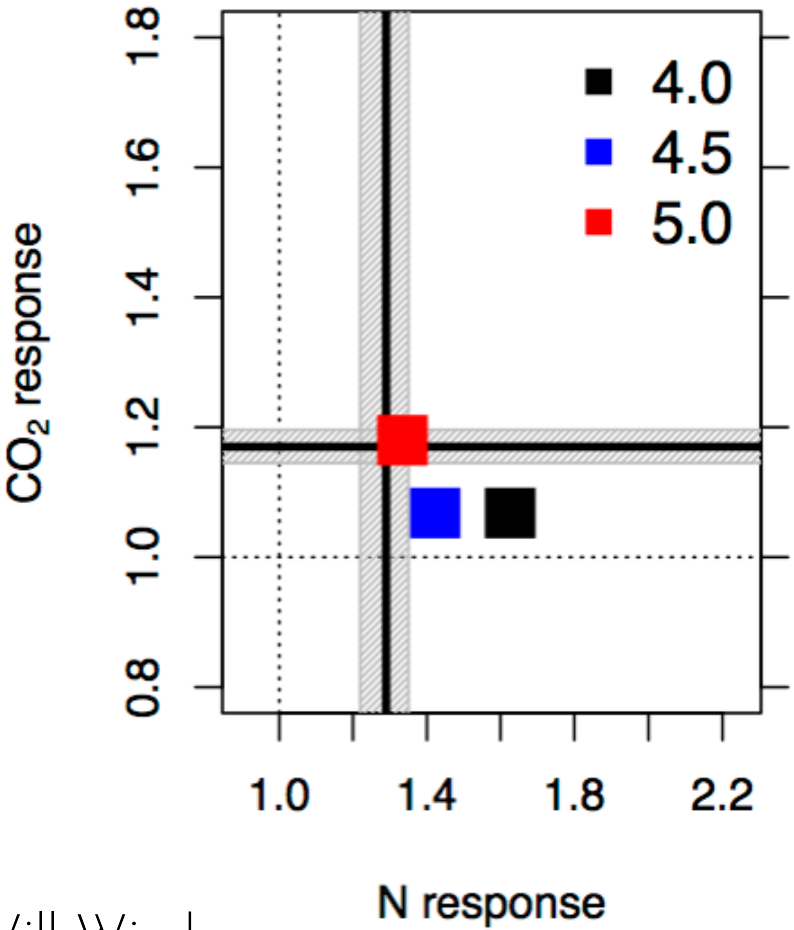




CLM5 has:

1. A new Nitrogen Cycle, with carbon marketplace for N uptake (FUN), optimal allocation of N within leaves based on optimal/co-limitation theory (LUNA) and flexible vegetation C:N ratios (FLEXCN)
2. Plant Hydrodynamics Scheme (based on Sperry & Love 2015)
3. Medlyn (2011) 'optimal' maximum stomatal conductance
4. Revised interception, snow, depth-to-bedrock map, soil evaporation and aquifers.
5. Dynamic crops, harvest, fertilizer, irrigation etc.

https://escomp.github.io/ctsm-docs/doc/build/html/tech_note/index.html



Productivity in **CLM5** responds
less to Nitrogen
and
more to CO2
than its forbears.

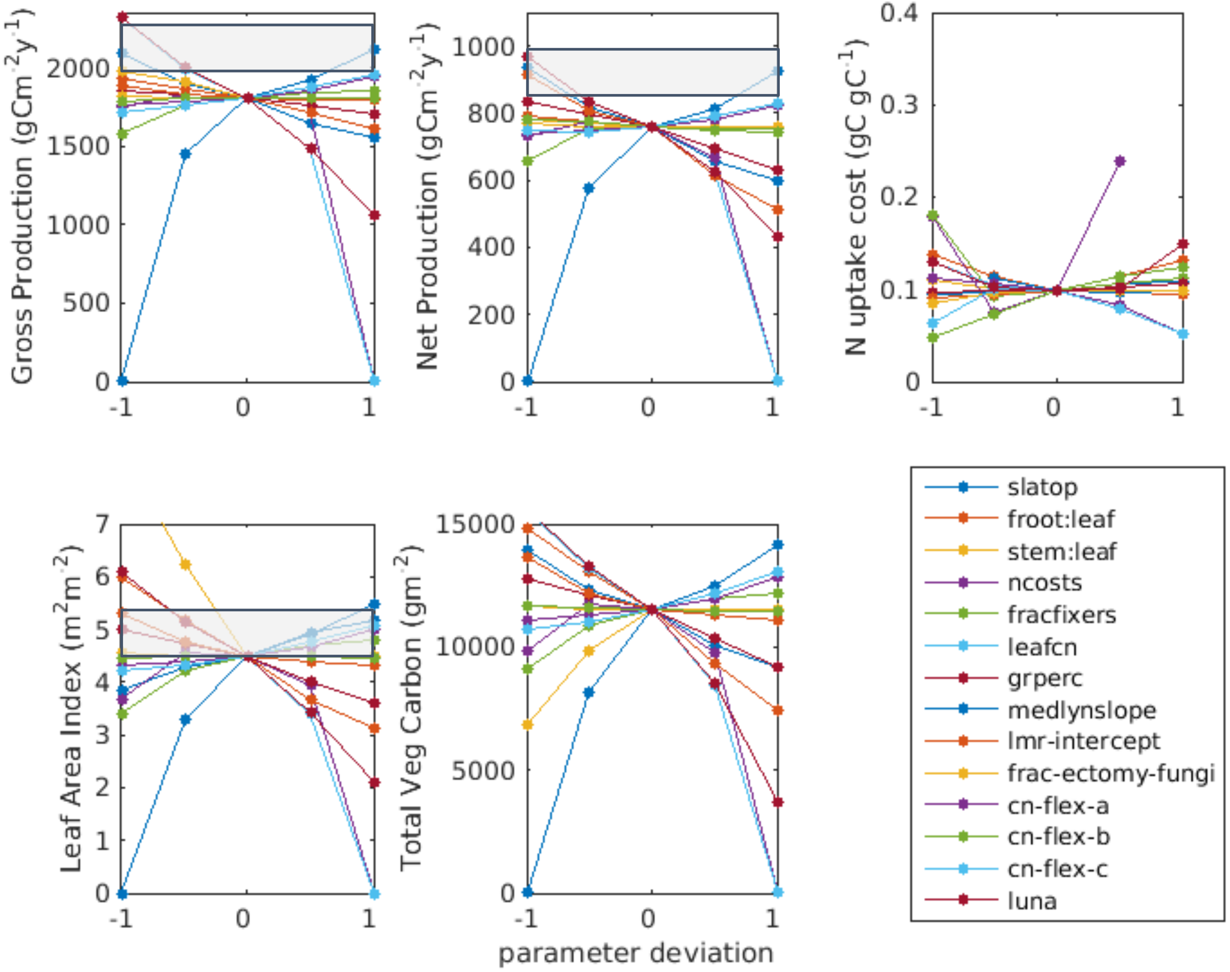
What controls this response?

credit @Will Wieder

Parameter Perturbations : Focus on Carbon and Nitrogen cycling parameters.

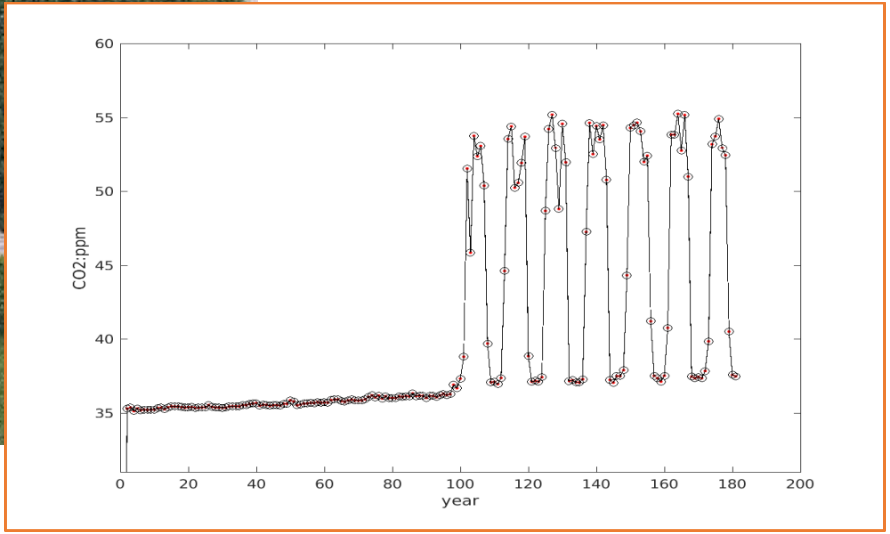
Parameter	Name	Range Determined By
Specific Leaf Area	SLATOP	TRY database
Leaf C:N ratio	LEAFCN	TRY database
Root:leaf ratio	FROOT_LEAF	Litton et al. (2011)
Stem:leaf ratio	STEM_LEAF	Litton et al. (2011)
Fraction N fixers	FRACFIXERS	Logical Range (0-1)
Growth Respiration	GRPERC	Atkin et al. 2018
Stomatal Slope	MEDLYN_SLOPE	Medlyn et al. 2011
Respiration BaseRate	LMR_INTERCEPT	Atkin et al. 2015
Fraction Ectomyccorrhizl fungi	PERECM	Logical Range (0-1)
Flexible CN ratio 'a'	FUN_FLEX_CN_A	Logical Range (0-1)
Flexible CN ratio 'b'	FUN_FLEX_CN_B	Sensitive Range (1-400)
Flexible CN ratio 'c'	FUN_FLEX_CN_C	Sensitive Range (1-32)
N Costs (x6 parameters)	N_COSTS	Sensitive range (4 ord.magnitude)

CLM5 Parameter Sensitivity: System State

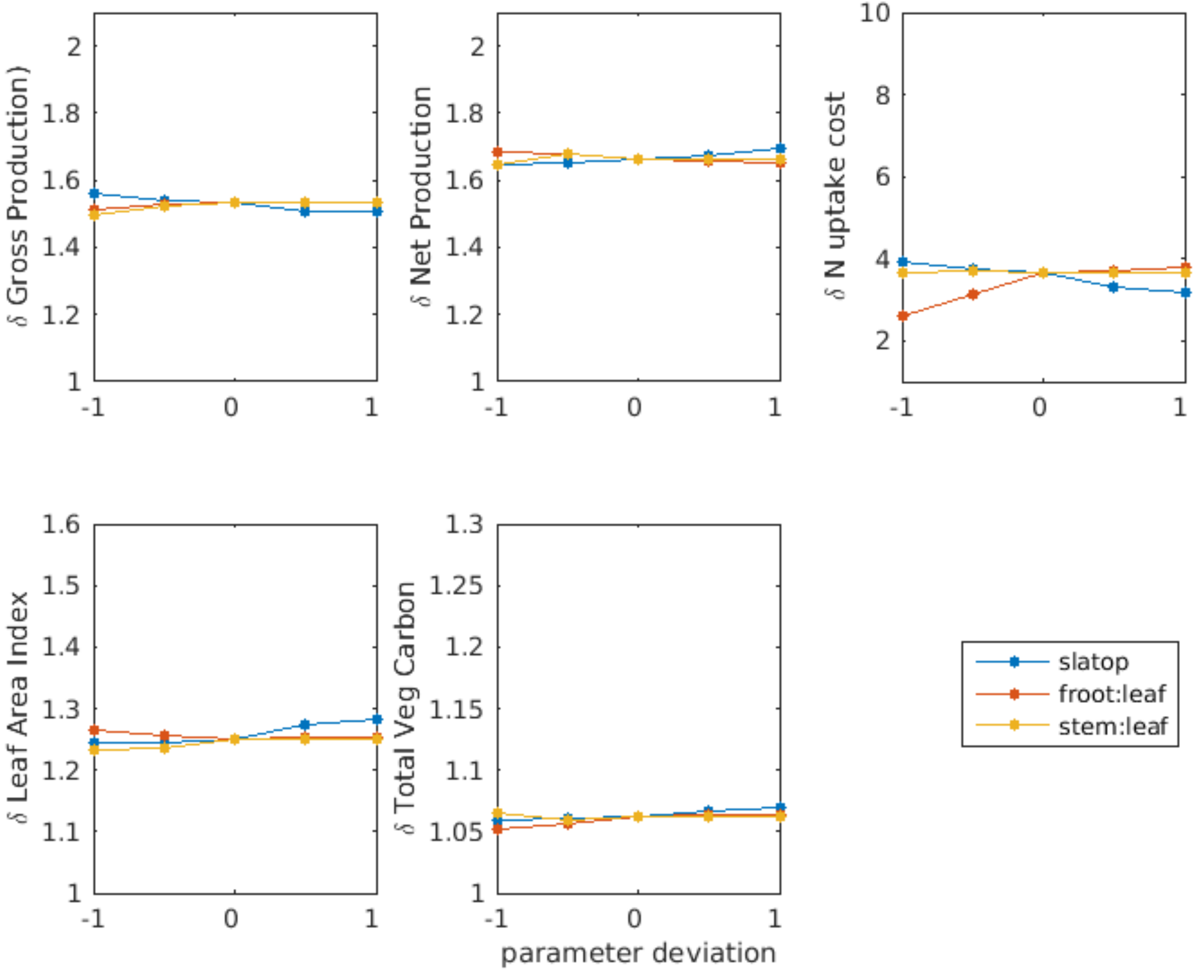


No-one should be very surprised if changing parameters affects state, etc.

Free Air Carbon Enrichment (FACE) @Oak Ridge.



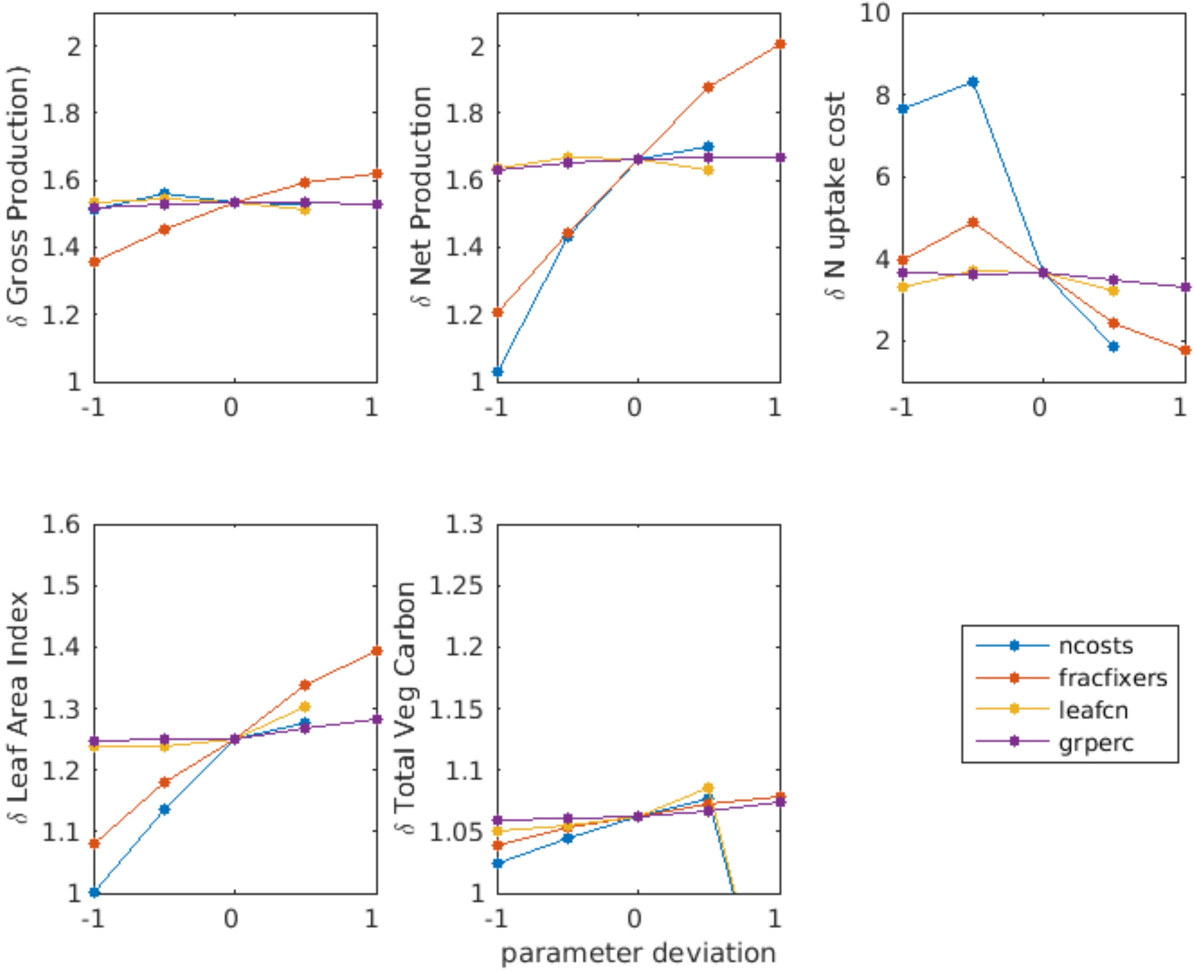
CO2 response: Higher leaf allocation



Allocation parameters don't affect CO2 response

(these act linearly on C cycle)

CO2 response: Higher leaf allocation



N uptake parameters DO affect response

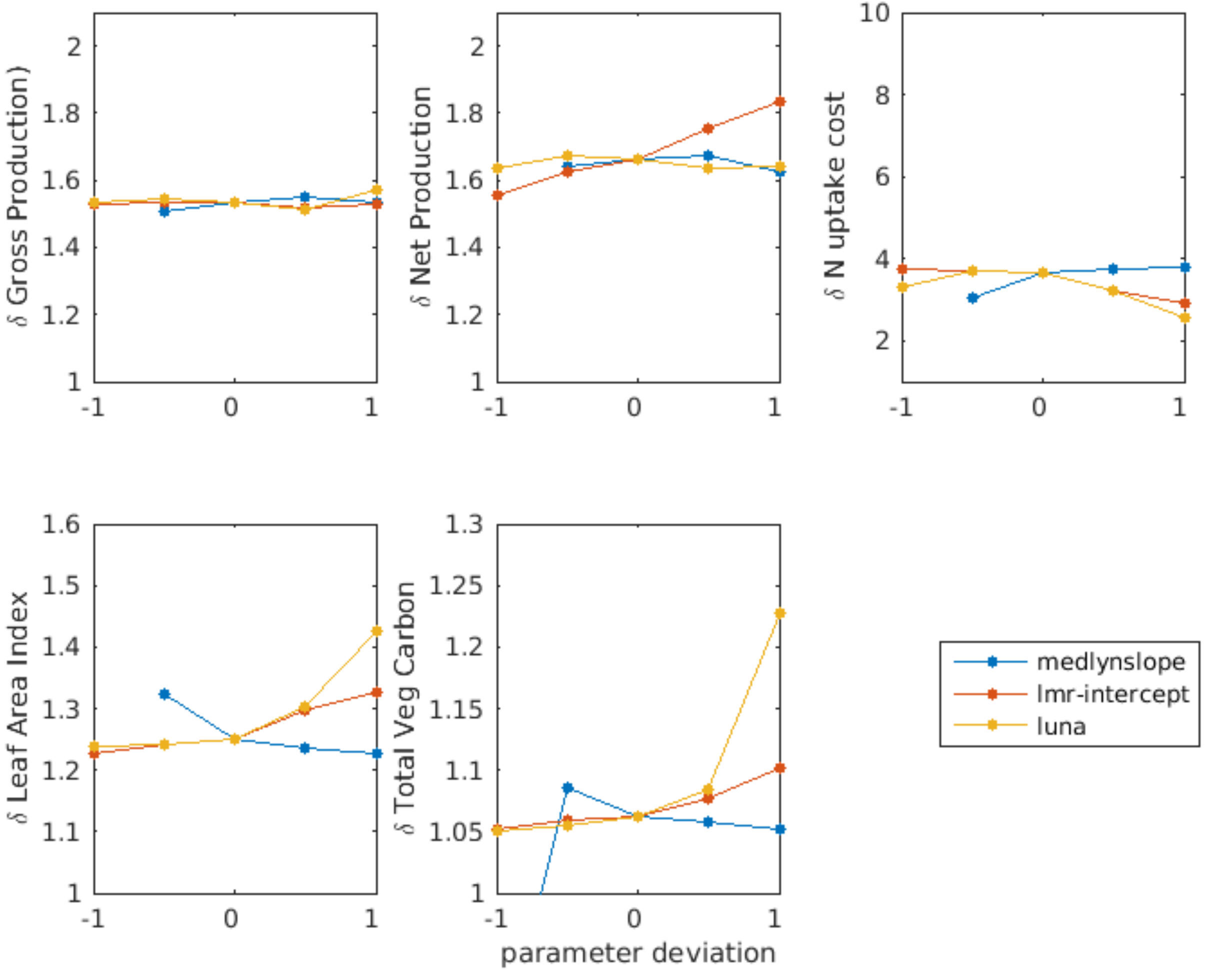
Fraction of fixers significantly alters result

As does cost of N uptake

So, the Nitrogen cycle **is** constraining the CO2 response…

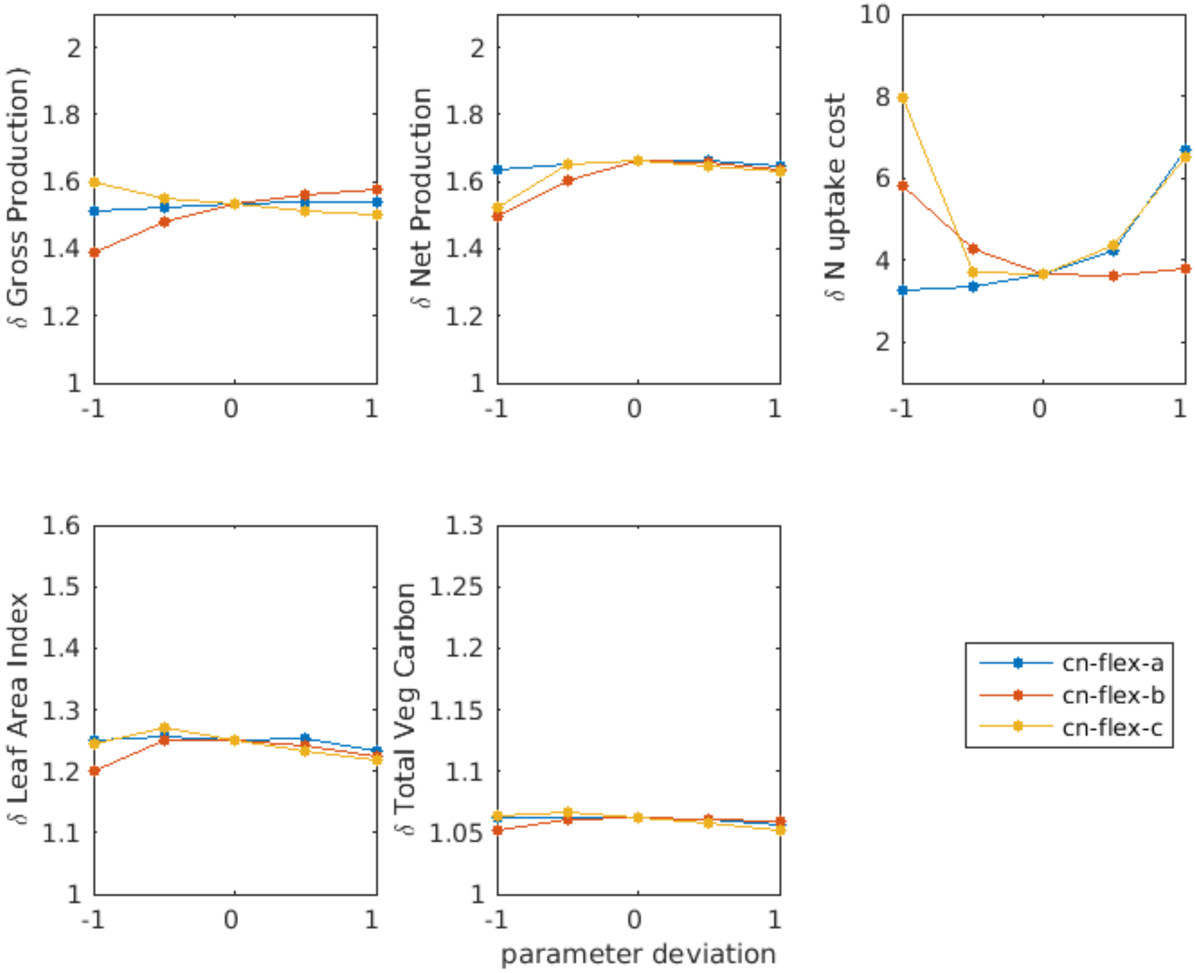
..and in CLM5, plants can **buy their way out** of that problem!

CO2 response: Higher leaf allocation



Photosynthesis parameters are less fundamental to impact

CO2 response: Higher leaf allocation



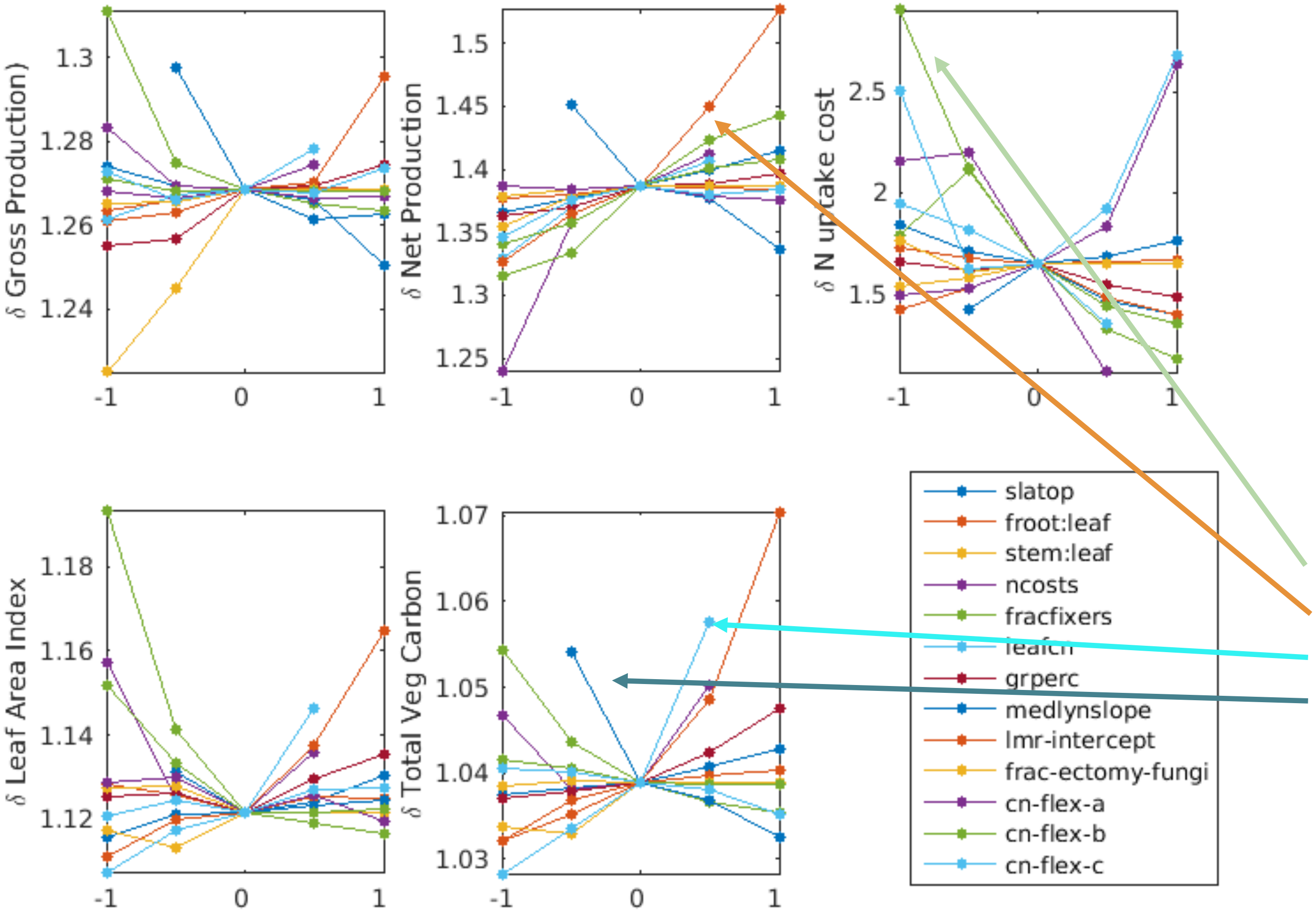
C:N flexibiility parameters are not of 1st order importance

This is mildly surprising, since 'diluting' Nitrogen is one way around limitation

(but diluting Nitrogen also reduces growth)

These parameters are highly unconstrained...

CLM5 Parameter Sensitivity: Nitrogen Deposition Response



Both CO2 and N responses are dominated by parameters related to Nitrogen cycling.

Model parameters of greatest impact are:
frac_fixers
lmr_intercept
leafcn
medlyn_slope

This is the simplest example. Across the CLM/ELM/FATES community we are making further efforts in:

1. Inverse Calibration using emulators (Dagon, Sanderson, Lawrence, Fisher et al.)

2. Global sensitivity analysis using FAST (Massoud, Xu, et al.)

3. Robust Assessment of structural uncertainty of individual components (Walker, Rogers, et al.)

4. Variance Decomposition in PECAN (Serbin, Dietze et al.)

5. Data Assimilation (Fox, Hoar et al.)

6. DREAM inverse calibration at site scale (Post, Fox et al.)

But global tuning (geographically and parameterically) remains slightly out of reach (see CLM5 parameter tuning exercise)

We shouldn’t let the perfect be the enemy of the good!

Community Tools for Predictive Ecosystem Assembly

Alternative vegetation representations in ESMs

Big Leaf Models
('DGVMs')

Cohort models
(ED, FATES, etc.)

Stochastic Individual Models
(LPJ-GUESS, SEIB, etc.)

1st generation DGVMs

Vegetation Demographics Models

Vegetation Demographics representation is becoming increasingly commonplace in ESMs

Workshop on the status of vegetation demographics in Earth system models. January 2016

TABLE 1 Table of attributes of vegetation demographics models discussed in this paper

Model acronym	Name	Vegetation representation	Coupled to ESM?	Stochastic?	Canopy structure	Disturbance history patches?
SEIB	Spatially Explicit Individual-Based model	Individual	MIROC-ESM	Yes	Individuals	No
LPJ-GUESS	Lund-Potsdam-Jena General Ecosystem Simulator	Individual or Cohort	EC-Earth, RCA-GUESS	Yes (optional for some processes)	Flat-top	Yes
LM3-PPA	Perfect Plasticity Approximation	Cohort	GFDL-ESM	No	PPA	No
ED	Ecosystem Demography model	Cohort	RAMS	No	Flat-top	Yes
ED2	Ecosystem Demography model v2	Cohort	RAMS	No	Flat-top	Yes
CLM(ED)	Community Land Model with Ecosystem Demography	Cohort	CESM	No	PPA	Yes

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RESEARCH REVIEW

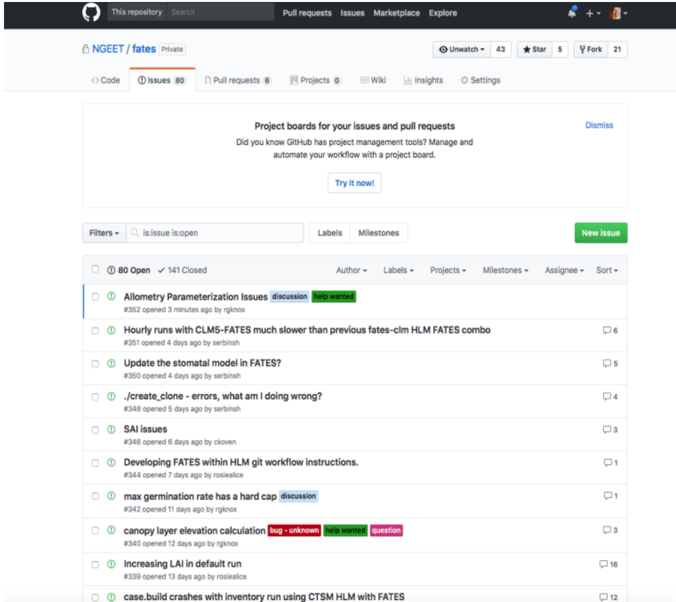
WILEY Global Change Biology

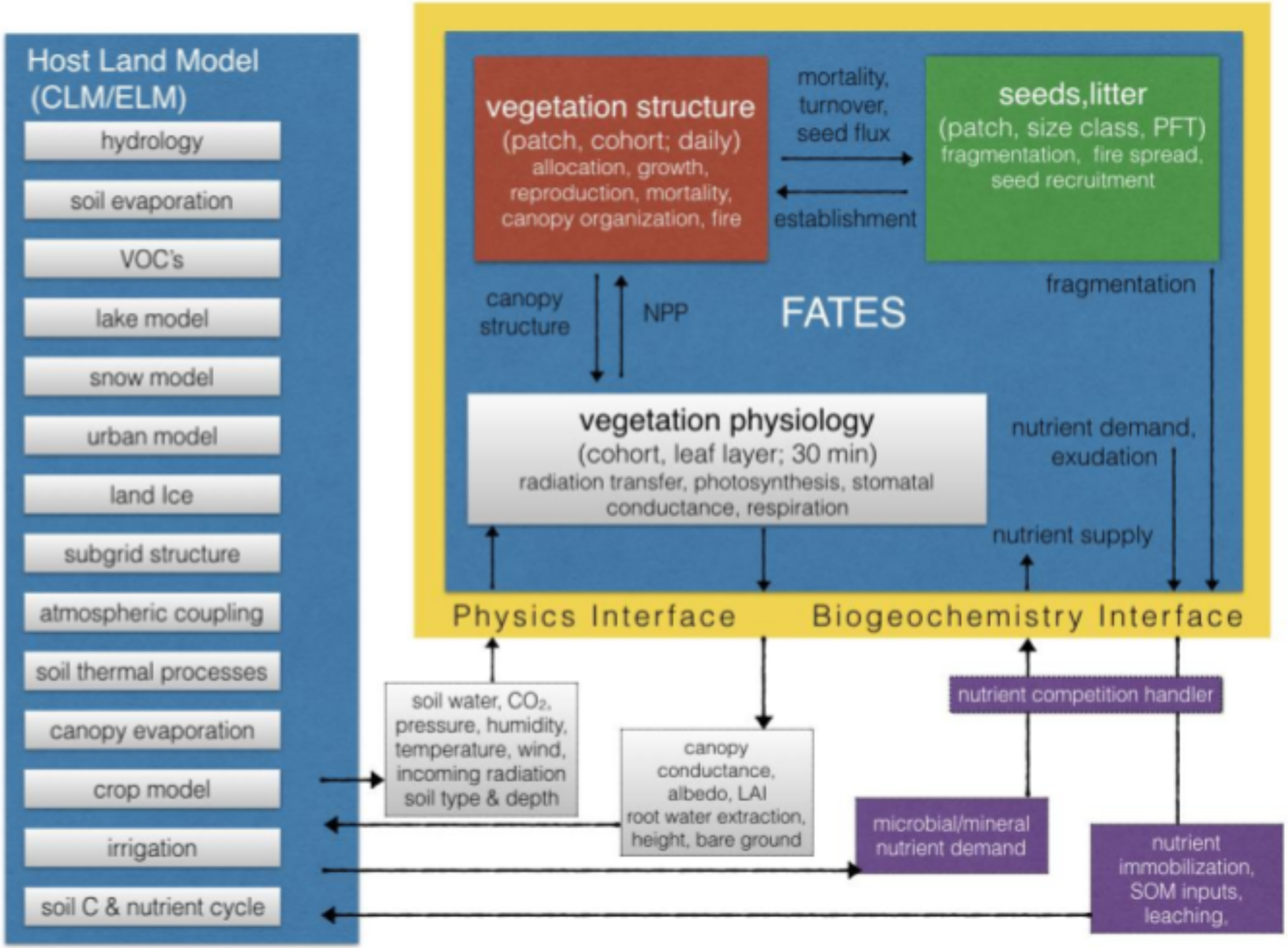
Vegetation demographics in Earth System Models: A review of progress and priorities

Rosie A. Fisher[1] | Charles D. Koven[2] | William R. L. Anderegg[3] | Bradley O. Christoffersen[4] | Michael C. Dietze[5] | Caroline E. Farrior[6] | Jennifer A. Holm[2] | George C. Hurtt[7] | Ryan G. Knox[2] | Peter J. Lawrence[1] | Jeremy W. Lichstein[8] | Marcos Longo[9] | Ashley M. Matheny[10] | David Medvigy[11] | Helene C. Muller-Landau[12] | Thomas L. Powell[2] | Shawn P. Serbin[13] | Hisashi Sato[14] | Jacquelyn K. Shuman[1] | Benjamin Smith[15] | Anna T. Trugman[16] | Toni Viskari[12] | Hans Verbeeck[17] | Ensheng Weng[18] | Chonggang Xu[4] | Xiangtao Xu[19] | Tao Zhang[8] | Paul R. Moorcroft[20]

A note on FATES

- FATES is the "Functionally Assembled Terrestrial Ecosystem Simulator"
- FATES is a module, designed to run within land surface models, that simulates plant physiology, competition processes, ecosystem assembly and vegetation distribution
- FATES is based on the Ecosystem Demography Model.
- FATES is managed by the NGEE-tropics team at LBNL
- It lives at: https://github.com/NGEET/fates
- …soon to be open source

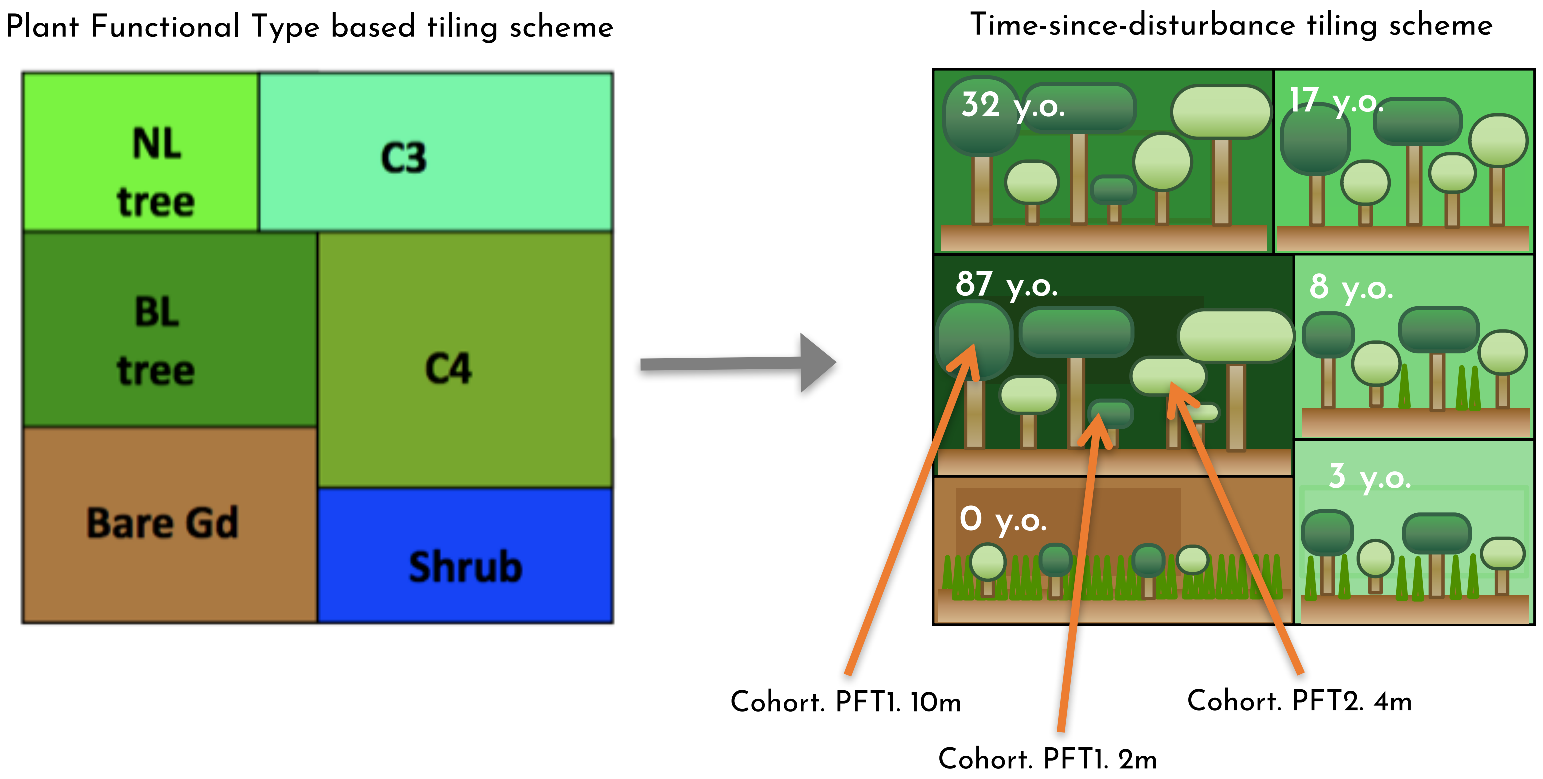




Host Land Model (CLM/ELM)
hydrology
soil evaporation
VOC's
lake model
snow model
urban model
land Ice
subgrid structure
atmospheric coupling
soil thermal processes
canopy evaporation
crop model
irrigation
soil C & nutrient cycle
vegetation structure
(patch, cohort; daily)
allocation, growth, reproduction, mortality, canopy organization, fire
mortality, turnover, seed flux
establishment
seeds,litter
(patch, size class, PFT)
fragmentation, fire spread, seed recruitment
canopy structure
NPP
FATES
fragmentation
vegetation physiology
(cohort, leaf layer; 30 min)
radiation transfer, photosynthesis, stomatal conductance, respiration
nutrient demand, exudation
nutrient supply
Physics Interface
Biogeochemistry Interface
soil water, CO_2, pressure, humidity, temperature, wind, incoming radiation soil type & depth
canopy conductance, albedo, LAI root water extraction, height, bare ground
nutrient competition handler
microbial/mineral nutrient demand
nutrient immobilization, SOM inputs, leaching,

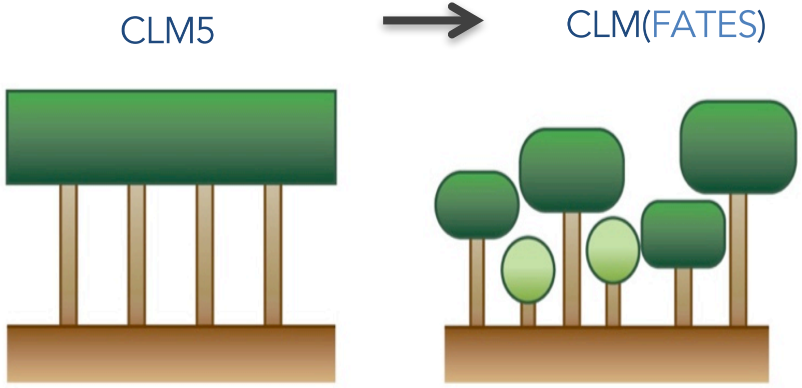
Vegetation structure in FATES

Each time-since-disturbance tile contains cohorts of plants, defined by PFT and size.



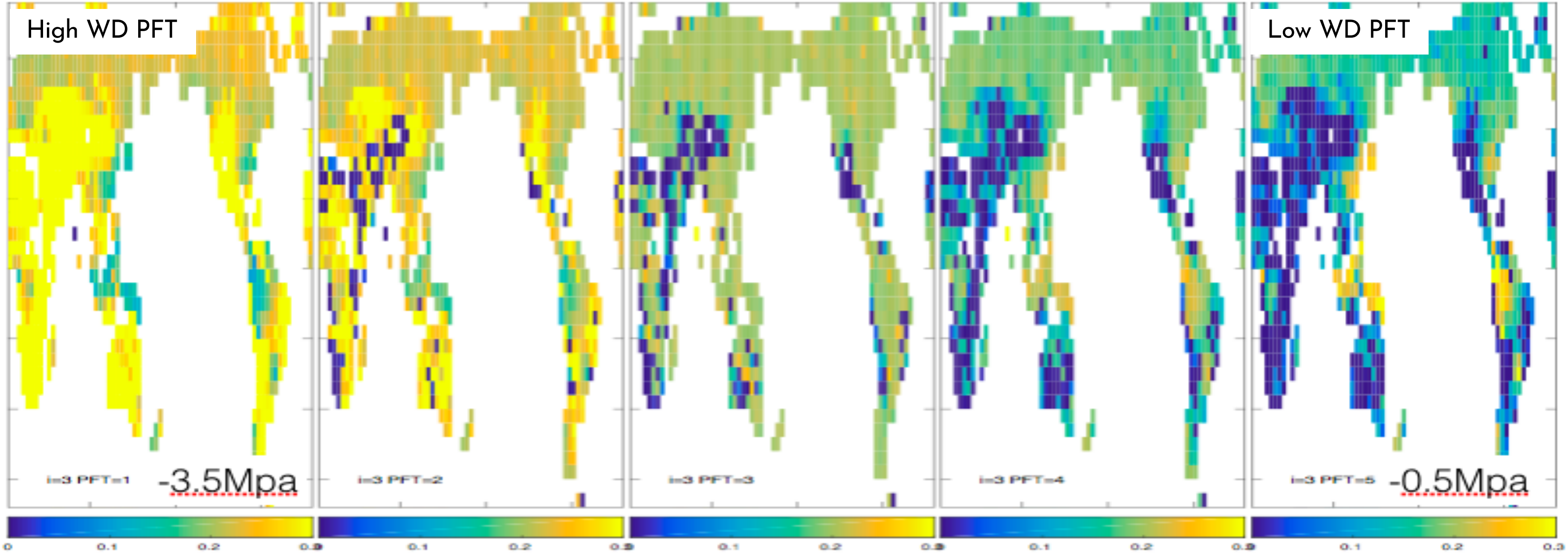
Benefits of FATES

What do we get for these two axes of extra complexity?



- Vertical Competition for light resources, gap formation, succession
- Representation of co-existence and functional diversity
- Functional diversity mediates responses to climate
- Recovery from disturbances
- Arbitrary (non-fixed) PFT definition
- **Closer links between model world and real-world observations**

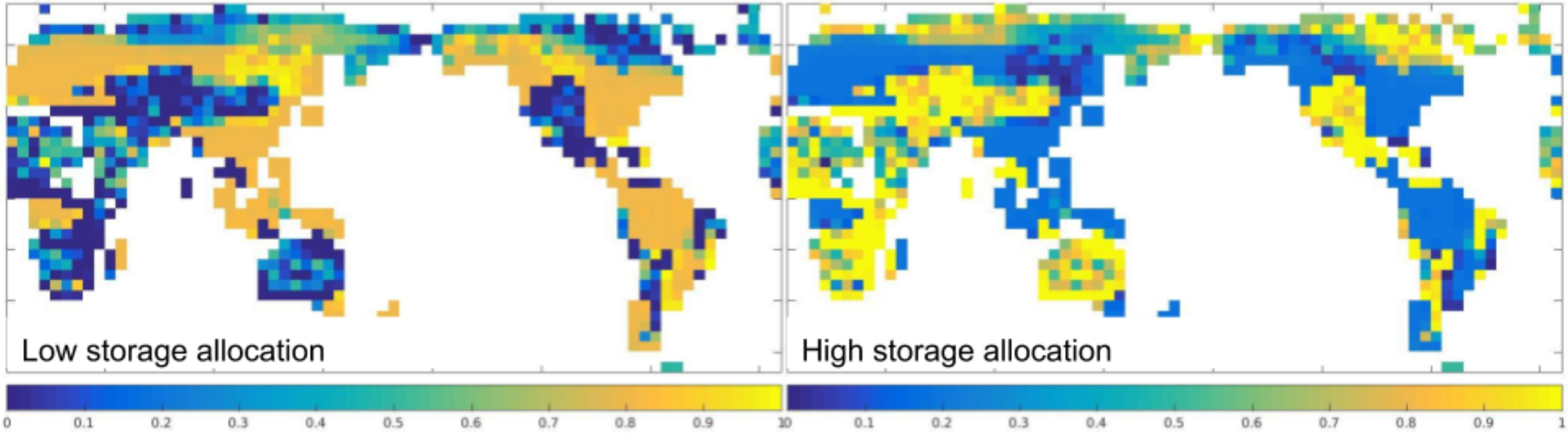
“Trait Filtering” example



PFT distribution depends only on assigned plant physiology…

Two PFT example

How much carbon do plants target in their savings account?



Growing, rather than storing, is a good idea wherever the canopy is closed...

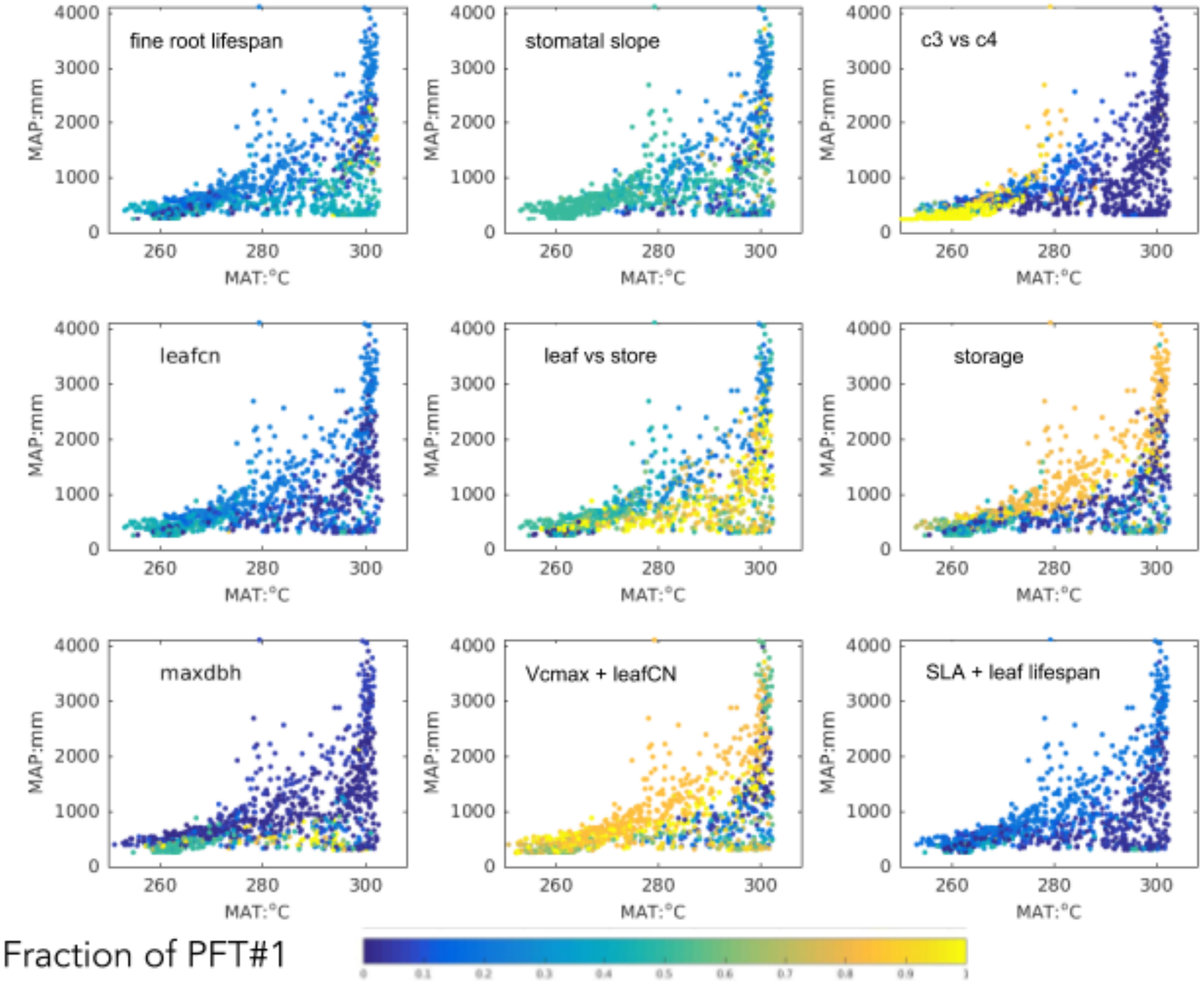
Biome boundary positions for nine different trait trade-offs

-Selection is typically not along only temperature or precip gradients.

-Most trait filtering is related to light competition intensity

-Are we missing processes/traits that allow filtering by temperature?

-Topt, freeze tolerance, recruitment traits?



Some concrete goals that remain for the VDM community

- **Process understanding of the location of biome boundaries**
  - "Default" global trait input set (tbd) is a superset of these problem
  - Requires extensive experimentation & detailed analysis of trait databases

- Achieve an operational multi-scale **model-data-fusion toolkit for VDMs**
  - Link site data and experiments into existing benchmarking software

- Closely and specifically **link emerging Earth Observation data streams** (hyperspectral, canopy structure, biomass, ecostress, etc.) with VDM structures for initialization & testing.

If we don't start again?
HOW MIGHT WE ORGANIZE IMPROVEMENT OF LSMs?
(with an emphasis on disturbance)

Inputs

Input needs (specific to dynamics & disturbance)

Drivers
Exogenous disturbances
Fire ignitions

Initial Conditions
Canopy Structure
Observable trait distributions?

Parameters:
Detailed analysis of trait databases
Add new traits critical to VDMs
Define trade-off surface & environmental responses

calibration

Model Development

Process gaps (specific to dynamics & disturbance)

Partial Disturbance (defoliation, burning, freezing, drought)

Resprouting (fire, hurricanes)

Seed Dispersal (also recruitment triggers)

Land Use Change Interpretation
Interaction with fire, crops

Insect Outbreaks

process updates

Testbeds

DVMs predict vastly more things than normal LSMs

Intensive testbeds: Internal mechanisms of resource competition, allocation, physiology etc.

Extensive testbeds: Predictions of trait distributions in space/time.

Software architectures (ILAMB, PECAN) for standardized model-data synthesis

\


The End

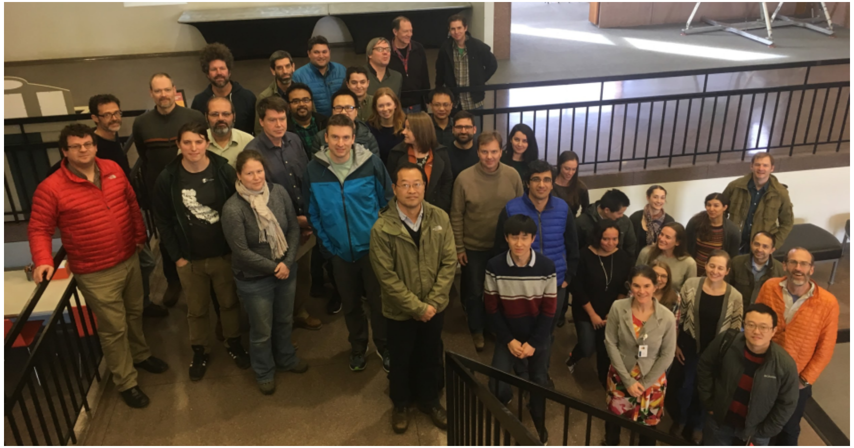
FATES tutorial (February 2018)

Tutorial lecture.

https://docs.google.com/presentation/d/1x5BDSgFfETdoQd_lxF49tQsDJZzDTaqxgrlYQfCy73Y

Practical session

https://github.com/NGEET/fates/wiki/Running-FATES:-A-Walk-Through,-February-2018



Methodological Issues

1. Open Code Development. Version Control. Testing.

1. Modularity: implementation of alternative physics in same codebase

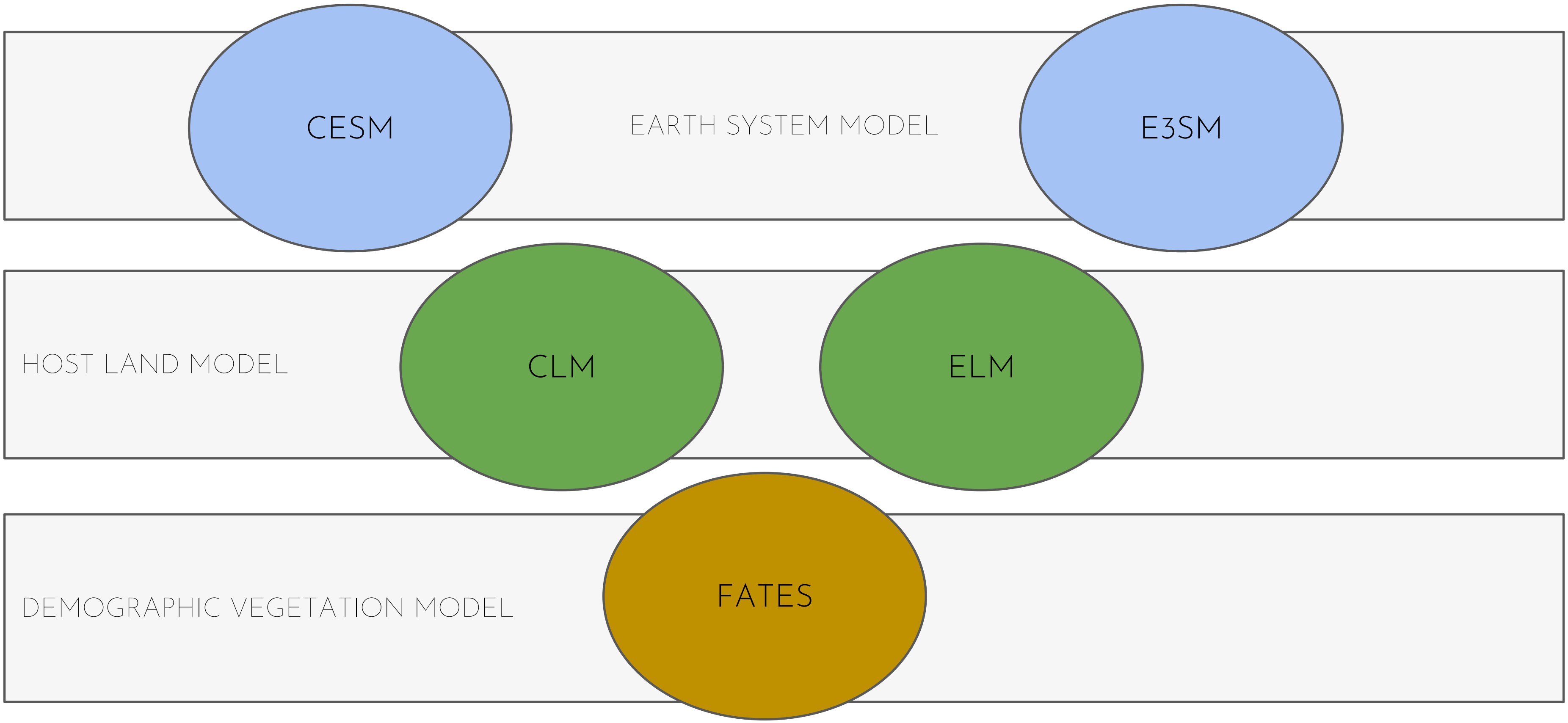
1. Collaboration. We can and must prevent conflicts and code divergence with frequent communication There are **always** more questions to answer than you think.

1. Robust and commonplace interrogation of uncertainties. '**The Model**' is one somewhat arbitrary instance of a massive structural and parametric space

1. Encourage use of common scientific 'testbeds'. (ILAMB, FLUXNET, NGEET)

1. Software Engineers are extremely important. Put them in your budget. Buy them chocolate. Don't be mean to them ever.

Where FATES lives inside a system of earth system models

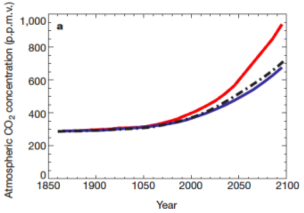


Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model

Peter M. Cox*, Richard A. Betts*, Chris D. Jones*, Steven A. Spall* & Ian J. Totterdell†

* *Hadley Centre, The Met Office*
† *Southampton Oceanography C*
UK

Abrupt changes in ecosystem type *might* produce large climate impacts!



Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs)

S. SITCH*, C. HUNTINGFORD†, N. GEDNEY*, P. E. LEVY‡, M. LOMAS§, S. L. PIAO¶, R. BETTS||, P. CIAIS¶, P. COX**, P. FRIEDLINGSTEIN¶, C. D. JONES||, I. C. PRENTICE†† and F. I. WOODWARD§

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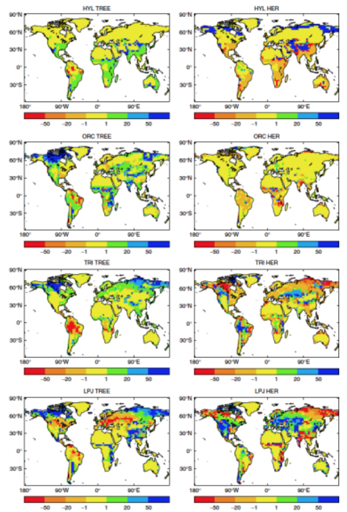

This depends a lot on which DGVM you use…

1st gen. DGVMs are not fit for purpose

A METHOD FOR SCALING VEGETATION DYNAMICS: THE ECOSYSTEM DEMOGRAPHY MODEL (ED)

P. R. Moorcroft,[1,3] G. C. Hurtt,[2] and S. W. Pacala[1]

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ystems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire 03824 USA

OK, that was hard. But now we have some amazing tools!

We need to integrate VDMs into ESMs

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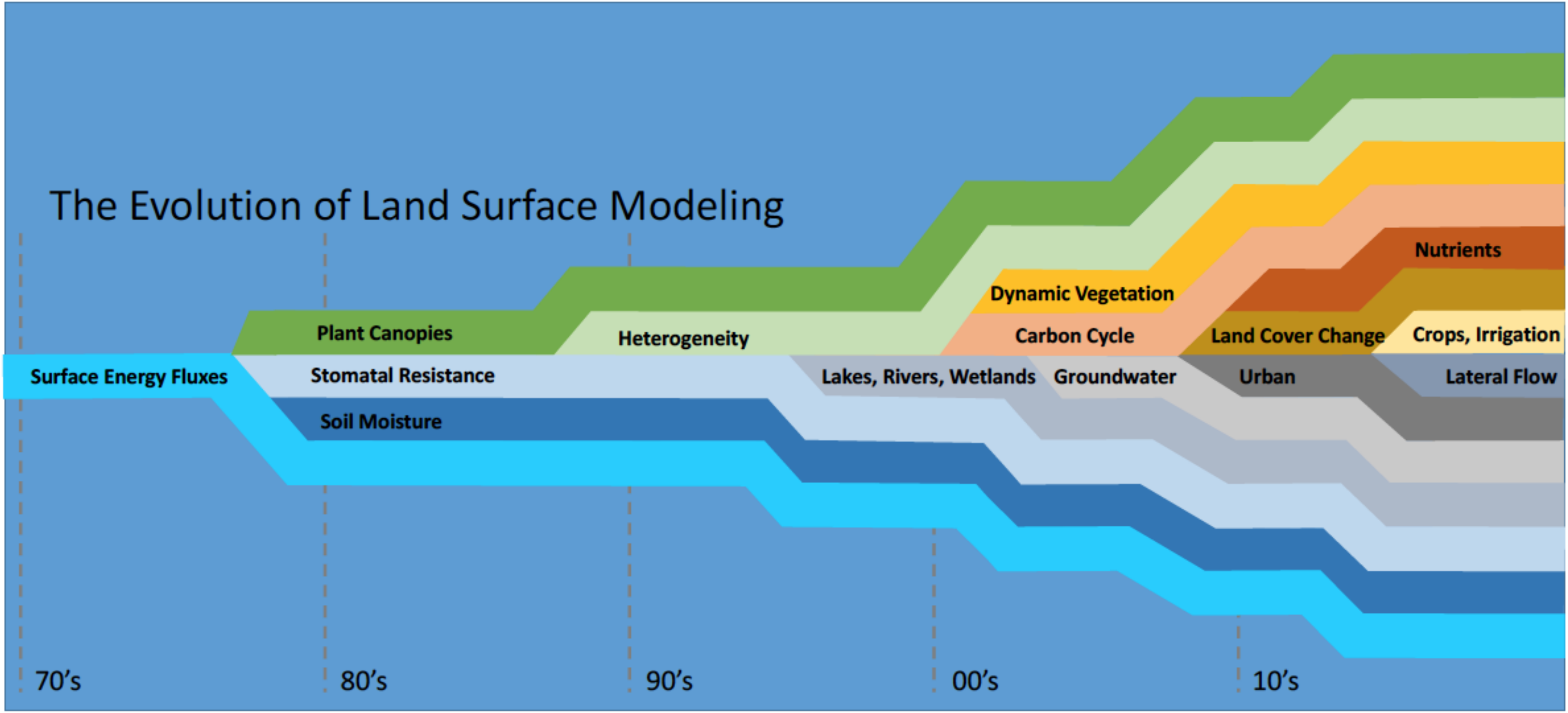
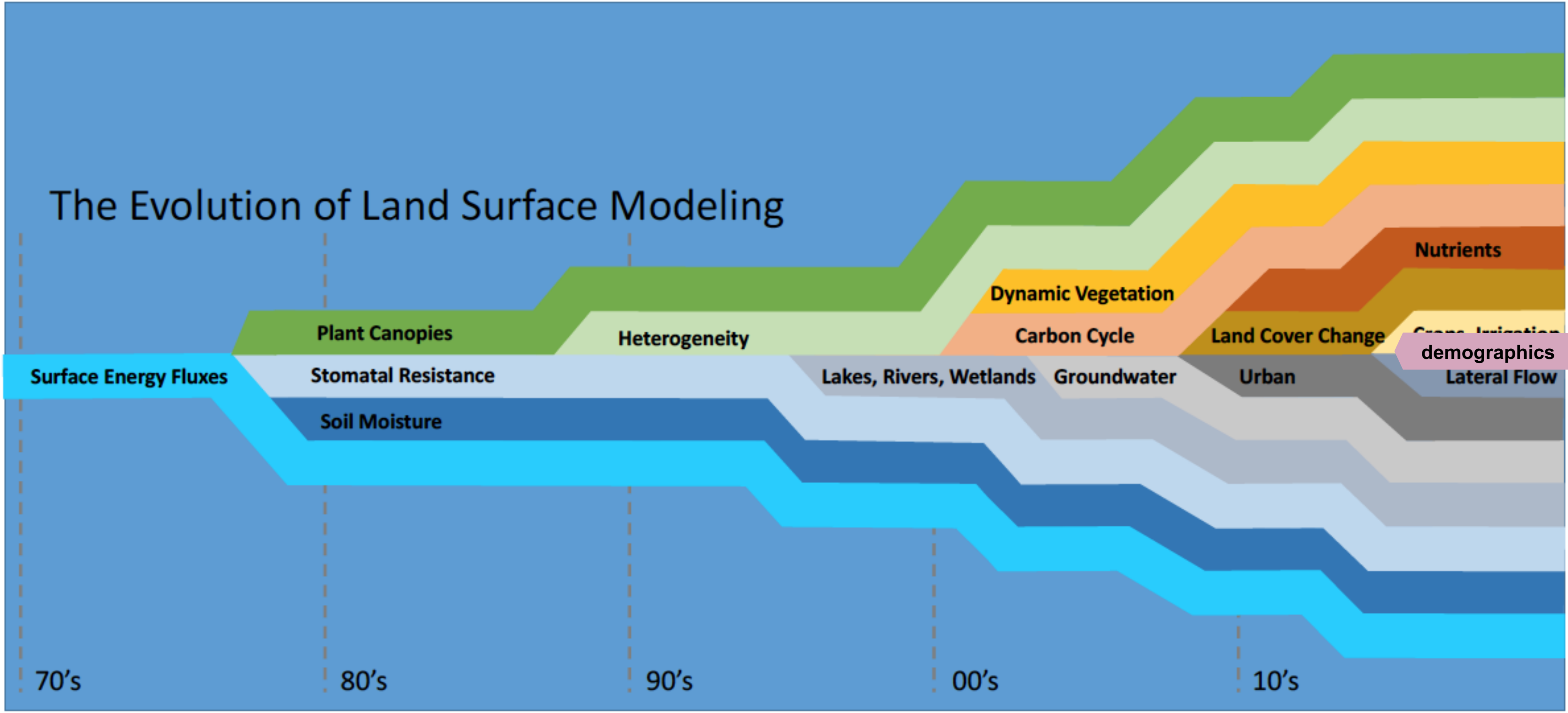
How close are we to a predictive science of the biosphere?

Paul R. Moorcroft

Department of Organismic and Evolutionary Biology, Harvard University, 22 Divinity Avenue, Cambridge, MA 02138, USA



The Evolution of Land Surface Modeling
Nutrients
Dynamic Vegetation
Plant Canopies
Heterogeneity
Carbon Cycle
Land Cover Change
Crops, Irrigation
Surface Energy Fluxes
Stomatal Resistance
Lakes, Rivers, Wetlands
Groundwater
Urban
Lateral Flow
Soil Moisture
70's
80's
90's
00's
10's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70's
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To DO

1. Benefits of fates slide