ELM-FATES Updates: Impacts of dynamic vegetation and plant demography in E3SM

July 22, 2021

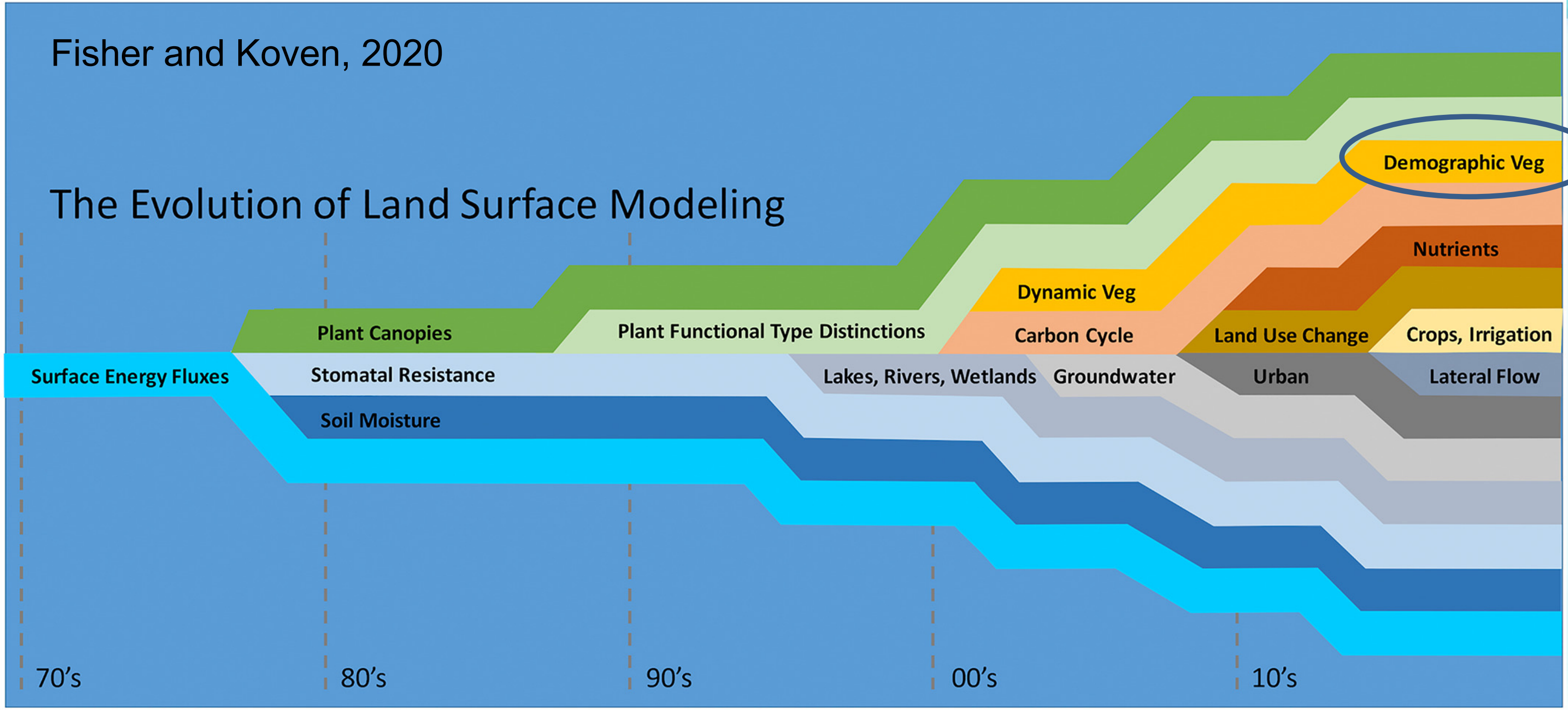
Jennifer Holm, Ryan Knox, FATES Modeling team

E3SM All Hands Meeting

E3SM Energy Exascale Earth System Model

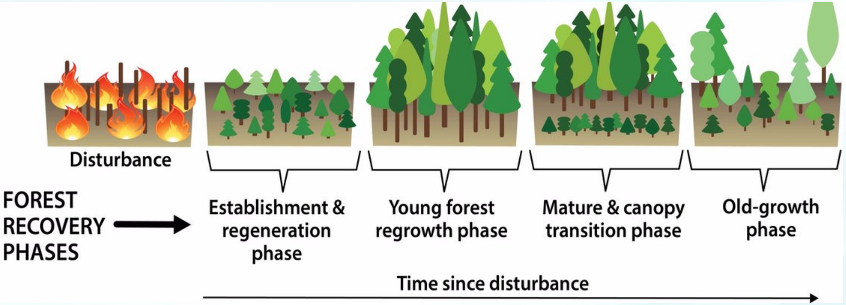
NGEE–TROPICS NEXT-GENERATION ECOSYSTEM EXPERIMENTS

U.S. DEPARTMENT OF ENERGY



“Big Leaf” Model
(sunlit and shaded leaf)

VS.



Motivation: Why have plant demography & dynamic vegetation?

Global Change Biology

RESEARCH REVIEW

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

Rosie A. Fisher, Charles D. Koven, William R. L. Anderegg, Bradley O. Christoffersen, Michael C. Dietze, Caroline E. Farrior, Jennifer A. Holm, George C. Hurtt, Ryan G. Knox ... See all authors

JGR Biogeosciences

Research Article | Open Access

The Central Amazon Biomass Sink Under Current and Future Atmospheric CO_2: Predictions From Big-Leaf and Demographic Vegetation Models

Jennifer A. Holm, Ryan G. Knox, Qing Zhu, Rosie A. Fisher, Charles D. Koven, Adriano J. Nogueira Lima, William J. Riley, Marcos Longo, Robinson I. Negrón-Juárez ... See all authors

"We demonstrate that VDMs are comparable to non-demographic (i.e., "big-leaf") models but also include finer scale demography and competition that can be evaluated against field observations."

JAMES Journal of Advances in Modeling Earth Systems

Commissioned Manuscript | Open Access

Perspectives on the Future of Land Surface Models and the Challenges of Representing Complex Terrestrial Systems

Rosie A. Fisher, Charles D. Koven

First published: 10 March 2020 | https://doi.org/10.1029/2018MS001453 | Citations: 5

"Land surface processes mediate the majority of the impacts of climate on human societies and ecosystems, and accurate representation of land surface processes is critical for our understanding of how climate and climate change actually affect living systems."

Geosci. Model Dev., 8, 3593–3619, 2015
www.geosci-model-dev.net/8/3593/2015/

Geoscientific Model Development
Open Access

Taking off the training wheels: the properties of a dynamic vegetation model without climate envelopes, CLM4.5(ED)

R. A. Fisher[1], S. Muszala[1], M. Verteinstein[1], P. Lawrence[1], C. Xu[2], N. G. McDowell[2], R. G. Knox[3], C. Koven[3], J. Holm[3], B. M. Rogers[4], A. Spessa[5,6], D. Lawrence[1], and G. Bonan[1]

"A major motivation of this development is to allow the prediction of biome boundaries directly from plant physiological traits via their competitive interactions."

ELM-FATES –> A Vegetation Demographic Model
(E3SM Land Model - Functionally Assembled Terrestrial Ecosystem Simulator)

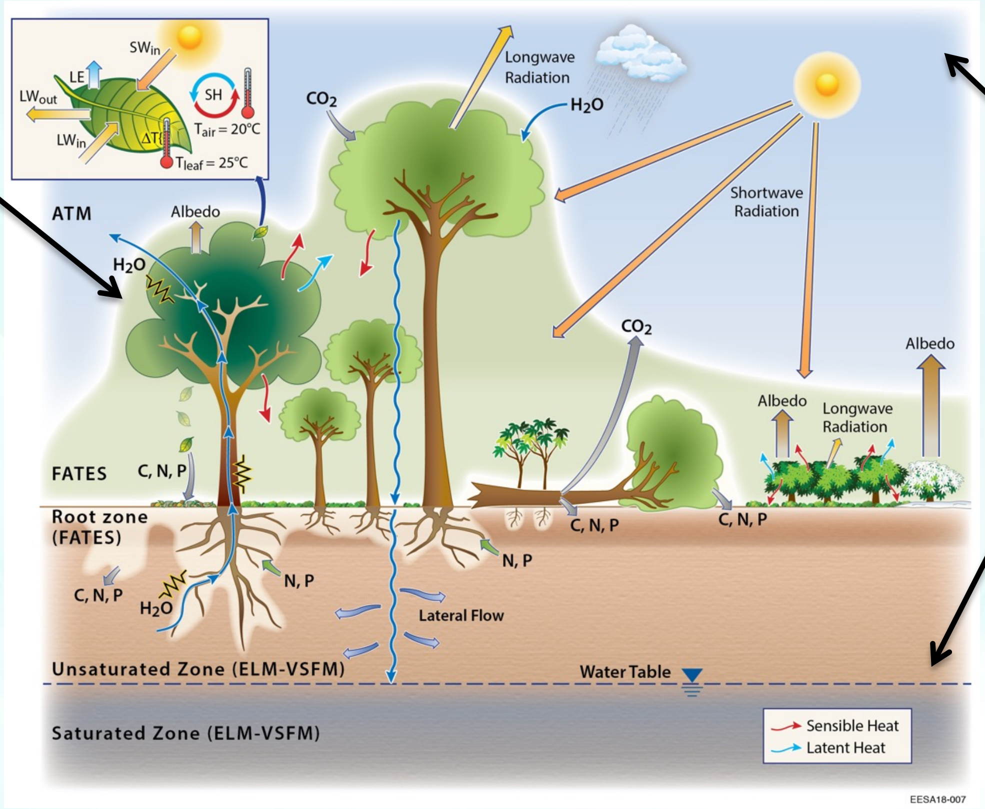
FATES

Fast processes

Photosynthesis
Canopy radiation
Respiration
NPP
Hydraulics

Slow processes

Stem growth
Turnover
Carbon storage
Allometry
Cohort splitting



ELM

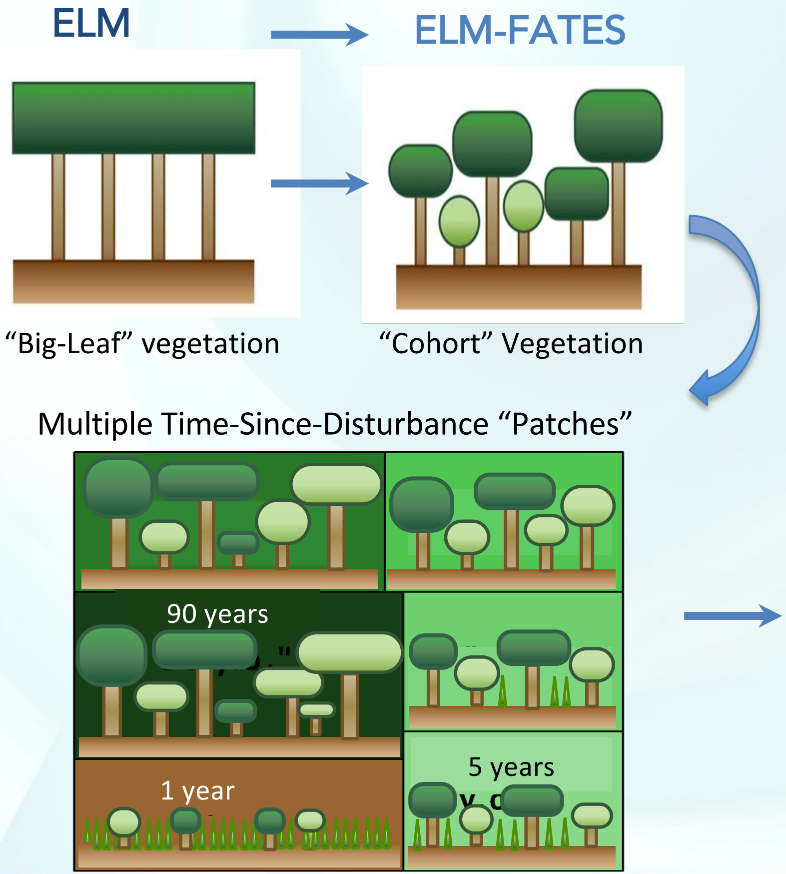
Energy Balancing
Soil carbon, water
Soil biogeochemistry
Subsurface hydrology
Land use drivers
everything else

Physics and
BGC Interface

Supported by DOE's
NGEE-Tropics & E3SM

Fisher et al. 2015, Geosci. Model Dev.

Benefits of ecosystem demography connected to global land models



Heterogeneity in light availability due to varying size and age structure of forest

Competition (for light, water, nutrients), exclusion & coexistence

Ecosystem based on different “cohorts” of vegetation, existing on multiple time-since-disturbance “patches”

Recovery after Disturbance (fire, land use, mechanistic mortality)

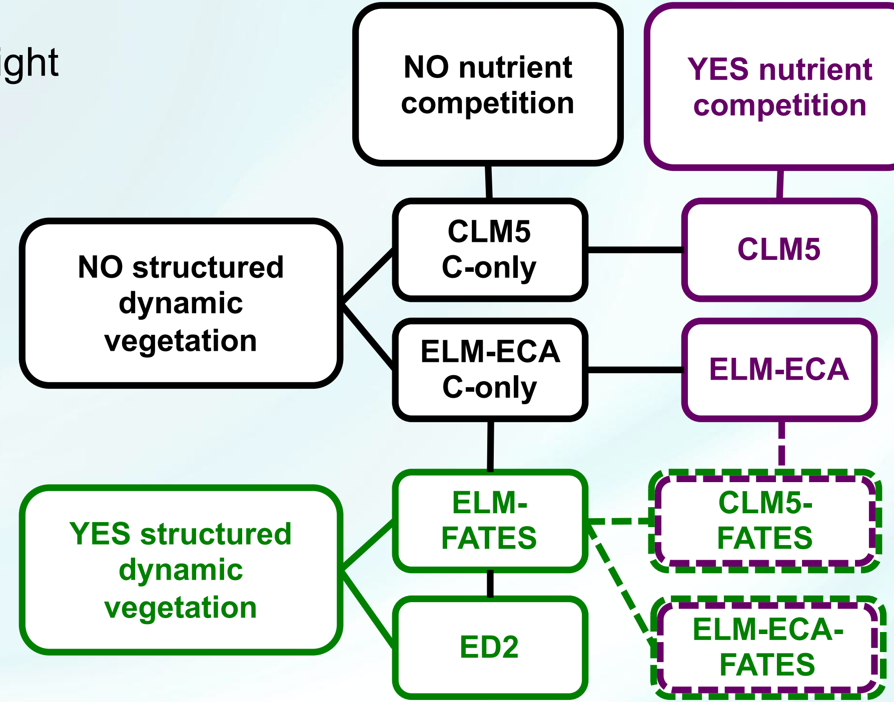
Plant distribution emerges from trait filtering

“Modeling the Central Amazon forest carbon sink under rising CO_2”
Holm et al. 2020, JGR-Biogeosciences (E3SM special issue)

2 dynamic vegetation models
- ED2
- ELM-FATES
- Dynamic plant competition in a vertical light environment
- Mechanistic mortality, size and age structured
- Highly resolved demography

2 ‘big-leaf’, biogeochemical models
- CLM5 (N cycle)
- ELMv1-ECA (N & P cycle)
- Nutrient competition on plant growth
- Fixed mortality
- Coarse, unstructured vegetation

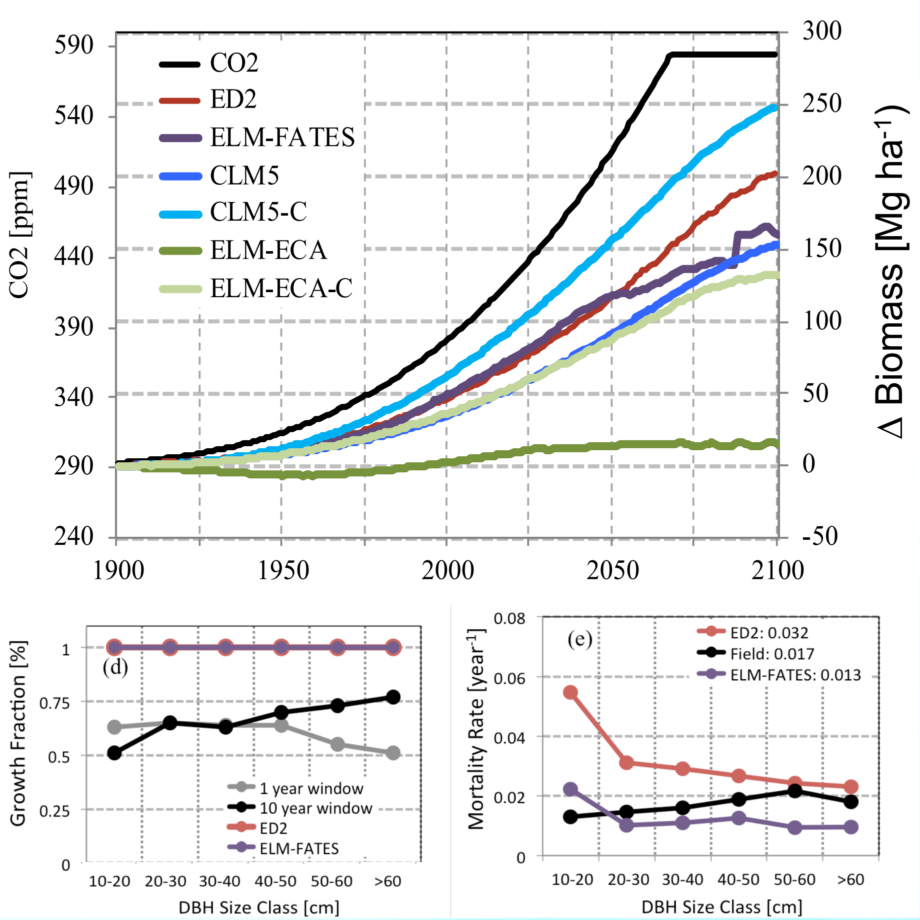
Quasi-factorial experimental design:



Long-term biomass response to rising CO_2 (out to 2100)

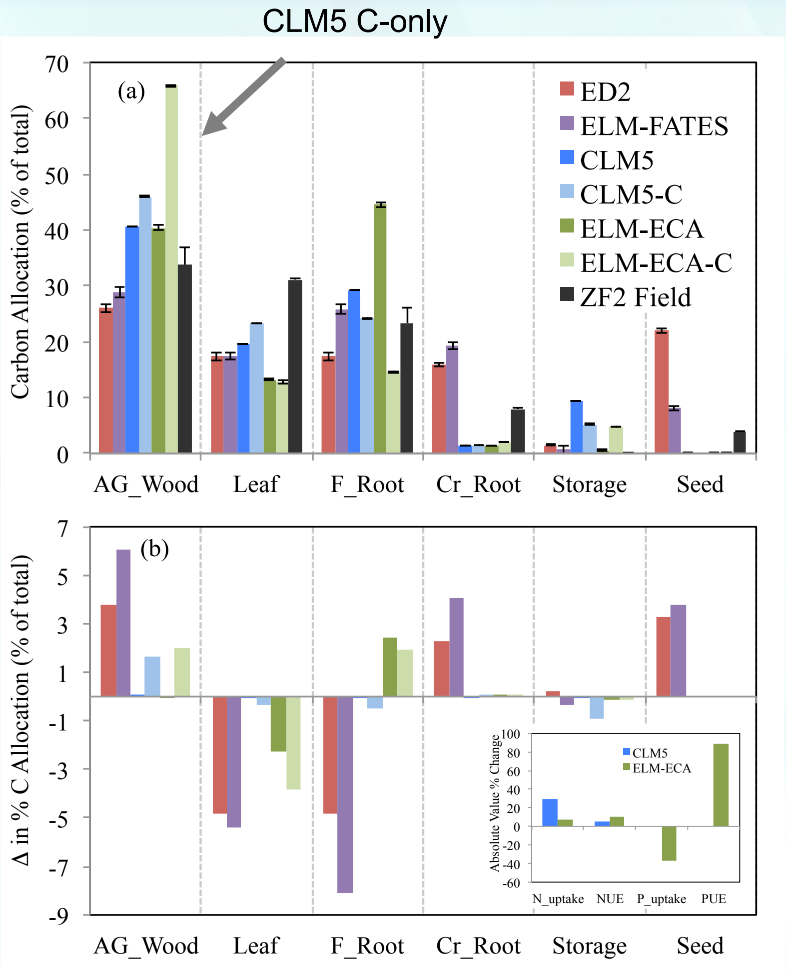
- ED2 and ELM-FATES = large carbon sinks.
- However C-only versions of big-leaf models similar or larger than VDMs.
  - Vegetation demography and competition reduced this sink to more realistic predictions while including fine-scale demography.
- ELMv1-ECA with P competition has lowest CO_2 response.
- **Challenge in capturing observed neutral biomass in ALL models. Continual increase in biomass accumulation.**
- **Improvement in how plant mortality is modeled.**

Holm et al. 2020 JGR-Biogeosciences
(See also Needham et al. 2020, GCB)



- VDMs have lower aboveground wood allocation, but much higher coarse root. Scaled with aboveground.
- All models have low leaf allocation

- ELMv1-ECA = forests are strongly P limited. Switch in allocation to fine roots.
- Increase in NUE and PUE, due to continually increasing NPP.



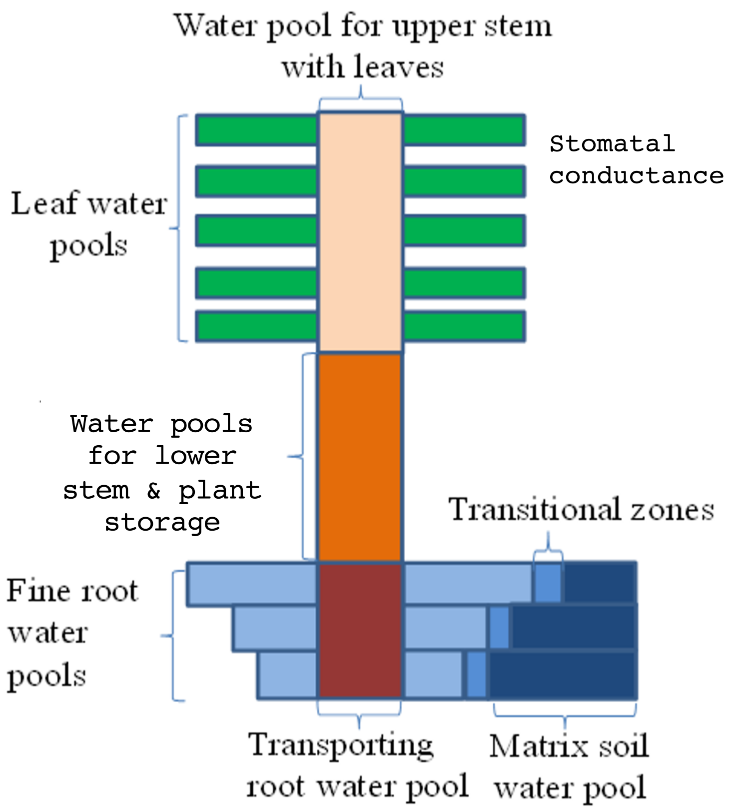
Current carbon allocation (%)

Long-term change in C allocation with rising CO_2 (2100 minus 2000)

Holm et al. 2020 JGR-Biogeosciences

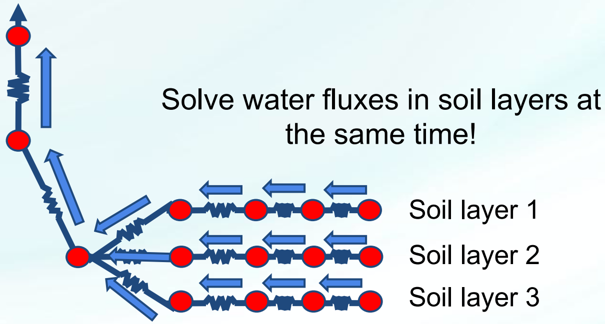
Land/Energy NGD: Plant Hydraulics

ELM-FATES Hydro Model

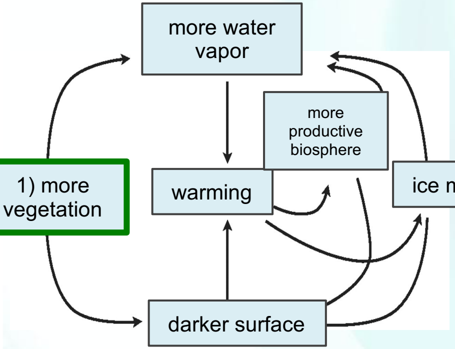


- Introduction of **continuous plant hydrodynamics** while plants dynamically grow and compete in ELM-FATES.
- Tracks water transport through new recruits, growth, and mortality of plants.
- Testing of plant-ecosystem water balance, plant mortality due to water stress and hydraulic failure, and shifts in vegetation due to water availability.

- Some current work (Yilin Fang): update from 1D to 2D Newton Solver to be able to solve all water fluxes, in multiple soil layers simultaneously.



Land/Energy NGD: Plant Hydraulics

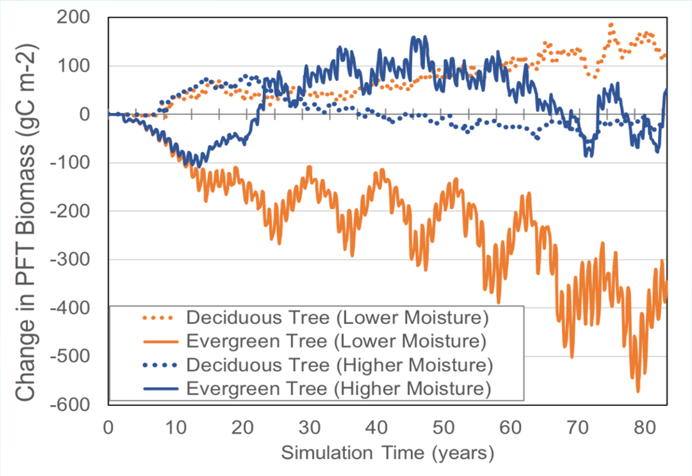


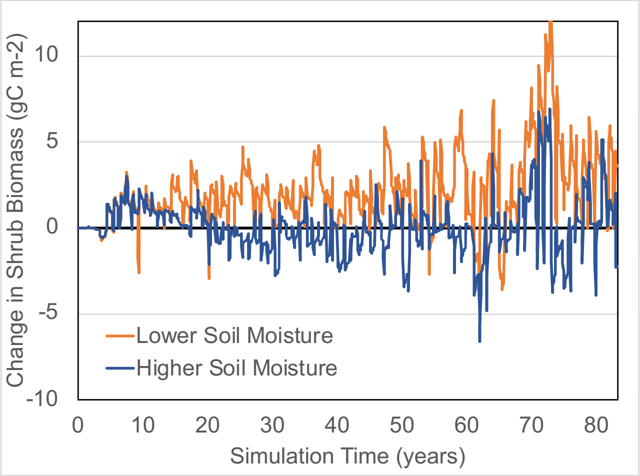
(Swann et al. 2010)

Motivation:

- Deciduous forest cover is expanding.
- Leads to more water uptake, higher transpiration rates, and decrease in biomass.
- Leads to land-climate feedbacks, and increased warming.

FATES-Hydro: Shift in vegetation type with +40% higher soil moisture (i.e. permafrost thawing) or -40% lower soil moisture scenarios (i.e. warming)





Successfully capturing decrease in evergreen trees and increase in deciduous trees with drying (orange) as seen in observations.

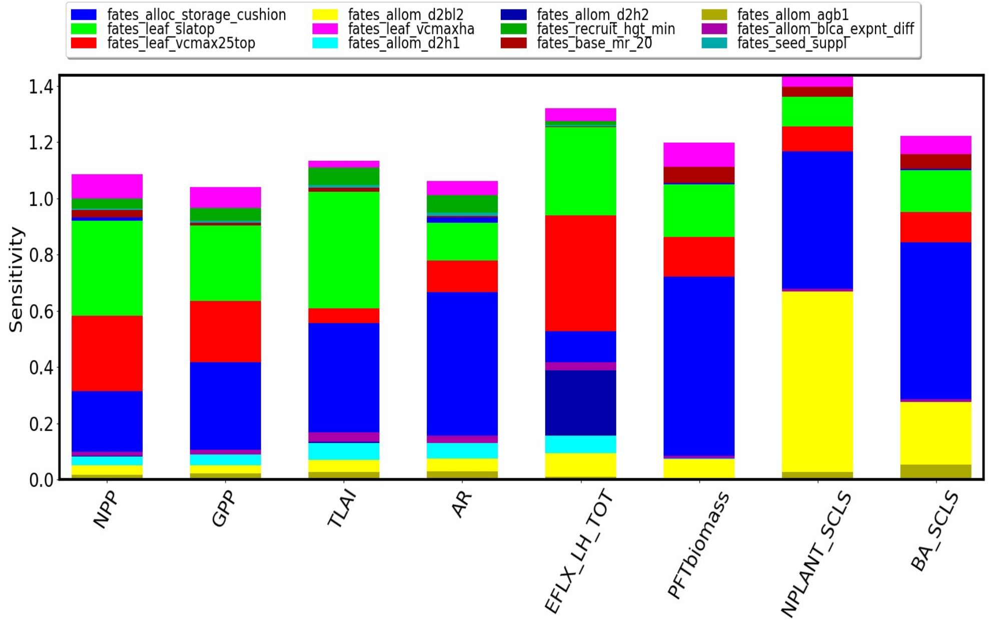
Over time increase in shrub biomass when plant hydraulics accounted for, even under both hydrology scenarios.

(Holm et al. in prep)

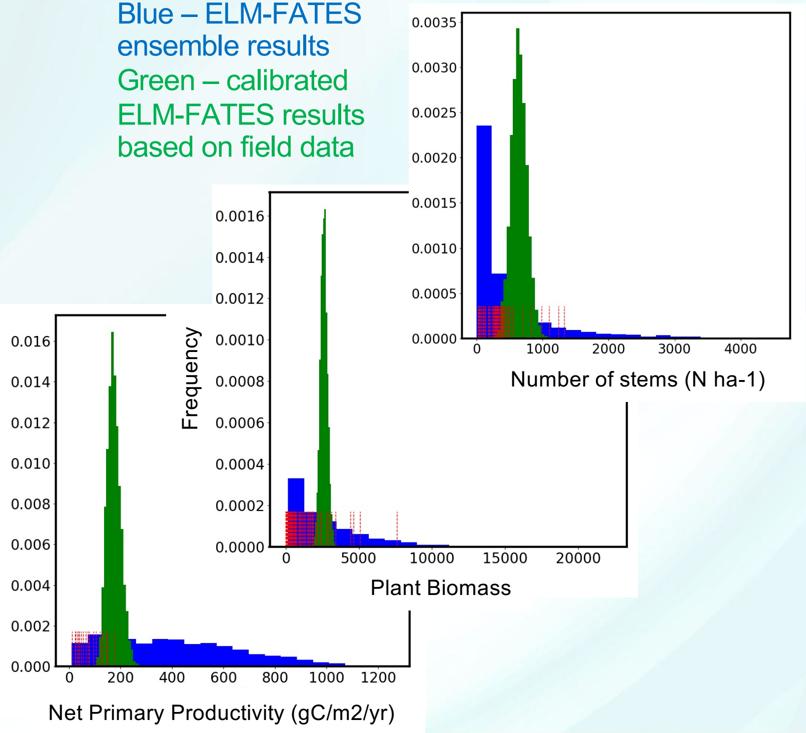
UQ and sensitivity analysis of FATES and PFT parameterization (Holm, Dan Ricciuto, Khachik Sargsyan)

Example of model calibration and UQ analysis for boreal forest conifer PFT

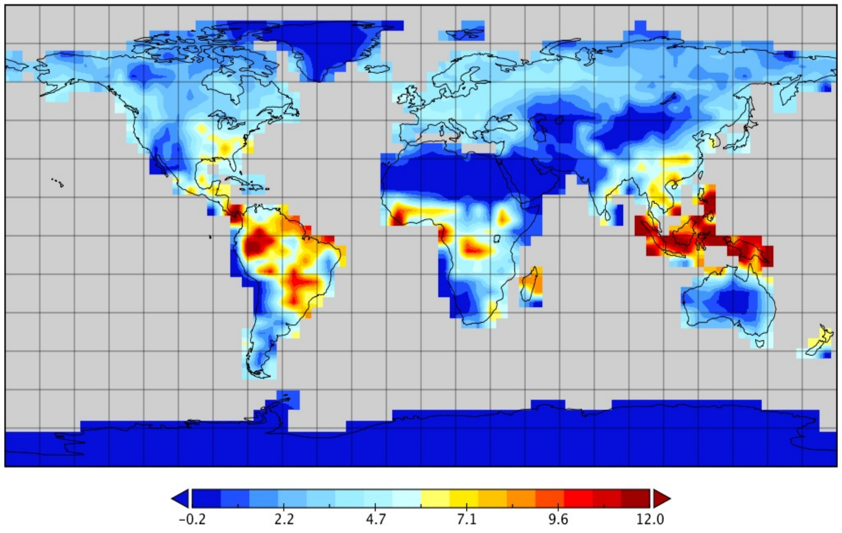
Top 12 parameters that contribute to the largest uncertainty in ELM-FATES results.



Red – field data
Blue – ELM-FATES ensemble results
Green – calibrated ELM-FATES results based on field data



Net Primary Productivity ELM-FATES (gC m^{-2} d^{-1})

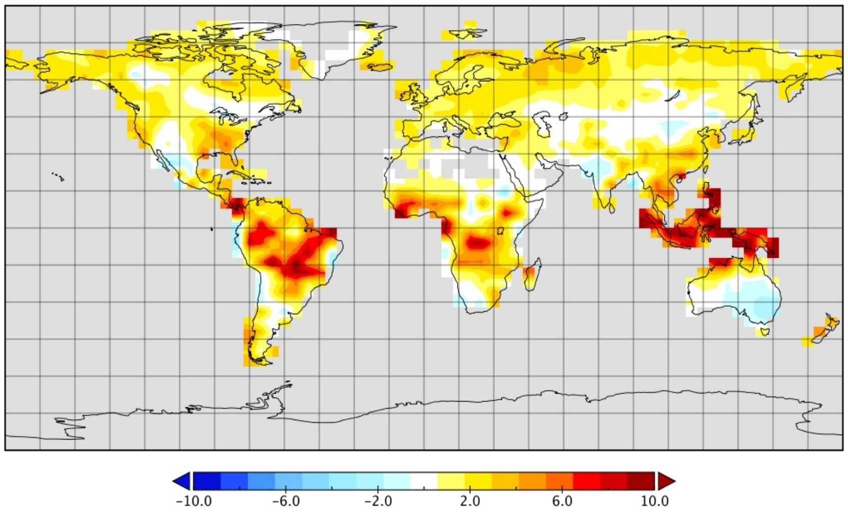


Mean 3.4 (gC /m2/d)

Global ELM-FATES Simulations with plant demography and dynamic trait-based competition.

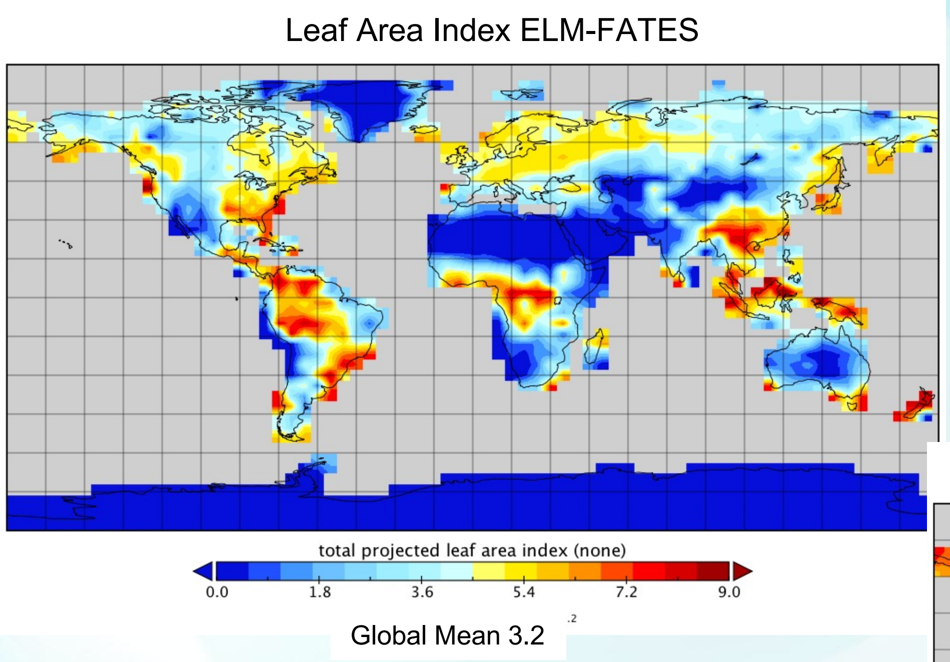
- Coarse global simulations for initial testing.
- 13 PFTs

NPP Difference (gC/m2/d) -- MODIS and FATES



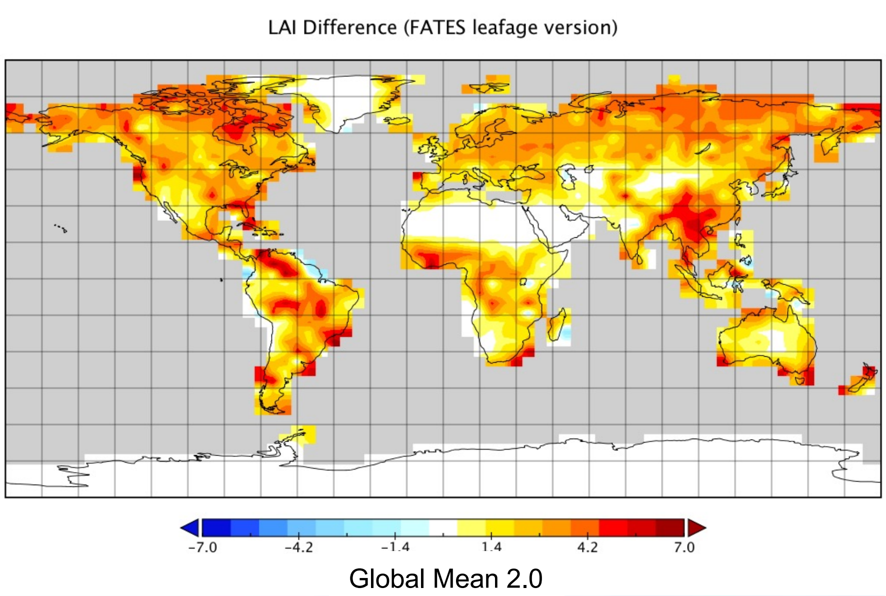
Mean +2.1 (gC /m2/d)

High NPP bias in ELM-FATES compared to MODIS



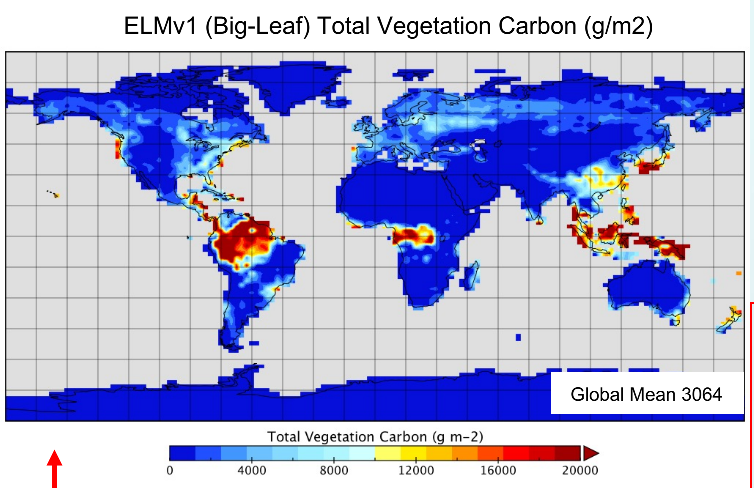
Over-productive canopies and vegetation in ELM-FATES compared to MODIS.

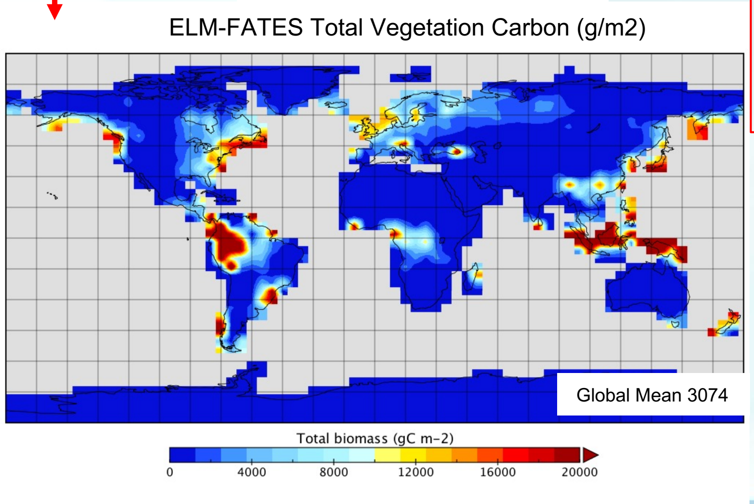
But what about compared to ELM-CNP ‘big-leaf’ version?



Also high LAI bias in FATES compared to MODIS

ELMv1 'big-leaf' version from Zhu et al. 2019 JAMES

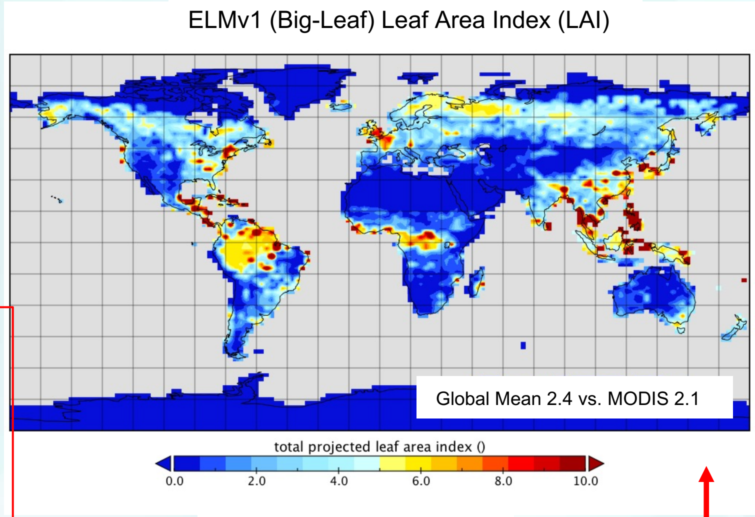


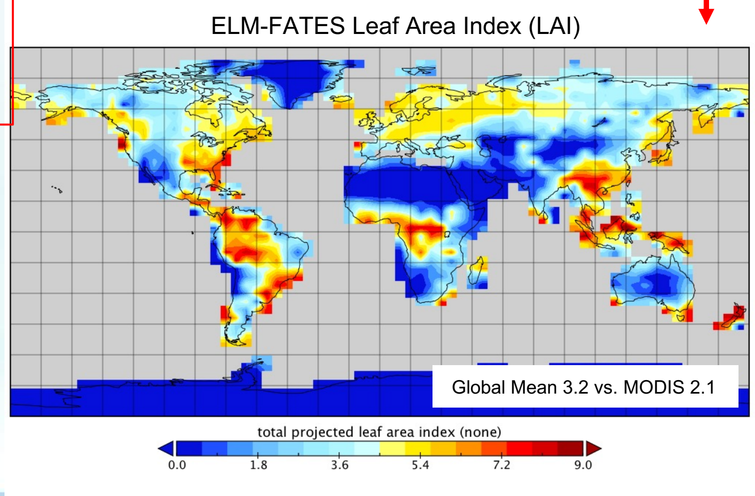


Big-leaf

vs.

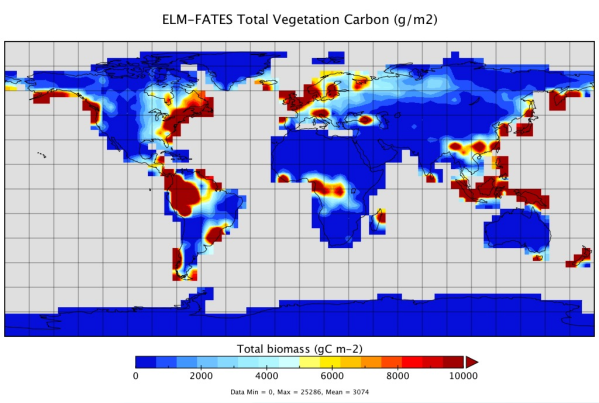
VDM



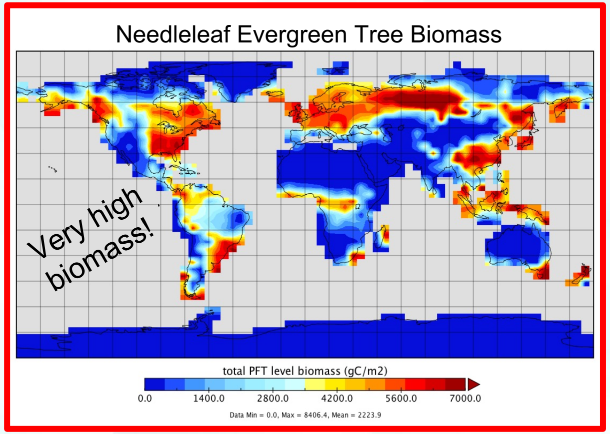


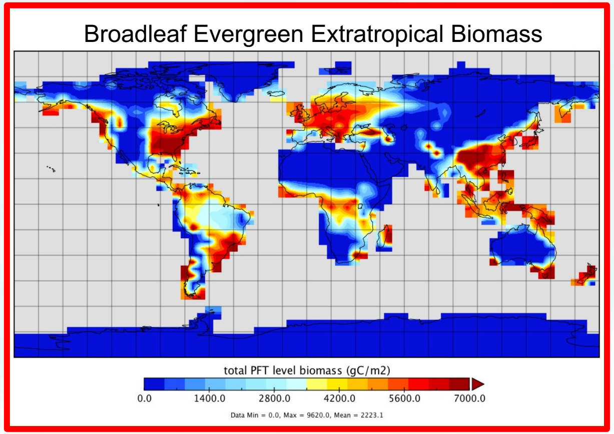
Global averages of fluxes and stocks good in ELM-FATES, but what about PFT distribution with no climate envelopes and emergent behavior from competition and disturbance?

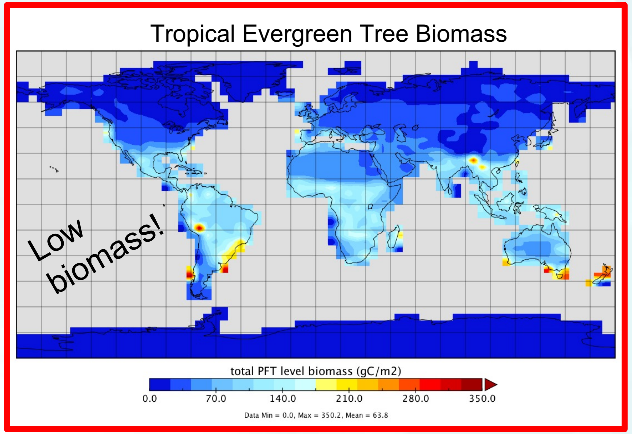
Global distribution of dynamic PFTs in ELM-FATES (baseline case)



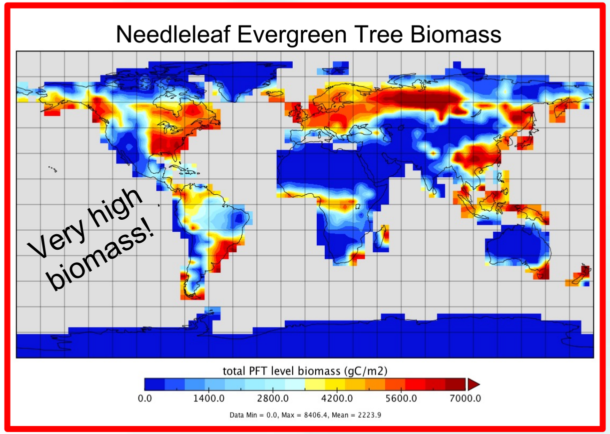
- Total vegetation biomass in default ELM-FATES (top figure)
- Very productive extra-tropical evergreen trees taking over (both needleleaf and broadleaf), in a lot of places even in the tropics.
- As a result low survival of tropical trees and other PFTs.
- New parameterization: adjusting parameters that are related to strategies of leaf production vs. allocation to storage.

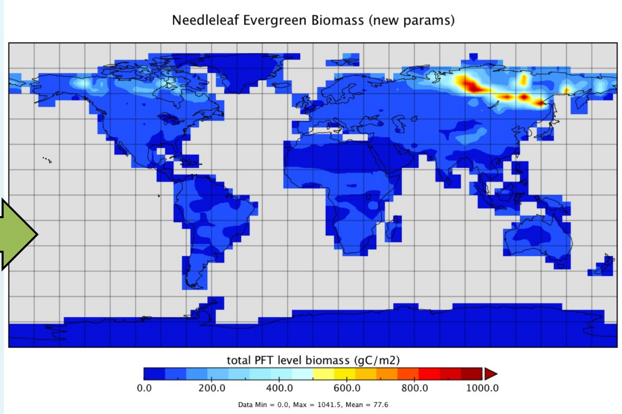




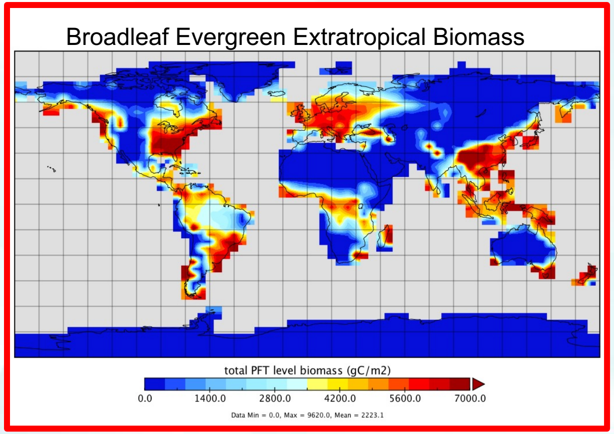


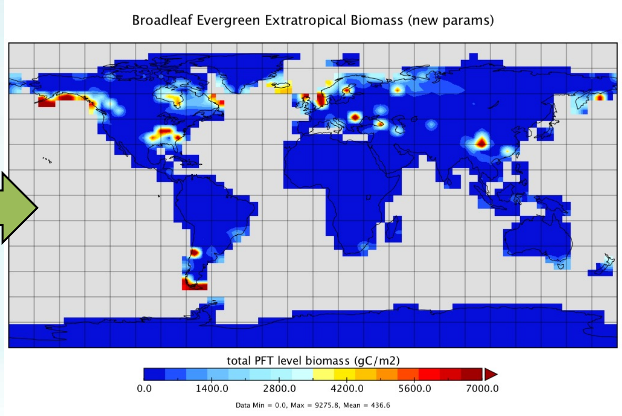
Parameterization updates improved global distribution of vegetation types, based on trait competition and tradeoffs



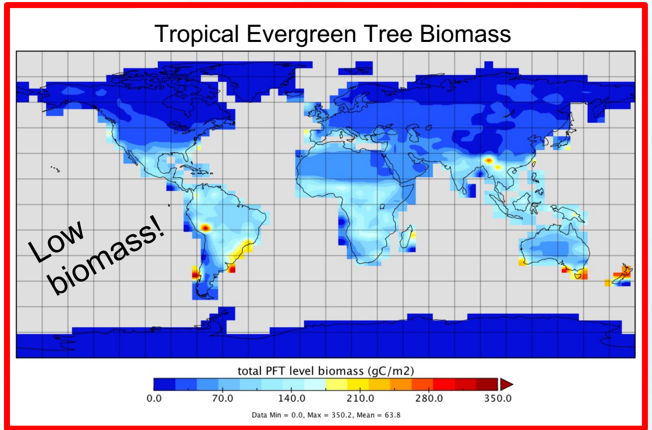


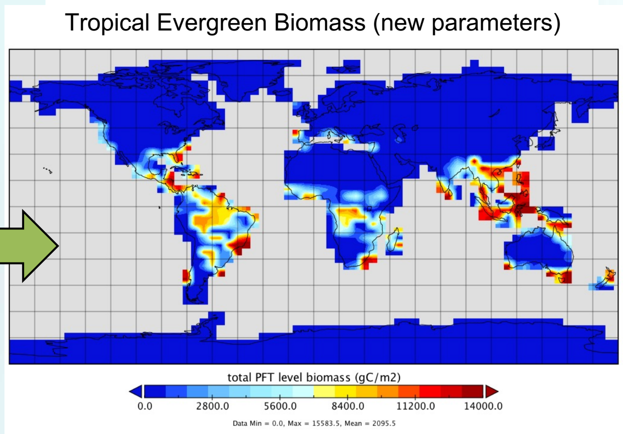
- Decrease in non-tropical needleleaf evergreen trees, but maybe too much.
- Decrease in leaf productivity.
- More testing needed here.



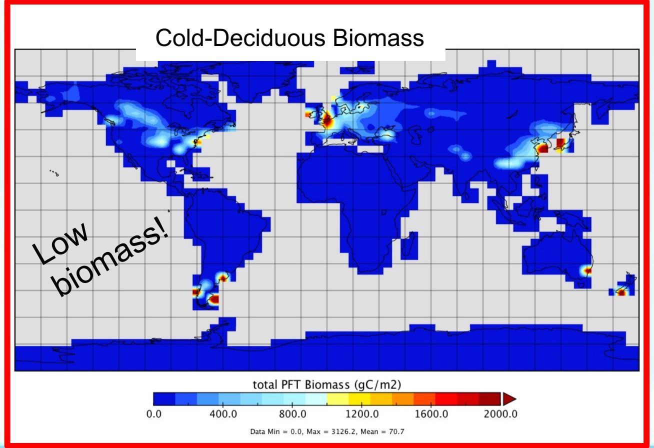


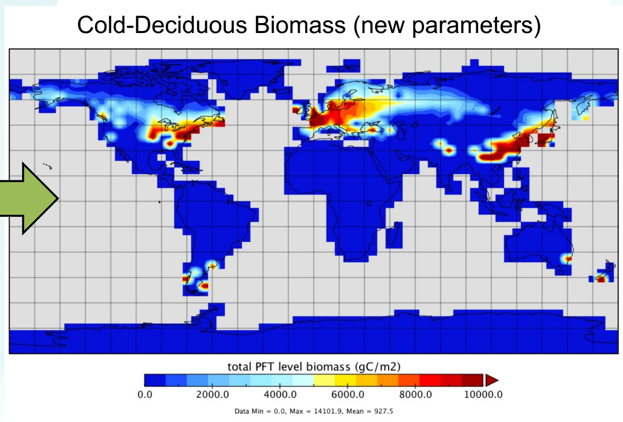
Parameterization updates improved global distribution of vegetation types, based on trait competition and tradeoffs





- New parameterization
- Very different scales, and realistic values here.
- Central Amazon: ~16 kgC/m2
- ELM-FATES: 10 kgC/m2



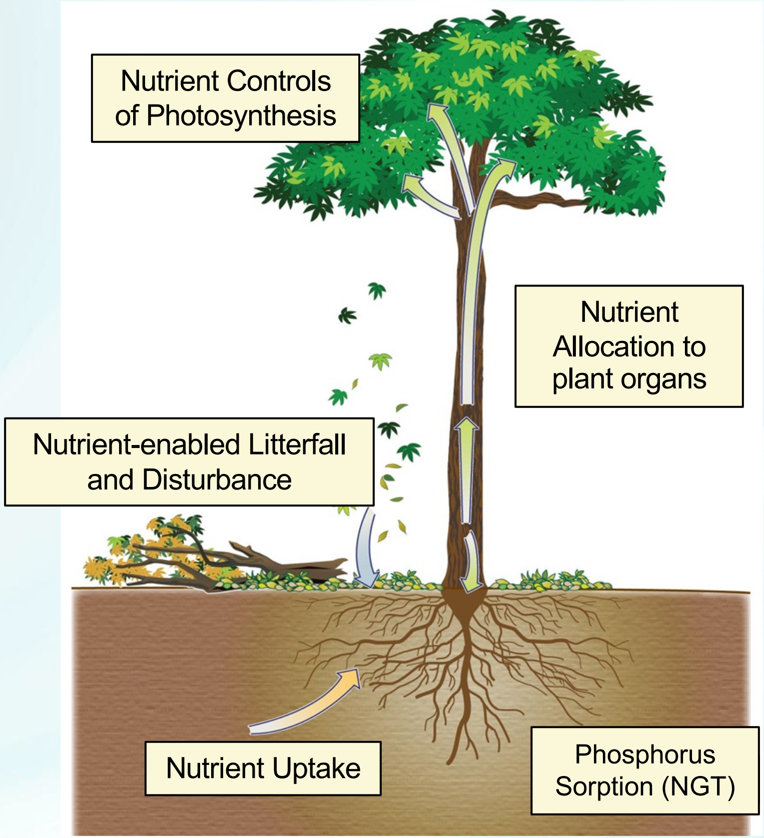


Nutrient-Enabled ELM-FATES (New feature!)

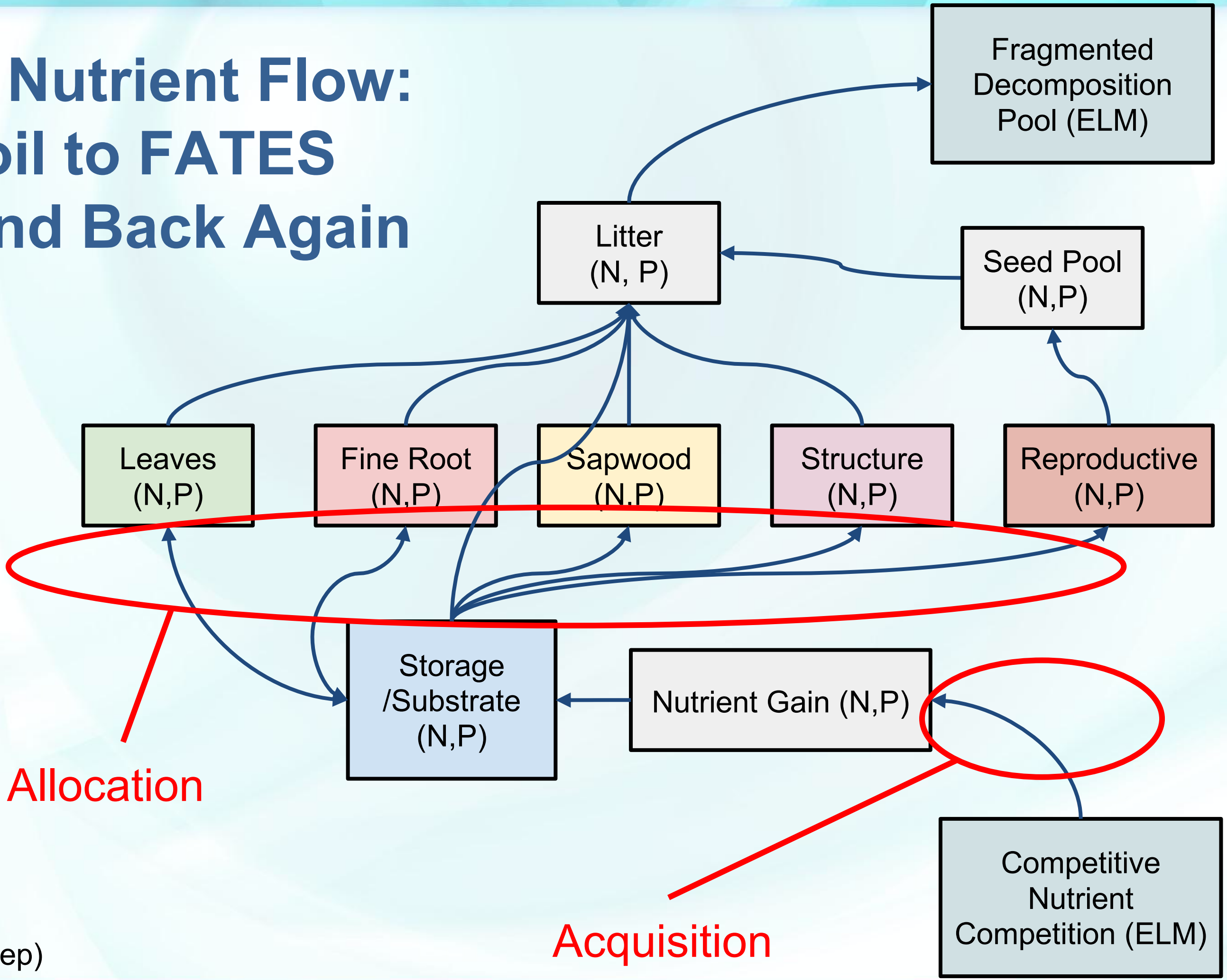
Developed to be a **stand-alone flexible** module to efficiently **test alternative representations of carbon-nitrogen-phosphorus competition**:

- Plant nutrient **acquisition** coupled with ELM's soil BGC.
- Allometry-aware **allocation** of C-N-P (PARTEH).
- Add **litter fluxes** from FATES plants to ELM's soil BGC.
- Testing different approaches of **plant nutrient needs during "spin-up"** of soil and plant BGC interactions.

- Pull Request (4325) for nutrient cycling in FATES in review: https://github.com/E3SM-Project/E3SM/pull/4325.



FATES Nutrient Flow: ELM Soil to FATES Plant and Back Again



Knox et. al. (In Prep)

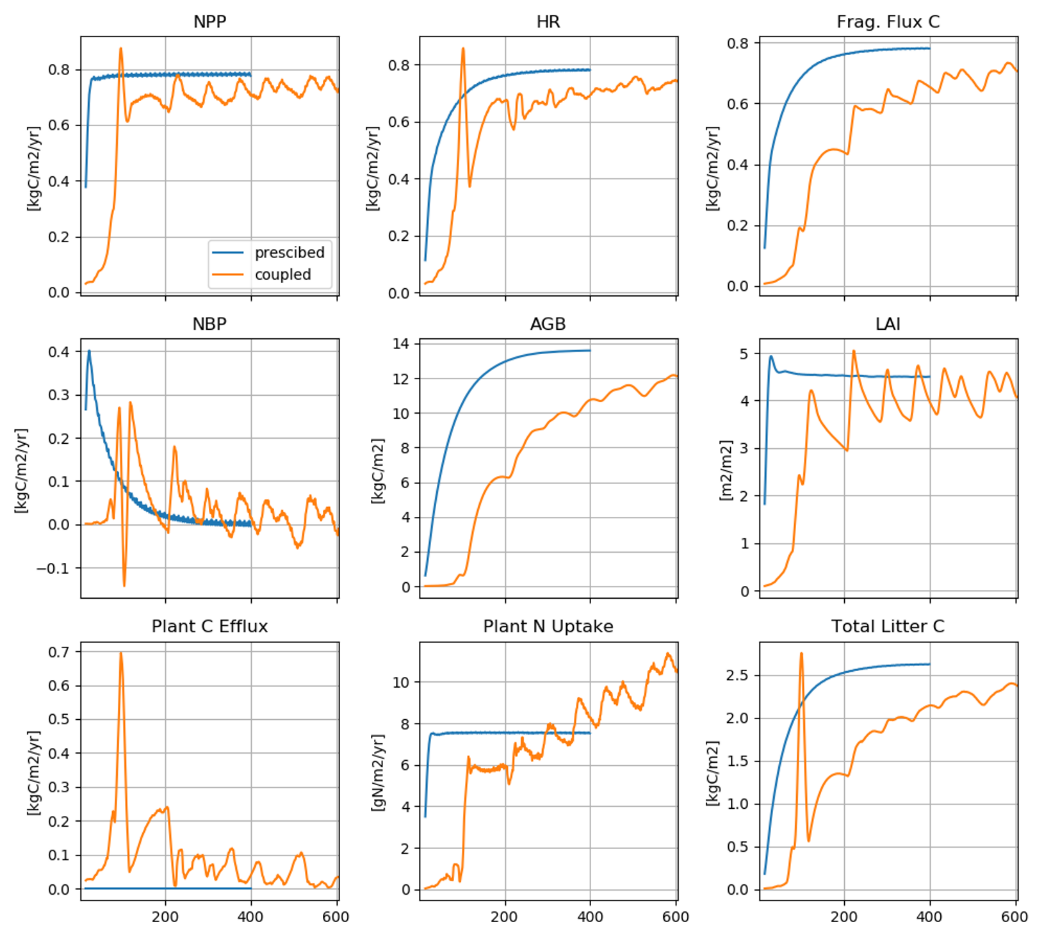
Coupled CNP vs. Uncoupled (c-only)

Decomposition in soil model is accelerated (i.e. rate constants increased).

FATES plants initialized at year-0 with an arbitrary number of seedlings.

Supplemental N is provided for a short number of years to "kick-start".

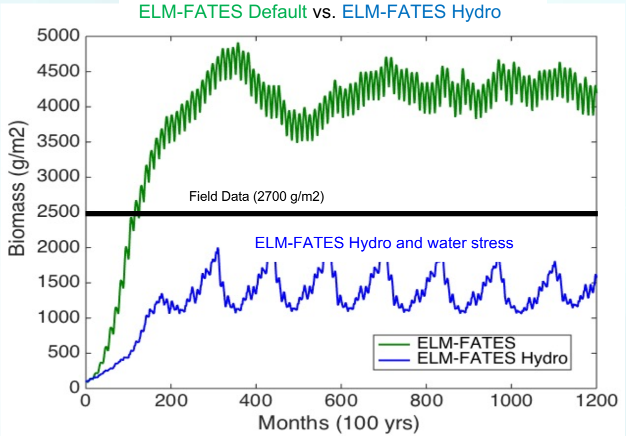
Supplemental P is always provided to all competitors (evaluating N-limitations only here).



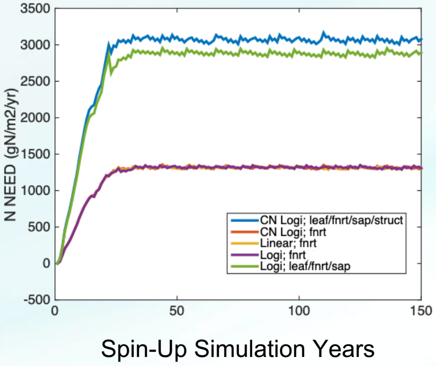
Knox et. al. (In Prep)

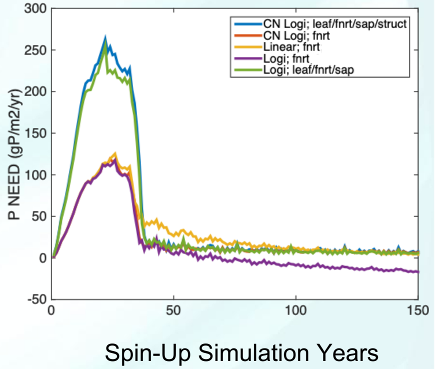
Summary and next steps:

- Carbon-only version of global ELM-FATES predicts “ok” globally averaged carbon stocks and fluxes, however overly-productive vegetation poor regional distribution, but:
    - Parameterization of extra-tropical PFTs substantially improved regional distribution of plant types.
    - Dynamic plant hydraulics and water stress (in boreal site) substantially lowered biomass.
    - Interactions with soil and plant BGC (N limitation) lowered all major forest metrics (NPP, LAI, biomass, litter C).



- Integration of nutrient cycling between ELM and FATES in complete and testing underway:
    - Underway: testing different theories of plant’s nutrient needs based on plant storage capacity/needs, and regulating demand.
    - Underway: finalizing leaf nutrient constraints on photosynthesis





- FATES and Land-Use Land-Cover Change
    - Global wood harvesting occurring via logging module and newly created secondary forest patches.

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Lawrence Berkeley National Laboratory

Some FATES or VDM related references:

Holm et al. 2020, JGR-Biogeosciences
Koven et al. 2020, Biogeosciences
Negron-Juarez, Holm, et al. 2020, Biogeosciences
Fisher and Koven 2020, JAMES
Needham et al. 2020, GCB
Fisher et al. 2015, Geosci. Model Dev.