FATES

The ELM-FATES model: representing the roles of natural and anthropogenic disturbance in the Earth system

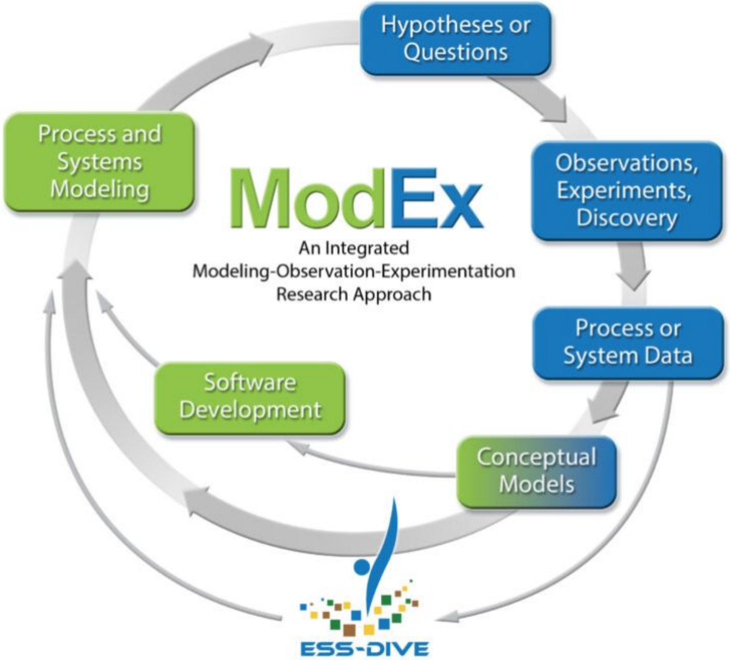
Charlie Koven, LBNL

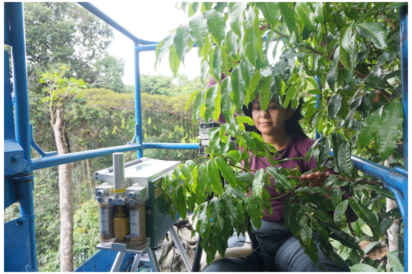
(with lots of slides borrowed from others)

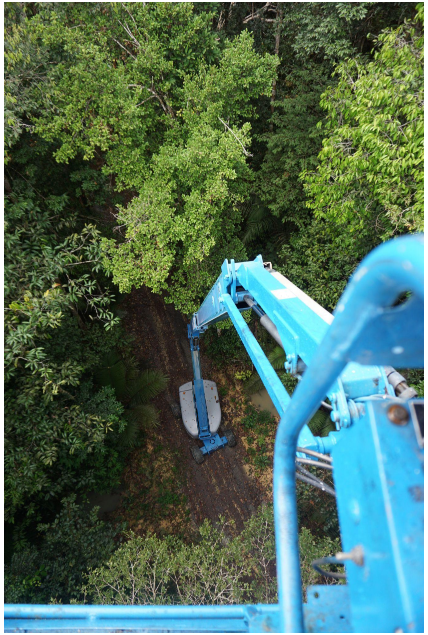
U.S. DEPARTMENT OF ENERGY | Office of Science

NGEE-Tropics Rationale: Model Improvements through ModEx

Advances in modeling key processes and projecting future global change requires a tight coupling of field data and experiments with model development at testing (“ModEx”)







NGEE-Tropics Decadal Vision

The NGEE-Tropics vision is a greatly improved predictive capacity of Earth system models in representing tropical forest responses and feedbacks to global change.

Unifying Modeling Platform

Integrated ModEx Field Sites

Strong National and International Partnerships

NGEE-Tropics Phased Approach

PHASE 1
(FY15-19)

- NGEE-Tropics model FATES developed and integrated into E3SM
- Pilot field study sites established with international partners and ModEx activities initiated

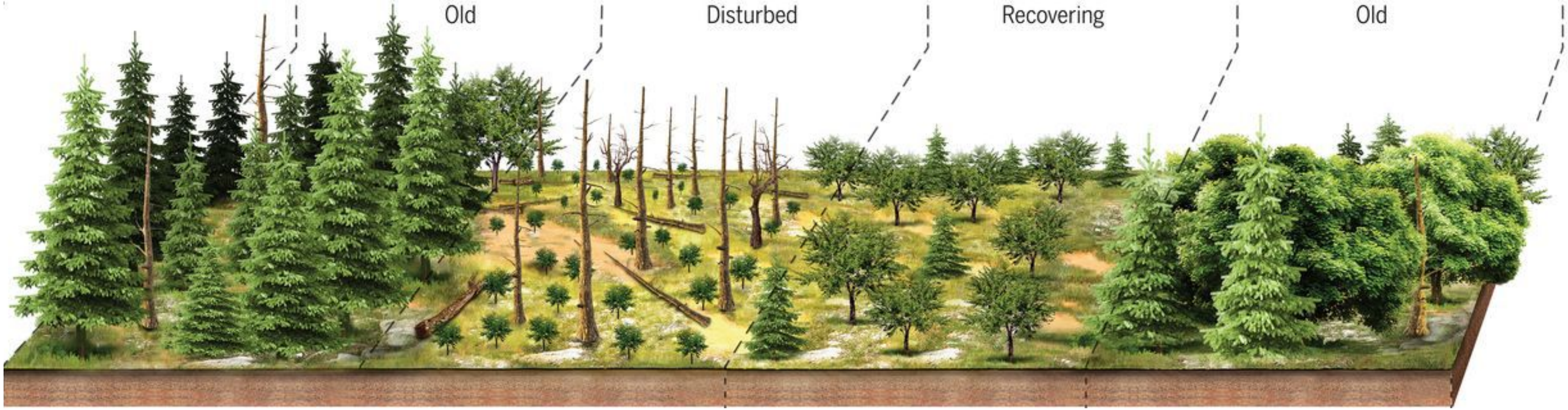
PHASE 2
(FY20-24)

- FATES model development:
  - Forest response to drought elevated temperatures;
  - Nutrient dynamics; and
  - Scaling across RFAs
- Field sites further developed, along with data synthesis and integration, as informed by ModEx requirements

PHASE 3
(FY25-28)

- Finalize FATES and ModEx activities for robust representation of tropical forest-Earth system interactions fully coupled with E3SM
- Carry out model experiments for key tropical forest global change scenarios

Basic Ecological Succession



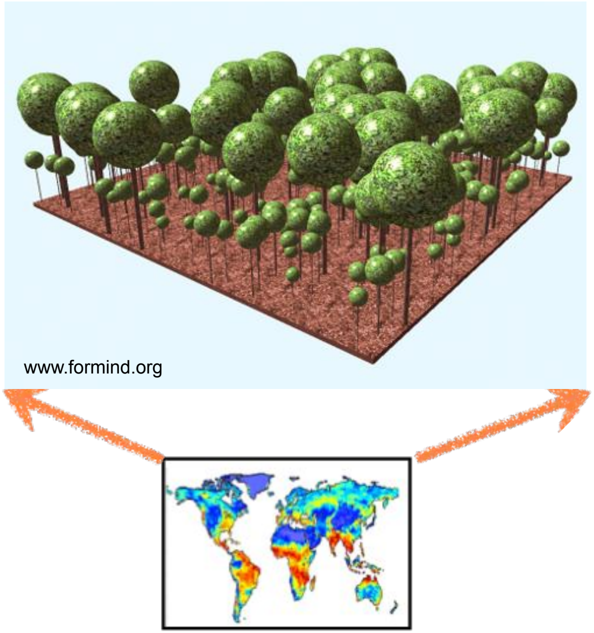
McDowell et al., 2020

'Gap' Models

(e.g. SORTIE, LPJ-GUESS, SEIB, aDGVM, FORMIND)

PROS

- Individual Based
- 3D light environment
- Simulate competition recruitment & disturbance



CONS

- Stochasticity
- Computational cost
- long timesteps, low sampling
- Inappropriate for climate simulations?

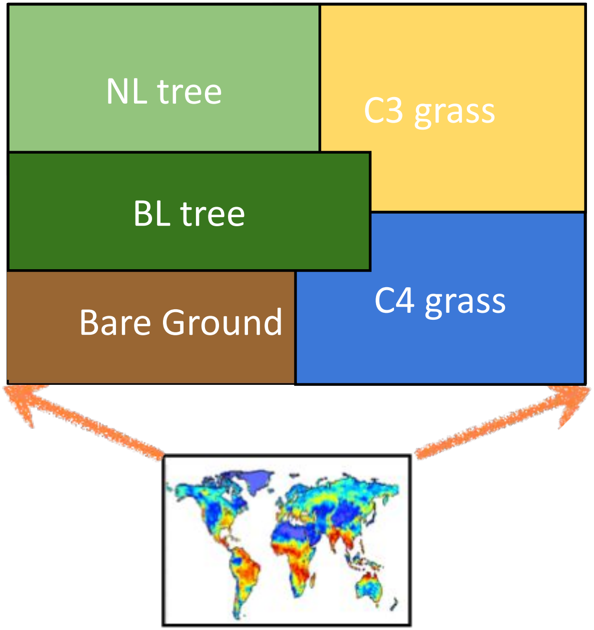
Slide: Rosie Fisher

Area-based Models

(e.g. ELM, CLM, TRIFFID, LPJ, IBIS - models used in IPCC assessments))

Pros

- Deterministic
- Efficient
- Default in ESMs

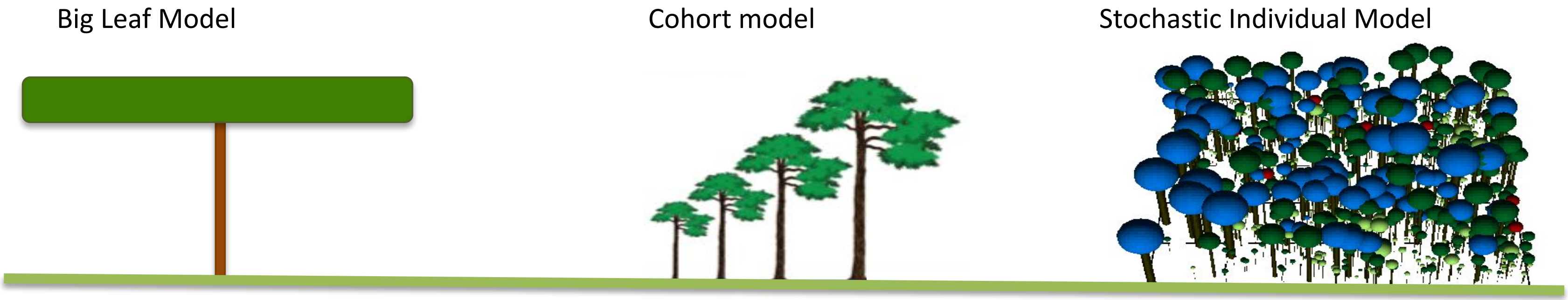


Cons

- One average tree per plant type.
- No height structure
- No light competition

Slide: Rosie Fisher

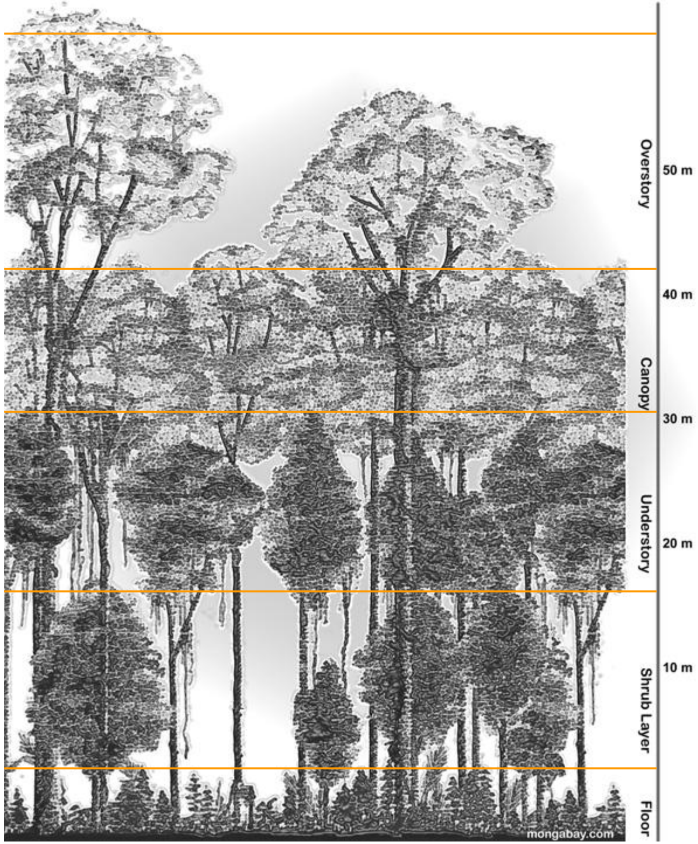
'Cohort-based' Models as intermediate solutions



Slide: Rosie Fisher

Ecosystem Demography Model (ED)

Moorcroft, Hurtt and Pacala. 2001



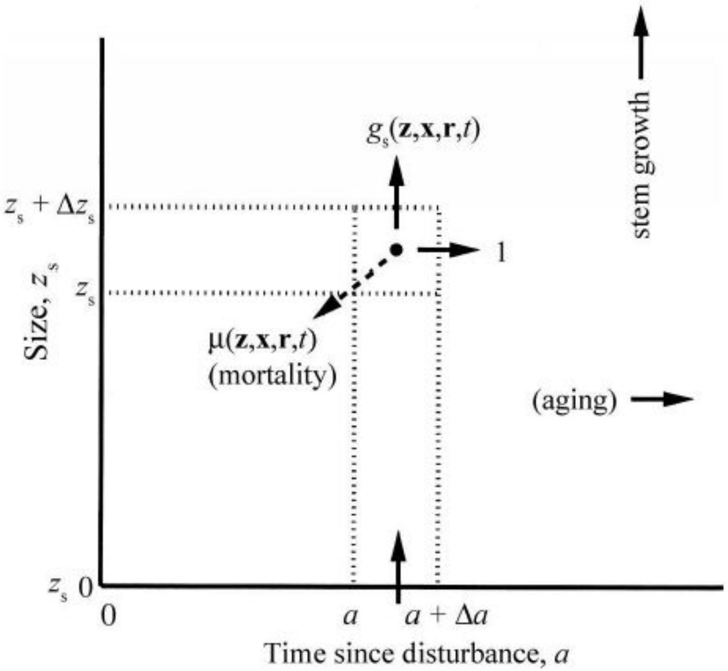
- 'Cohorts' of trees, grouped according to:
  - Plant type
  - Height
  - Successional stage

Slide: Rosie Fisher

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

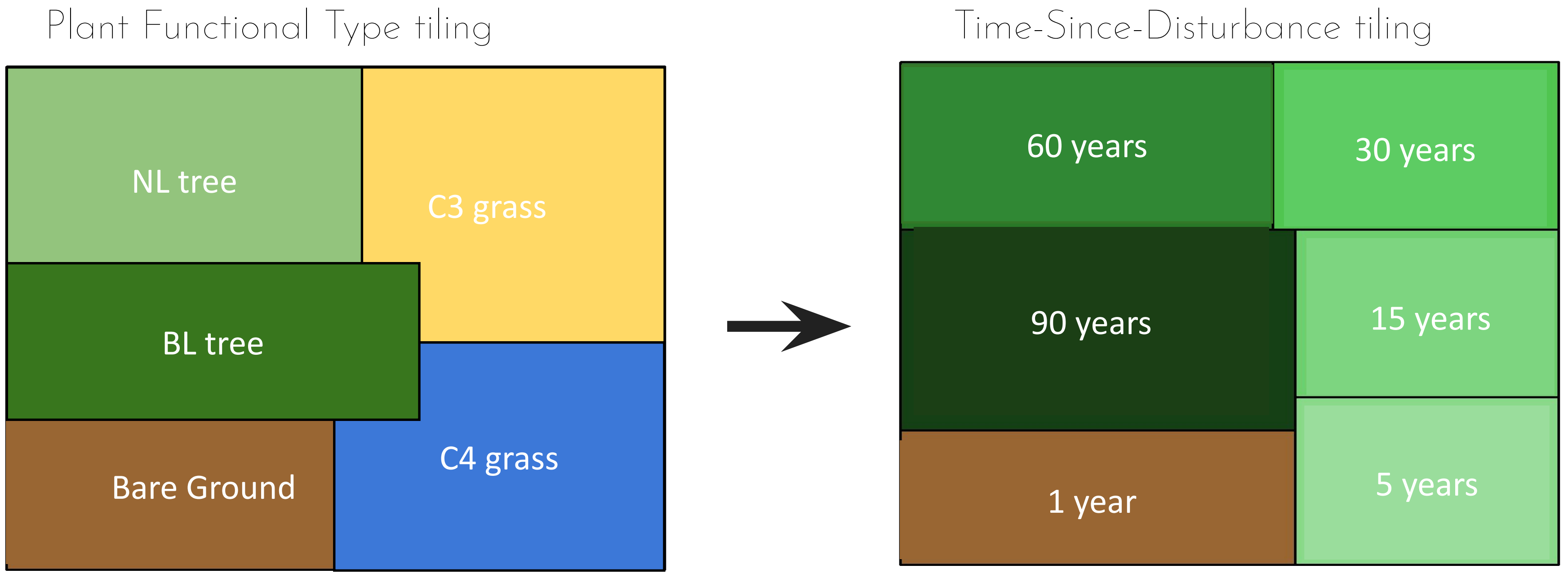
P. R. Moorcroft,[1,3] G. C. Hurtt,[2] and S. W. Pacala[1]

[1]*Department of Ecology and Evolutionary Biology, Princeton University, Princeton, New Jersey 08544-1003 USA*
[2]*Complex Systems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire 03824 USA*



$$\underbrace{\frac{\partial}{\partial t} n(\mathbf{z}, \mathbf{x}, a, t)}_{\text{change in plant density}} = \underbrace{-\frac{\partial}{\partial z_s}[g_s(\mathbf{z}, \mathbf{x}, \bar{\mathbf{r}}, t) n(\mathbf{z}, \mathbf{x}, a, t)]}_{\text{growth in stem}} \underbrace{- \frac{\partial}{\partial z_a}[g_a(\mathbf{z}, \mathbf{x}, \bar{\mathbf{r}}, t) n(\mathbf{z}, \mathbf{x}, a, t)]}_{\text{growth in active tissue}} \underbrace{- \frac{\partial}{\partial a} n(\mathbf{z}, \mathbf{x}, a, t)}_{\text{aging of plant community}} \underbrace{- \mu(\mathbf{z}, \mathbf{x}, \bar{\mathbf{r}}, t) n(\mathbf{z}, \mathbf{x}, a, t)}_{\text{mortality}}. \quad (4)$$

Vegetation structure: CLM/ELM vs ED models



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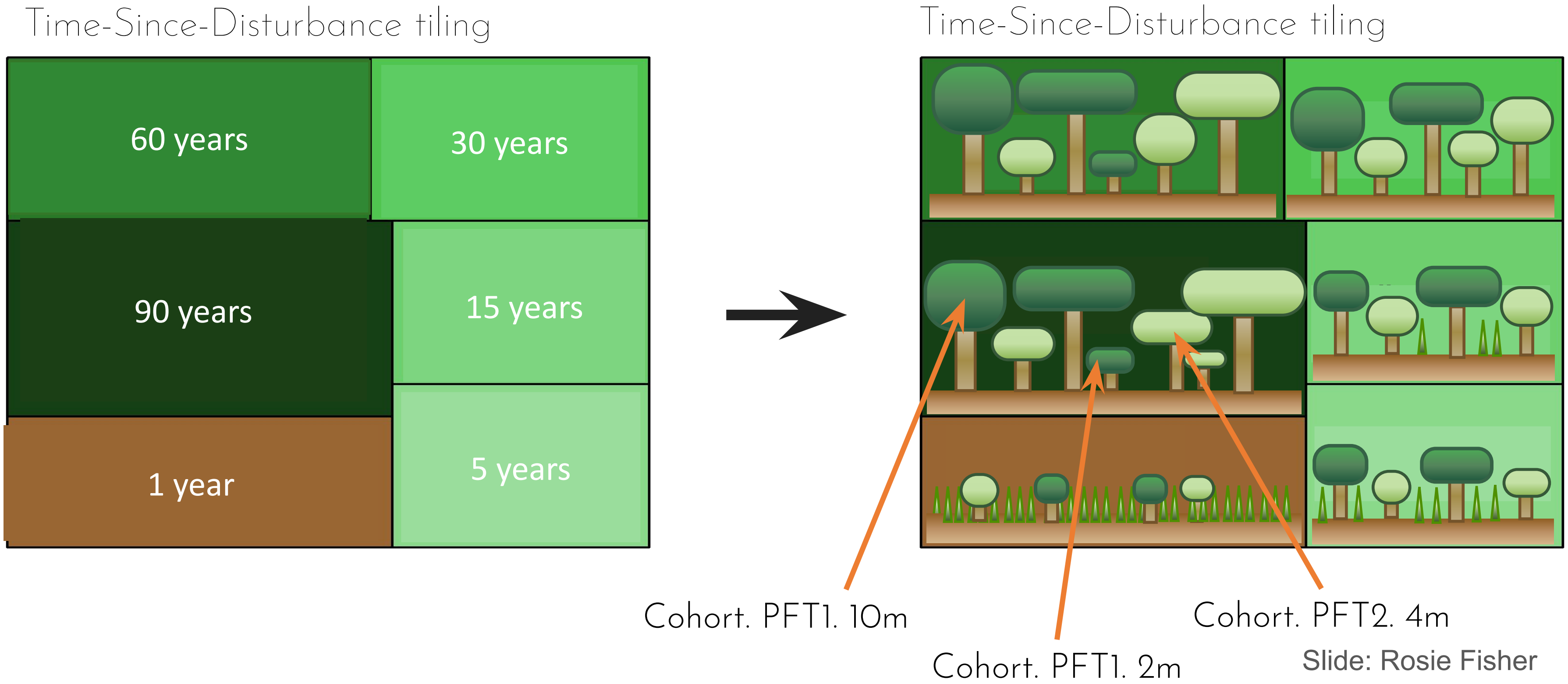
Vegetation structure in ED models

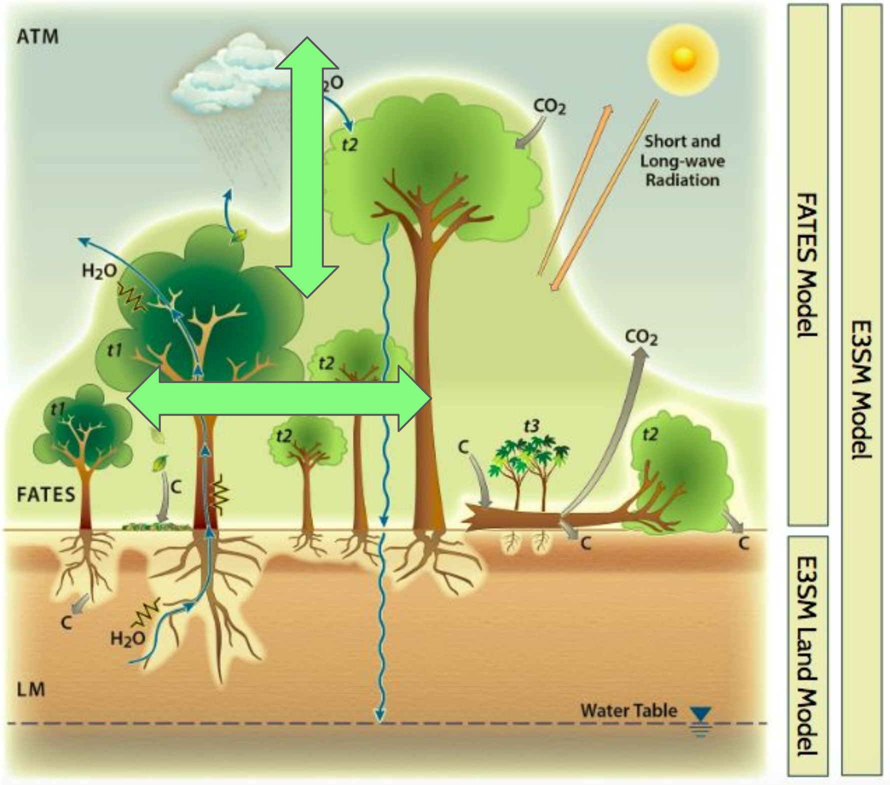
Each time-since-disturbance tile contains cohorts of plants, defined by PFT and size.



Slide: Rosie Fisher

FATES can be flexibly configured to allow ModEx at multiple temporal and spatial scales.

- Cohort-scale physiological dynamics can be tested by prescribing the observed forest structure at a site.
- Community-scale ecosystem assembly can be tested by allowing physiology and structure to both evolve at a site.
- Pantropical dynamics can be tested using large-scale simulations and tested against remote sensing, plot network, or other large-scale data.



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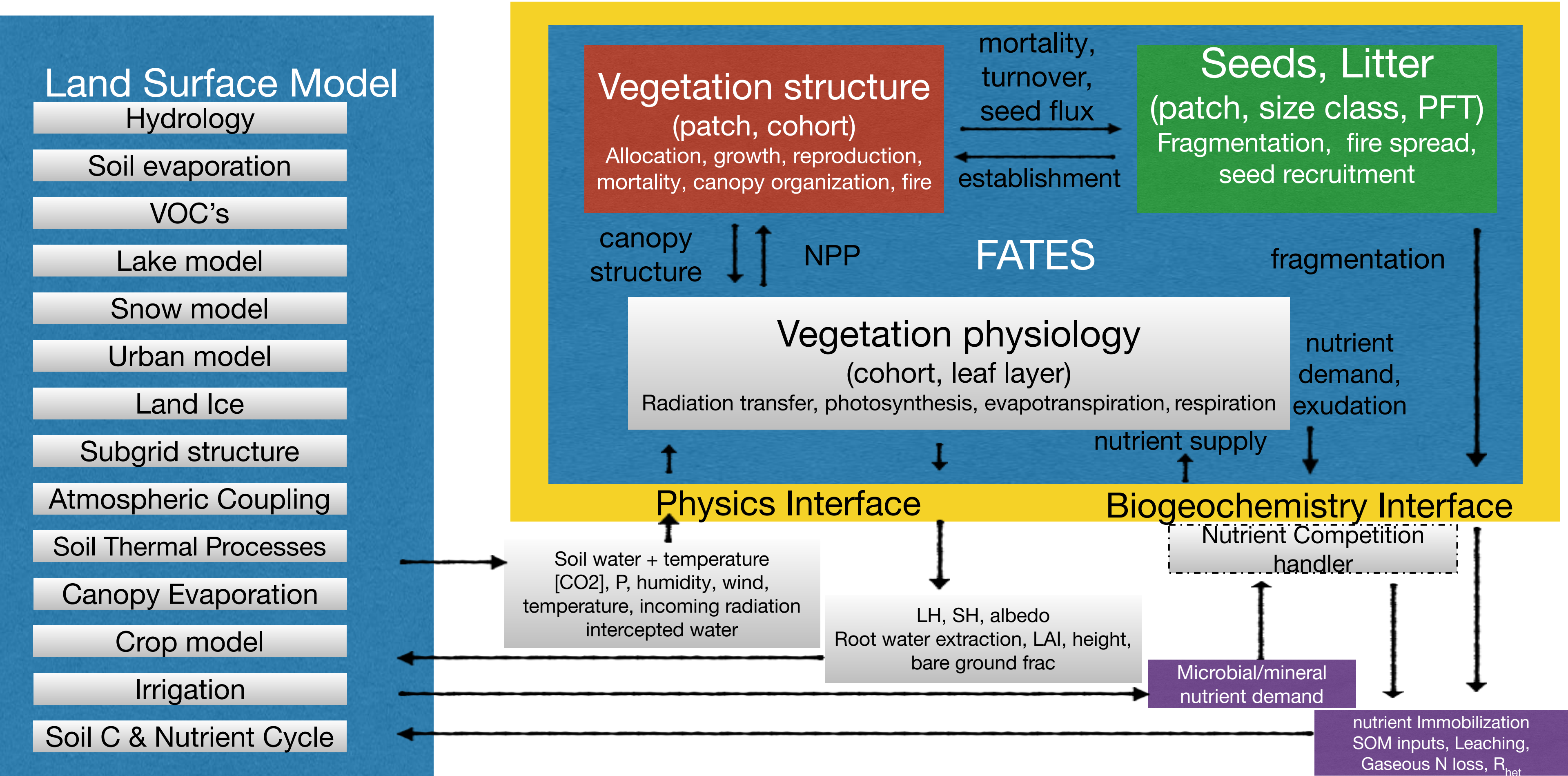
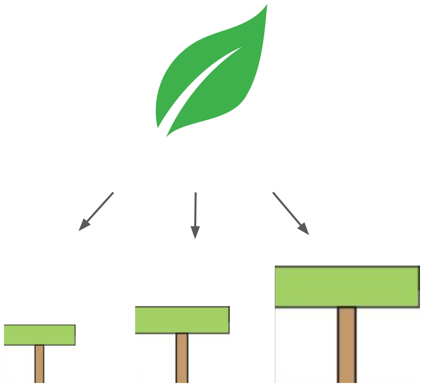
Overall FATES modularity and design (circa 2015)



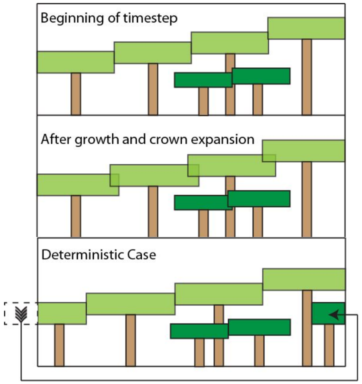
Scaling scheme built into FATES

Tissues → Plant



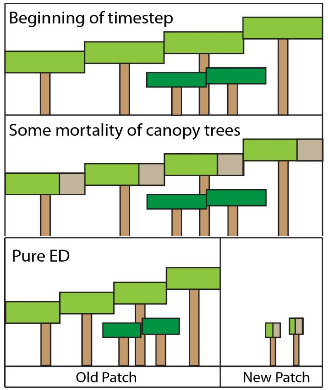
Allometric Scaling

Plants → Stand



Perfect Plasticity Approximation

Stands → Ecosystem



Ecosystem Demography

Ecosystems → Globe

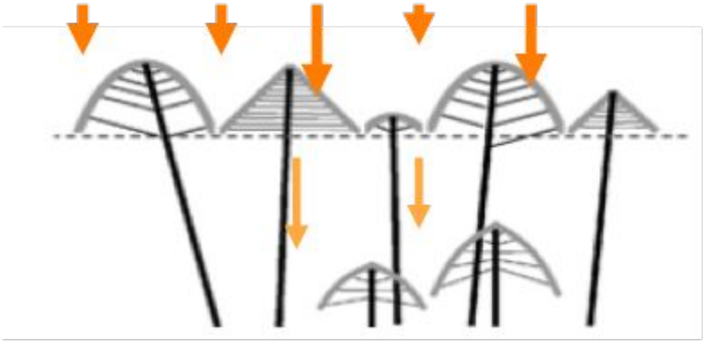
Directly Resolved

The 'Perfect Plasticity Approximation' (PPA)

- Tree canopies are 'perfectly plastic' and fill in all the gaps.
- The forest canopy splits into distinct layers.

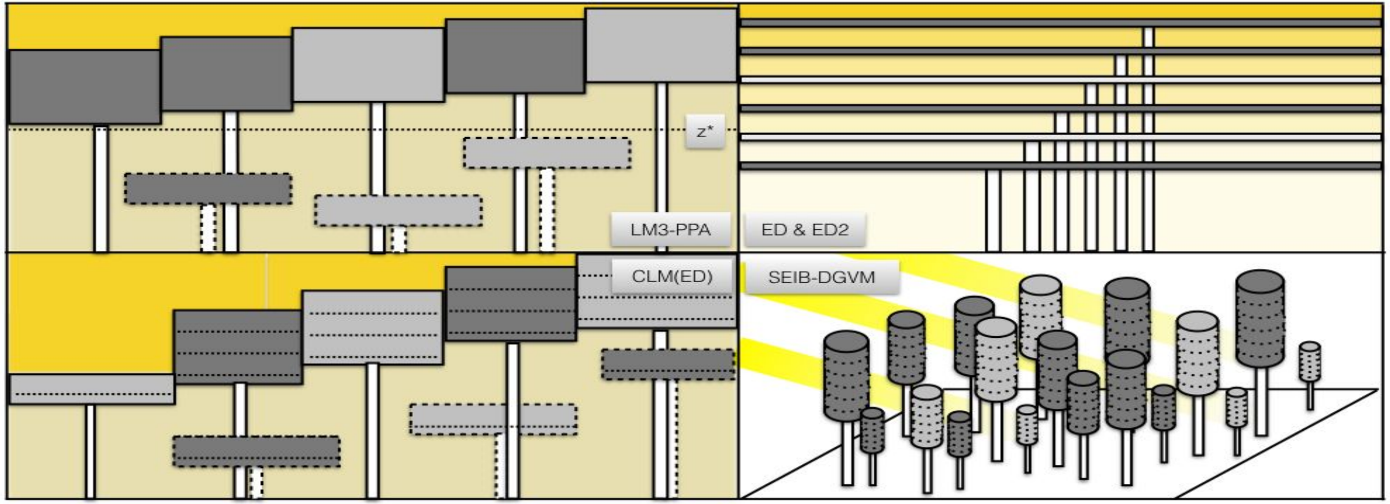
Canopy Layer : All plants receive 100% of incoming radiation on top leaf surface for

Under-story Layer : All plants receive the same reduced incoming radiation light



Purves et al. 2007

Different models make different assumptions about the organization of canopies relative to each other

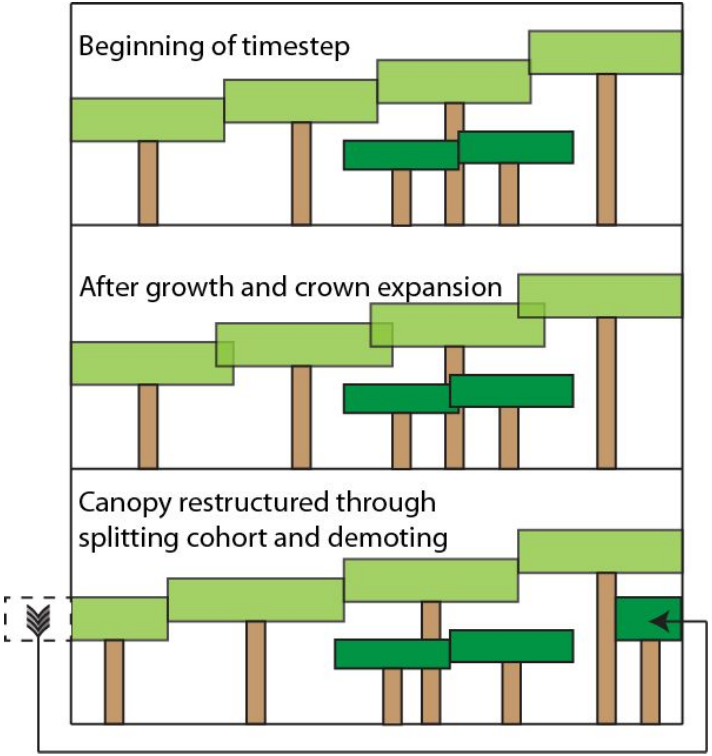


Fisher et al., GCB 2017

FATES Cohort organization within the Patch

- Cohort organization by PPA-based rank organization
- As cohorts grow their crown areas expand via allometry, overfilling canopy. This leads to a constant demotion of cohorts into the understory
- Competitive exclusion parameter allows changes to efficiency of sorting from deterministic PPA to a degree of stochasticity

Deterministic PPA Sorting



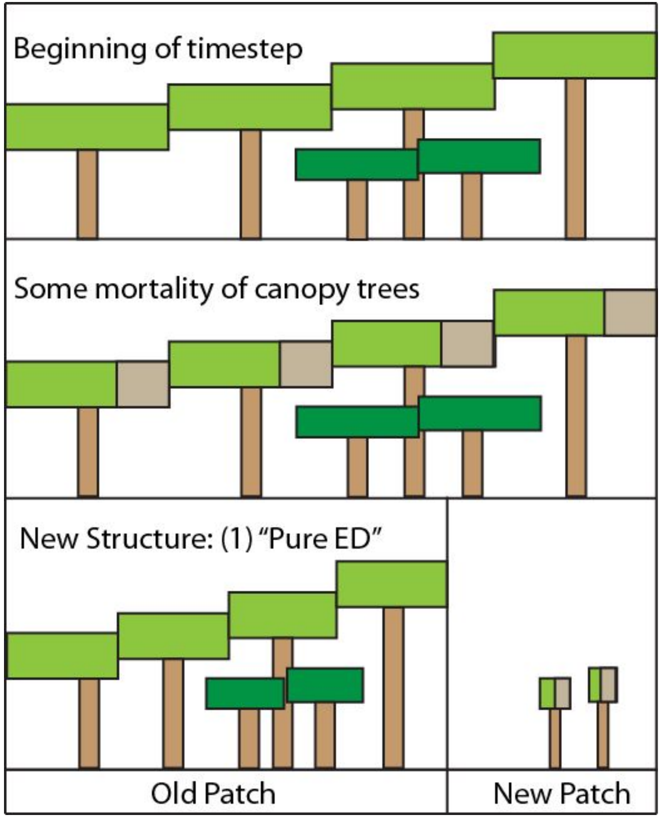
FATES Patch Dynamics

3 key questions during disturbance:

- How much new patch area is generated?
- How much mortality of understory trees occurs?
- Which patch do surviving understory trees end up on?

Multiple possibilities, along a “PPA” to “ED” continuum:

- First, “ED” endmember: all crown area of deceased trees goes to new patch area.



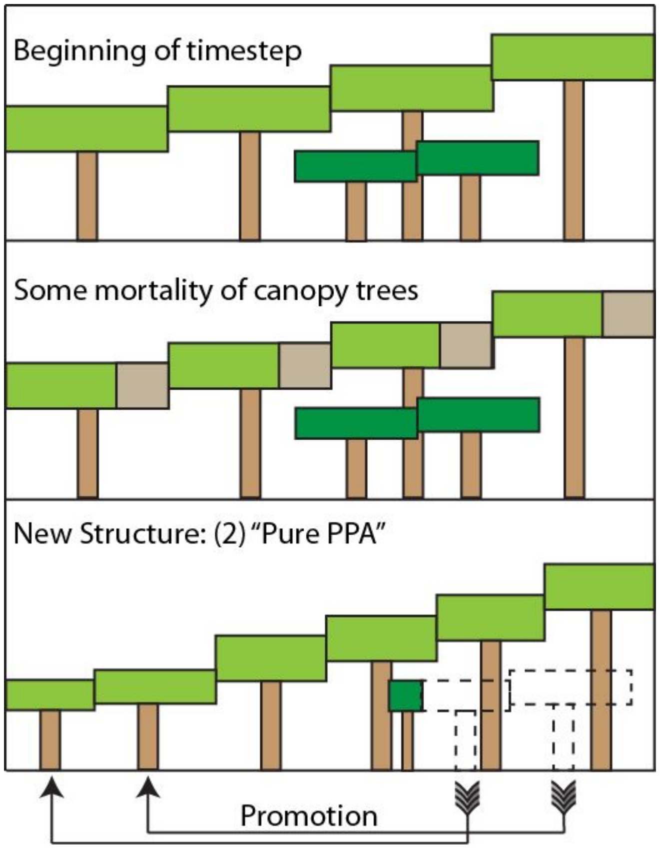
FATES Patch Dynamics

3 key questions during disturbance:

- How much new patch area is generated?
- How much mortality of understory trees occurs?
- Which patch do surviving understory trees end up on?

Multiple possibilities, along a "PPA" to "ED" continuum:

- Second, "PPA" endmember: no disturbance at all!



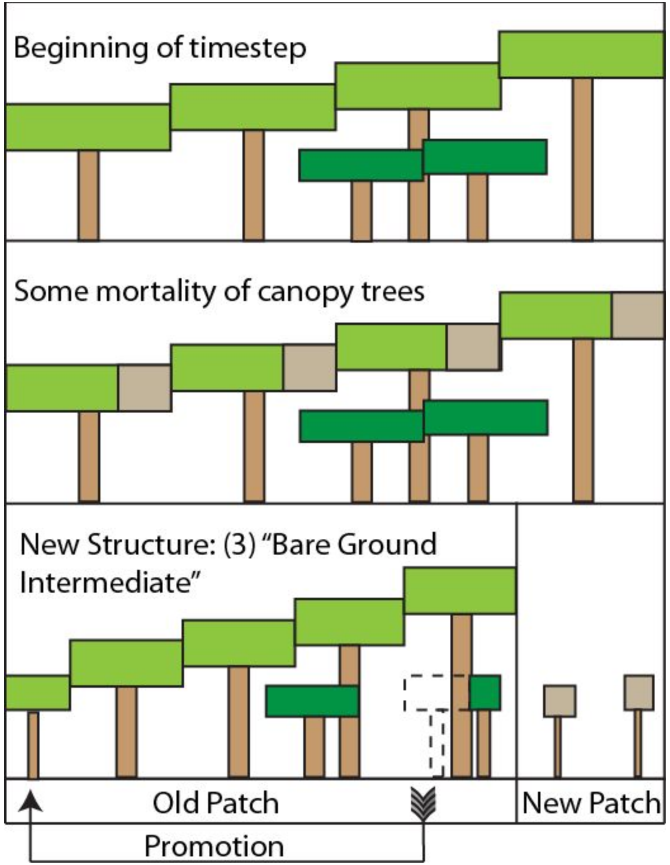
FATES Patch Dynamics

3 key questions during disturbance:

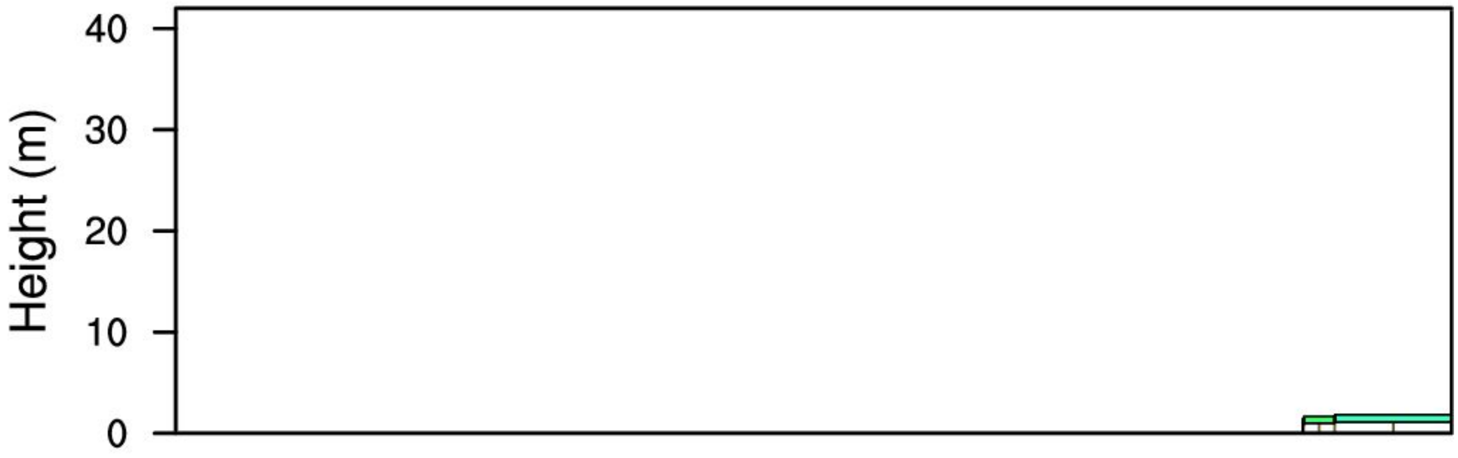
- How much new patch area is generated?
- How much mortality of understory trees occurs?
- Which patch do surviving understory trees end up on?

Multiple possibilities, along a “PPA” to “ED” continuum:

- Third, intermediate case: Some fraction of crown area of deceased trees goes to new patches.



Allows for emergence of complex ecosystem structures that allow for feedbacks between physiology and community ecology



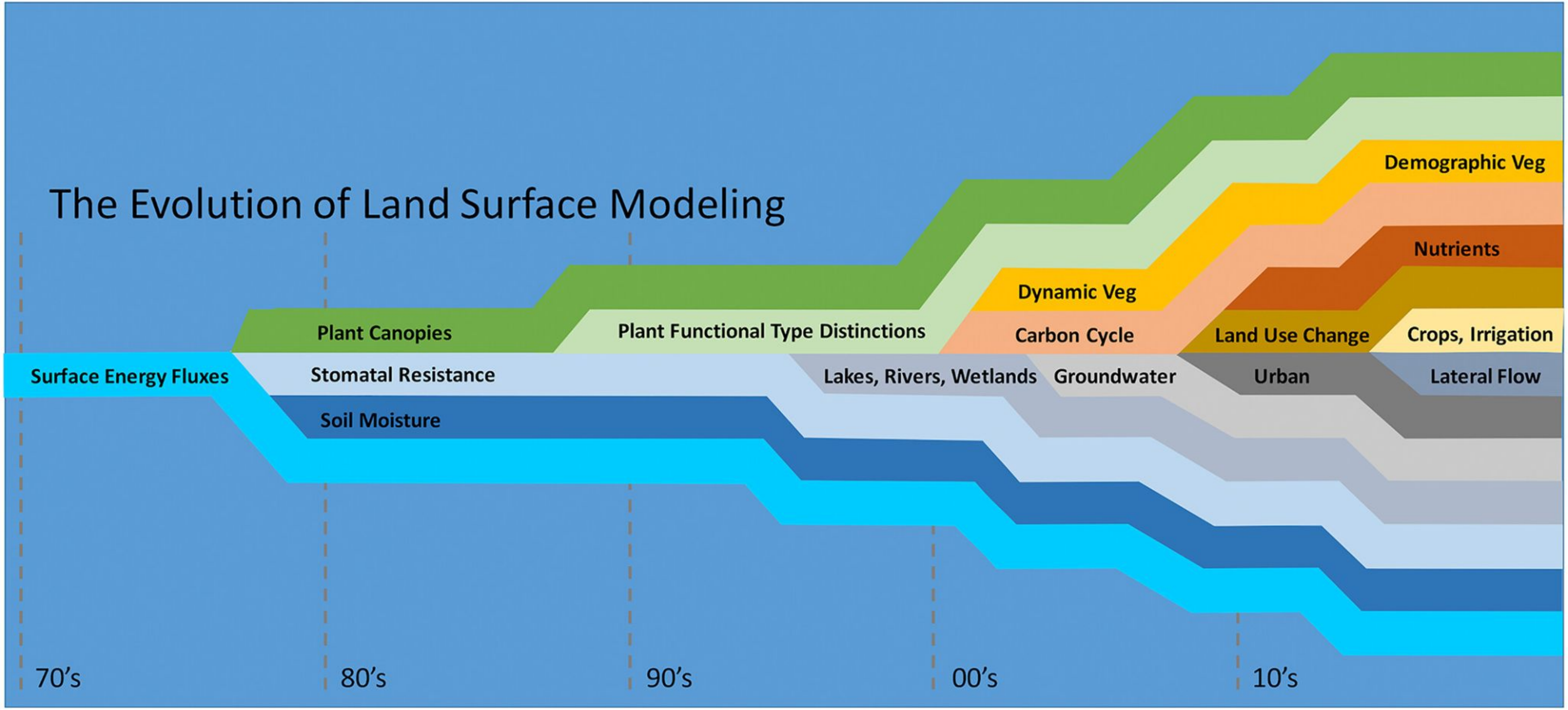
Koven et al. 2020

Short Tree Cohorts
Recently-disturbed Patches

Early Successional PFT
Late Successional PFT

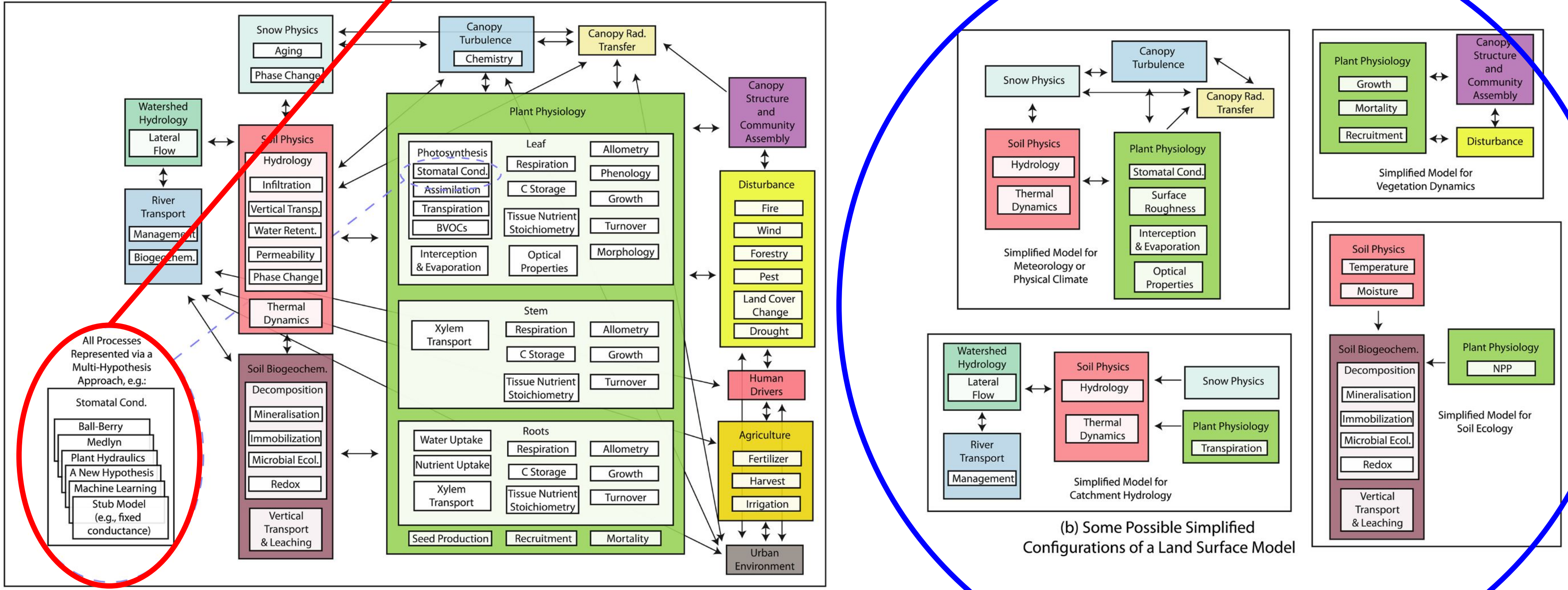
Tall Tree Cohorts
Old Patches

FATES approach for handling complexity

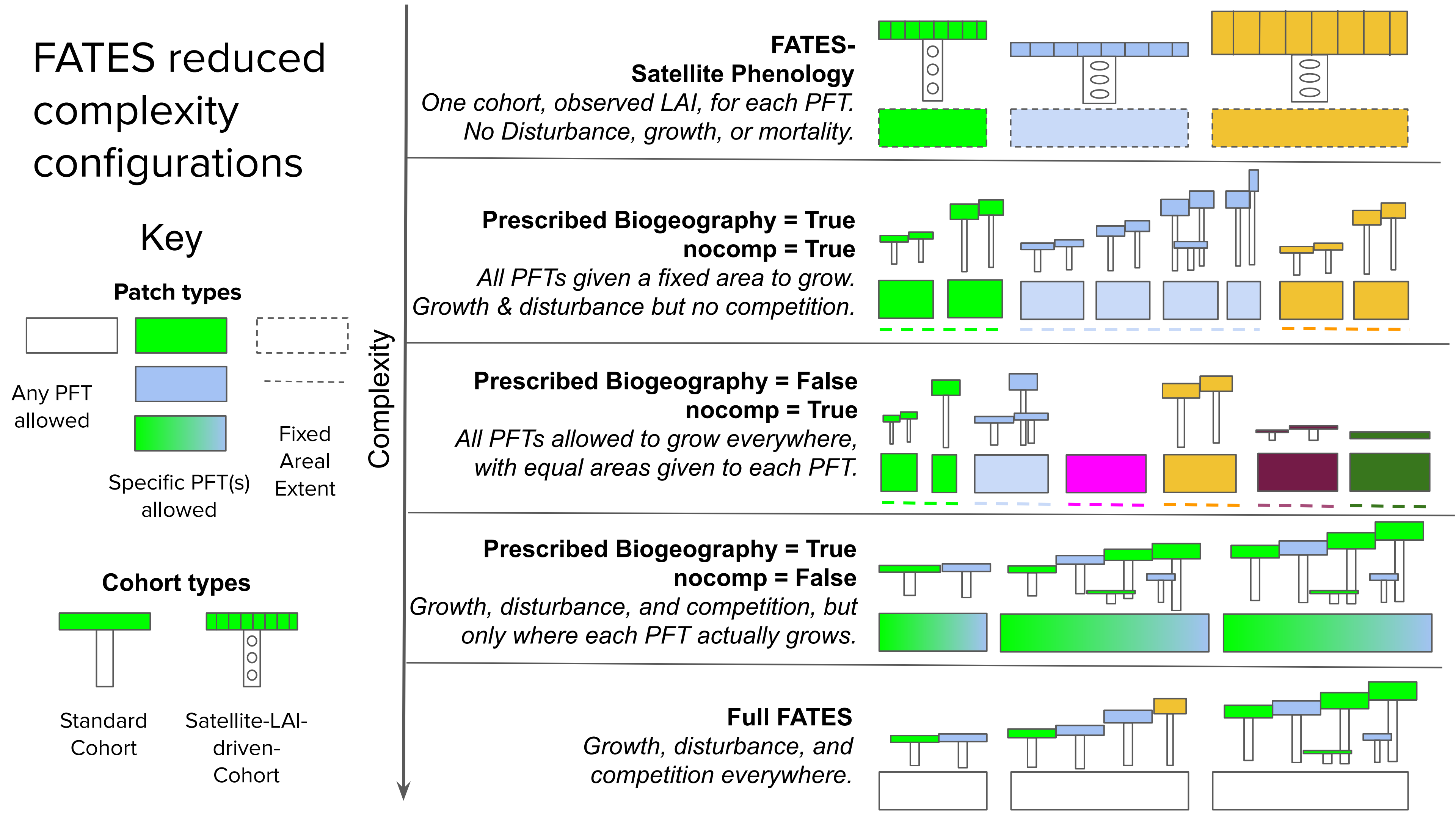


Fisher and Koven, 2020

Process-level modularity vs configurability (We have focused on both with FATES)

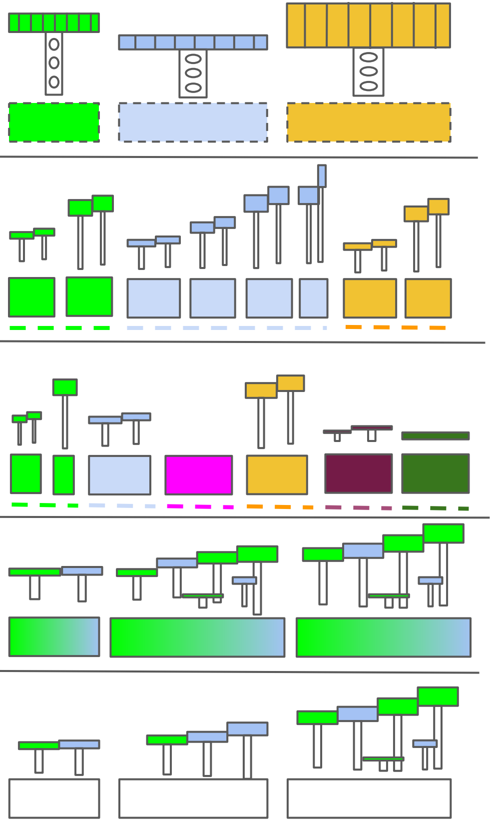


Fisher and Koven, 2020



FATES reduced complexity configurations
Key
Patch types
Any PFT allowed
Specific PFT(s) allowed
Fixed Areal Extent
Cohort types
Standard Cohort
Satellite-LAI-driven-Cohort
Complexity
FATES-Satellite Phenology
One cohort, observed LAI, for each PFT.
No Disturbance, growth, or mortality.
Prescribed Biogeography = True
nocomp = True
All PFTs given a fixed area to grow.
Growth & disturbance but no competition.
Prescribed Biogeography = False
nocomp = True
All PFTs allowed to grow everywhere,
with equal areas given to each PFT.
Prescribed Biogeography = True
nocomp = False
Growth, disturbance, and competition, but
only where each PFT actually grows.
Full FATES
Growth, disturbance, and
competition everywhere.

“Complexity cascade” approach to model calibration



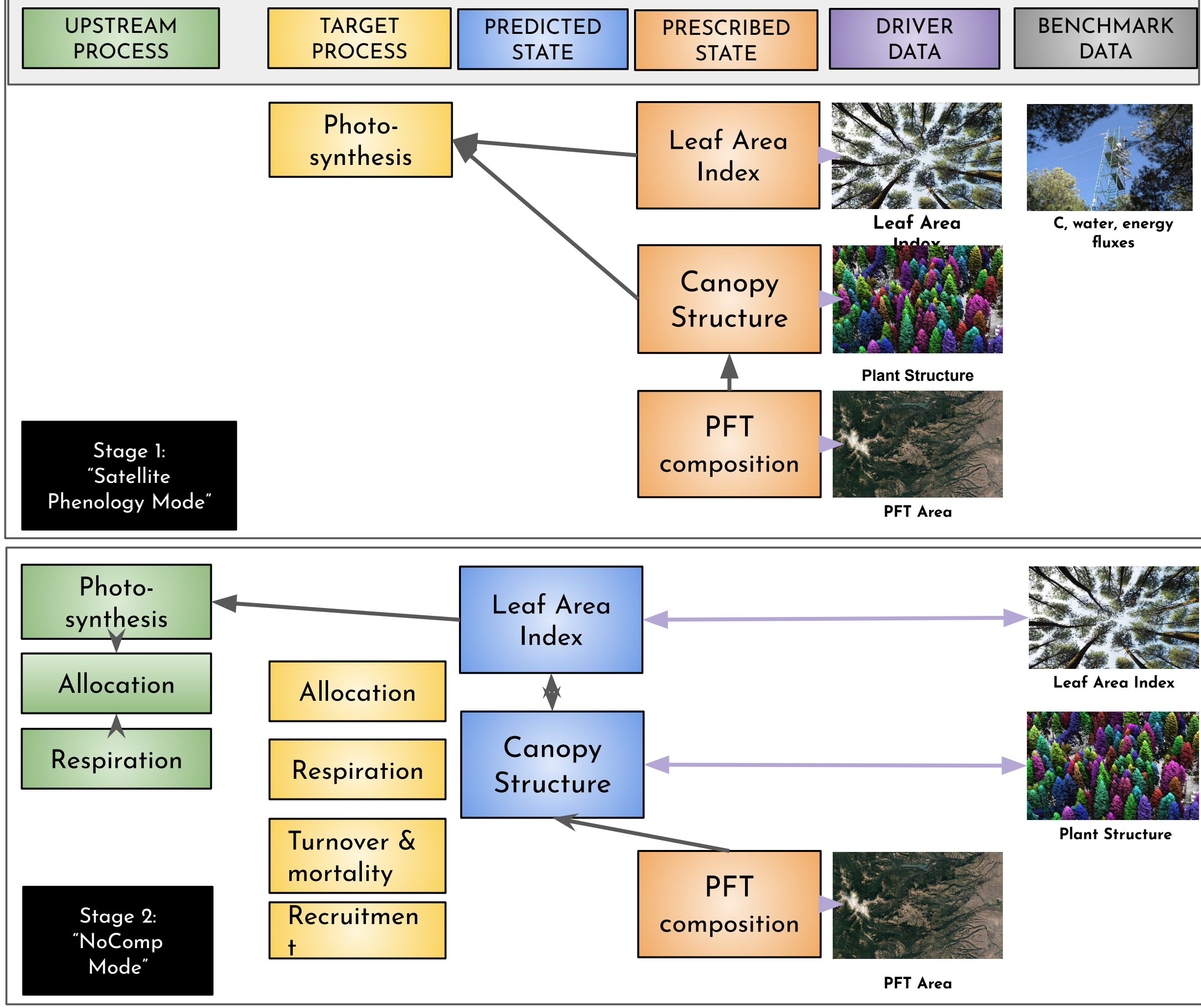
FATES configuration	Role of FATES configuration in calibration cascade	What variables to calibrate?
FATES-Satellite Phenology *One cohort, observed LAI, for each PFT. No Disturbance, growth, or mortality.*	Biophysics and land-atmosphere exchange. Fast spinup, few feedbacks.	Leaf traits, soil parameters, hydraulic conductivities
Prescribed Biogeography = True **nocomp = True** *All PFTs given a fixed area to grow. Growth and disturbance but no competition.*	Carbon cycling and demography in absence of competition between PFTs for light	Allometry, allocation, phenology, growth, respiration, mortality parameters
Prescribed Biogeography = False **nocomp = True** *All PFTs allowed to grow everywhere, with equal areas given to each PFT.*	What is the fundamental vs the realized niche of a PFT?	Environmentally-sensitive growth and mortality parameters
Prescribed Biogeography = True **nocomp = False** *Growth, disturbance, and competition, but only where each PFT actually grows.*	Competition of plants, with some controls over what PFTs can compete	Environmentally-sensitive growth and mortality parameters
Full FATES *Growth, disturbance, and competition everywhere.*	Full dynamics of model	Test of final outcome: does the model capture observed patterns?

FATES "calibration cascade" logic.

- Start with LAI, biomass, PFT area as boundary conditions.

- At each stage, make more of these prognostic

- Each stage calibrates a different set of target processes against a new set of observations



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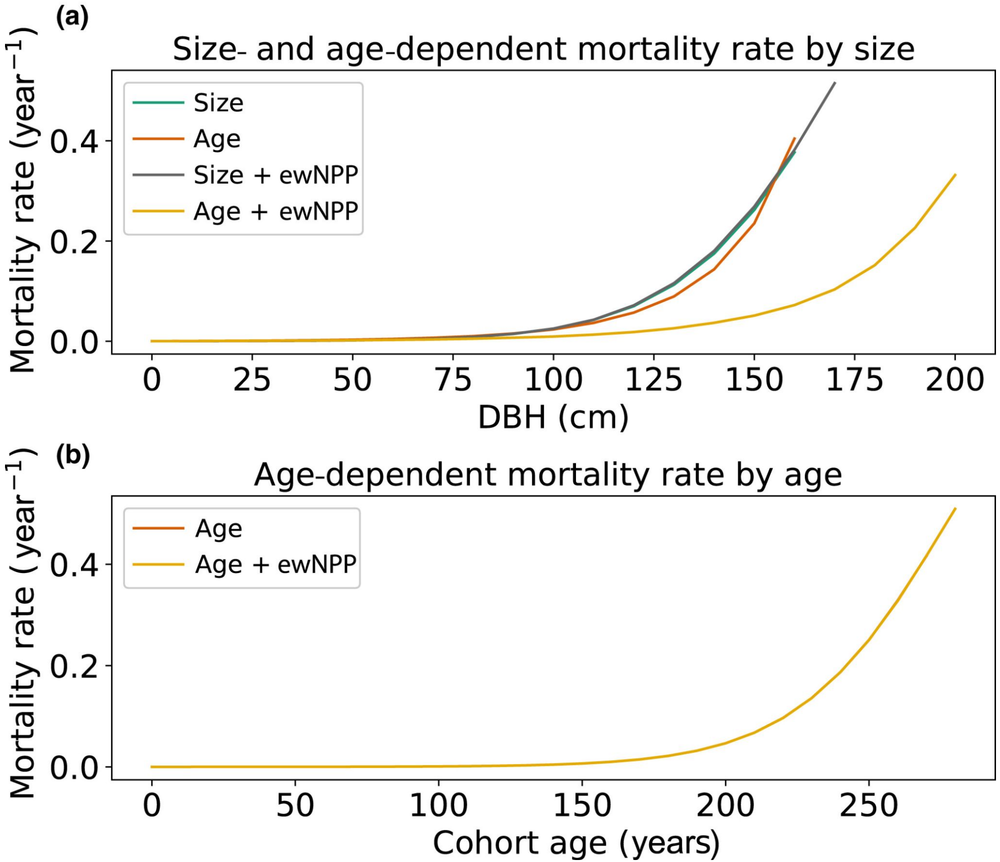
Slide via Rosie Fisher, CICERO

A few examples of the kind of science that FATES enables: 1

Large, old trees are observed to have higher mortality rates.

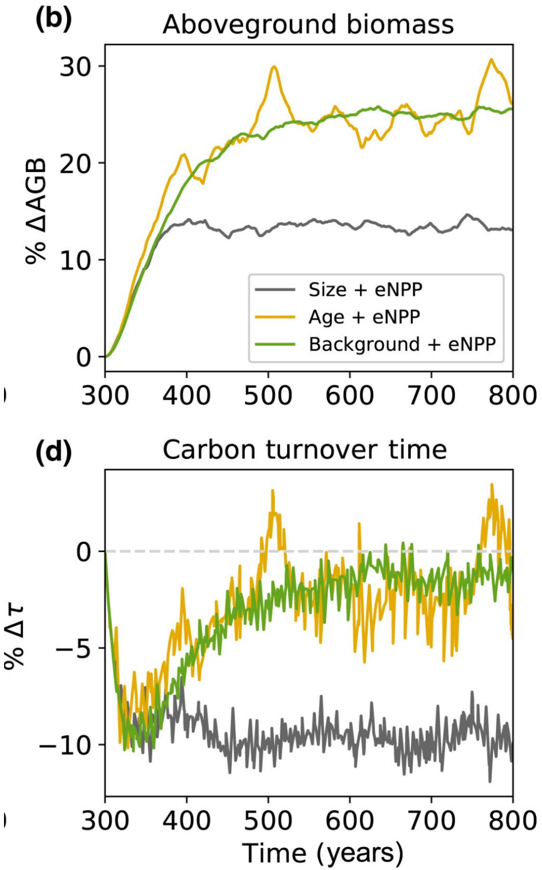
Unclear if this is because of their size, or age.

Under elevated CO2, we expect trees to grow faster – does that mean they will die faster as well?



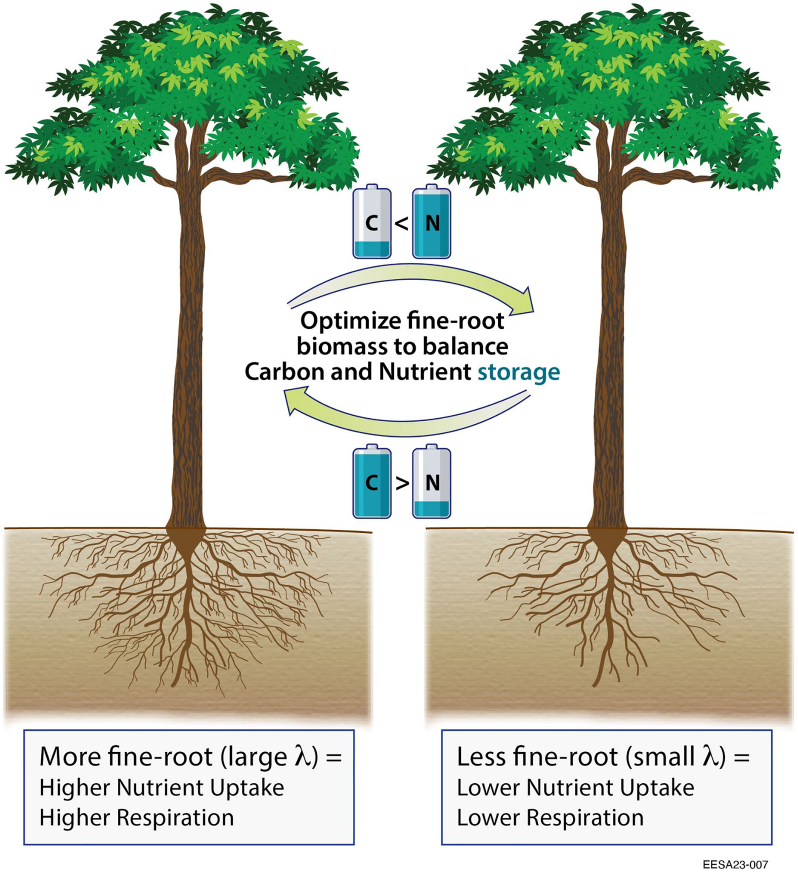
Needham et al., 2020

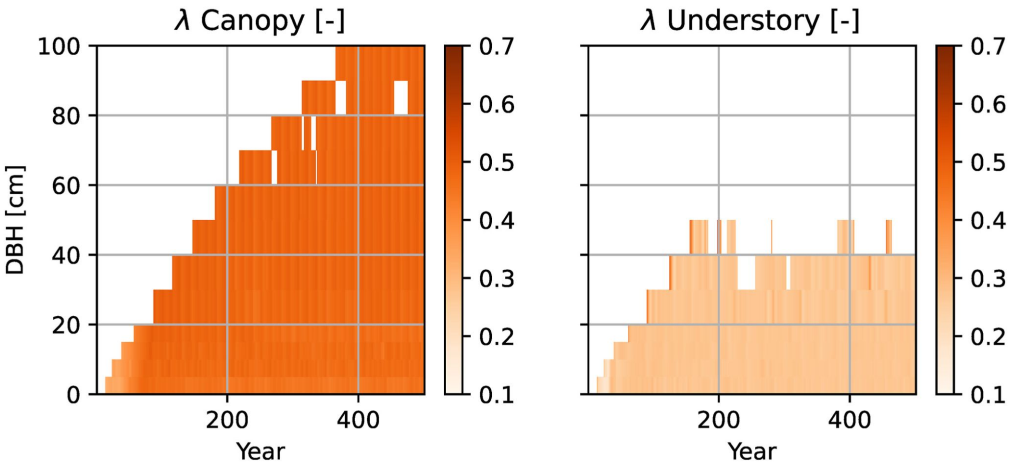
Depending on whether we assume that the observed elevated mortality rates are linked to size versus age, FATES projects a halving of the biomass response to elevated CO_2 due to this demographic feedbacks



Needham et al., 2020

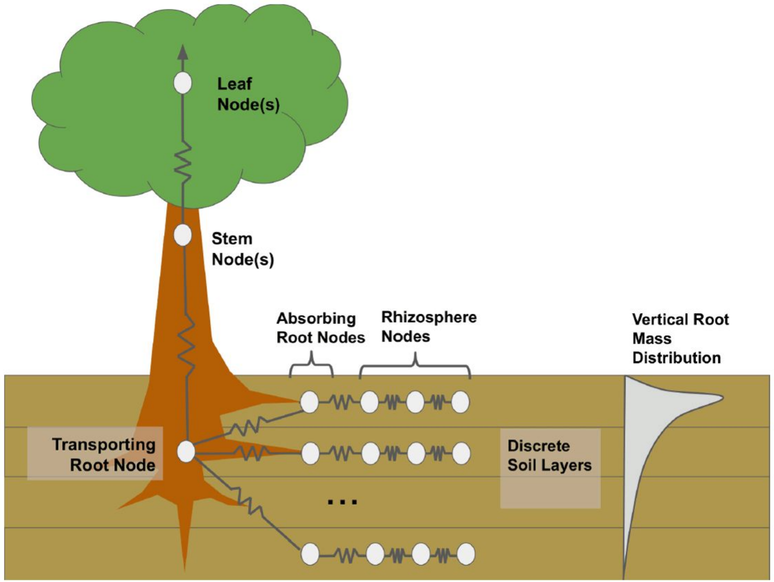
Example 2: nutrient cycling and niche differentiation



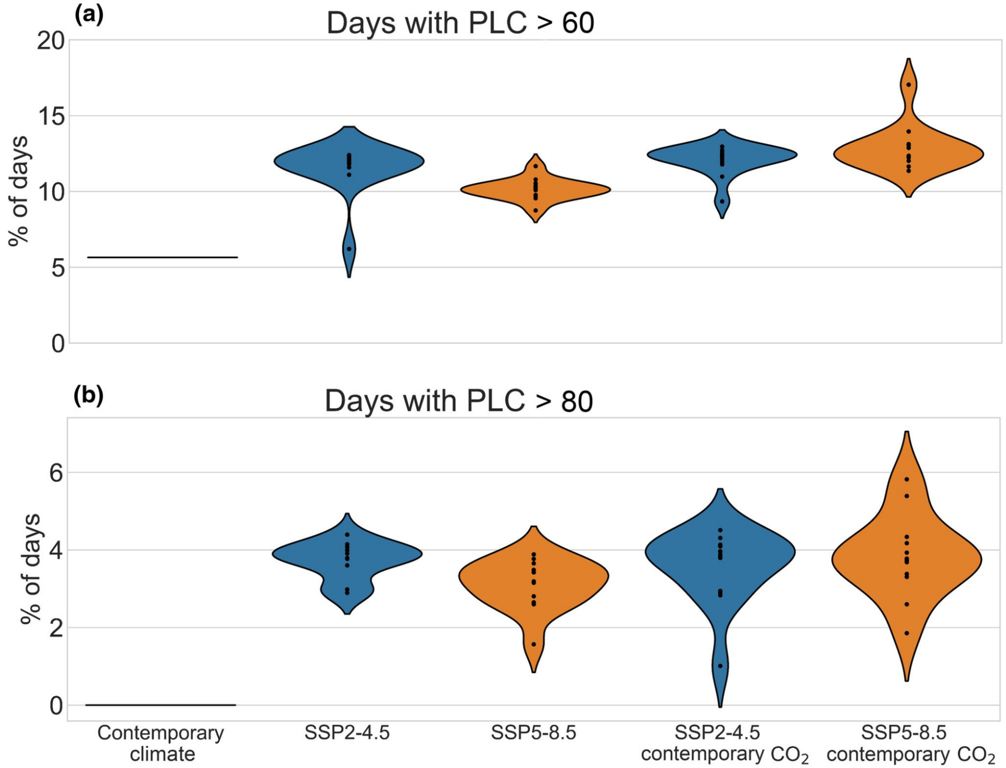


Knox et al., 2023

Example 3: plant hydraulic trait diversity



Xu et al., 2023



Robbins et al., 2024

Thanks!