Agenda

Morning Lectures (The Main Seminar Room)
8:30: Introductions.
8:45: Theory of FATES introduction lectures
   - Introduction to Ecosystem Demography
   - FATES in Earth System Models.
   - Information flow in FATES
   - Fast timescale processes
   - Carbon Allocation
   - Demographic processes
     - Recruitment, mortality, fire
9:45 - 10:15: Coffee break
   - Patch and Cohort Dynamics
   - Different modes for running FATES
   - Plant Functional Types
   - Example PFT experiments
   - FATES-HYDRO
   - Future Plans (nutrients, land use, etc.)
12:00: Lunch (NCAR cafeteria, on your own)

Afternoon Practical Sessions
(Main Seminar Room for lecture)
1:15: Running FATES presentation
(Library for practical)
2:00: Running FATES practical session
3:00: Tea break (Chapman room)
4:45: General Discussion/Q&A session
5:15: Bus pickup

Slides here:
https://docs.google.com/presentation/d/1kztSEnCOOw54XpjDCebcOLWciC8kqJegkMJGnuQKisI/edit?ts=5c48ed2a#slide=id.g309b6d9659_0_47
Two Useful Resources:

FATES Github PAGE:  
https://github.com/NGEET/fates

FATES is a cohort-based vegetation demographics model.

What does that mean?
Basic Ecological Succession

- Recruitment
- Growth
- Competition
- Co-existence
- Exclusion
- Mortality
'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?

www.formind.org
Area-based Models

(e.g. 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
‘Cohort-based’ Models as intermediate solutions

Big Leaf Model

Cohort model

Stochastic Individual Model
Ecosystem Demography Model (ED)
Moorcroft, Hurtt and Pacala. 2001

- ‘Cohorts’ of trees, grouped according to:
  - Plant type
  - Height
  - Successional stage
Vegetation structure: CLM/ELM vs ED models

Plant Functional Type tiling

- NL tree
- BL tree
- Bare Ground
- C4 grass
- C3 grass

Time-Since-Disturbance tiling

- 60 years
- 90 years
- 30 years
- 15 years
- 1 year
- 5 years
Vegetation structure in ED models

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

<table>
<thead>
<tr>
<th>Time-Since-Disturbance tiling</th>
<th>Time-Since-Disturbance tiling</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 years</td>
<td>30 years</td>
</tr>
<tr>
<td>90 years</td>
<td>15 years</td>
</tr>
<tr>
<td>1 year</td>
<td>5 years</td>
</tr>
</tbody>
</table>

- Cohort. PFT1. 10m
- Cohort. PFT1. 2m
- Cohort. PFT2. 4m
**Benefits of Ecosystem Demography**

- **CLM5**
- **CLM(FATES)**

- "Big-Leaf" vegetation
- Demographic Vegetation

- Heterogeneity in light availability
- Competition (for light), exclusion & coexistence
- Mechanistic Ecosystem Assembly
- Recovery after Disturbance (fire, land use, mortality)
- Arbitrary PFT definition
- PFT distribution emerges from trait filtering
Instances where big-leaf models hinder realistic process representation

- **Hydrodynamics**
  - Need a representation of path length, rooting depth, with plant size
  - Need representations of canopy position to determine atmospheric demand

- **Nutrients**
  - N fixation only makes energetic sense early in succession
  - Allometric growth is necessary to provide sensible nutrient budgets

- **Fire**
  - Fire has lasting impacts on canopy structure, which in turn affect fire behavior
  - Tree-grass coexistence in fire regions is either along successional or vertical gradients, not captured by big leaf approach.

- **Snow**
  - Snow covers short vegetation early in succession but not older taller vegetation
Instances where big-leaf models hinder realistic process representation

- **Pests**
  - Bark beetles preferentially attack larger trees

- **Harvest**
  - Selective logging only takes out large trees of particular functional classes.
  - Recovery alters biophysical properties

- **Canopy turbulence**
  - Simulation of internal canopy air space requires estimate of which leaves are where in canopy

- **VOCs**
  - Most major models critically dependant upon leaf age

- What about my favourite process? Is it affected (discussion..)
Where does FATES live within the ecosystem of earth system models?
FATES is a module and so must be associated with a “Host Land Model” (HLM)
Host Land Model

- hydrology
- energy balancing
- soil carbon
- soil biogeochemistry
- everything else

FATES

- canopy radiation (hourly)
- water stress (btran) (hourly)
- photosynthesis / respiration (hourly)
- growth/allocation (daily)
- mortality, recruitment (daily)

Processes:
- soil water state
- atm radiation
- air state (co2, p, h20)
- mean temp, water memory
- leaf sun fraction
- root water uptake profile
- canopy resistance
- litter fluxes, area indices
- albedo
How is information organized in FATES
CLM and ELM: Normal Subgrid Hierarchy
The Structure of FATES: Linked Lists
List of example state variables at each level

Cohort variables
PFT, ‘N’, DBH, height, biomass: leaves, roots(c+f), stem(live+dead), storage, canopy layer.

Patch variables
Area, age, CWD(size class (x4), leaf+froot litter, LAI profile, canopy height.

Site variables
Lat, long, seed bank(pft), phenology status & counters, all HLM column properties
FATES and HLM: Connecting the Hierarchies
Fast timescale process in FATES

1. Radiation Transfer
2. Photosynthesis and Respiration
3. Stomatal Conductance
4. Boundary layer physics
An overview of processes in FATES

CLM or ACME Land Model
- Energy balance
- Soil Water
- Land Use Drivers
- Decomposition

FATES Fast Timestep Processes
- Canopy Rad. Transfer
- Photosynthesis
- Plant Respiration
- NPP

FATES Slow Timestep Processes
- Canopy Structure
- Leaf & Root Growth
- Allocation to Growth & Repr.
- Leaf & Root Turnover
- Carbon Storage
- Recruitment
- Seed Production
- Stem Growth
- Crown & Tissue Allometry
- PPA Promotion & Demotion
- Cohort Splitting & Fusion
- Patch Gen. & Fusion
- Disturbance
- Mortality

Cohort scale
Patch scale

Fire
Litter
Perfect plasticity approximation

Canopy organization in fates
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

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

Purves et al. 2007
Canopy construction and vertical light environment: The “PPA” simplifies the light environment into two regimes: **canopy** and **understory**.
Radiation Transfer in FATES (Norman, 1979)

Reflectance, absorption and transmittance calculated for multiple leaf layers for each PFT.

Spatially average the direct and diffuse radiation transmitted onto the understory layer.

Light transmitted onto soil/snow reflected back up through canopy (iterative solution)
Photosynthesis

Photosynthesis, stomatal conductance etc. is mostly derived from ~CLM4.5

This, and much of the rest of this lecture, is documented the FATES technical documentation:

The photosynthesis part is at:
https://fates-docs.readthedocs.io/en/latest/fates_tech_note.html#photosynthesis
Each PFT has a user defined parameters “vcmax_25_top” and “longevity”, which have an age dimension now.

Leaf carbon ($C_{leaf}$) flows from newer to older bins ($a$) based on longevity:

$$\text{Flux } C_{leaf}(a \rightarrow a+1) = C_{leaf}(a) \times \Delta T / \text{longevity}(a)$$
How FATES passes info from Fast to slow timesteps

c = cohort, h = half-hourly, d = daily

“PARTEH” module handle daily allocation (see later slides)
‘PARTEH’
Plant Allocation and Reactive Transport Extensible Hypotheses
Knox et al. (in prep)

FATES’ new *allocation* scheme, and basis for planned nutrient cycling implementation

1) extensible and modular software, using robust numerical methods
   2) changes in states are cast as fluxes
   3) allows an arbitrary number of elements or pools
   4) Modular options for alternative hypotheses
Modular structure:
PARTEH has a clean interface with the rest of the FATES code.

- Does not use FATES globals
- Clearly defined initialization of states and fluxes
- Clearly defined boundary conditions with FATES
Photosynthesis
Cohort structures
Everything ...

PARTEH

Wrapper
Fortran
Code

Python
Functional Unit
Testing Scripts
(SINGLE TREE SIMULATOR)

Diagnostics/Plots/etc
Example of Single Tree Simulator:
20 year “smoke test”: 3 different parameterizations, 1 carbon only case with seasonal oscillation, 1 C+N+P case with seasonal oscillation and 1 C+N+P case without oscillation.
Default allocation/ hypothesis #1: Carbon Allocation along allometric trajectories
Allocation

Daily Carbon Gain (all respiration already paid)

C1 = NPP

Prognostic Pools (Carbon Only)

- Fine-root
- Sapwood
- Seed
- Leaf
- Storage
- Dead
Step 1: Remove turnover from live pools

Assumption: “stature” (dbh) of plant stays same, and so do the target pool sizes
Step 2: Replenish Pools towards allometry

*Each organ is given a priority level.

Replenish pools in priority order based on availability and relative distance to target

*Same principal for C & N & P
Step 3: Stature Growth

Grow all pools concurrently.

Integrate along the derivative of the allometric curves for each carbon pool.

The amount of concurrent growth is limited by whichever C or N or P would generate the least amount of equivalent C growth.
Stature Growth Follows Allometry

Take home points:

- Allometry governs proportionality
- Allometry equations are either trivial or dependent on diameter
- Allometry of tissue pools describe the ideal or maximum carrying capacity for the stature
- Code allows for new functional forms to be added
Stature Growth Follows Allometry

Height - Diameter Allometry
Stature Growth Follows Allometry

AGB - Diameter Allometry
Phenology (Abridged Edition)
Phenology - very similar to phenology in CLM

- Timing of cold deciduous leaf-on and leaf-off is governed by integrating growing degree days, and counting cold days (respectively) (Botta et al.)
- Timing of stress deciduous leaf-on and leaf-off is governed by mean soil moisture and thresholds
- On/Off status is a site (column) scale variable, not a plant scale variable (but it should be...?)
- A plant must be one of evergreen, stress deciduous or cold deciduous
- Leaf-on and leaf-off status has minimum window requirements to prevent flickering
- Triggering “leaf-on” will flush a fraction of the plants carrying capacity
- Triggering “leaf-off” will drop all leaves instantaneously
Patch-scale

Demographic processes

Recruitment, Mortality, Fire
1. Reproduction & Recruitment

- Seed flux is in mass units as a fraction of NPP

- Seeds from all patches mixed at site level => perfectly efficient dispersal within sites

- Population of recruits is function of carbon flux out of seed pool and recruit size
Plant Mortality

1. Background mortality
2. Carbon starvation mortality
3. 'Hydraulic failure' mortality
4. Cold-stress mortality
Plant Mortality

1. Background mortality
\[ \text{bmort} = \text{bmort}(\text{pft}) \]

1. Carbon starvation mortality
\[ \text{frac} = \frac{\text{bstore}}{\text{b\_leaf}} \]
\[ \text{cmort} = \text{ED\_val\_stress\_mort} \times (1.0 - \text{frac}) \]

1. 'Hydraulic failure' mortality
\[ \text{if (btran\_ft(\text{pft}) < hf\_sm\_threshold) then} \]
\[ \text{hmort} = \text{mort\_scalar\_hydrfailure} \]
\[ \text{If hydro is on:} \]
\[ \text{hmort} = \frac{\text{flc-hf\_flc\_threshold}}{(1.0 - \text{hf\_flc\_threshold})} \times \text{mort\_scalar\_hydrfailure} \]

1. Cold-stress mortality
\[ \text{temp\_dep} = \max(0.0, \min(1.0, (1.0 - (\text{temp}\_\text{freezetol(\text{pft})}/\text{frost\_mort\_buffer}))) \]
\[ \text{frmort} = \text{frost\_mort\_scalar} \times \text{temp\_dep} \]
n.b. In principle ‘background’ is all the as-yet unexplained mortality

As well add more mechanisms of mortality, ‘background’ should decline

e.g. windthrow insects/fungi phloem failure heat stress
FIRE
FATES fuel moisture changes with climate

LITTER and FIRE

FATES tracks six fuel classes

These gradually ‘fragment’ into soil organic matter pools, and are passed into the host land model decomposition routines.

Trunks
Large branches
Small branches
Twigs
Leaves
Live grass

Cellulose
Lignin
Labile
FATES-HLM Transfer of Litter

Flammable CWD and litter held on FATES patches

Mechanically breaks down to decomposable litter and passed to HLM for decomposition routines

Vertical profiles of belowground litter outputs defined by root profiles
VEGETATION and FIRE

Mortality for trees depends on:
Flame height (relative to canopy height)
Bark thickness (varies by age and PFT)
Fire intensity and residence time

Grasses are not protected, and burn with fire

FATES retains the fire-affected canopy structure, e.g. altering future fire behavior
Challenge in Forest/Savanna areas:
- Climate
- Seasonality (# dry months)
- Vegetation state/ Species Traits

Impact of initial conditions

Burned fraction (% year\(^{-1}\))
FATES patch and cohort dynamics
The life of a cohort
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
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
The life of a patch

1. Patches made from disturbance
2. Fused to similar patches
3. Reduced by subsequent disturbances
4. Terminated when too small/old
5. Age
Patch Generation and Fusion

Disturbance occurs when canopy trees die.

Disturbance generates new zero-aged patches.

Patches fuse when they become sufficiently similar.
Sensitivity to Patch heterogeneity

Accommodate all disturbance by rearranging within patch

Create smaller amount of unoccupied patch area

Resolve disturbance by creating new (occupied) patch area

"Pure PPA Disturbance"

"Mixed ED-PPA Disturbance"

"Pure ED Disturbance"
Different ‘modes’ for running fates
Simplified FATES Versions: Separate Along Timescale

CLM or ACME Land Model

Energy balance

Soil Water

Land Use Drivers

Decomposition

FATES Fast Timestep Processes

Canopy Rad. Transfer

Photosynthesis

Hydraulics

Plant Respiration

NPP

FATES Slow Timestep Processes

Canopy Structure

Leaf & Root Growth

Allocation to Growth & Repr.

Leaf & Root Turnover

Carbon Storage

PPA Promotion & Demotion

Crown & Tissue Allometry

Stem Growth

Recruitment

Seed Production

Cohort Splitting & Fusion

Patch Gen. & Fusion

Disturbance

Mortality

Fire

Litter
### Simplified FATES Versions: Separate Along Timescale

<table>
<thead>
<tr>
<th>CLM or ACME Land Model</th>
<th>FATES Fast Timestep</th>
<th>FATES Slow Timestep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy balance</td>
<td></td>
<td></td>
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<tr>
<td>Soil Water</td>
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<tr>
<td>Decomposition</td>
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</tr>
</tbody>
</table>

- Fire
- Litter
Simplified FATES Modes: ST3 and PPM

Static Stand Structure (ST3):
Holds the slow processes constant and calculates only biophysics (can be initialized from inventory data).

Prescribed Physiology Mode (PPM):
Overwrites NPP, mortality, and (optionally) recruitment with specified rates (set in FATES parameter file).
Why would one want to use **ST3** Mode?

- Breaks feedback loop between ecosystem structure and function.
- Allows cleaner experimental design to look at changes to a given parameter or structure directly rather than the effects of those changes as propagated through ecosystem structure.
- If initialized from inventory, allows understanding of physiological rates conditional on the observed forest structure.
- Analogous to CLM’s SP mode, except that, for now at least, there is no phenology. (Which should change.)
Why would one want to use PPM?

- Allows a direct assessment of how vital rates—which have much lower dimensionality than physiological traits—govern ecosystem structure.
- Allows testing of model structure and parameters that govern slow vegetation dynamical processes given a known set of vital rates.
- Possible to sample different / larger physiological rate parameter spaces than might be possible using full model.
- Separation of forced from internal modes of variability (which, in ecology language, means an ability to isolate things like a storage effect on coexistence)
- Ability to test generality of behavior by applying it in reduced-complexity model.
FATES History File Structures
How FATES Passes Info to History Files:

Site = column

Patches and their ages:
- 1y
- 7y
- 20y
- 50y

Cohorts and their diameters:
- 0.1cm
- 1cm
- 2cm
- 10cm
- 1cm
- 5cm
- 10cm
- 1cm
- 10cm
- 30cm
- 1cm
- 20cm
- 50cm
- 100cm

History Variable on Size Axis (cm):

1 2 4 8 16 32 64 128
Example of Patch Age Dynamics in a Tropical Forest Simulation
Cohort Dynamics
Cohort Dynamics
(Canopy Trees Only)
Cohort Dynamics (Under-Canopy Trees Only)
More Complex, Multi-Dimensional Output:

- Multiple dimensions available for output:
  - Cohort Size,
  - Patch Age,
  - Cohort Canopy Position,
  - Leaf Layer,
  - Cohort PFT, &
  - time since start of run.
- E.g: number of plants as binned along axes of size and age:
Plant Functional types
Plant Functional Types in CLM/ALM

Typically, land surface model PFTs are defined by:

- Phenology (evergreen, cold dec, stress dec)
- Growth Form (tree, shrub, grass)
- Leaf Habit (broadleaf, needleleaf)
- Photosynthesis (C3, C4)

These are unambiguous traits, mostly identifiable from space.

But they don’t tell us much about ecosystem function or responses to change.
A note on climate envelopes

Paradigm: Vegetation climate limits are a function of simple climate variables, defined from current vegetation distributions

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

<table>
<thead>
<tr>
<th>Plant Functional Type</th>
<th>Temp coldest month (°C)</th>
<th>Temp hottest month (°C)</th>
<th>Growing Degree Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical broad-leaved evergreen</td>
<td>15.5</td>
<td>-</td>
<td>-</td>
</tr>
<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>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>Tropical herbaceous (TrH)</td>
<td>15.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Sitch et al. 2003

Used in:
- ORCHIDEE (IPSL)
- CTEM (CanESM)
- SEIB (MIROC-ESM)
- CLM-DV (CESM)
The idea of FATES is that PFT definitions are flexible.

Fundamentally, a plant functional type is a vector of plant traits.

In FATES, this vector can be configured however you want.

n.b. the EDv1 and EDv2 PFTS (early, mid-late successional tropical trees) are not the default in FATES.

As yet, none of these traits are climate envelopes... (tbc)
PFTs in FATES - Special Case (vcmx and leaf lifespan)

VCMAX and leaf lifespan are dimensioned by PFT and "age bin".

User can specify any number of each 1 age bin is allowed.
FATES parameters in CLM/ALM

FATES has 187 parameters, but you have options.

- Hydro (18), Fire (23), Nitrogen/Phos (6), Special Modes (14), Obvious/Developer (23), Special Modes (i.e. logging, prescribed physiology, etc.) (14)
- Allometry (leaf, height, aboveground biomass, sapwood, root) (27)

Now you only have 66 other parameters to calibrate

For regional/site calibration start here:

- Allometric relationships (DBH to H, DBH to biomass, DBH to crown area)
- Wood Density
- Vcmax
- Specific Leaf Area
- Leaf C:N ratio
- Leaf Longevity
Example plant functional types experiments in fates
Example single trait competition experiments in FATES
Growing, rather than storing, is a good idea wherever there is closed canopy forest.
LeafCN & Vc,max

High photosynthesis. High respiration

Low photosynthesis. Low respiration

High leaf N is beneficial in high resource environments. In dry environments it is sub-optimal
Climate envelopes

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

- Most trait filtering is related to light competition intensity.

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

Fraction of PFT#1
What happens if we put the CLM parameters into FATES?
Global PFT distribution status (Jennifer Holm)

- Global simulations of FATES
- One approach to FATES globalization (other simpler representations are possible and planned)
- Coupled to E3SM Land Model (ELM)

- 13 PFTs:
  - Default FATES specific parameters
  - Non-FATES parameters based on CLM4.5 values

- Goal with global simulations:
  - Latitudinal gradient of plant distribution based on emergent dynamic vegetation processes
  - With FATES, no climate envelopes boundaries (i.e. no pre-defined climate tolerances for recruitment and survival).
  - BUT some climate tolerances are real (i.e. freezing tolerances)
4x5 degree resolution simulations

FATES has reasonable biomass, etc.
MODIS PFT distribution

The graph shows the distribution of various vegetation types across different latitudes. The x-axis represents latitude, ranging from -80 to 80 degrees, and the y-axis represents the average grid cell abundance (%) of each vegetation type.

Key to colors and types:
- Blue = Boreal
- Orange = Temperate
- Green = Tropical
- Purple = Shrub

Vegetation types include:
- NL Evergreen Boreal
- NL Decid. Boreal
- Broad. Decid. Boreal
- NL Evergreen Temp.
- Broad. Evergreen Temp.
- Broad. Evergreen Trop.
- Broad. Ever. Temp. Shrub
- Broad. Decid. Temp. Shrub
- Broad. Decid. Boreal Shrub
Lots to be done.

Are CLM PFT definitions what we are targeting in FATES?

Do we need to expand to greater physiological functionality?
Fates-Hydro
Plant hydrodynamics

BRAD CHRISTOFFERSEN, CHONGGANG XU, NATE MCDOWELL &
THE NGEE-TROPICS MODELING TEAM
FATES-HYDRO

Plant hydraulic status represented for each cohort

Soil moisture resources pooled across column

Soil discretized into ‘shells’ to represent drying at root surface
FATES-HYDRO
### FATES-HYDRO: key hydraulic parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure-Volume (PV) curve (water content – water potential relationship)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>saturated water content</td>
<td>$\theta_s$</td>
<td>cm$^3$ cm$^{-3}$</td>
</tr>
<tr>
<td>turgor loss point</td>
<td>$\pi_{tip}$</td>
<td>MPa</td>
</tr>
<tr>
<td>bulk elastic modulus</td>
<td>$\varepsilon$</td>
<td>MPa</td>
</tr>
<tr>
<td>residual fraction</td>
<td>$RWC_r$</td>
<td>unitless</td>
</tr>
<tr>
<td>fraction of water in capillary reserve</td>
<td>$f_{cap}$</td>
<td>unitless</td>
</tr>
<tr>
<td>Xylem Vulnerability Curve (water potential – hydraulic conductivity relationship)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>xylem water potential at 50% loss of max conductivity</td>
<td>$P_{50,x}$</td>
<td>MPa</td>
</tr>
<tr>
<td>xylem vulnerability curve shape parameter</td>
<td>$\alpha_x$</td>
<td>unitless</td>
</tr>
<tr>
<td>maximum xylem conductivity per unit sapwood area</td>
<td>$k_{s,max}$</td>
<td></td>
</tr>
<tr>
<td>Stomatal Vulnerability Curve (new Btран formulation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>leaf water potential at 50% loss of max gs</td>
<td>$P_{50,gs}$</td>
<td></td>
</tr>
<tr>
<td>stomatal vulnerability shape parameter</td>
<td>$\alpha_{gs}$</td>
<td></td>
</tr>
</tbody>
</table>

### Plant Hydraulic Architecture

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xylem taper exponent</td>
<td>$P$</td>
<td>(-)</td>
</tr>
<tr>
<td>Leaf to sapwood area ratio</td>
<td>$A_1:A_2$</td>
<td>m$^2$ cm$^{-2}$</td>
</tr>
</tbody>
</table>

### Root/shoot Architecture

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>specific root length (converts biomass to root length)</td>
<td>$SRL$</td>
<td>m g$^{-1}$</td>
</tr>
<tr>
<td>absorbing root radius (sets length scale for soil-root water flux)</td>
<td>$r$</td>
<td>mm</td>
</tr>
<tr>
<td>Leaf mass per unit area</td>
<td>$I_{ma}$</td>
<td>g/m$^2$</td>
</tr>
<tr>
<td>root tissue density (controls root PV parameters)</td>
<td>$RTD$</td>
<td>g cm$^{-1}$</td>
</tr>
<tr>
<td>Fine root to leaf ratio</td>
<td>$a$</td>
<td>unitless</td>
</tr>
<tr>
<td>fraction of total tree resistance that is aboveground</td>
<td>$frac$</td>
<td>Unitless</td>
</tr>
</tbody>
</table>


Example FATES-HYDRO output

<table>
<thead>
<tr>
<th>Trait</th>
<th>$k_s$</th>
<th>$P_{50}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>More negative; resistant</td>
<td>Less negative; vulnerable</td>
</tr>
</tbody>
</table>

Water use of more conductive PFT eventually falls below that of less conductive PFT (did it suck up all the water?)
Future development plans

1. Nutrients
2. Land use
3. Static vegetation mode
Simple Allocative Case for nutrients within PARTEH:

- Instantaneous Allocation of NPP
- Reaction Costs paid by the NPP pool
- Single Pools for each tissue type

\[ C = \text{single carbon pool} \]
\[ N_k = k\text{-th nutrient pool} \]
FATES-fvd (fixed vegetation distribution). Tbd.

We need a mode to turn off the DGVM capability

1. Read in a PFT map from the surface dataset
2. Discover which PFTs are ‘allowed’ in each grid cell
3. Only allow seeding/recruitment with those PFTs

Could we mask parts of the globe and test dynamics in certain regions??
Some Shorter- and Longer-term Development Plans

1: Land-Use

- Current (no land use)
  - FATES Patch n
  - FATES Patch 3
  - FATES Patch 2
  - FATES Patch 1

- Initial Land Use Model: Labeled Patches
  - FATES Primary Patch n
  - FATES Primary Patch 3
  - FATES Primary Patch 2
  - FATES Primary Patch 1
  - FATES Second. Patch n
  - FATES Second. Patch 3
  - FATES Second. Patch 2
  - FATES Second. Patch 1

- Long-Term Goal: Multiscale heterogeneity
  - FATES Primary Patch n
  - FATES Primary Patch 3
  - FATES Primary Patch 2
  - FATES Primary Patch 1
  - FATES Second. Patch n
  - FATES Second. Patch 3
  - FATES Second. Patch 2
  - FATES Second. Patch 1

- CLM & ALM Naturally Vegetated Column
- CLM & ALM Naturally Vegetated Column
- CLM/ALM Naturally Vegetated Column
- CLM/ALM Secondary Vegetation Column
Future FATES
Open Code Development

FATES is at https://github.com/NGEET/FATES

+ More eyes on code better
+ Better coordination of development/overlaps
+ Forum for collaboration: questions can be directed to whole community

This requires

+ Solid funding for maintenance of system (add software support to your proposals!)
+ Community ethical guidelines:

https://github.com/NGEET/fates/blob/master/CODE_OF_CONDUCT.md
Ongoing and planned FATES projects (non-exhaustive!)

- **NGEE-tropics (DoE/LBL-led tropics-focused project. Phase II proposal ongoing)**
  - Nutrient cycling, allocation
  - Fire, Gas Exchange, physiology testbeds
  - Tropical forest testbeds
  - Coexistence & trait filtering
  - FATES-Hydro testing & calibration
  - Tropical phenology
  - Radiation transfer

- **E3SM (DoE ESM)**
  - Land-use implementation (LUH2)
  - Global PFT calibrations

- **California/LBL proposals**
  - Parameters for Western US forests
  - Wildfire simulation & benchmarking
  - FATES x Hillslope model
  - Regeneration parameterization

- **Emerald (NorESM/University of Oslo-boreal focused project)**
  - High latitude PFTs & processes
  - Moss PFTs

- **LANL**
  - Insect dynamics, wetlands, fire-atmosphere interactions

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**Biweekly FATES teleconferences**
starting soon
+ Thurs, 11am Pacific; 12am MDT, 8pm CET:
+ Sign up for alerts at:
  fates_model@googlegroups.com