Development of a tree-level hydrodynamics model for ELM to study competition for water

Gautam Bisht[1]
William Riley[2]
Gil Bohrer[3]
Ashley Matheny[4]

E3SM Energy/Land Group Meeting

Nov 20, 2019

[1]PNNL, [2]LBNL, [3]OSU, [4]UTexas, Austin

U.S. DEPARTMENT OF ENERGY BATTELLE
PNNL is operated by Battelle for the U.S. Department of Energy

Motivation

- Vegetation mortality due to drought and rising temperature has increased under current climate condition and expected to further increase due to climate change

Motivation

- Vegetation mortality due to drought and rising temperature has increased under current climate condition and expected to further increase due to climate change
- Drivers of drought induced vegetation mortality hydraulic failure, carbon starvation, and biotic attack

Motivation

- Vegetation mortality due to drought and rising temperature has increased under current climate condition and expected to further increase due to climate change
- Drivers of drought induced vegetation mortality hydraulic failure, carbon starvation, and biotic attack
- Changes to transpiration due to vegetation mortality will have significant impacts to water, energy, and carbon cycle

Motivation

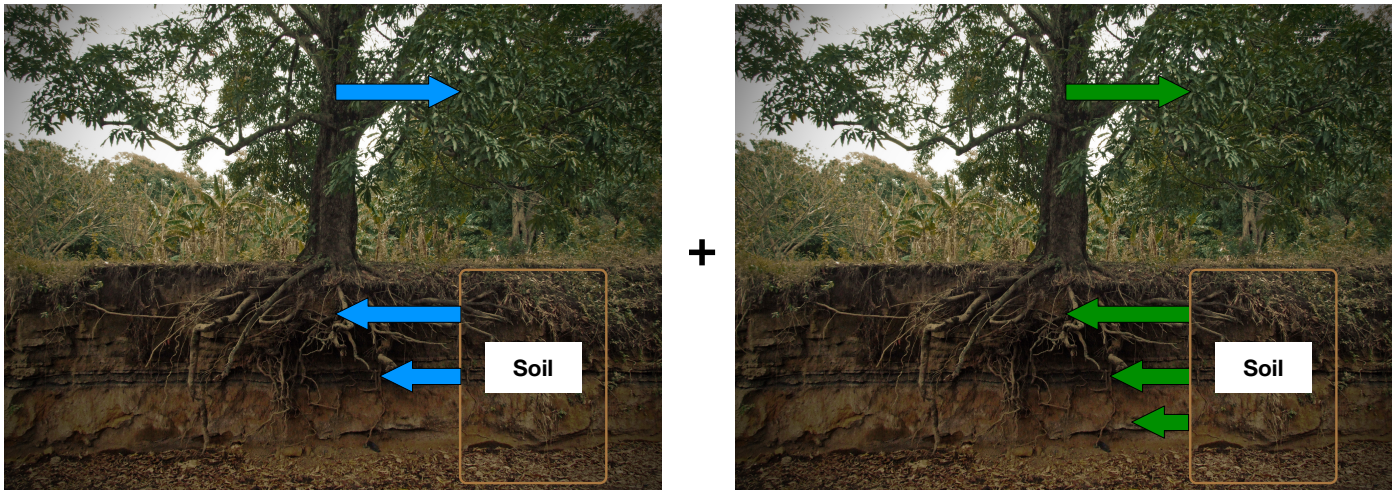
- Vegetation mortality due to drought and rising temperature has increased under current climate condition and expected to further increase due to climate change
- Drivers of drought induced vegetation mortality hydraulic failure, carbon starvation, and biotic attack
- Changes to transpiration due to vegetation mortality will have significant impacts to water, energy, and carbon cycle
- At present, most land surface models (LSMs) exclude the transport of water through vertical vegetation structure

Motivation

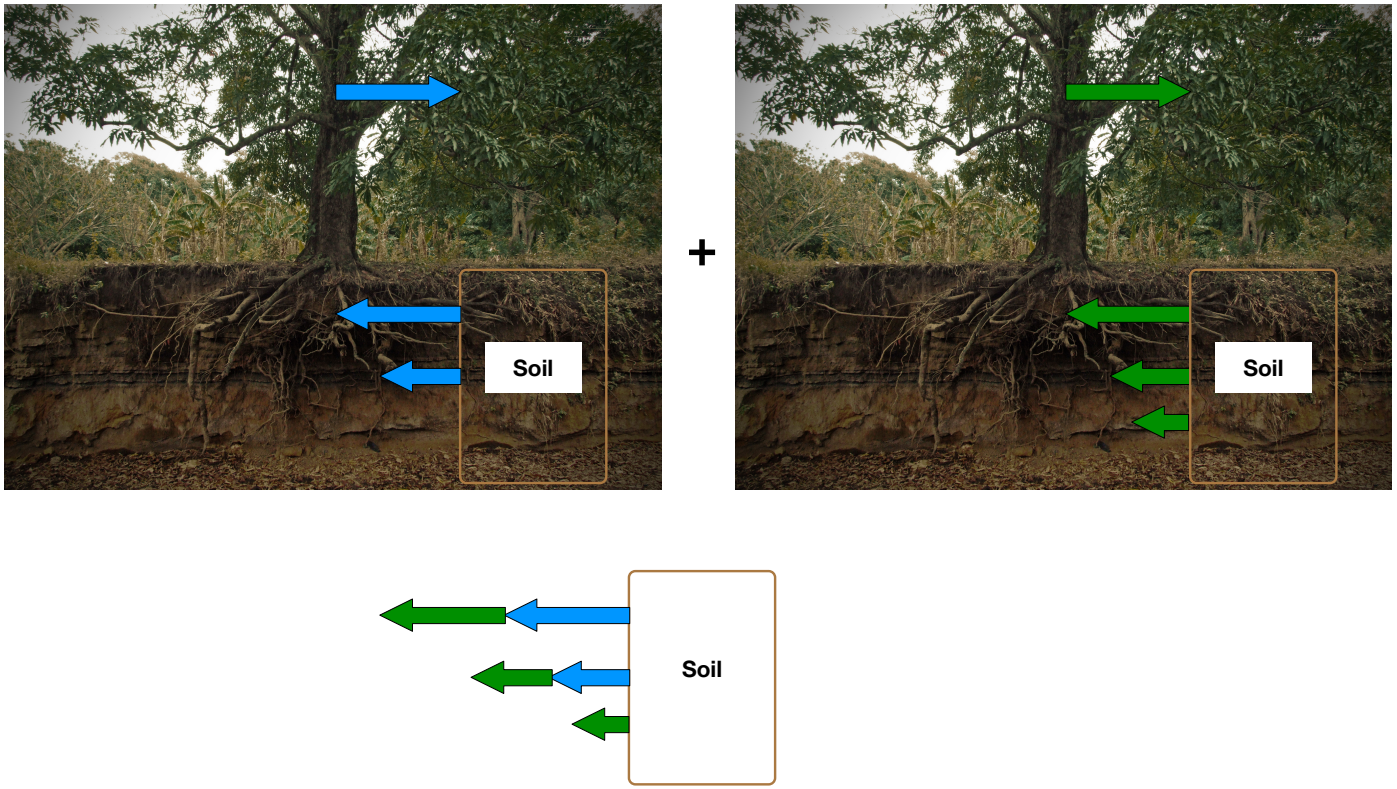
- Vegetation mortality due to drought and rising temperature has increased under current climate condition and expected to further increase due to climate change
- Drivers of drought induced vegetation mortality hydraulic failure, carbon starvation, and biotic attack
- Changes to transpiration due to vegetation mortality will have significant impacts to water, energy, and carbon cycle
- At present, most land surface models (LSMs) exclude the transport of water through vertical vegetation structure
- Recently sophisticated modeling approaches that resolve water transport through the soil–plant–atmosphere continuum coupled to stomatal conductance model based on optimization theory are starting to get incorporated within LSMs

Shortcomings of root water update by ELM v1.0

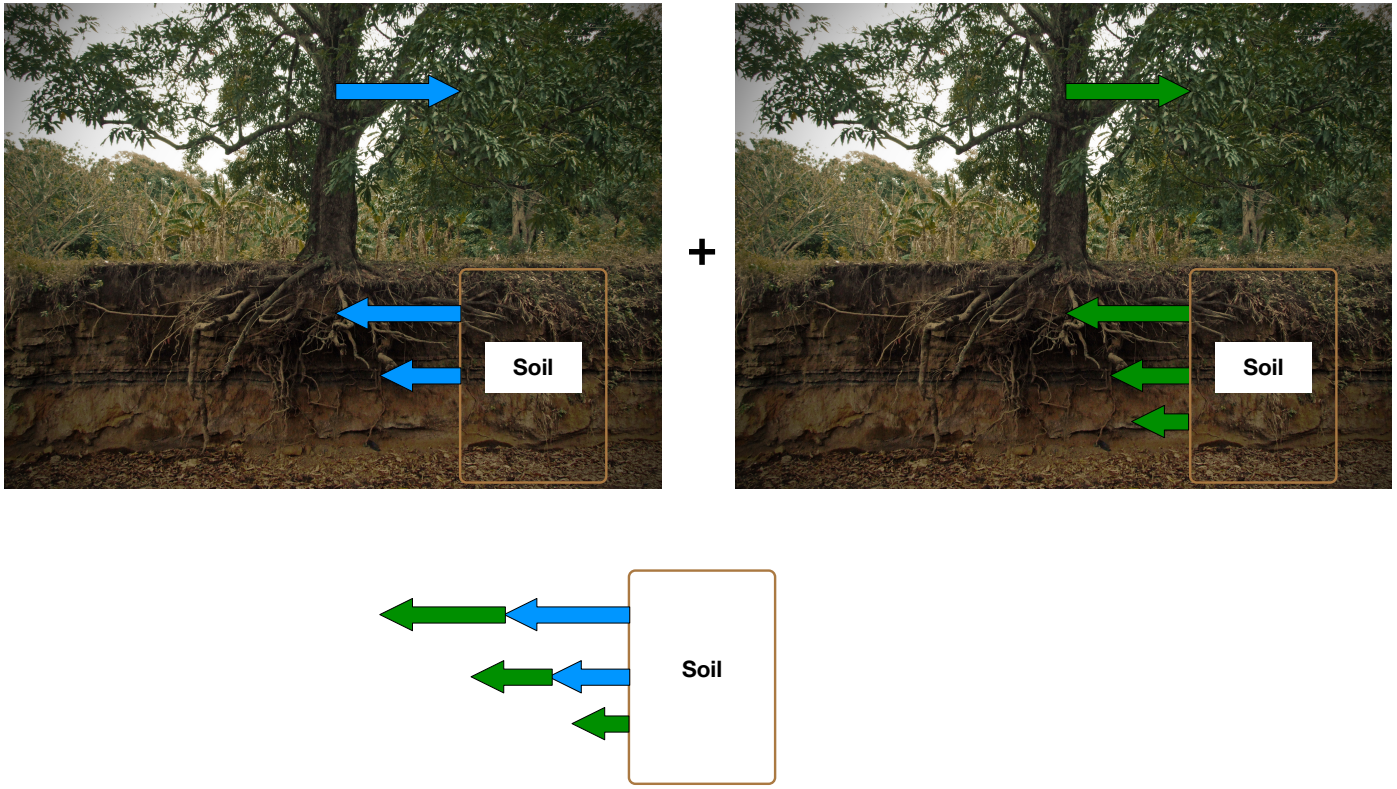
Shortcomings of root water update by ELM v1.0



Shortcomings of root water update by ELM v1.0



Shortcomings of root water update by ELM v1.0



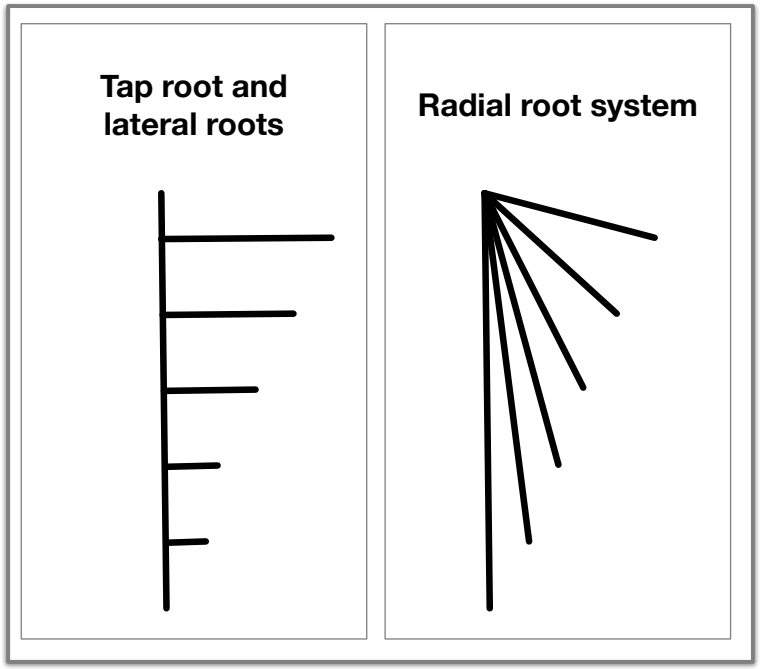
- Ignores the soil–root–xylem transport pathway
- Excludes competition among PFTs for soil water uptake

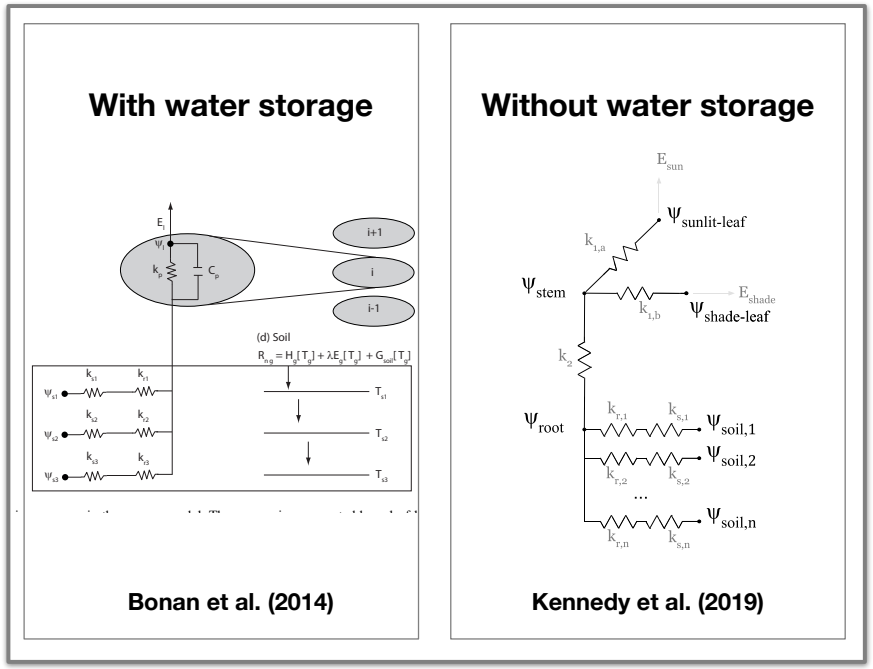
Objectives

- Develop a tree-level hydrodynamics model that accounts for:
  - Different hydraulics strategies (e.g. isohydric/anisohydric, less/more xylem conductivity, shallow/deep roots)
  - Explicitly represents competition among vegetation for soil water

Objectives

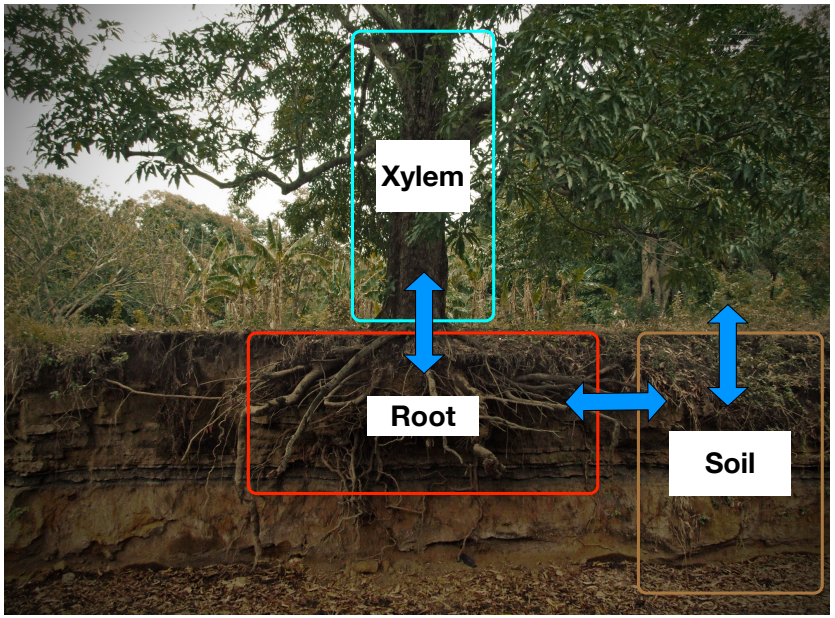
- Develop a tree-level hydrodynamics model that accounts for:
  - Different hydraulics strategies (e.g. isohydric/anisohydric, less/more xylem conductivity, shallow/deep roots)
  - Explicitly represents competition among vegetation for soil water
- Study the impact of model structure





Tree-level hydrodynamics model using `libMPP`

- `libMPP` is a standalone library for solving global terrestrial multi-physics processes and included in E3SM-v1.0
- `libMPP` uses PETSc to provide numerical solution of discretized equations
- PETSc's `DMComposite` provides an extensible framework to resolve tightly coupled transport of water through the soil-plant continuum



Tree-level hydrodynamics model using `libMPP`

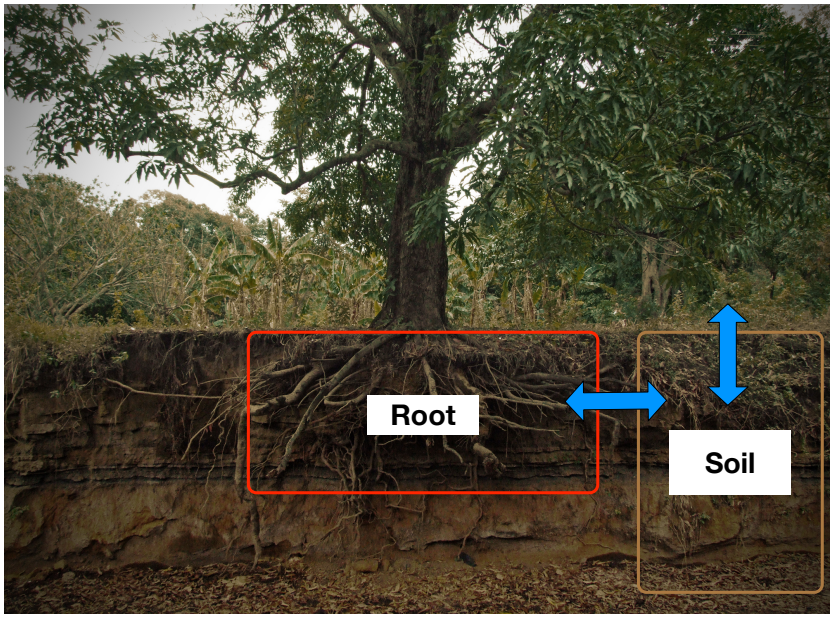
- `libMPP` is a standalone library for solving global terrestrial multi-physics processes and included in E3SM-v1.0
- `libMPP` uses PETSc to provide numerical solution of discretized equations
- PETSc's `DMComposite` provides an extensible framework to resolve tightly coupled transport of water through the soil-plant continuum

Solution of nonlinear equations for a soil system

$$\left(J_{s,s} \right) \left(\Delta X_s \right) = - \left(R_s \right)$$

Tree-level hydrodynamics model using `libMPP`

- `libMPP` is a standalone library for solving global terrestrial multi-physics processes and included in E3SM-v1.0
- `libMPP` uses PETSc to provide numerical solution of discretized equations
- PETSc's `DMComposite` provides an extensible framework to resolve tightly coupled transport of water through the soil-plant continuum

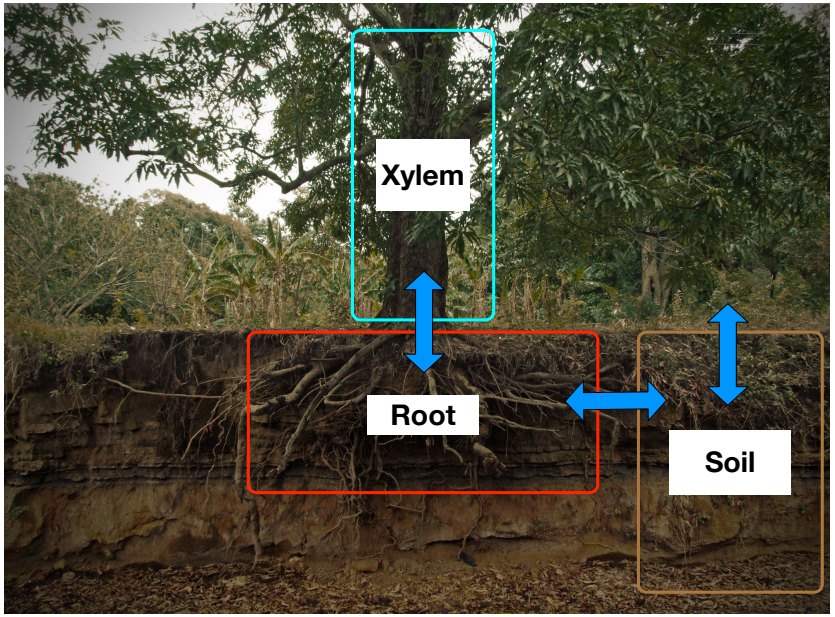


Solution of nonlinear equations for a soil-root system

$$\begin{pmatrix} J_{s,s} & J_{s,r} \\ J_{r,s} & J_{r,r} \end{pmatrix} \begin{pmatrix} \Delta X_s \\ \Delta X_r \end{pmatrix} = - \begin{pmatrix} R_s \\ R_r \end{pmatrix}$$

Tree-level hydrodynamics model using `libMPP`

- `libMPP` is a standalone library for solving global terrestrial multi-physics processes and included in E3SM-v1.0
- `libMPP` uses PETSc to provide numerical solution of discretized equations
- PETSc's `DMComposite` provides an extensible framework to resolve tightly coupled transport of water through the soil-plant continuum



Solution of nonlinear equations for a soil-root-xylem system

$$\begin{pmatrix} J_{s,s} & J_{s,r} & 0 \\ J_{r,s} & J_{r,r} & J_{r,x} \\ 0 & J_{x,r} & J_{x,x} \end{pmatrix} \begin{pmatrix} \Delta X_s \\ \Delta X_r \\ \Delta X_x \end{pmatrix} = - \begin{pmatrix} R_s \\ R_r \\ R_x \end{pmatrix}$$

Model setup for US-UMB site: Multiple PFTs

- Following PFTs share a single soil column
  1. E (early successional): 22 [m] tall with 6 [m] deep roots
  2. M (maple) : 22 [m] tall with 3 [m] deep roots
  3. O (oak) : 22 [m] tall with 6 [m] deep roots
  4. P (pine) : 22 [m] tall with 6 [m] deep roots

Model setup for US-UMB site: Multiple PFTs

- Following PFTs share a single soil column
  1. E (early successional): 22 [m] tall with 6 [m] deep roots
  2. M (maple) : 22 [m] tall with 3 [m] deep roots
  3. O (oak) : 22 [m] tall with 6 [m] deep roots
  4. P (pine) : 22 [m] tall with 6 [m] deep roots
- Boundary/source-sink conditions
  - A time-varying top pressure boundary condition is applied to the soil column
  - A time-invariant water table is assumed as the lower boundary condition for the soil column
  - A time and space varying potential T is prescribed over the xylem

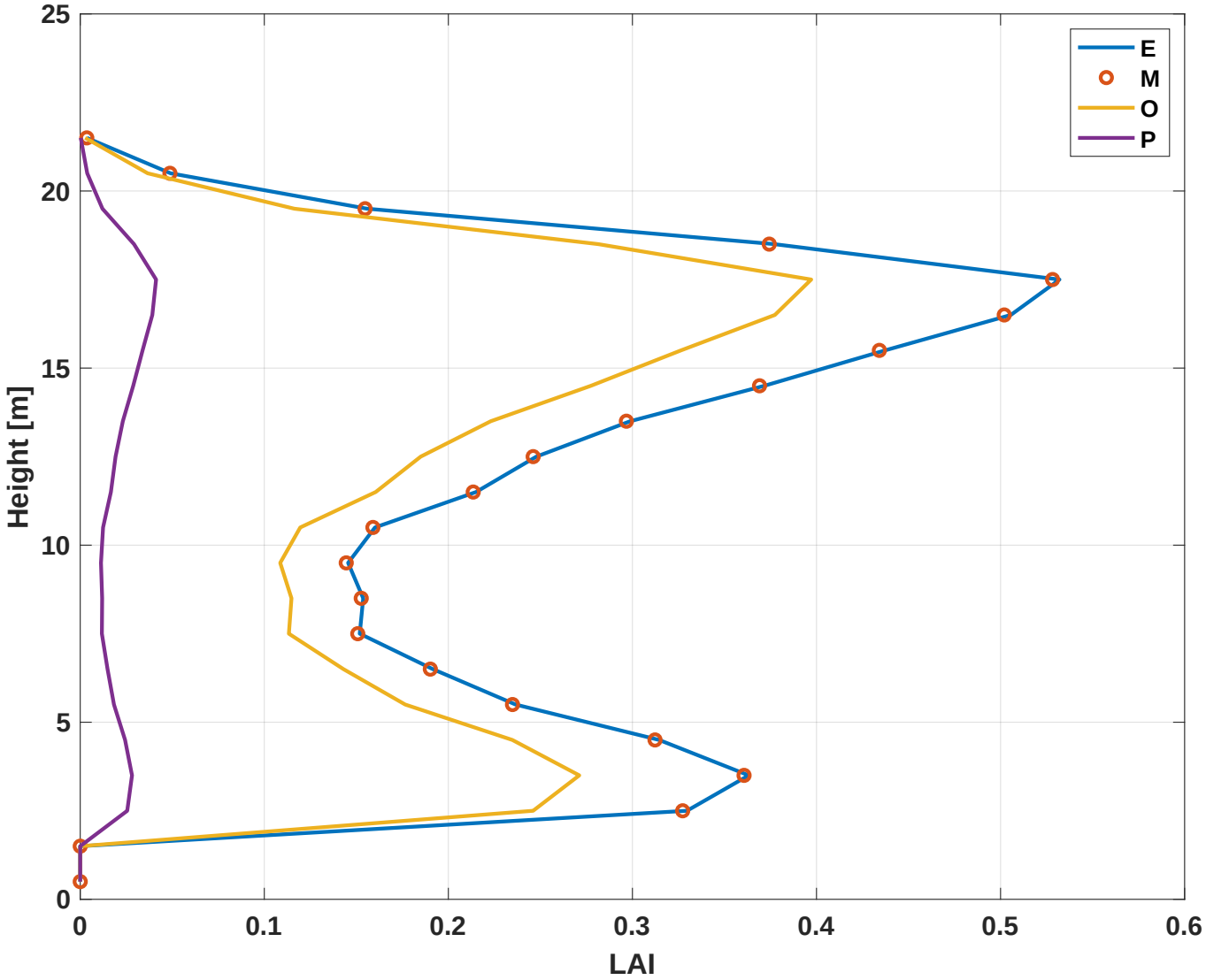
Model setup for US-UMB site: Multiple PFTs

- Following PFTs share a single soil column
  1. E (early successional): 22 [m] tall with 6 [m] deep roots
  2. M (maple) : 22 [m] tall with 3 [m] deep roots
  3. O (oak) : 22 [m] tall with 6 [m] deep roots
  4. P (pine) : 22 [m] tall with 6 [m] deep roots
- Boundary/source-sink conditions
  - A time-varying top pressure boundary condition is applied to the soil column
  - A time-invariant water table is assumed as the lower boundary condition for the soil column
  - A time and space varying potential T is prescribed over the xylem
- Mesh geometry
  - `nxylem = 110` with `dz = 0.2 [m]`
  - `nroot = nsoil = 60` with `dz = 0.1 [m]`

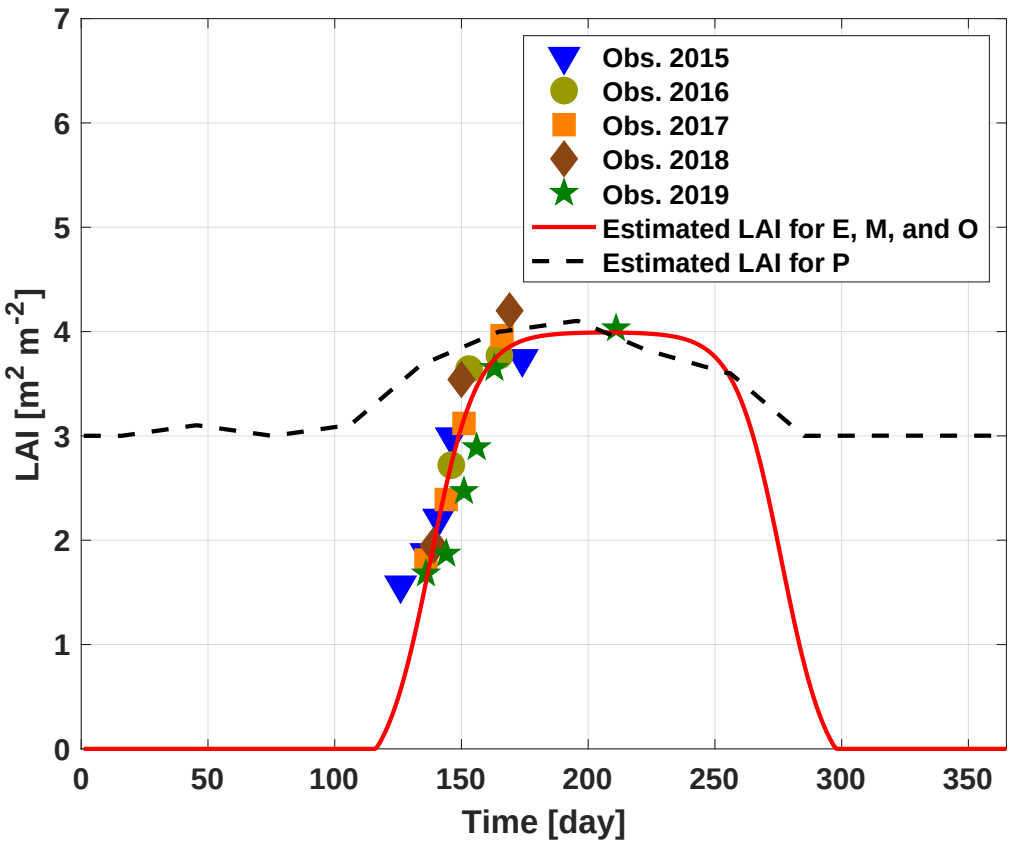
Model setup for US-UMB site: Multiple PFTs

- Following PFTs share a single soil column
  1. E (early successional): 22 [m] tall with 6 [m] deep roots
  2. M (maple) : 22 [m] tall with 3 [m] deep roots
  3. O (oak) : 22 [m] tall with 6 [m] deep roots
  4. P (pine) : 22 [m] tall with 6 [m] deep roots
- Boundary/source-sink conditions
  - A time-varying top pressure boundary condition is applied to the soil column
  - A time-invariant water table is assumed as the lower boundary condition for the soil column
  - A time and space varying potential T is prescribed over the xylem
- Mesh geometry
  - `nxylem = 110` with `dz = 0.2 [m]`
  - `nroot = nsoil = 60` with `dz = 0.1 [m]`
- Study period: 2015-2017* (Data for 2017 does not span the full year)

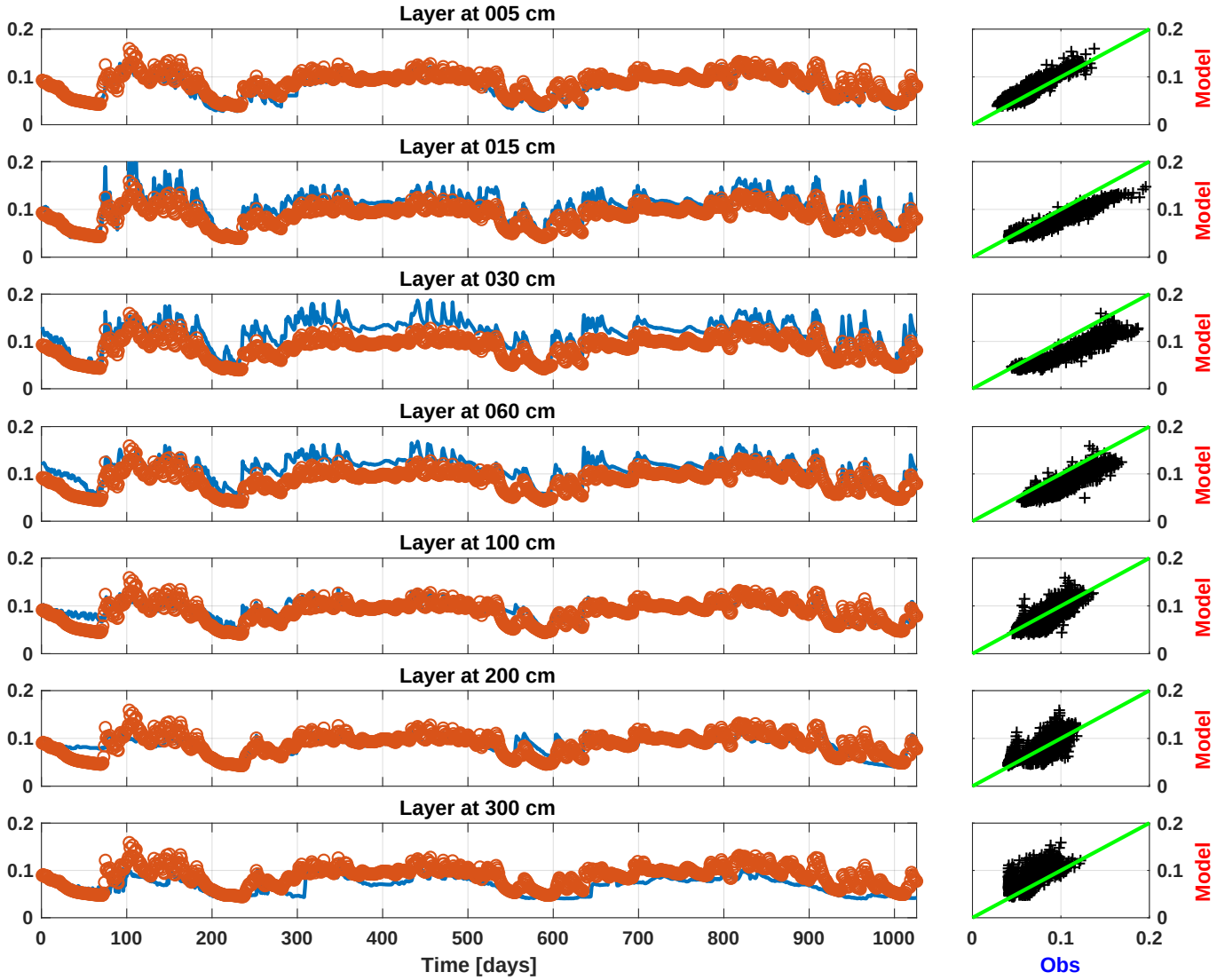
LAI profile of PFTs



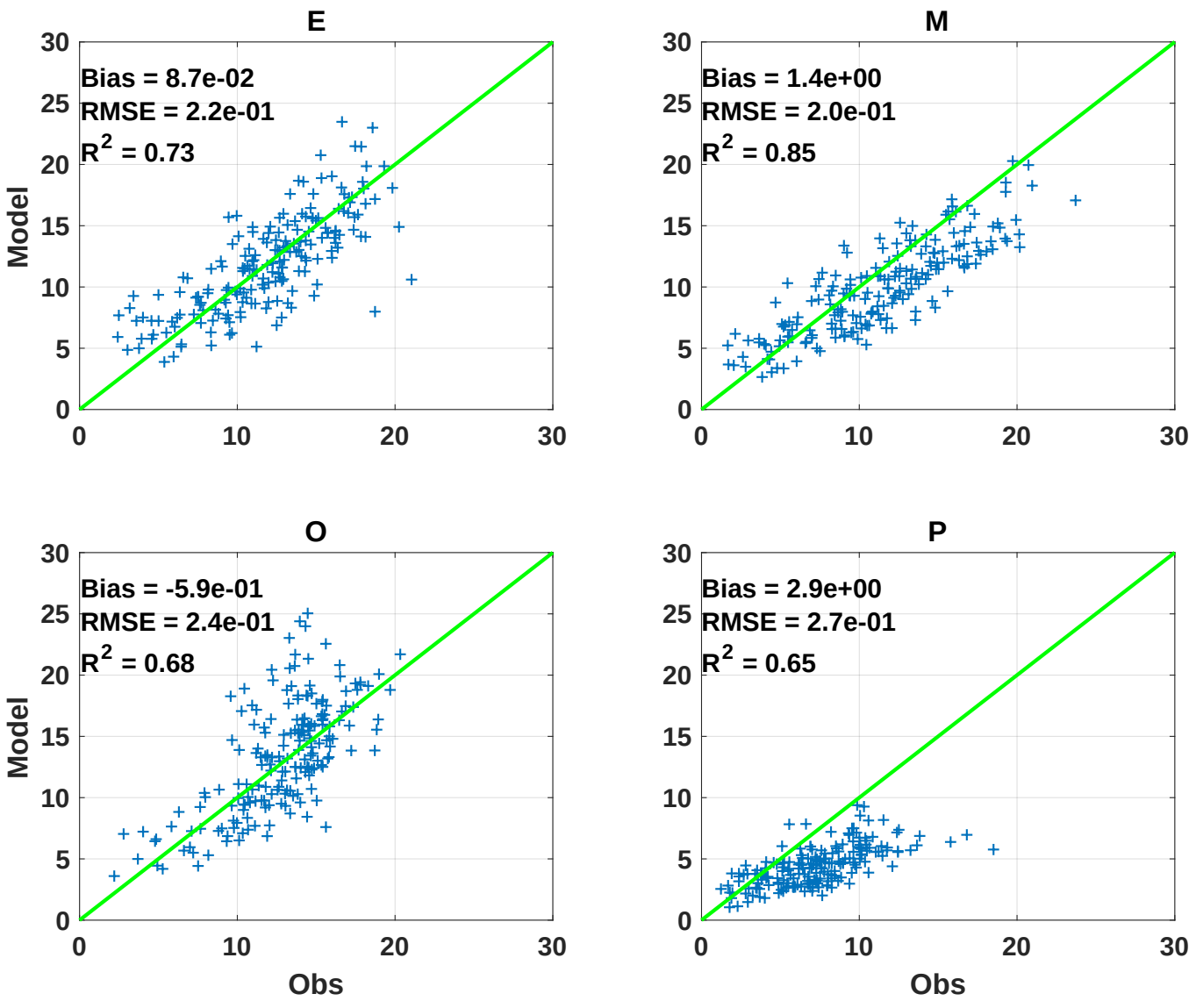
Time varying LAI



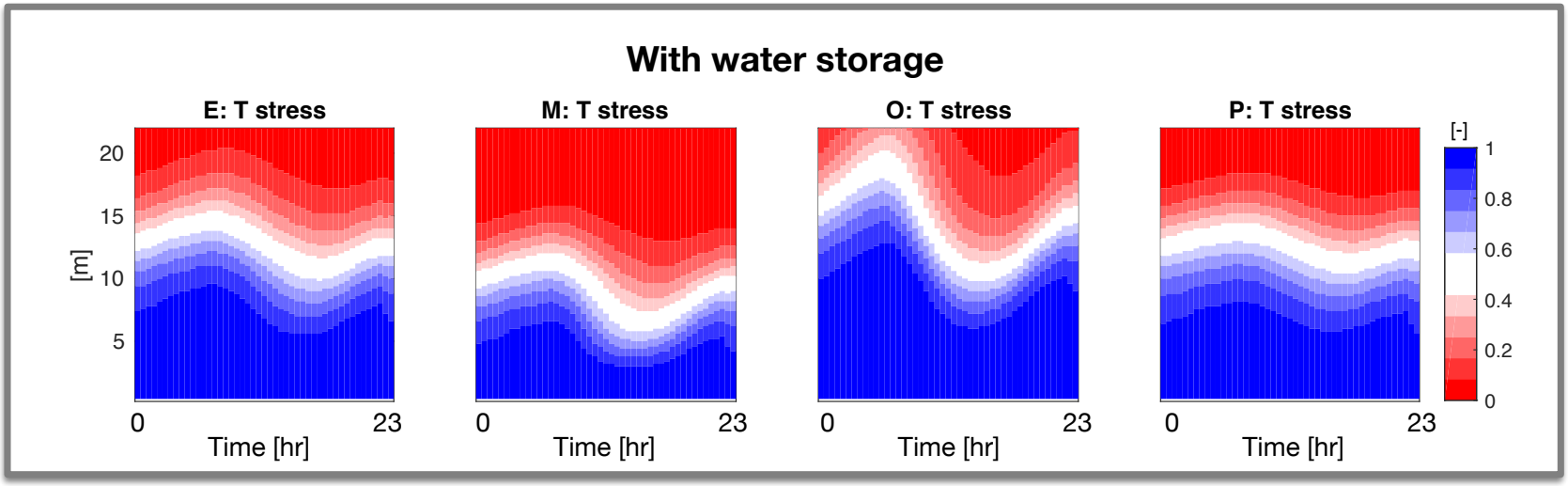
Soil moisture



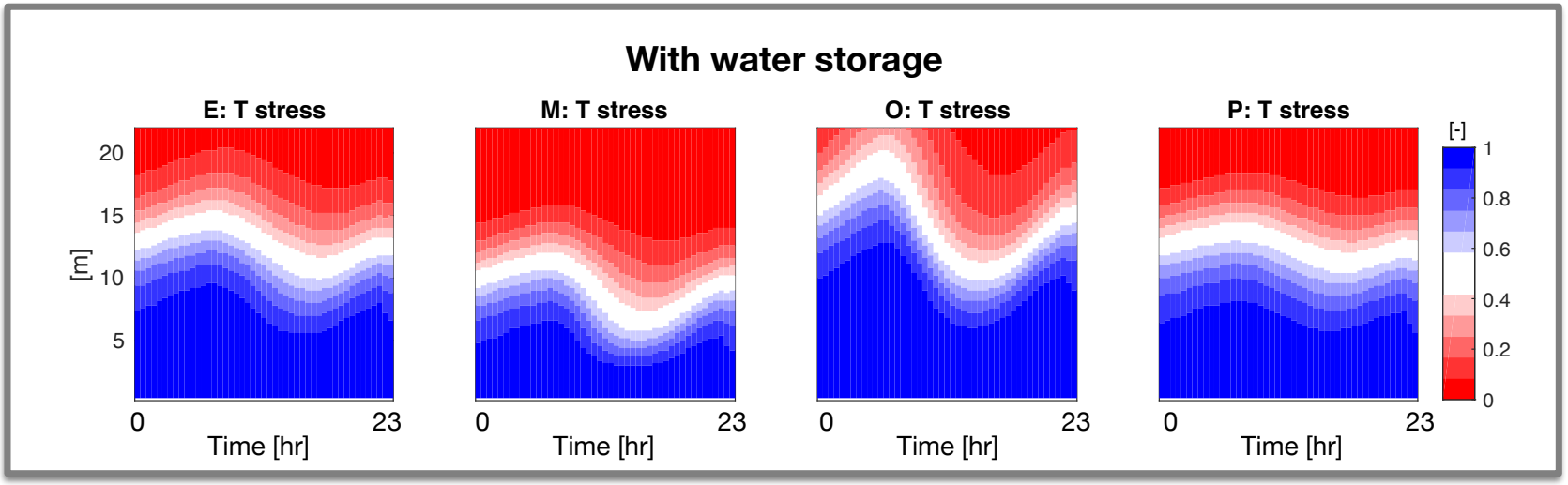
Sapflow

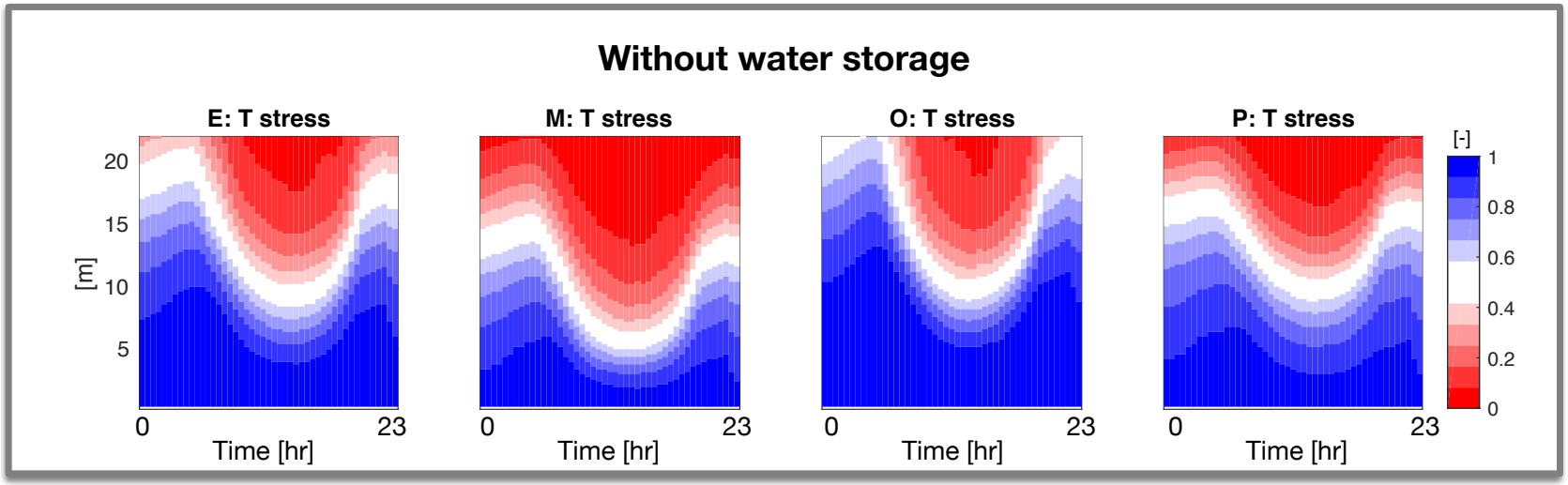

E
Bias = 8.7e-02
RMSE = 2.2e-01
R2 = 0.73
M
Bias = 1.4e+00
RMSE = 2.0e-01
R2 = 0.85
O
Bias = -5.9e-01
RMSE = 2.4e-01
R2 = 0.68
P
Bias = 2.9e+00
RMSE = 2.7e-01
R2 = 0.65
Model
Obs
0
5
10
15
20
25
30

Impact of model structure: Vertical profile of $T_{actual}/T_{potential}$ for JJA



Impact of model structure: Vertical profile of $T_{actual}/T_{potential}$ for JJA



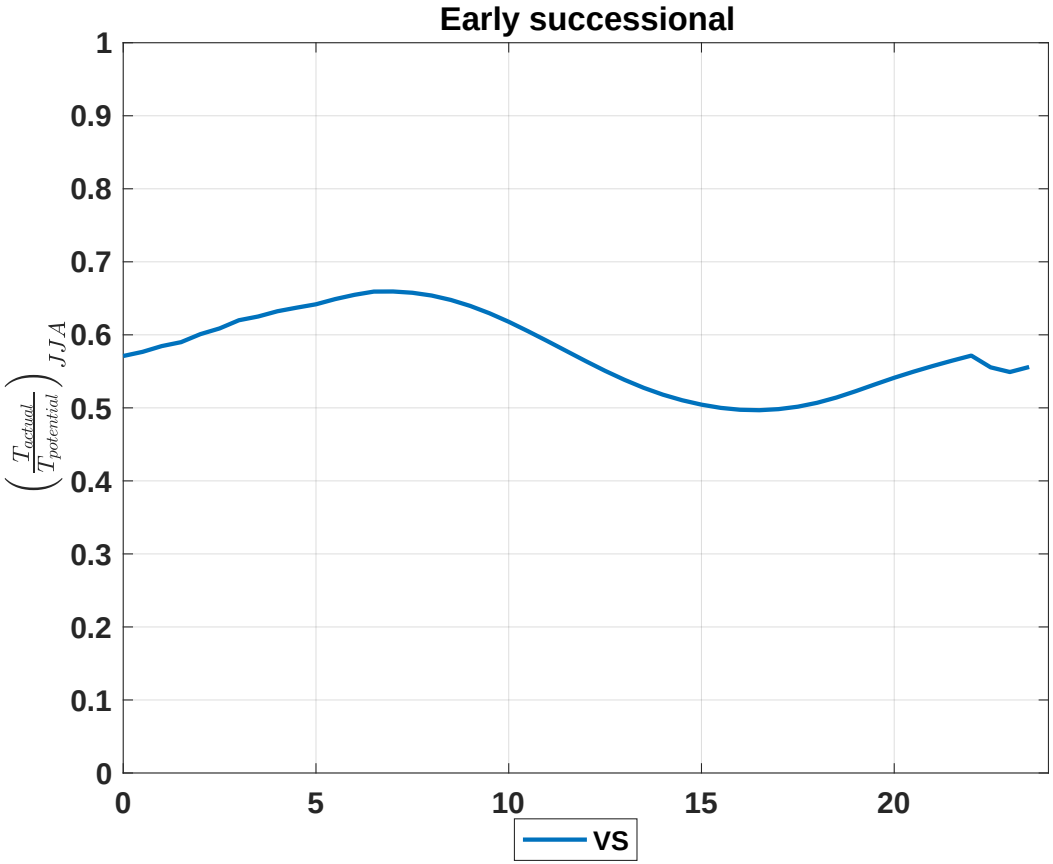


Impact of model structure: Vertical aveg. of $T_{actual}/T_{potential}$ for JJA

VS : **V**ertical root system + water **S**torage
VnS: **V**ertical root system + **n**o water **S**torage
RS : **R**adial root system + water **S**torage
RnS: **R**adial root system + **n**o water **S**torage

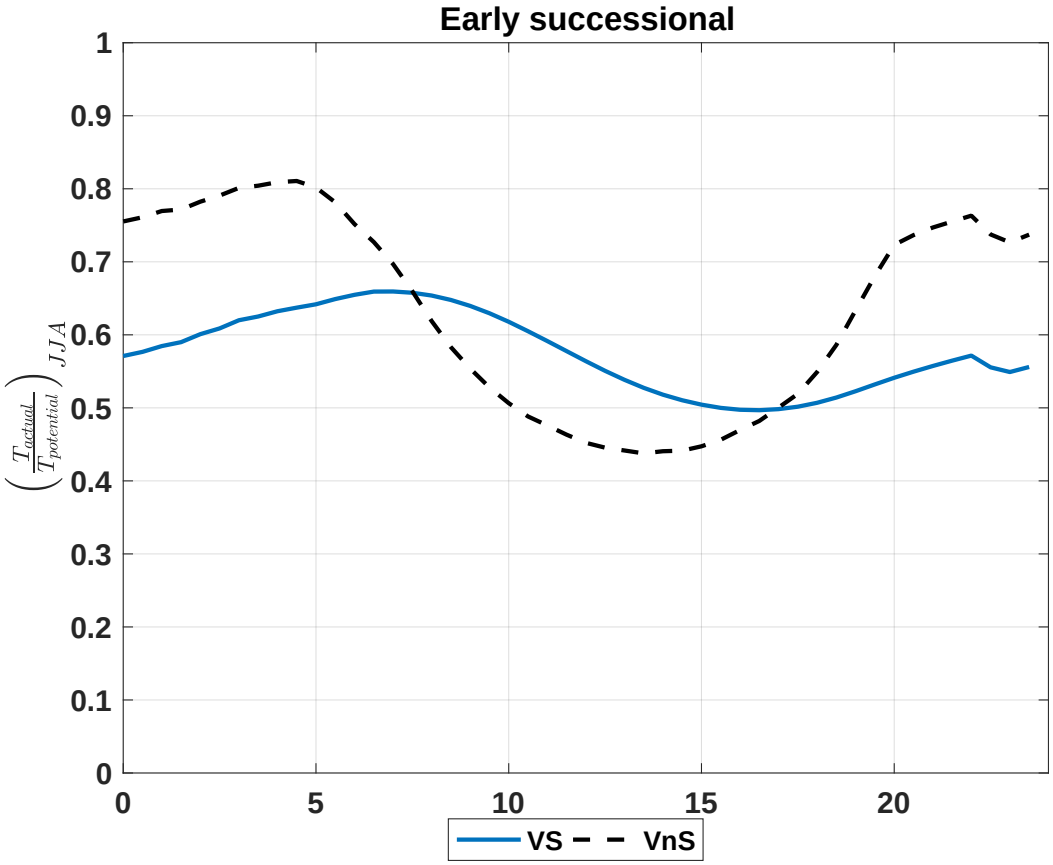
Impact of model structure: Vertical aveg. of $T_{actual}/T_{potential}$ for JJA

VS : **V**ertical root system + water **S**torage
VnS: **V**ertical root system + **n**o water **S**torage
RS : **R**adial root system + water **S**torage
RnS: **R**adial root system + **n**o water **S**torage



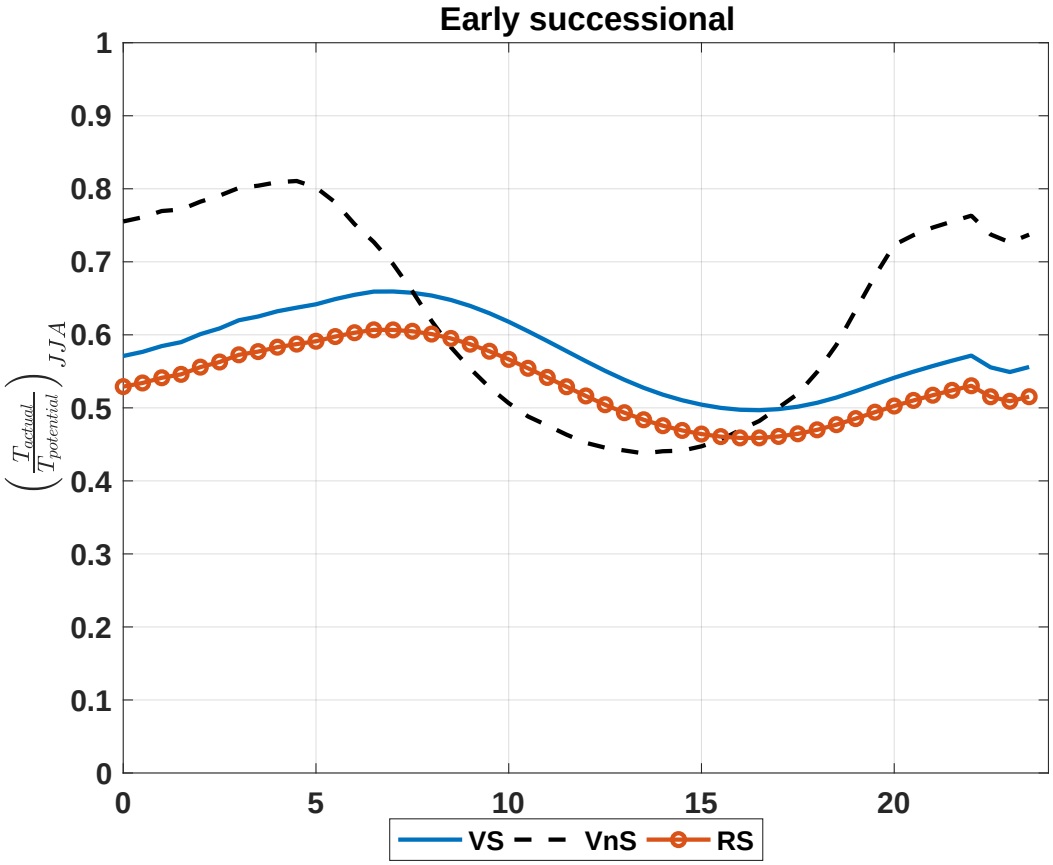
Impact of model structure: Vertical aveg. of $T_{actual}/T_{potential}$ for JJA

VS : **V**ertical root system + water **S**torage
VnS: **V**ertical root system + **n**o water **S**torage
RS : **R**adial root system + water **S**torage
RnS: **R**adial root system + **n**o water **S**torage



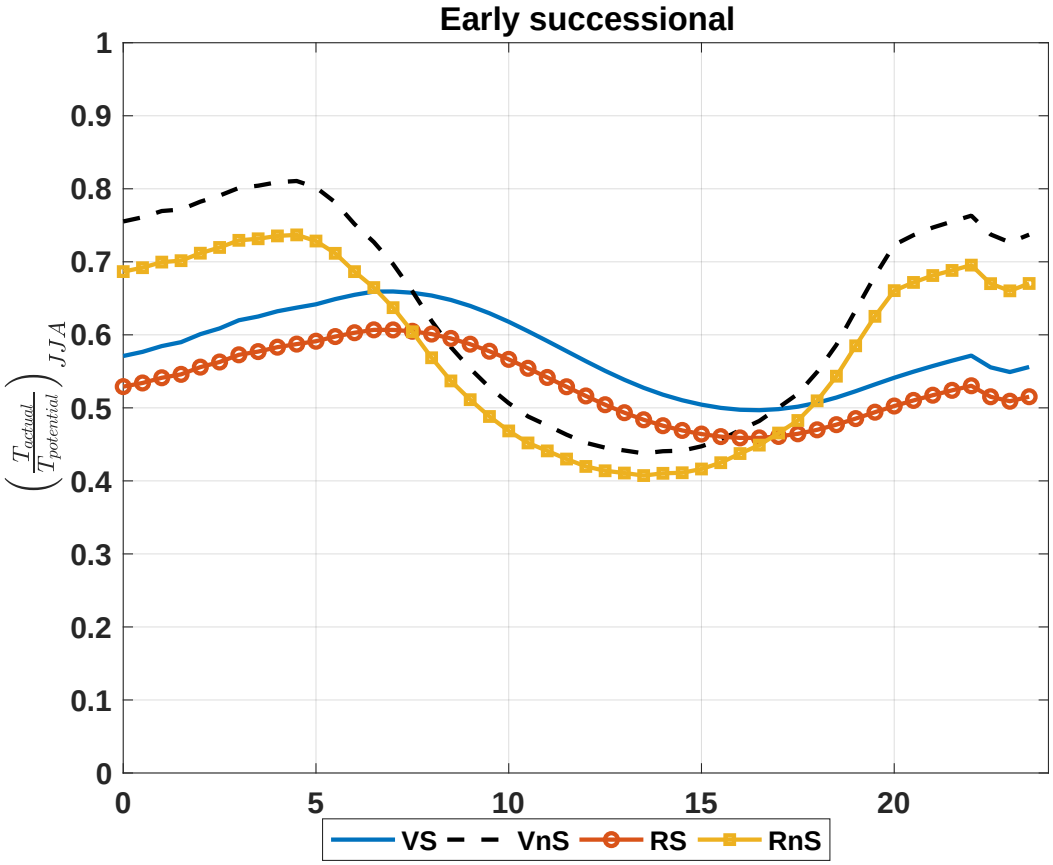
Impact of model structure: Vertical aveg. of $T_{actual}/T_{potential}$ for JJA

VS : **V**ertical root system + water **S**torage
VnS: **V**ertical root system + **n**o water **S**torage
RS : **R**adial root system + water **S**torage
RnS: **R**adial root system + **n**o water **S**torage

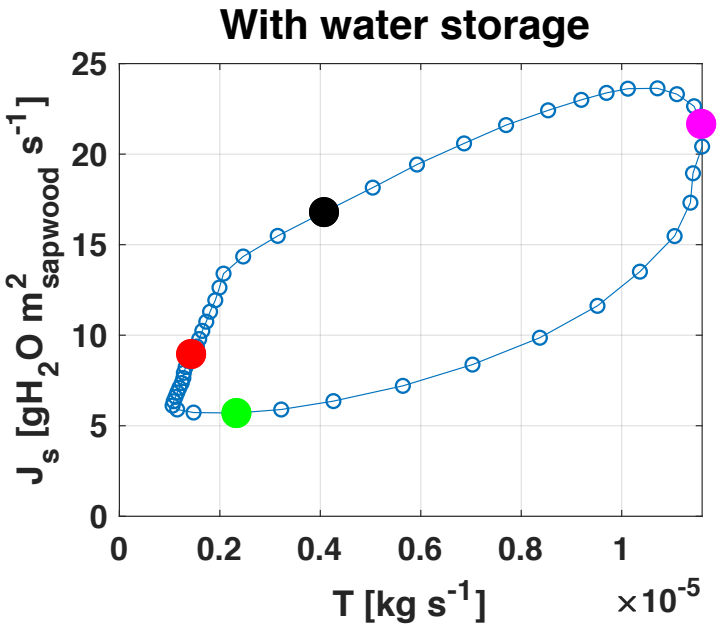


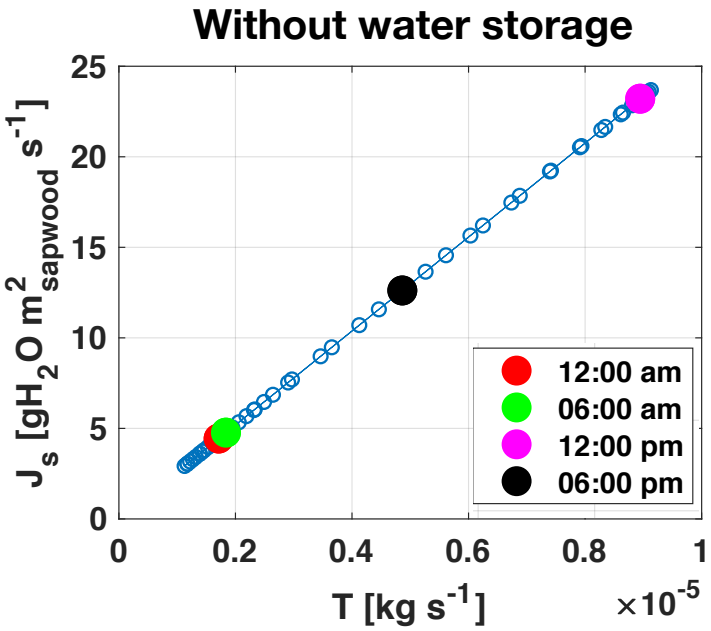
Impact of model structure: Vertical aveg. of $T_{actual}/T_{potential}$ for JJA

VS : **V**ertical root system + water **S**torage
VnS: **V**ertical root system + **n**o water **S**torage
RS : **R**adial root system + water **S**torage
RnS: **R**adial root system + **n**o water **S**torage



Impact of model structure: Sapflow vs actual transpiration





Next steps

- Analyze additional model output variables
- Prepare a manuscript summarizing the findings and submit for publication
- Integrate this development into ELM's vegetation model: (i) Big-leaf, and (ii) FATES