Inferring tropical carbon allocation shifts due to drought and quantifying their effect on carbon fluxes

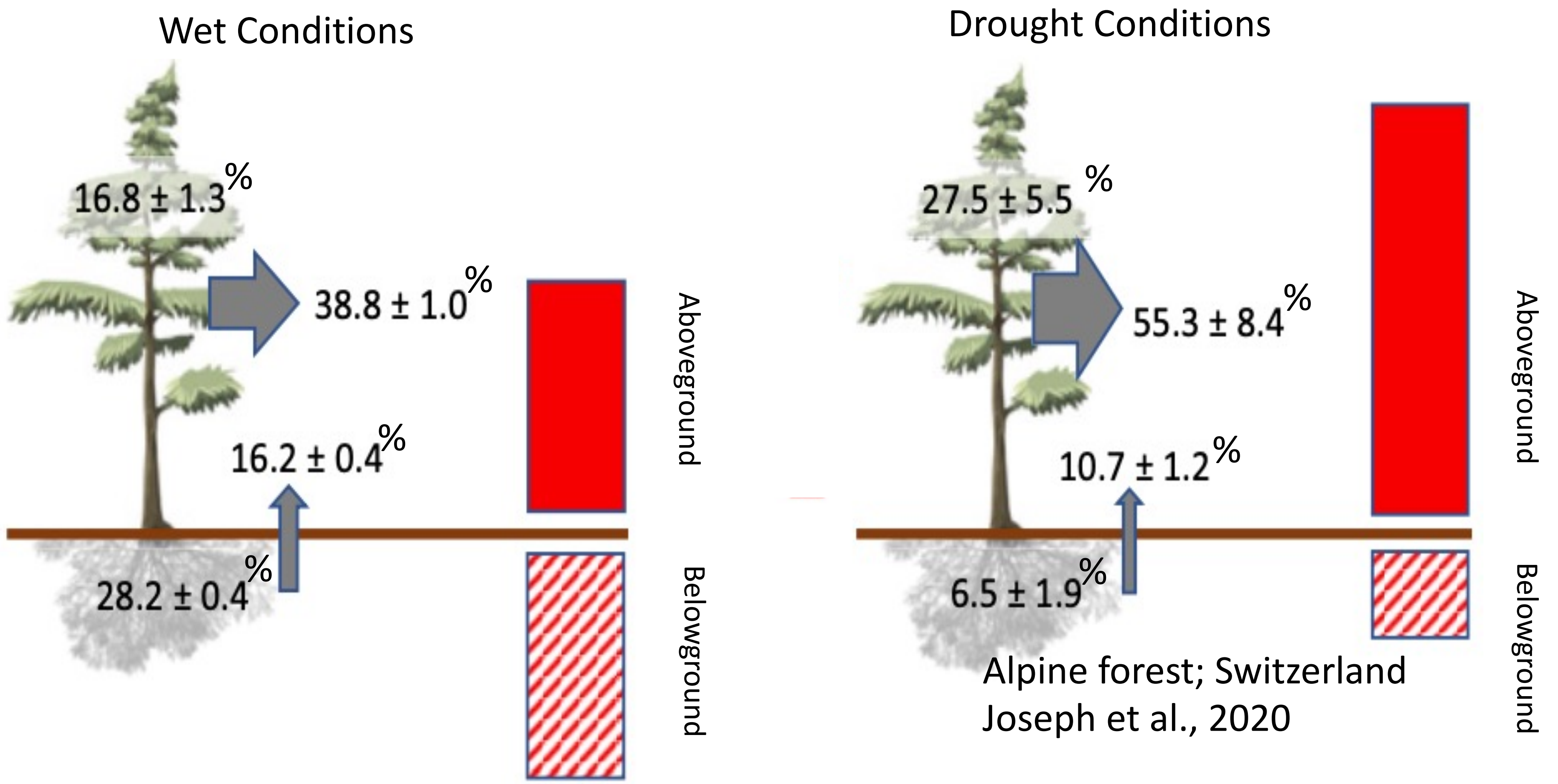
Matthew Worden[1]

Caroline Famiglietti[1], Alexandra Konings[1], Paul Levine[2], Anthony Bloom[2], Shuang Ma[2], Damien Bonal[3], Clement Stahl[4]
[1]Stanford University, [2]Jet Propulsion Laboratory/Caltech, [3]Université de Lorraine, [4]University of Antwerpen

Outline

- Introduction
- CARDAMOM structure adjustments
- Testing hypothesis 1 (can we infer allocation shifts) and hypothesis 2 (do they improve model predictions)
- Proposed experiment for hypothesis 3 (allocation shifts contribute significantly to drought recovery magnitude and time)

Vegetation can respond to drought by shifting where photosynthetic-derived carbon (GPP) is allocated within the plant



Alpine forest; Switzerland
Joseph et al., 2020

In the figure above, the tree at this site responds to drought by allocating more carbon to its foliage and wood at the expense of its roots

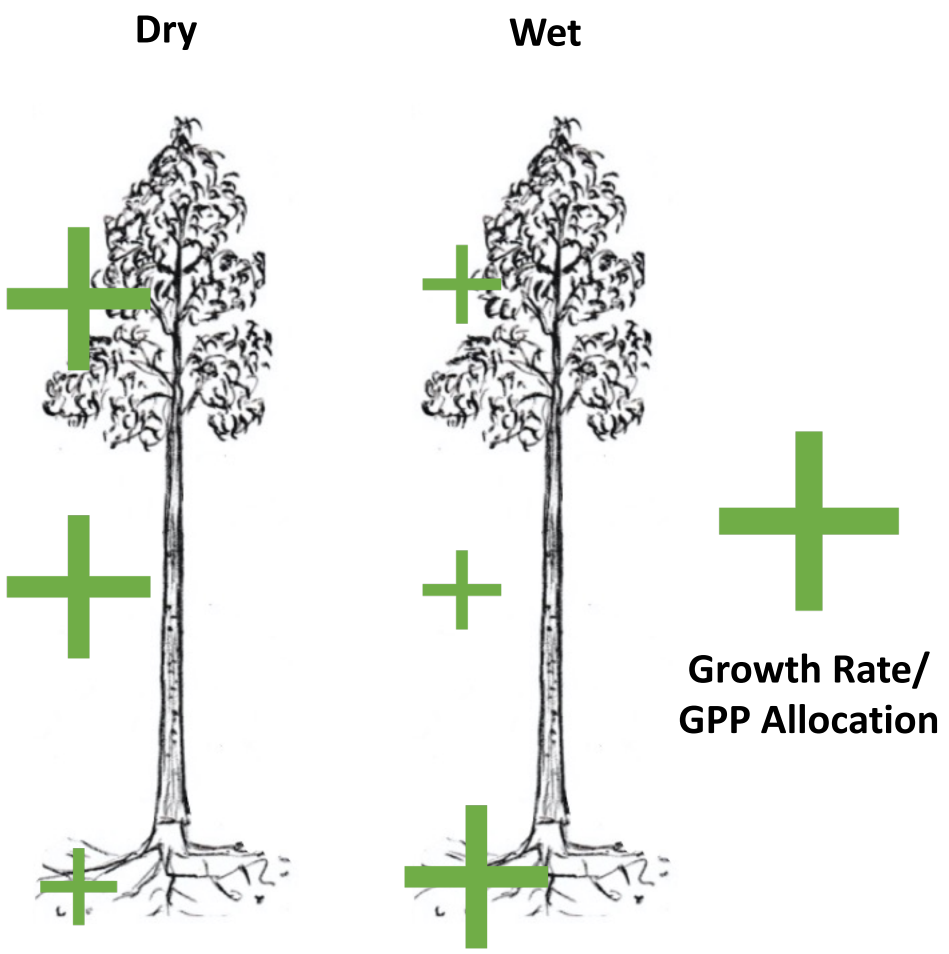
These changes can persist even after meteorological conditions have returned to normal

Site studies find that allocations shift differently for different reasons

Decreased allocation to roots due to damage from drought (Joseph et al., 2020)

Increase allocation to roots to acquire more water resources (Rowland et al., 2014)

Increased allocation to foliage in order to maintain growth (Doughty et al., 2014)



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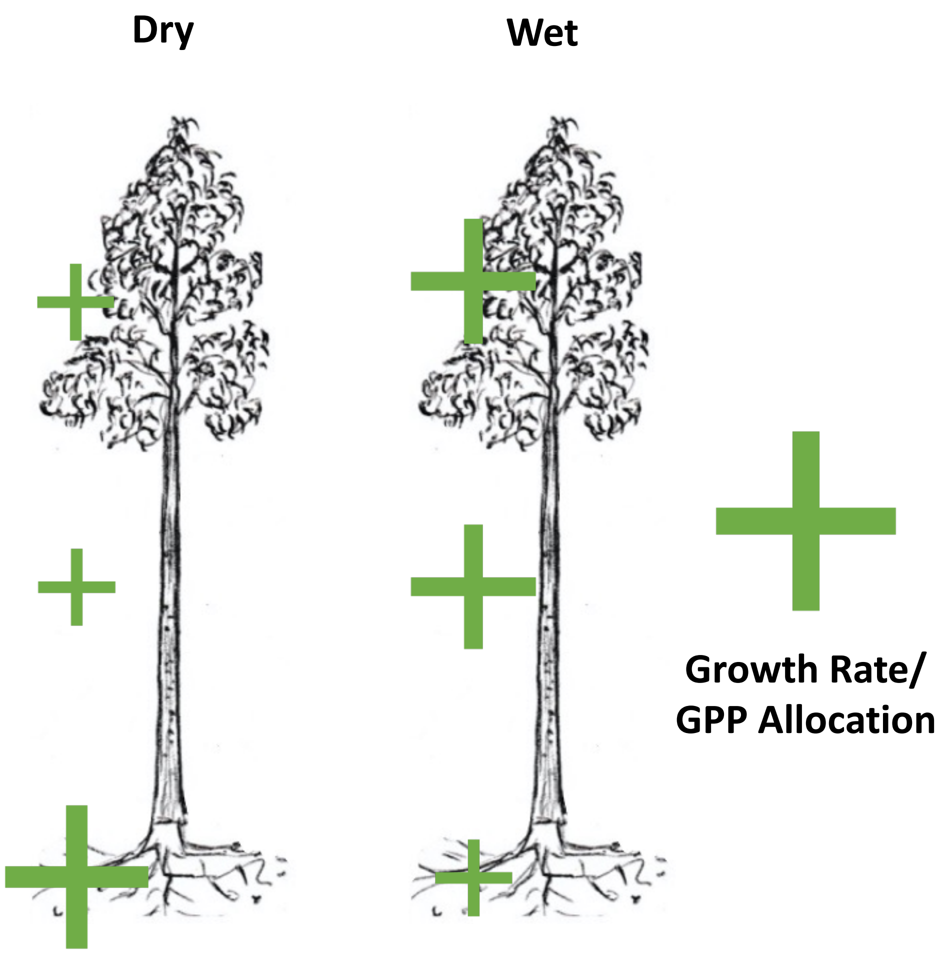

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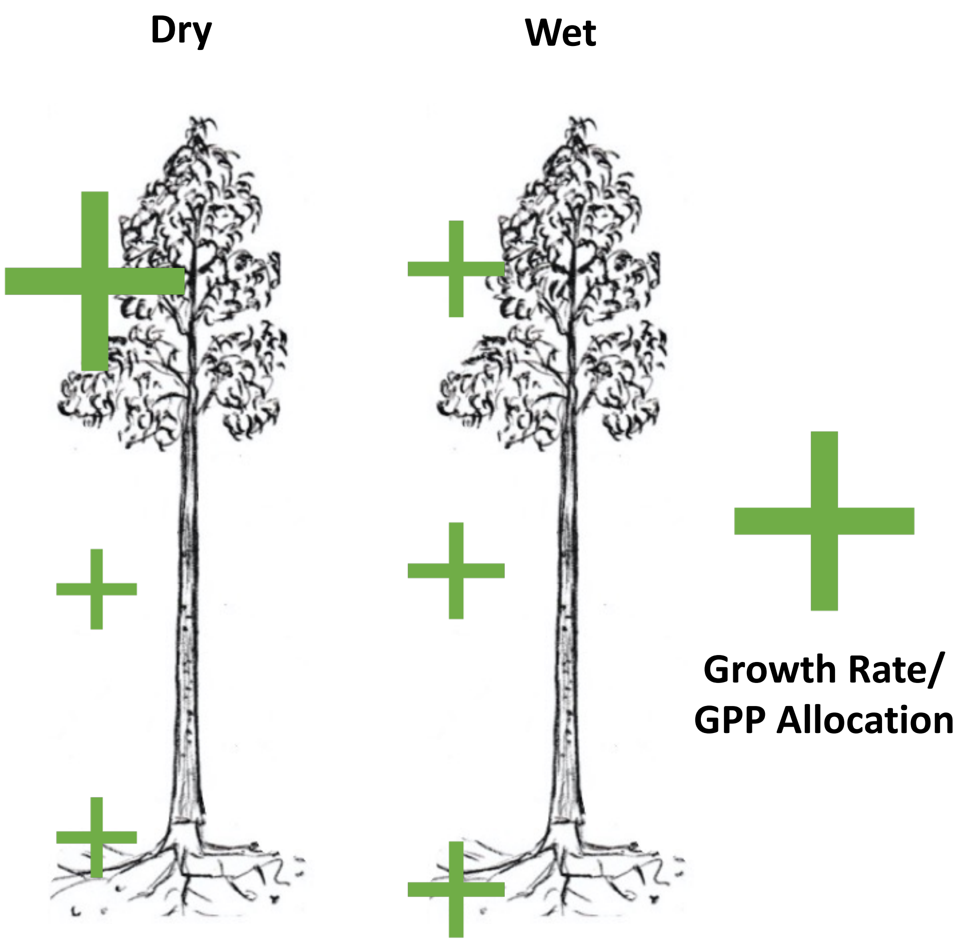


Allocation shifts are heterogeneous across not only ecosystems (the different site studies) but also within species

The partitioning of gross primary production for young *Eucalyptus tereticornis* trees under experimental warming and altered water availability

John E. Drake[1,2], Mark G. Tjoelker[1], Michael J. Aspinwall[1,3], Peter B. Reich[1,4], Sebastian Pfautsch[1,5] and Craig V. M. Barton[1]

Found **no** allocation shifts in Eucalyptus Trees

Production and carbon allocation in a clonal *Eucalyptus* plantation with water and nutrient manipulations

Jose Luiz Stape[a,*], Dan Binkley[b], Michael G. Ryan[c]

Found allocation shifts in Eucalyptus Tress

- Prevents upscaling of behavior based on site studies and plant functional type
- Widespread site studies are not a viable option however

It is hard to acquire data on allocation shifts

- It is hard to measure non-structural carbohydrates and belowground carbon pools

- The few site studies available with allocation shift measurements, due to measurement techniques, required sampling of the hard to measure biomass pools

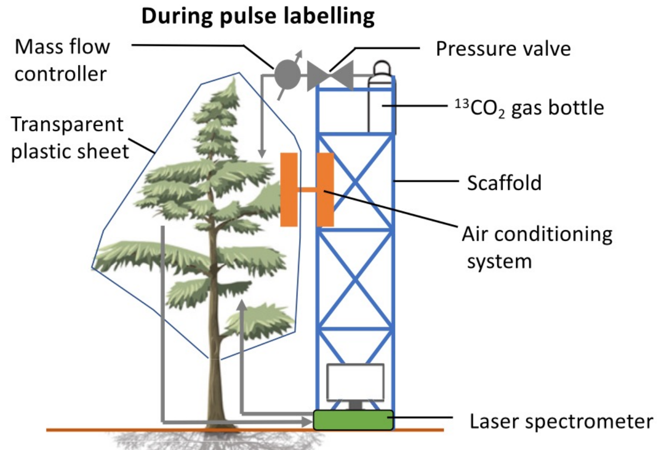
Method 1

$$\text{TBCA} = F_S - F_A + \Delta[C_S + C_R + C_L + C_T]$$

Requires periodic sample of belowground biomass

Stape et al., 2014

Method 2



^{13}C tracking still requires belowground sampling

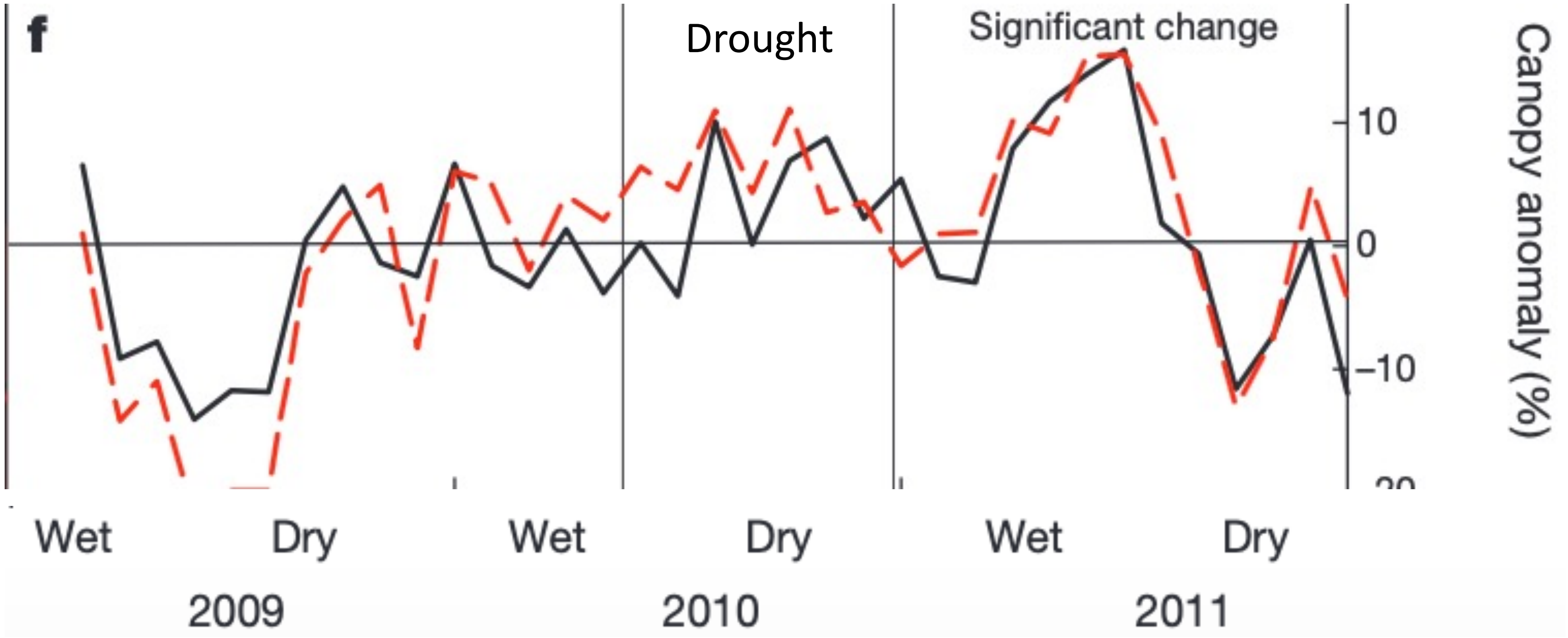
Joseph et al., 2020

Due to the difficulty of acquiring data on allocation shifts and the necessity of site-specific measurements, we propose the following hypothesis:

Hypothesis 1): **Allocation shifts can be inferred from indirect constraints with model-data fusion, instead of from direct measurements of different C pools**

The following slides describe why we infer allocation shifts

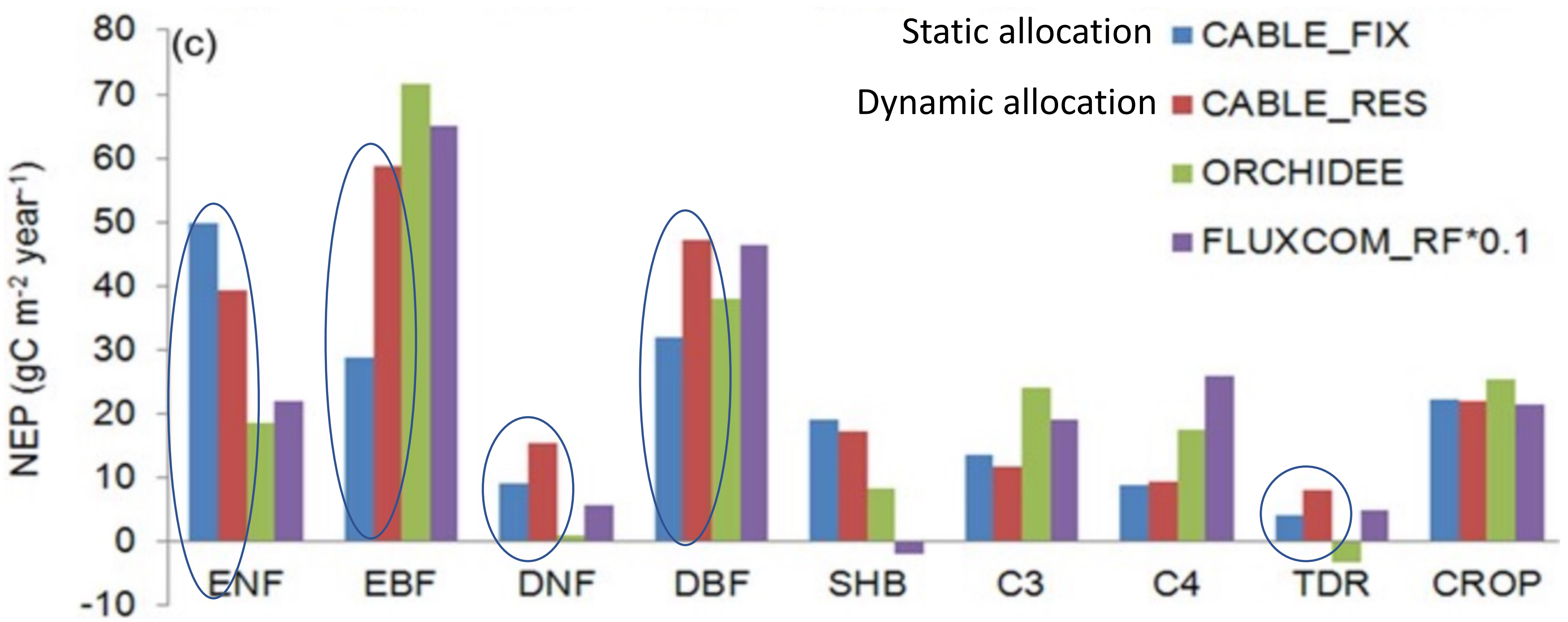
Drought induced carbon allocation shifts impact carbon fluxes in in-situ studies



Doughty et al., 2015

Allocation shifts to foliage in the study above were responsible for increase in foliage and consequently GPP post drought

Allocation shifts have a significant impact in land surface model NBE



Xia et al., 2017

Dynamic allocation model in CABLE resulted in significantly different NBE values compared to when static allocation is used

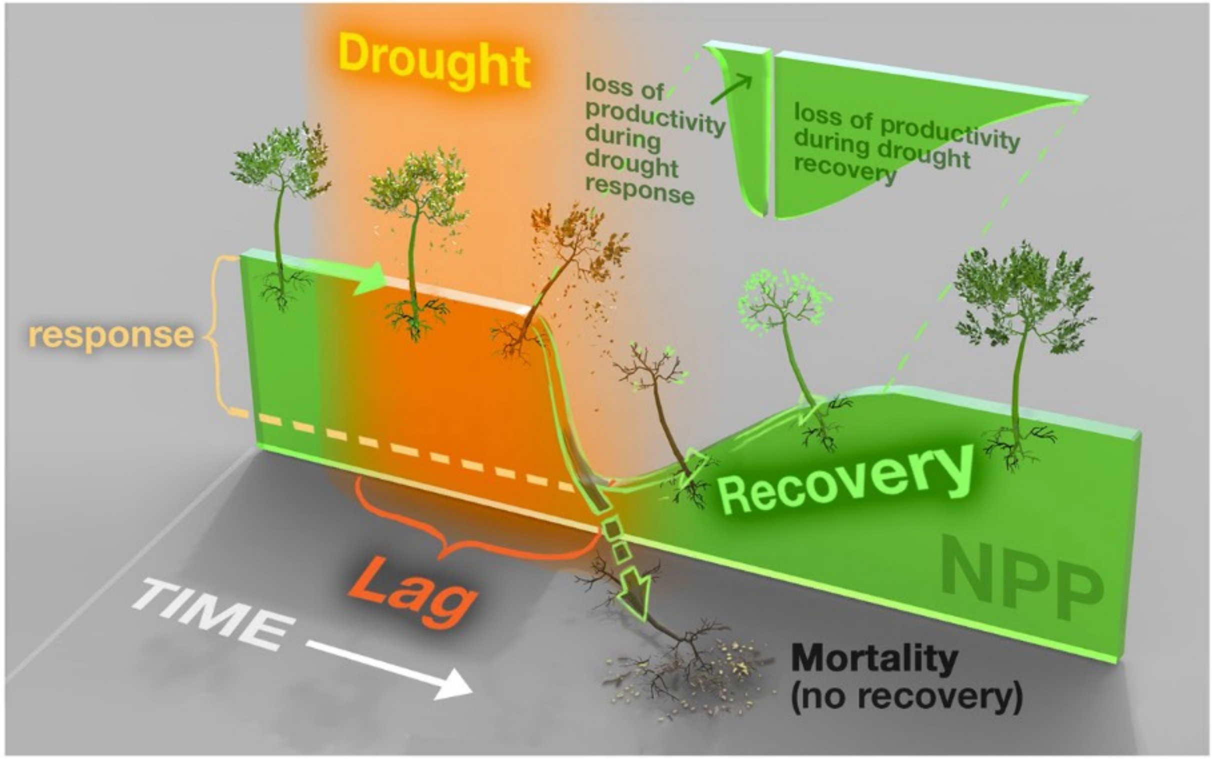
Land surface models poorly implement allocation shifts

- Many vegetation models still use constant allocations (Merganicova et al., 2019)

- Those that do base shifts on environmental factors are often poorly parameterized (De Kauwe et al., 2014)

Allocation shifts possible reason why land surface models mismodel drought recovery, due too their effect on carbon fluxes post drought

Land surface models overestimate drought NBE recovery magnitude and time by a factor of 4 when compared to estimates of NBE from tree rings (Kolus et al., 2019)



Kolus et al., 2019

The importance of allocation shifts to carbon fluxes (both measured and modeled), leads to the following two hypothesis:

Hypothesis 2): ***Inferred dynamic carbon allocations improve model predictions of net biosphere exchange (NBE)***

Hypothesis 3): ***Inferred dynamic carbon allocations contribute significantly to drought legacy effects on NBE***

Test hypothesis using data from a dry and wet tropical flux tower

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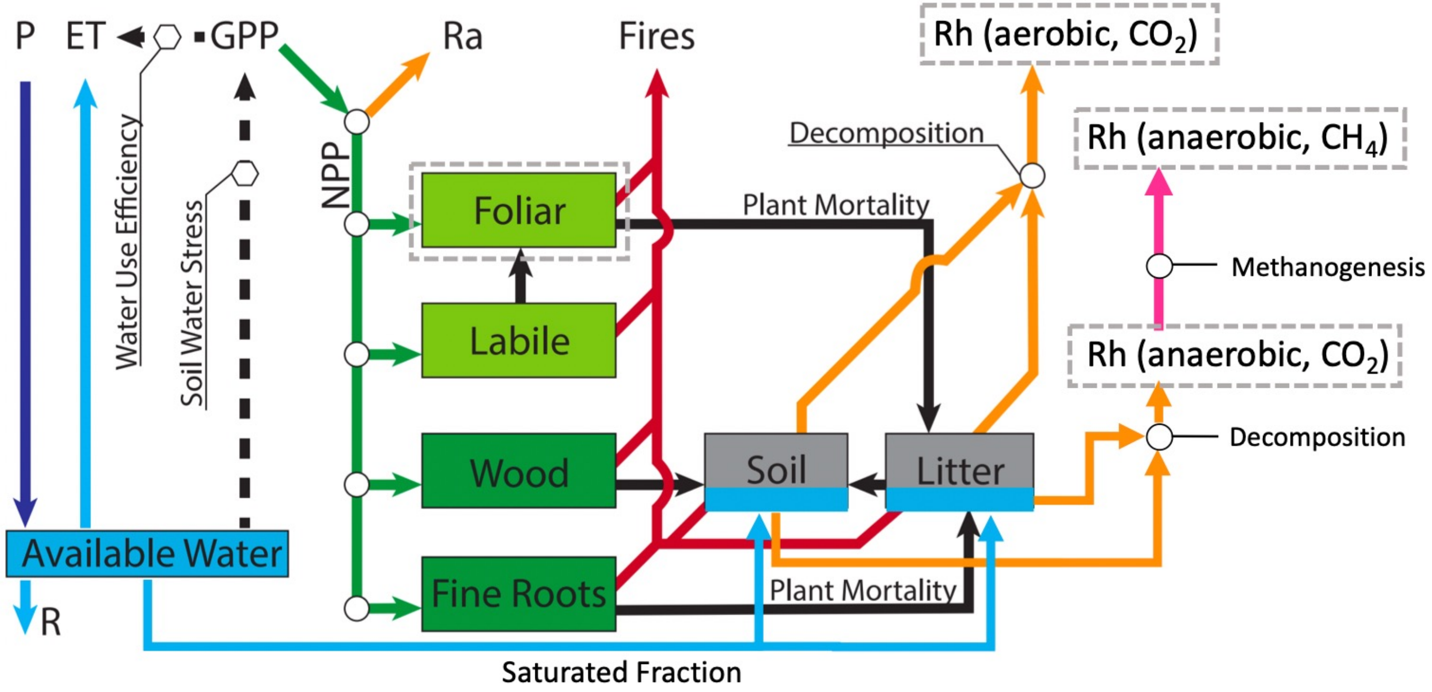
CARDAMOM - a tool to infer allocation shifts using site data (eventually satellite)

CARDAMOM is a model data fusion framework that optimizes DALEC parameters to match assimilated observations such as LAI

DALEC allocates GPP to autotrophic respiration, as well as foliar, labile, wood, and fine root pools

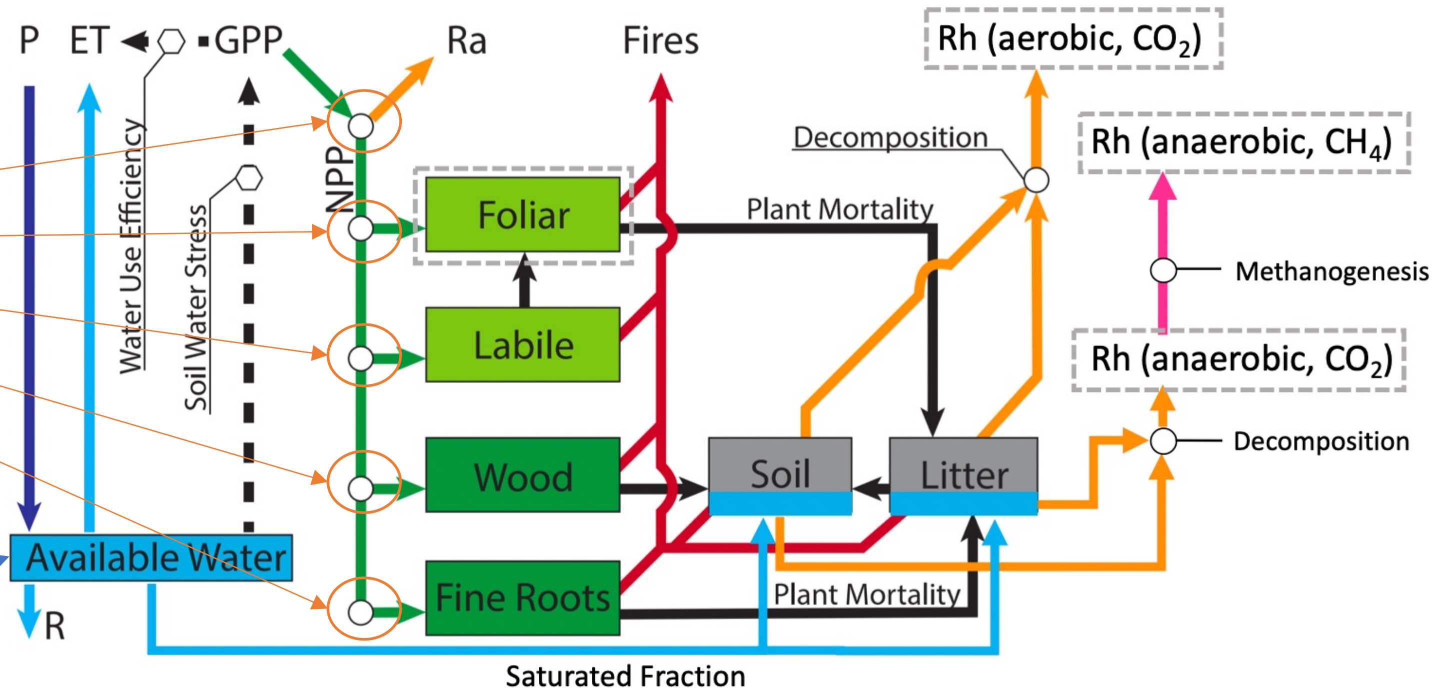


DALEC a ”simple” land surface model within the CARDAMOM data assimilation framework (Shuang et al., 2022)

CARDAMOM - a tool to infer allocation shifts using site or satellite data

DALEC usually has a static allocation structure **(allocation does not change based on water availability)**

We adjust this structure to make the allocation based on the plant available water pool (PAW)



DALEC a "simple" land surface model within the CARDAMOM data assimilation framework (Shuang et al., 2022)

Current static allocation formula within DALEC

$$f_{fol} + f_{lab} + f_{wood} + f_{root} + f_{autoresp} = 1$$

4 parameters within DALEC are used to model allocation

- Allocation to wood is a residual of these 4 parameters

f_{wood} = 1 - (f_{fol}+f_{lab} +f_{root} +$f_{autoresp}$)

We switch this static allocation structure with one that responds to DALEC's plant available water pool

Flexible dynamic allocation with logistic function
(allocation changes as a function of plant available water)

Retrieved Parameters (10)

- s_f: Allocation during wet periods
- d_f: Allocation during dry periods
- k: Rate of change parameter
- W_o: Plant available water at midpoint

Other

- A_f: CARDAMOM allocation
- W: CARDAMOM plant available water
- f = {Autotroph resp, Labile, Foliar, Root}

If $d_f > s_f$

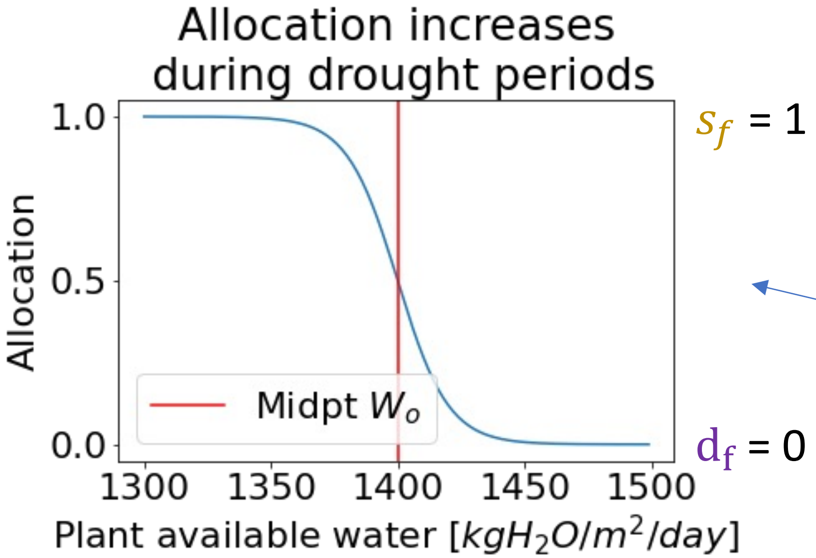
$$A_f(W) = s_f + \frac{(d_f - s_f)}{1 + \exp(k(W - W_o))}$$

If $d_f < s_f$

$$A_f(W) = d_f + \frac{(s_f - d_f)}{1 + \exp(-k(W - W_o))}$$

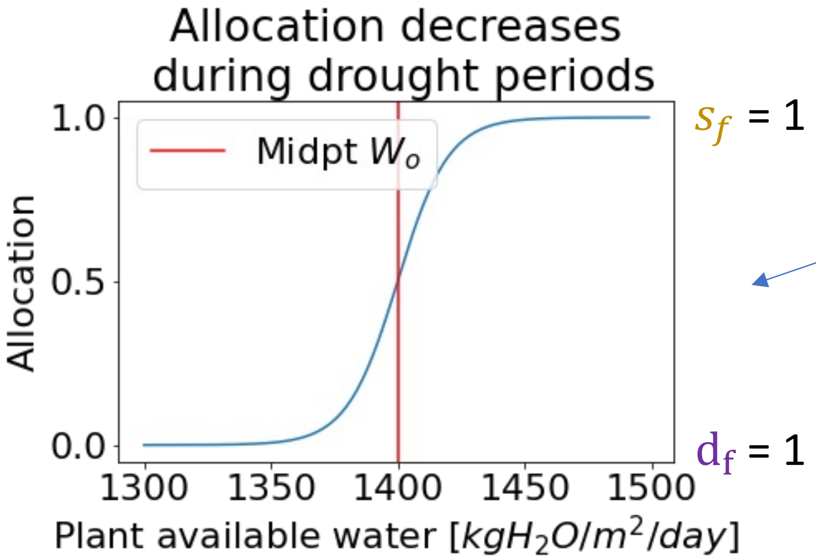
*Note Allocation to the wood pool is still a residual of the other 4 allocations but also takes the form of a logistic function

Flexible dynamic allocation structure incorporates two equations to allow for increasing and decreasing allocation shifts



If $d_f > s_f$

$$A_f(W) = s_f + \frac{(d_f - s_f)}{1 + \exp(k(W - W_o))}$$



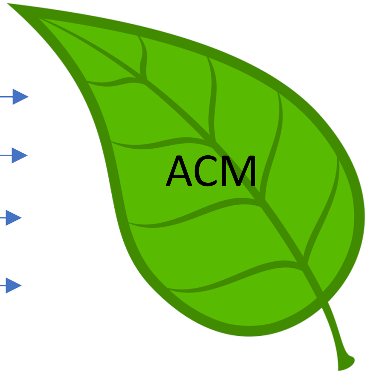
If $d_f < s_f$

$$A_f(W) = d_f + \frac{(s_f - d_f)}{1 + \exp(-k(W - W_o))}$$

Drought carbon flux feedbacks (components of NBE) within DALEC as a result of allocations shifts

Gross Primary Productivity= GPP_ACM*(PAW/Wilting Point)

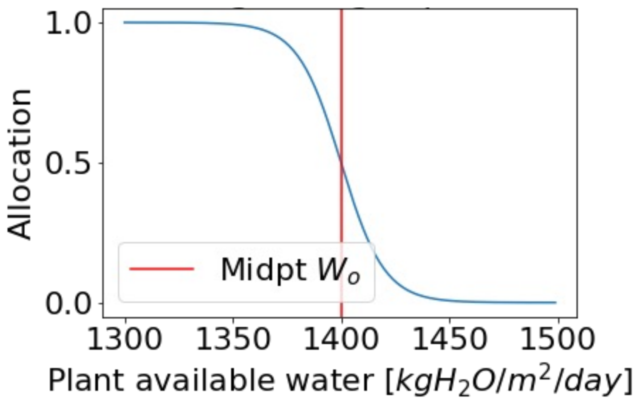
LAI
TEMP
CO2
SSRD



GPP_ACM (William et al 2005)

Autotropic Respiration

PAW



Autotropic Respiration

Heterotrophic Respiration (Shuang et al 2022)

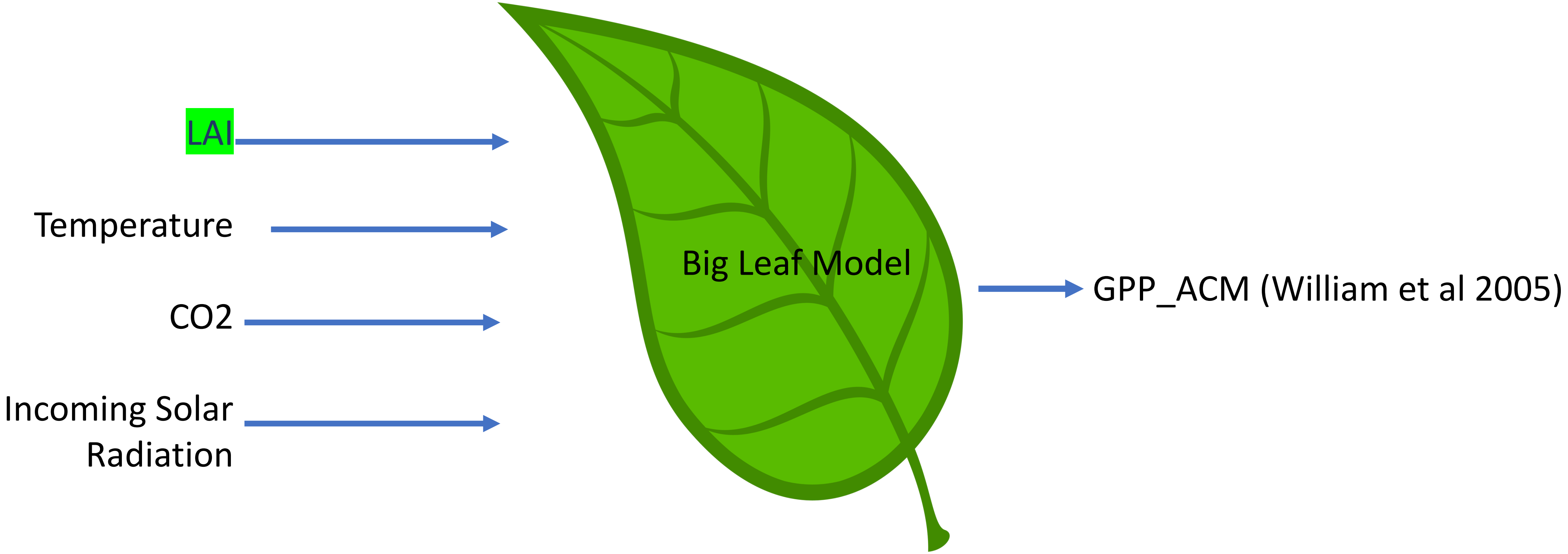
TEMP
PAW
SOM
LITTER

Heterotrophic Respiration

Green highlight: Allocation shift immediate effect
Yellow Highlight: Allocation shift tertiary effect

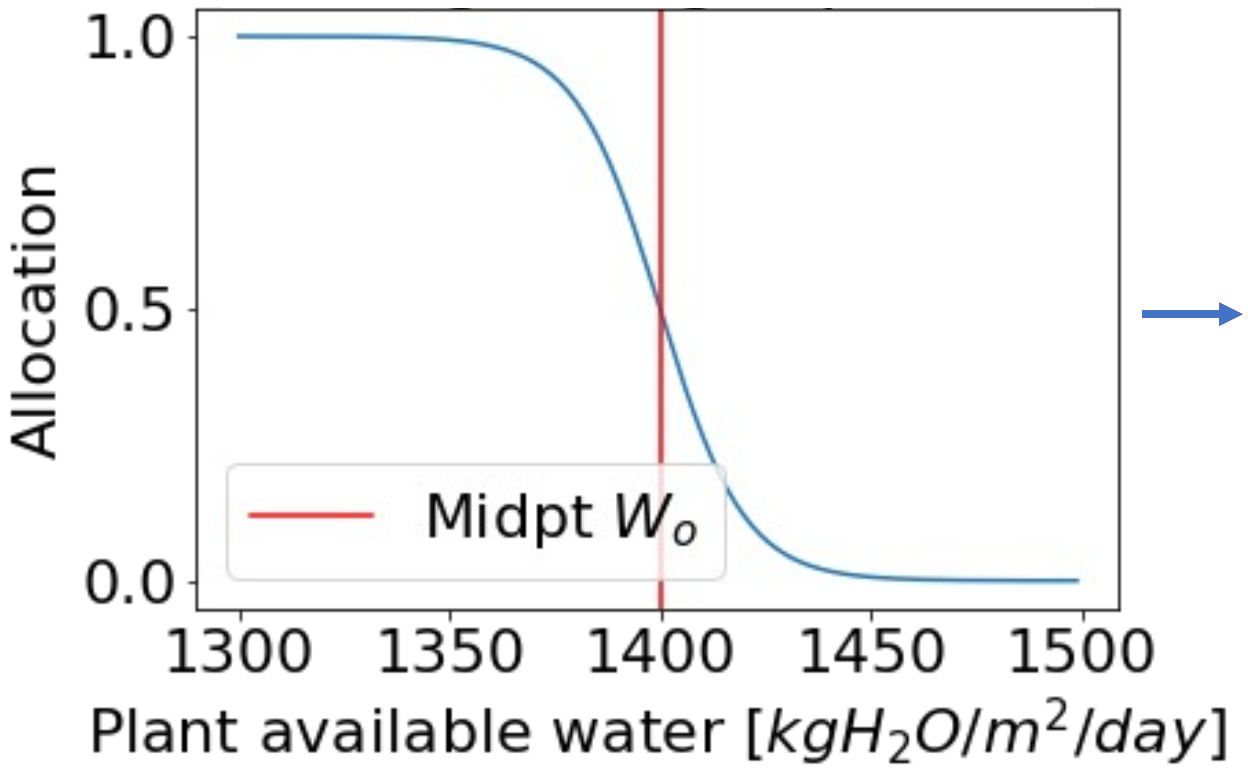
Allocation shifts affect GPP within DALEC through changes in allocation to foliage, which changes LAI

Gross Primary Productivity= GPP_ACM*(PAW/Wilting Point)



Allocation shifts directly impact autotrophic respiration (the only control on Autotrophic respiration within DALEC)

Plant Available Water (PAW) →



→ Autotropic Respiration

Allocation shifts contribute to SOM and Litter pools in DALEC by changing the size of the live biomass pools

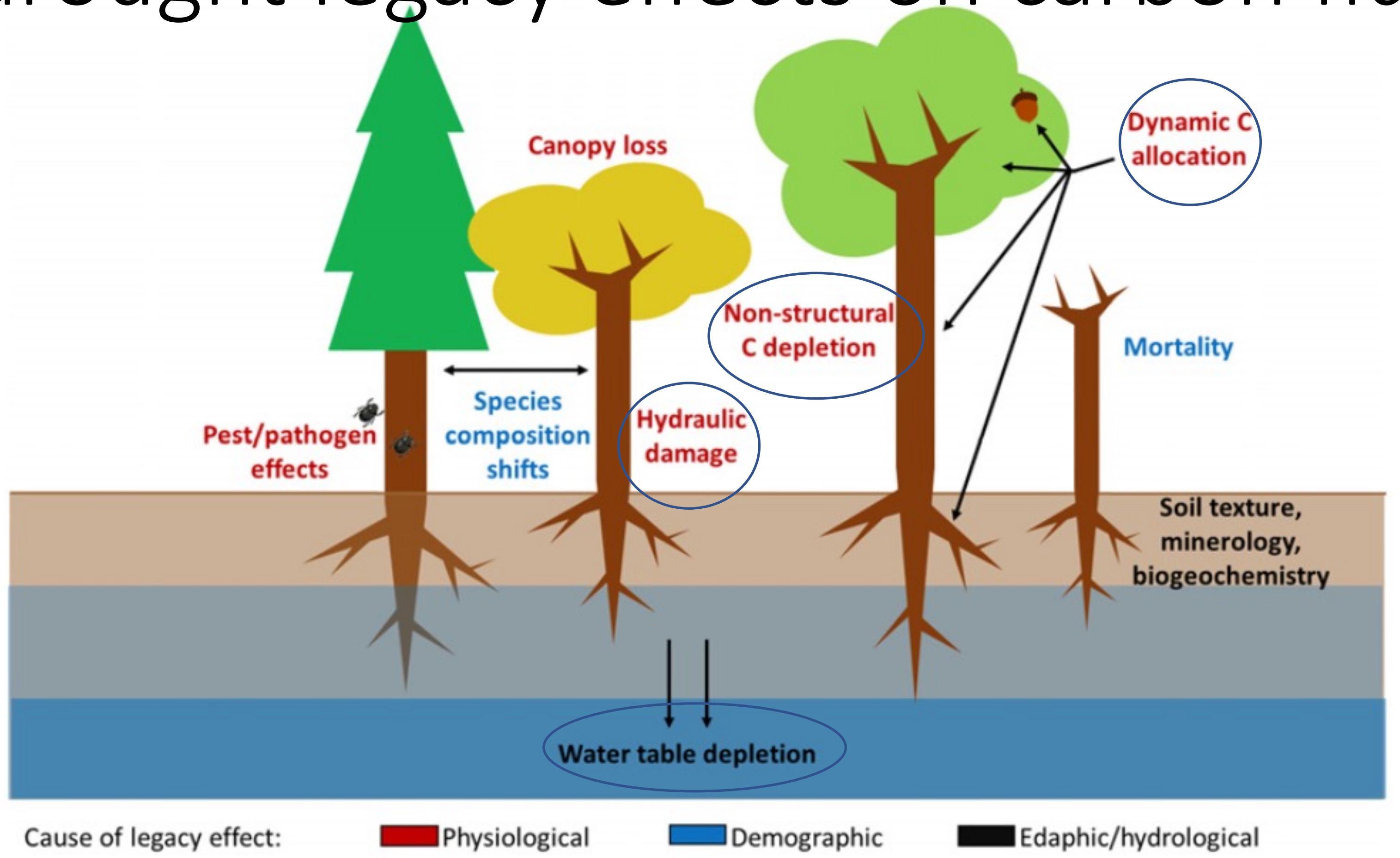
Heterotrophic Respiration (Shuang et al., 2022)

TEMP
PAW
SOM
LITTER

Heterotrophic Respiration

Quicker effect through Litter pool due to quicker turnover times of the Foliage pool

DALEC does not model all hypothesized controls of drought legacy effects on carbon fluxes



Kannenberg et al., 2020

- Circled processes show feedbacks currently implemented within DALEC
- If we can isolate the impact of the allocation shifts on carbon fluxes within DALEC we can get an idea of their significance

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  *Cumberland Plains
- Proposed experiment for hypothesis 3 (allocation shifts contribute significantly to drought recovery magnitude and time)

Cumberland Plains Setup

Old Growth Forest with Eucalyptus *(moluccana & fibrosa)* and *Melaleuca decora* (tea trees)

Droughts occurred in 2014, 2018-2019

Observations:

Flux tower:

- Net biosphere exchange (NBE),
- gross primary productivity (GPP) evapotranspiration (ET)
- Meteorology

In-situ: Soil organic matter and above ground biomass

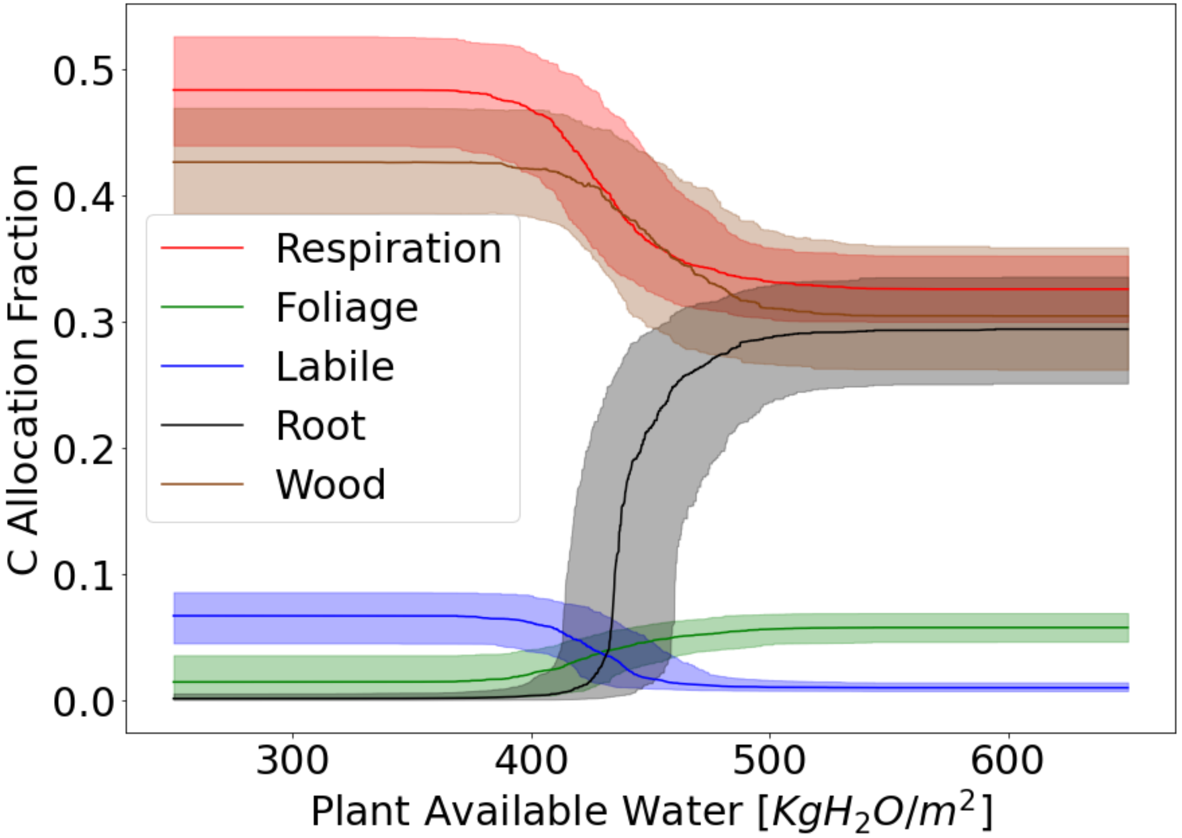
MODIS: Leaf area index (LAI)

Inferred Allocation for Cumberland Plains Site

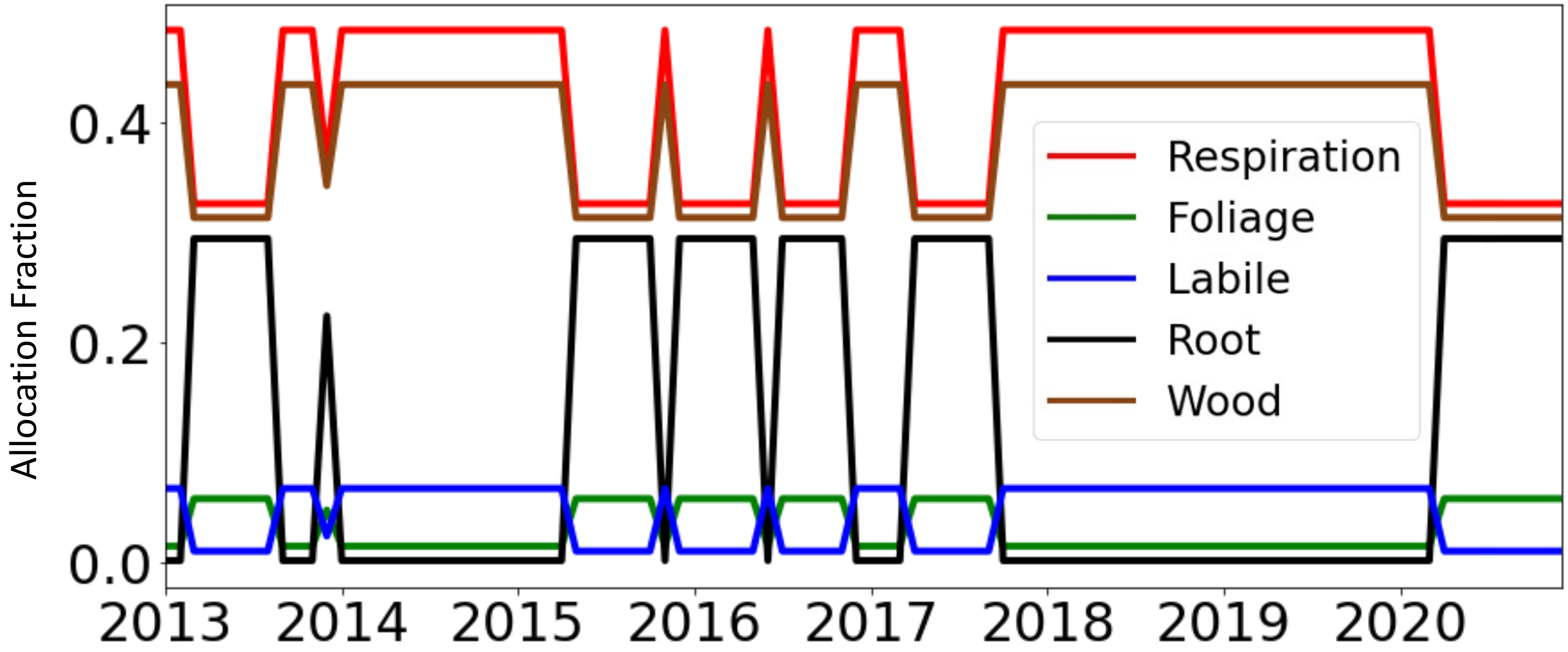
Autotrophic respiration, wood, and labile growth increase during dry periods, whereas fine root and foliar growth decrease

Trees increase xylem density to avoid cavitation (Trugman et al., 2019):

Reduce root allocation due to damaged roots (Joseph et al., 2020)

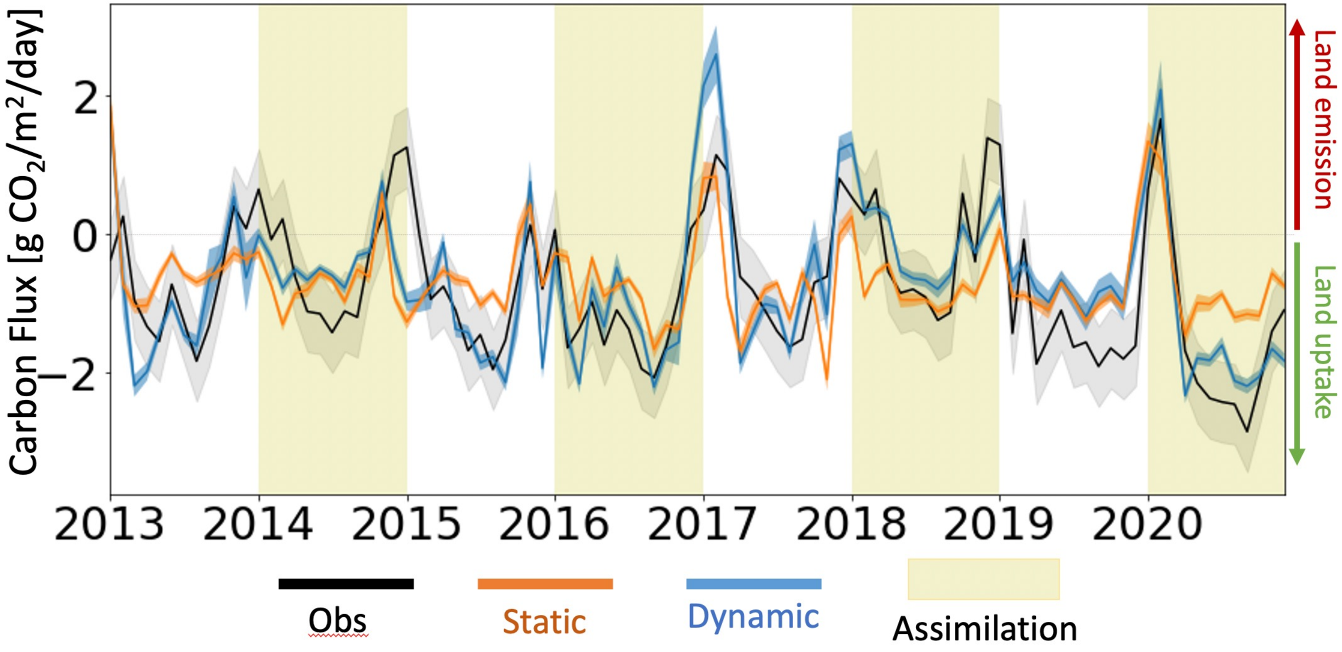


Persistent allocation changes during drought (2014, 2018-2019)



Sharp allocation shifts due to monthly timescales (allocation shifts tend to have a weekly/daily timescale)

Model with dynamic C allocation shifts shows improved NBE predictive ability



Prediction R^2	Static	Dynamic
NBE	0.14	0.42
LAI	0.32	0.41
ET	0.24	0.25

(RMSE pattern qualitatively similar)

The Dynamic allocation version of CARDAMOM better predicts NBE and LAI significantly during non assimilated periods (the nonshaded parts of the timeseries)

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  - *French Guiana
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French Guiana

Observations:

Flux tower:

- Net biosphere exchange (NBE)
- Evapotranspiration (ET)
- Meteorology

In-situ: Above and Belowground Biomass (ABGB)

Copernicus: Mean leaf area index (LAI)

GRACE: Equivalent water thickness (EWT)

Allocation shifts from previous study

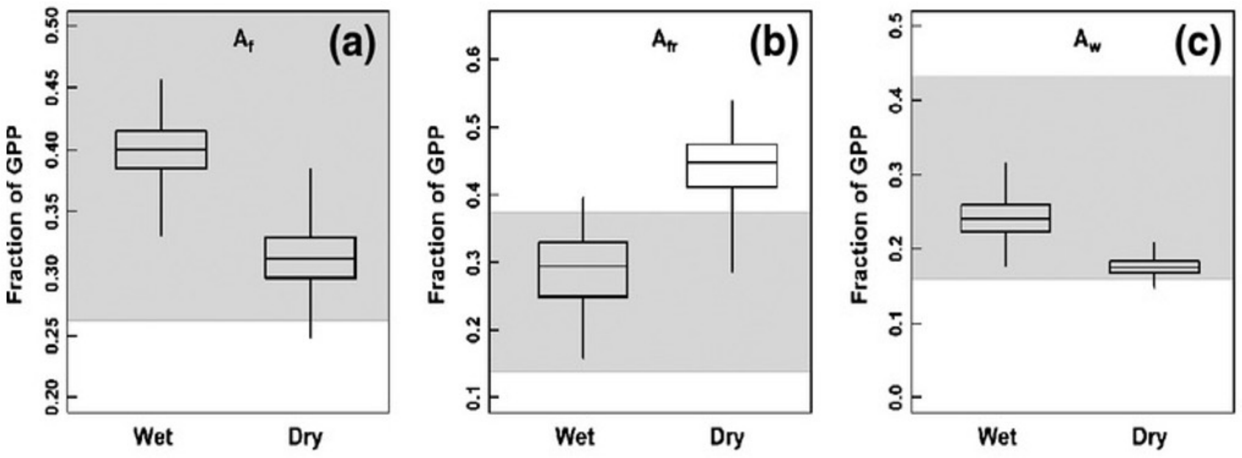
A study at this site assimilated wet and dry season observations into separate CARDAMOM simulations and derived separate static allocation parameters

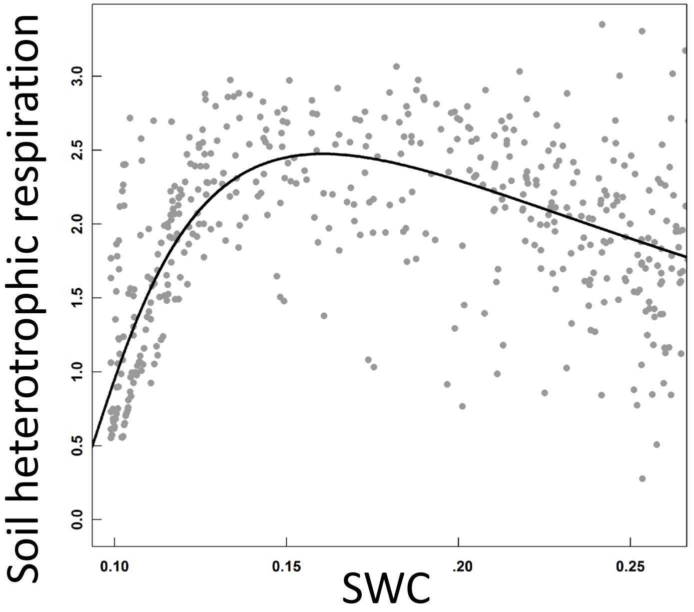
Compared those derived static allocations to quantify a shift in allocation

Included an empirical soil heterotrophic respiration curve within DALEC

Rowland et al., 2014 GCB

Allocation Foliage   Allocation Fine Roots   Allocation Wood

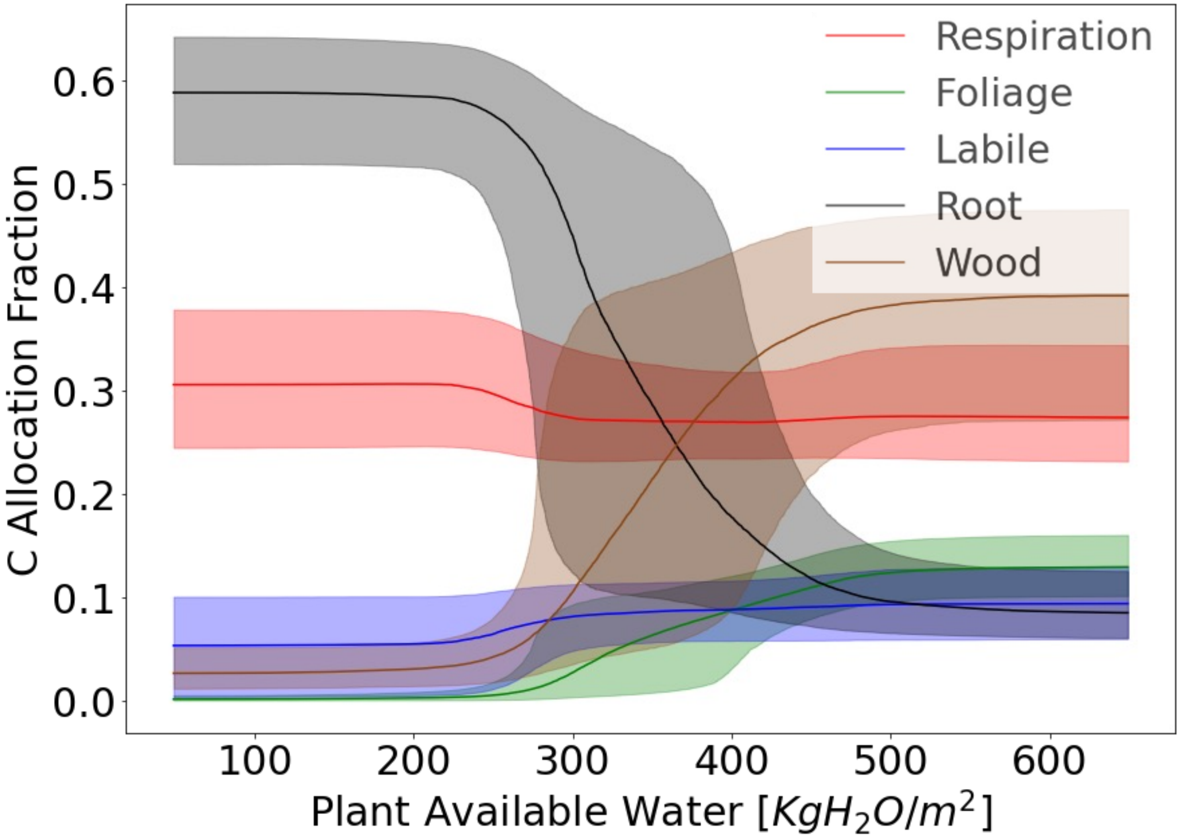




Our model finds allocation shifts Consistent with Rowland et al., 2014 GCB

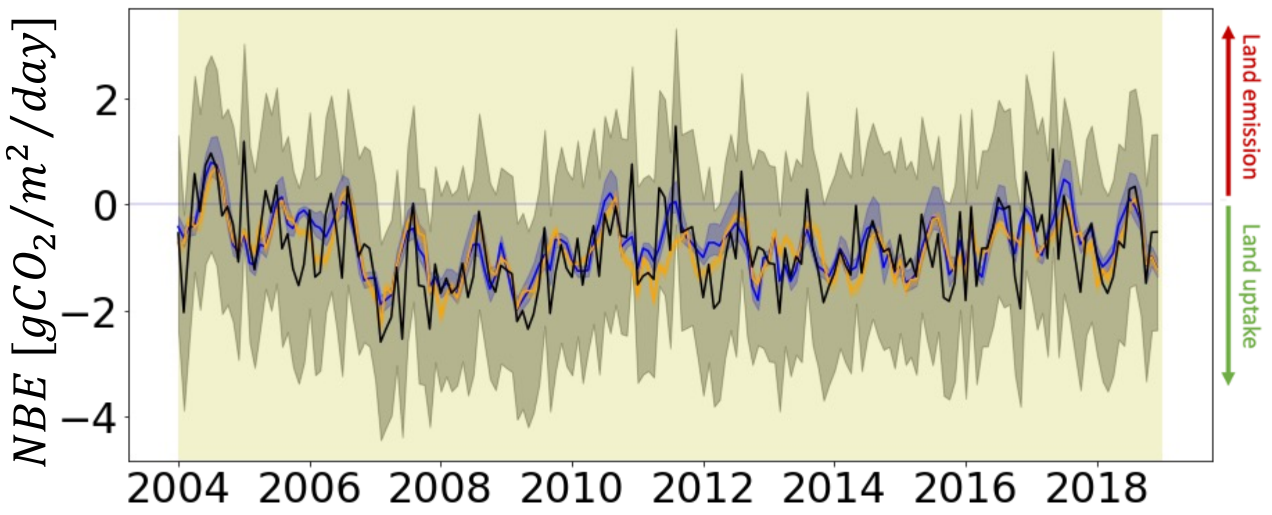
Rowland Allocation	**Magnitude of shift**	**Direction of shift**
Foliage	.4 -> .3 [±.05]	decrease
Fine Roots	.3 -> .45 [±.1]	increase
Wood	.25 -> .18 [±.06]	decrease

My Allocation	**Magnitude of shift**	**Direction of shift**
Foliage	.1 -> 0 [±.10]	decrease
Fine Roots	.12 -> .61 [±.07]	increase
Wood	.4 -> 003[±.07]	decrease



*In-situ measurement of wood growth also found wood allocation decreasing with water stress (Wagner et al., 2011)

Model with dynamic C allocation shifts shows improved NBE Fit

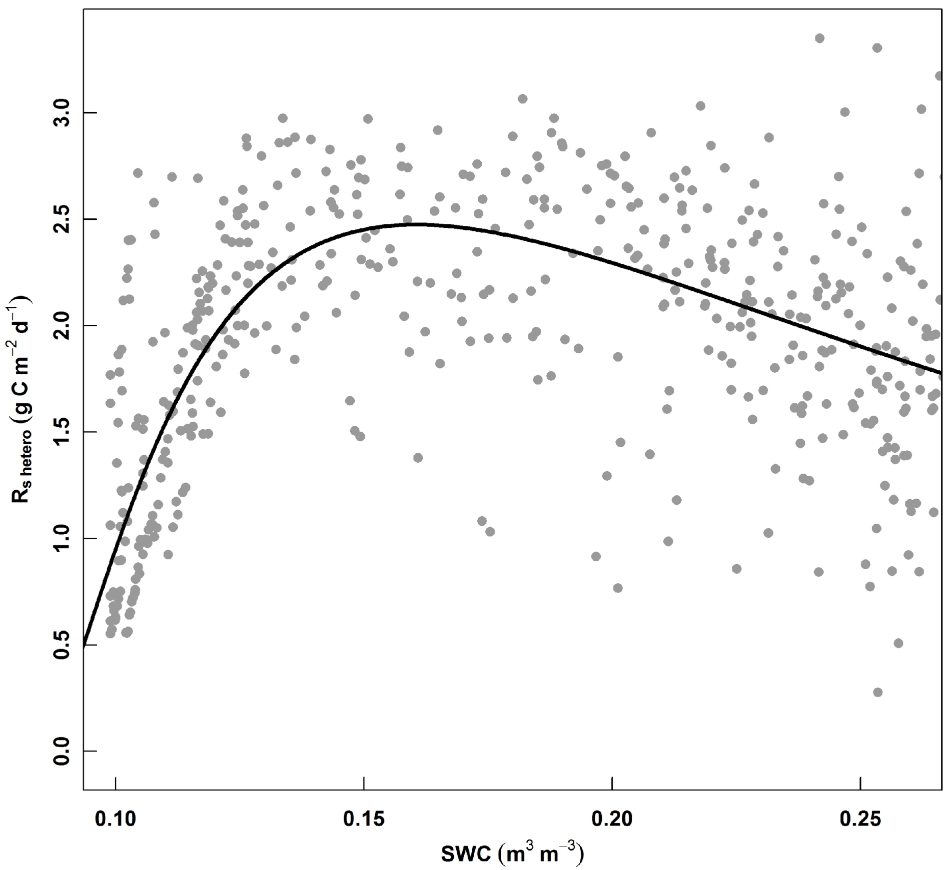


R^2	Static	Dynamic
NBE	0.34	0.42
ET	0.35	0.51

The Dynamic allocation version of CARDAMOM better models NBE and LAI significantly

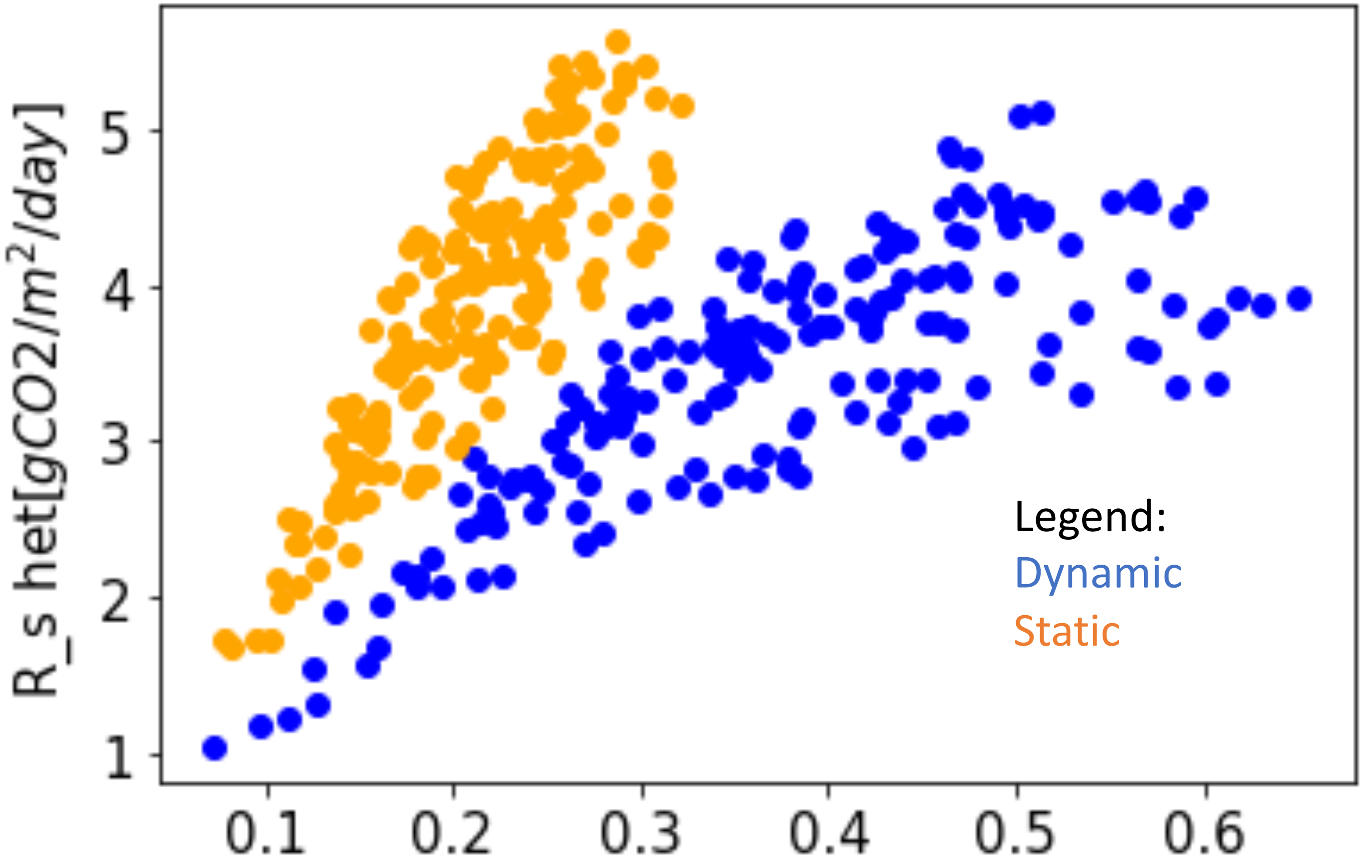
Comparison of modeled monthly respiration curve to respiration curve from daily observations

French Guiana observations



Rowland et al., 2014 GCB

CARDAMOM



Soil Moisture (PAW/PAW_fs)

Our version of CARDAMOM infers the respiration vs soil moisture relationship instead of the empirical implementation within the study by Rowland et al., 2014

These are preliminary results for French Guiana

New data to be assimilated:

- In-situ LAI
- 3 more years of NBE
- In-situ CH_4 measurements to better constrain heterotrophic respiration
- Extra biomass measurements

Data to be compared against:

- Litter measurements
- Representative soil moisture measurements

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How much do allocation shifts affect the magnitude and timing of recovery in NBE and GPP after drought?

Perturb the meteorology of the DALEC drivers by replacing drought meteorology with their climatological average using SPEI index

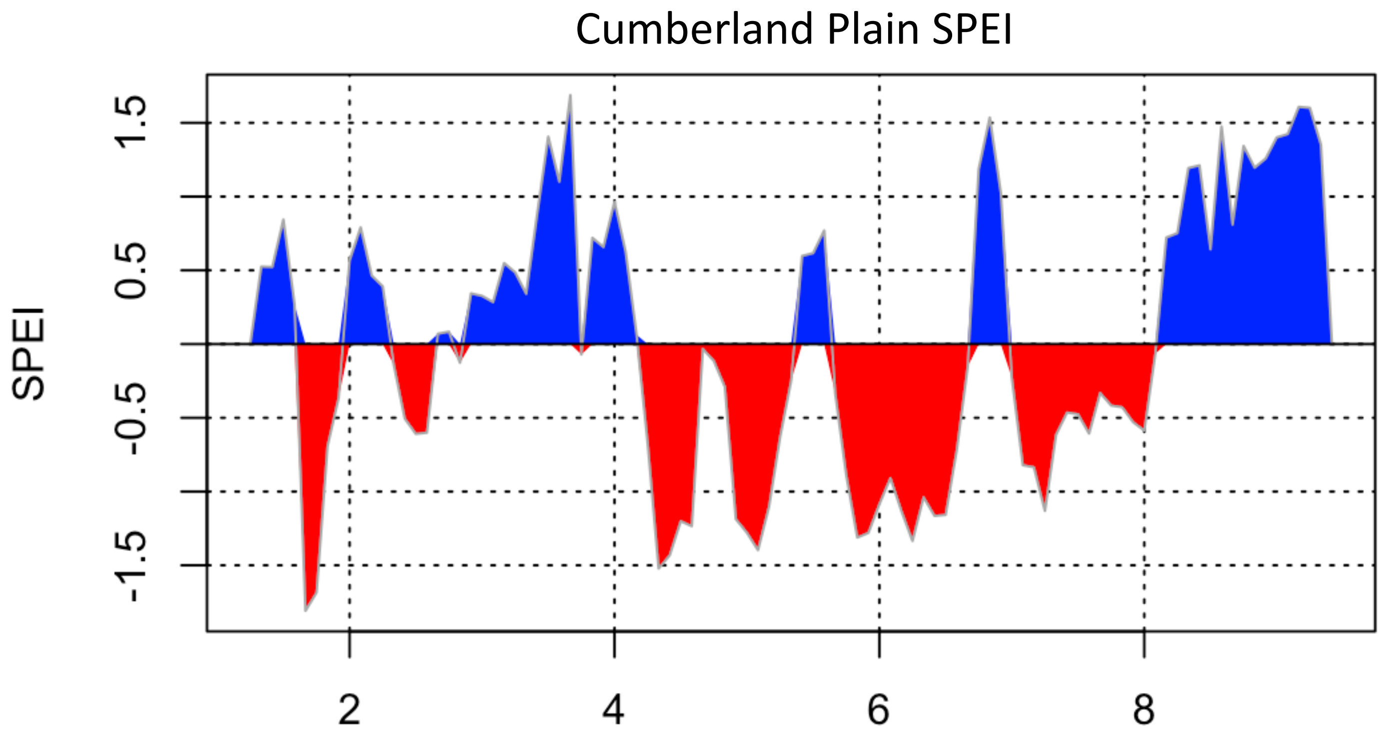
- Vapor pressure deficit
- Precipitation
- Temperature
- Shortwave Radiation

Prevent allocations from shifting during drought by switching dynamic allocation to its temporal average

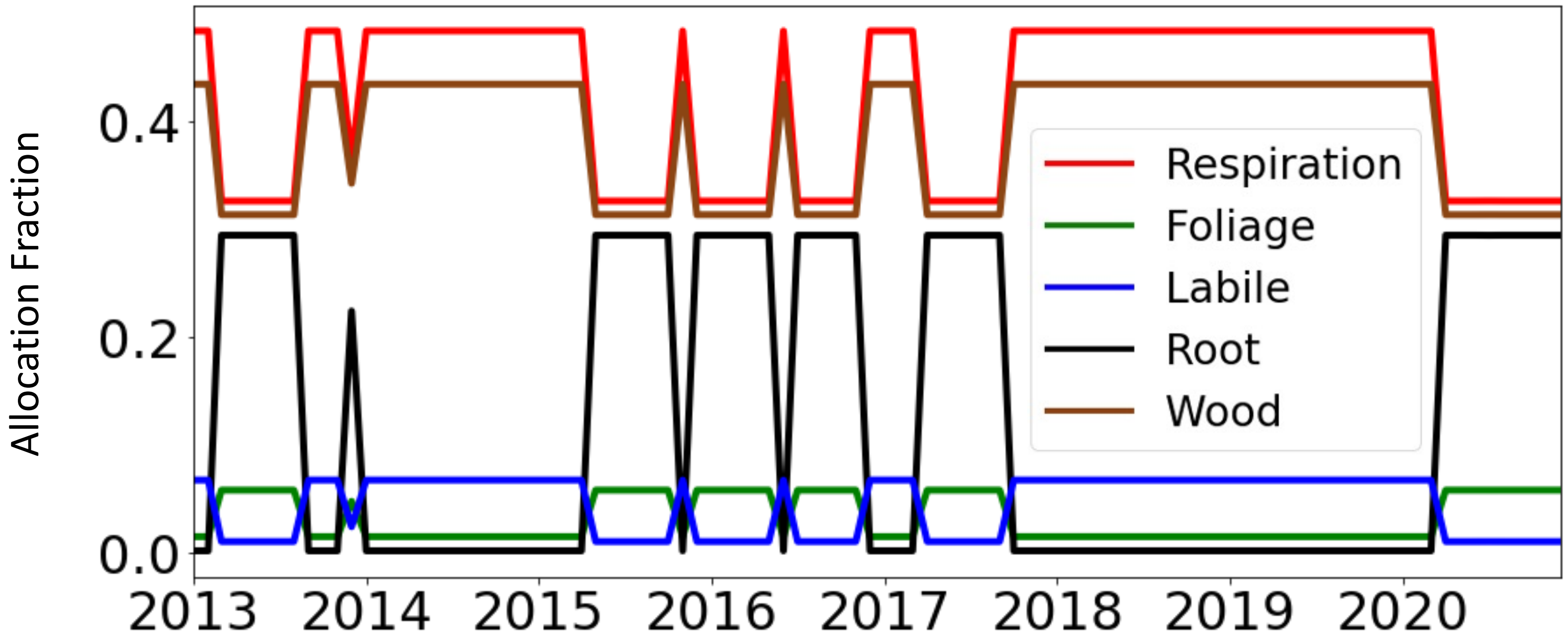
Calculate Drought times with SPEI Index

Calculate average climatological values using non-drought times from the SPEI Index

Replace drought times from SPEI index with climatological averages to get meteorology without drought ($\widehat{\boldsymbol{M}}$)



Replace allocation shift parameters with average allocation ($\hat{y}$)



We take the average value across the time series for allocation to autotrophic respiration, foliage, labile, root and wood.

Isolating the impact of allocation shift due to drought with 4 Runs with DALEC (Dynamic Model)

Run 1

Drought, Allocation Shift
*DALEC (**M, y**)*

The first run models NBE with both the normal meteorology (M) and the optimized parameters from CARDAMOM (y)

This gives us a baseline timeseries of modeled net biosphere exchange that includes all the feedbacks from drought: $NBE = DALEC\ (M, y)$

This timeseries is the Dynamic Model time series shown in slides 30 and 35

Isolating the impact of allocation shift due to drought: 4 Runs with DALEC

The second run models NBE with the adjusted meteorology without drought conditions ($\widehat{M}$) and the optimized parameters (y)

This gives us a timeseries of net biosphere exchange that is unaffected by drought and any of the feedback mechanisms: $NBE = DALEC(\widehat{M}, y)$

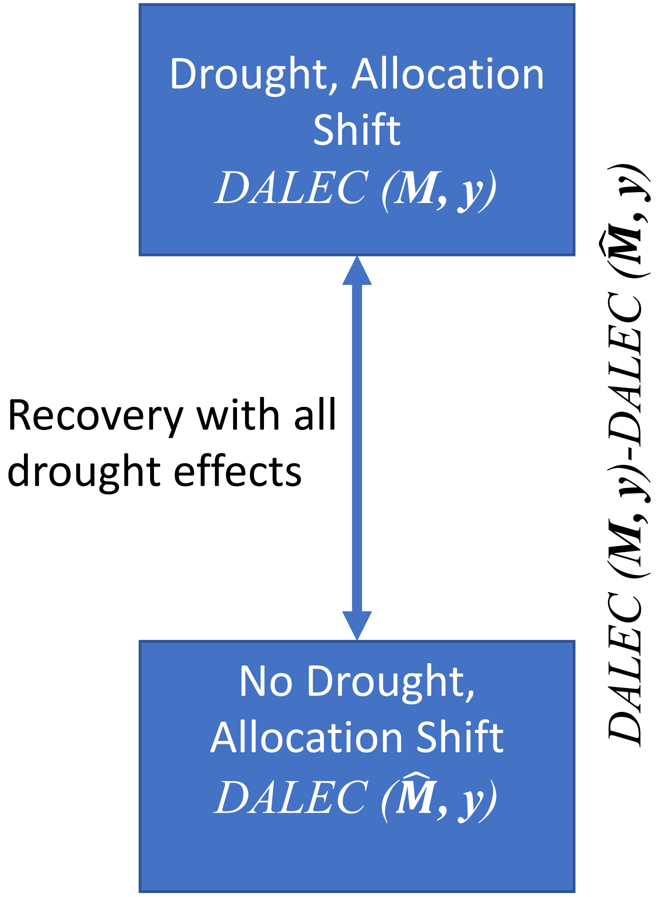
Run 2

No Drought,
Allocation Shift
$DALEC\ (\widehat{\mathbf{M}}, y)$

Isolating the impact of allocation shift due to drought: 4 Runs with DALEC

By comparing the NBE from these two runs we quantify how severely drought impacts NBE magnitude:

$$\frac{\Delta NBE}{\Delta drought} = DALEC(M, y) - DALEC(\widehat{M}, y)$$



Isolating the impact of allocation shift due to drought: 4 Runs with DALEC

Run 3

Drought, Averaged Allocation
$DALEC\ (\boldsymbol{M}, \hat{\mathbf{y}})$

The third run models NBE with the normal meteorology (M) and the averaged allocations along with the other optimized parameters ($\hat{y}$).

This gives us a time series of NBE that includes all the feedbacks from drought **except** for allocation shifts: $NBE = DALEC(M, \hat{y})$.

Isolating the impact of allocation shift due to drought: 4 Runs with DALEC

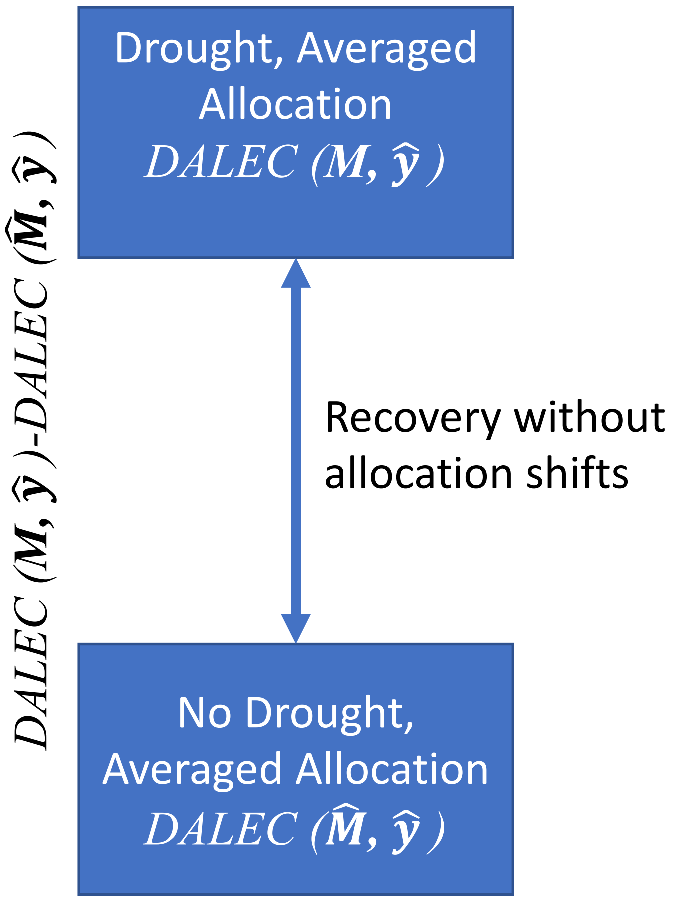
The fourth run models NBE with the adjusted meteorology without drought ($\widehat{M}$) and the averaged allocations along with the other optimized parameters ($\hat{y}$).

This gives us a time series of NBE that includes none of the feedbacks from drought as well as the impact of static, average allocation shifts: $NBE \;=\; DALEC(\widehat{M}\;, \hat{y})$.

Run 4

No Drought,
Averaged Allocation
$DALEC\;(\widehat{\mathbf{M}}, \hat{\mathbf{y}}\;)$

Isolating the impact of allocation shift due to drought: 4 Runs with DALEC



By comparing the NBE from these two runs we quantified the extent to which all the drought mechanisms **excluding** allocation shifts impact NBE magnitude:

$$\frac{\Delta NBE}{\Delta drought\ \notin allocation\ shifts} = DALEC(M, \hat{y}) - DALEC(\hat{M}, \hat{y})$$

Isolating the impact of allocation shift due to drought: 4 Runs with DALEC

Drought, Averaged Allocation
DALEC $(\mathbf{M}, \hat{\mathbf{y}})$

Recovery without allocation shifts

No Drought, Averaged Allocation
DALEC $(\hat{\mathbf{M}}, \hat{\mathbf{y}})$

Drought, Allocation Shift
DALEC $(\mathbf{M}, \mathbf{y})$

Recovery with all drought effects

No Drought, Allocation Shift
DALEC $(\hat{\mathbf{M}}, \mathbf{y})$

Therefore, to quantify the impact of just the allocation shifts we compared the difference between the first two runs with the difference of the second two runs:

$$\frac{\Delta NBE}{\Delta allocation\ shift} = \frac{\Delta NBE}{\Delta drought} - \frac{\Delta NBE}{\Delta drought \notin allocation\ shifts}$$

Isolating the impact of allocation shift due to drought: 4 Runs with DALEC

Drought, Averaged Allocation
$DALEC\ (\boldsymbol{M}, \hat{\boldsymbol{y}})$

Drought, Allocation Shift
$DALEC\ (\boldsymbol{M}, \boldsymbol{y})$

No Drought, Averaged Allocation
$DALEC\ (\widehat{\boldsymbol{M}}, \hat{\boldsymbol{y}})$

No Drought, Allocation Shift
$DALEC\ (\widehat{\boldsymbol{M}}, \boldsymbol{y})$

Recovery without allocation shifts

Quantify allocation shift impact on recovery

Recovery with all drought effects

$$\frac{\Delta NBE}{\Delta allocation\ shift} = \frac{\Delta NBE}{\Delta drought} - \frac{\Delta NBE}{\Delta drought \notin allocation\ shifts}$$

***M* = meteorological drivers**
***y* = cardamom parameters**
$\widehat{\boldsymbol{M}}$ **= meteorological drivers with drought replaced**
$\hat{\boldsymbol{y}}$ **= cardamom parameters with allocation shift averaged**
***NBE or GPP* =** $DALEC\ (\boldsymbol{M}, \boldsymbol{y})$

Conclusion

Demonstrate the ability to infer drought induced carbon allocation shifts (a hard to measure quantity) from flux measurements

Showed improvements in predicting carbon fluxes when using inferred drought induced carbon allocation shifts

Proposed experimental setup to quantify the contribution of allocation shifts to drought recovery time and magnitude of NBE and GPP