Model Validation and Sensitivity Analysis on Tropical Dry Forest Response to Nutrient Fertilization

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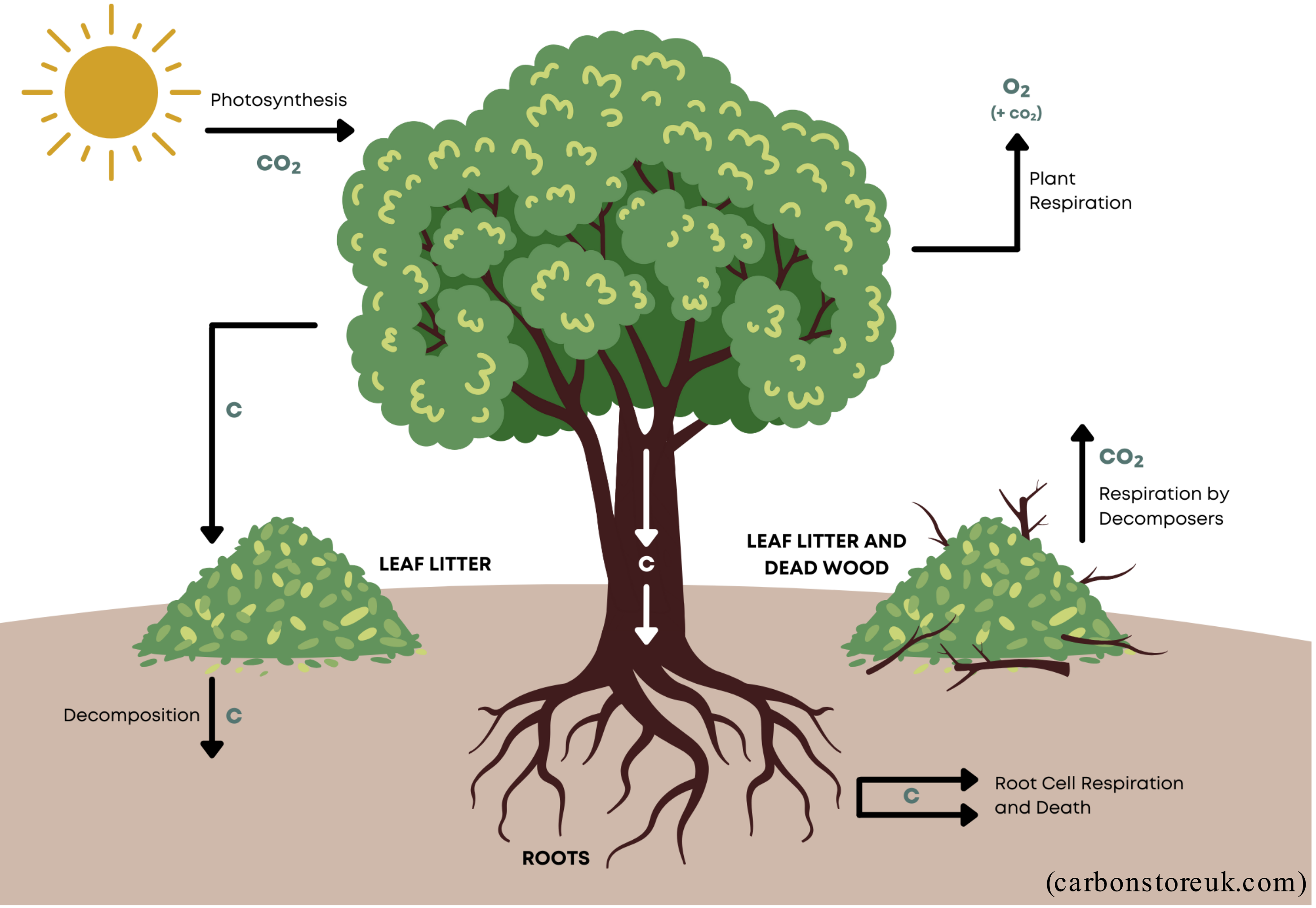
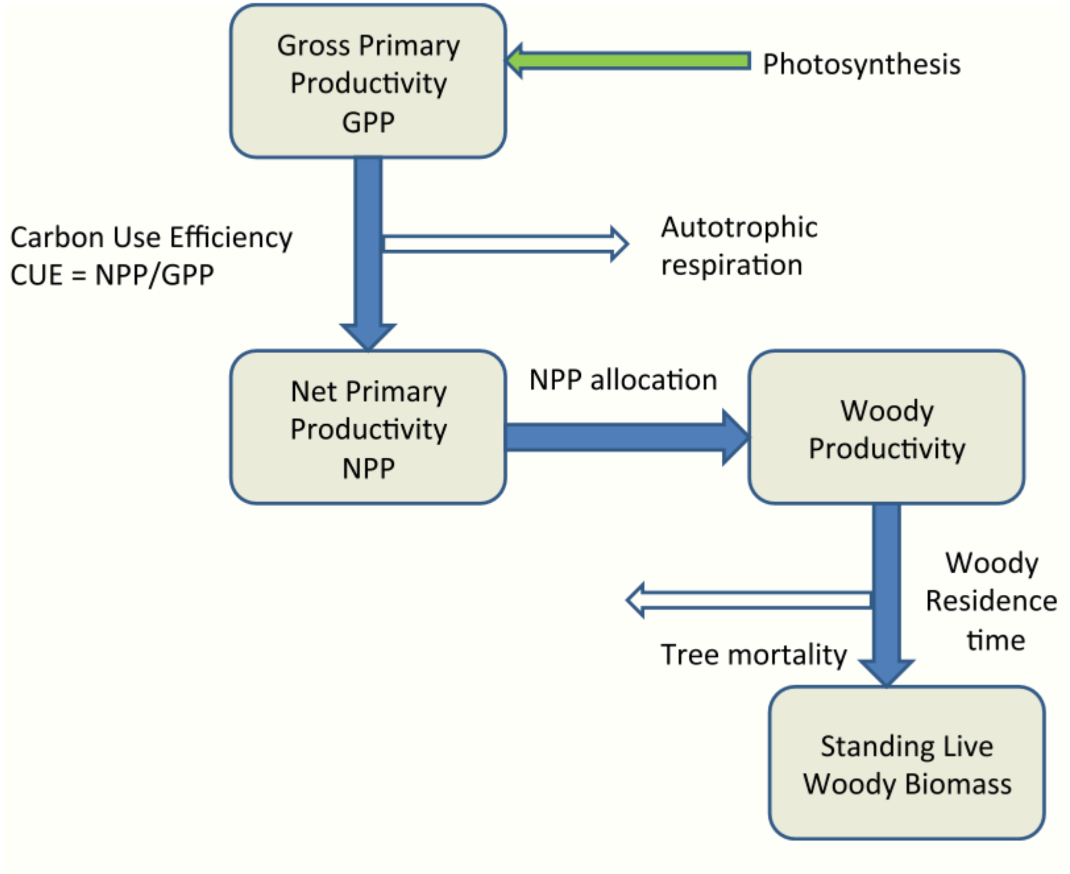
Representation of forest carbon cycle in Earth System Models

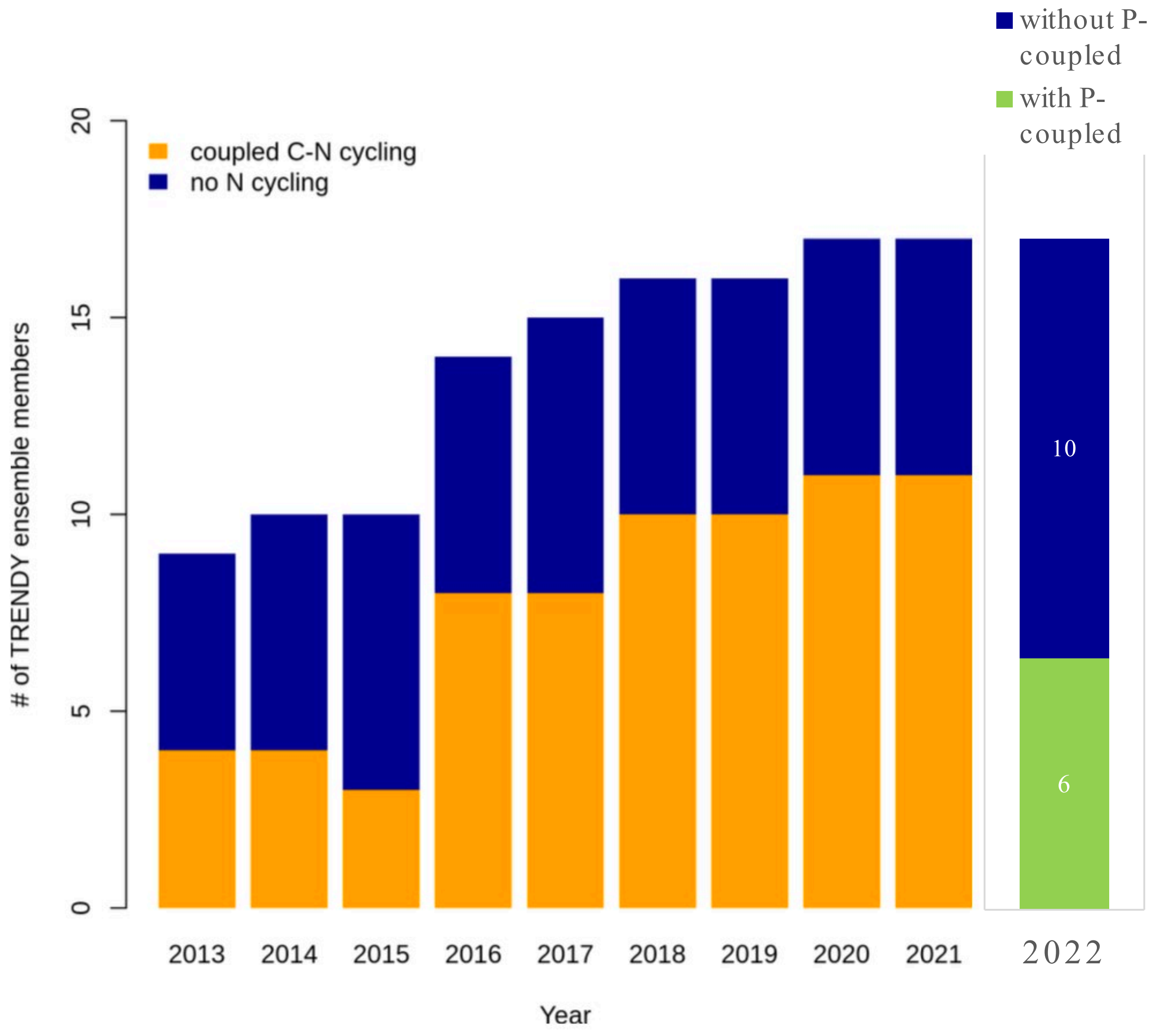


(carbonstoreuk.com)



Malhi et al., 2012

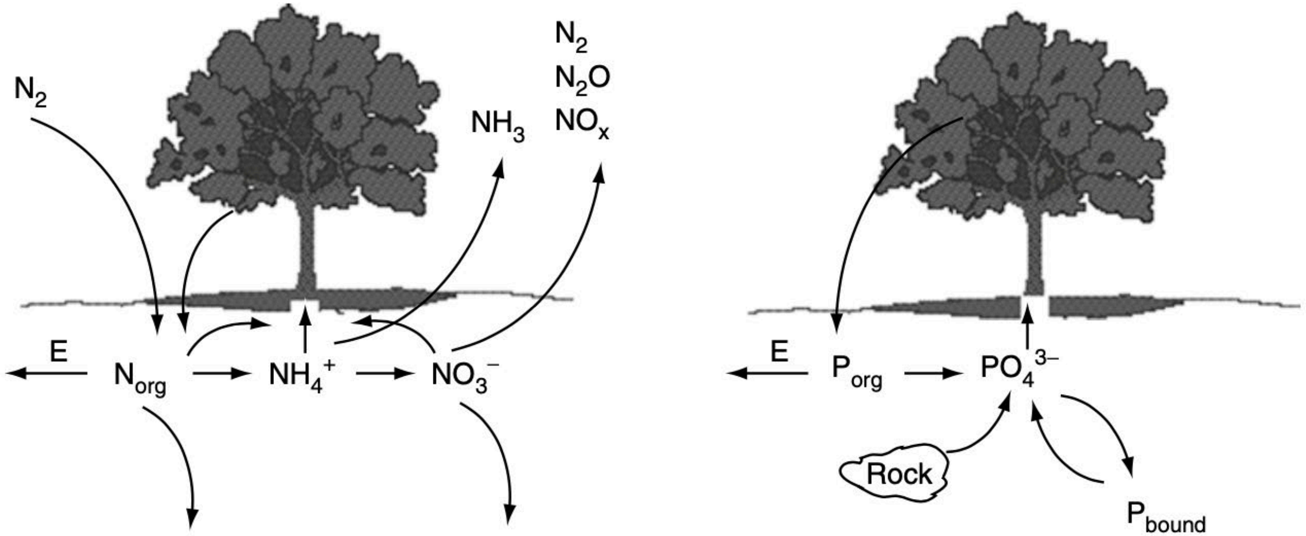
Inaccurate/insufficient representation of forest carbon cycle in ESMs



Number of terrestrial biosphere models contributing to the Global Carbon Project (the TRENDY ensemble) with and without coupled C–N-P cycling.

(Kou-Giesbrecht et al. 2023; Menge et al. 2023)

Soil nutrient availability influences carbon budget globally



Chapin et al.
Principles of Terrestrial Ecosystem Ecology

Ecology, 89(2), 2008, pp. 371–379

NITROGEN LIMITATION OF NET PRIMARY PRODUCTIVITY IN TERRESTRIAL ECOSYSTEMS IS GLOBALLY DISTRIBUTED

David S. LeBauer[1,3] and Kathleen K. Treseder[2]

nature geoscience LETTERS
PUBLISHED ONLINE: 20 APRIL 2015 | DOI: 10.1038/NGEO2413

Future productivity and carbon storage limited by terrestrial nutrient availability

William R. Wieder[1,2★], Cory C. Cleveland[3], W. Kolby Smith[3,4] and Katherine Todd-Brown[5,6]

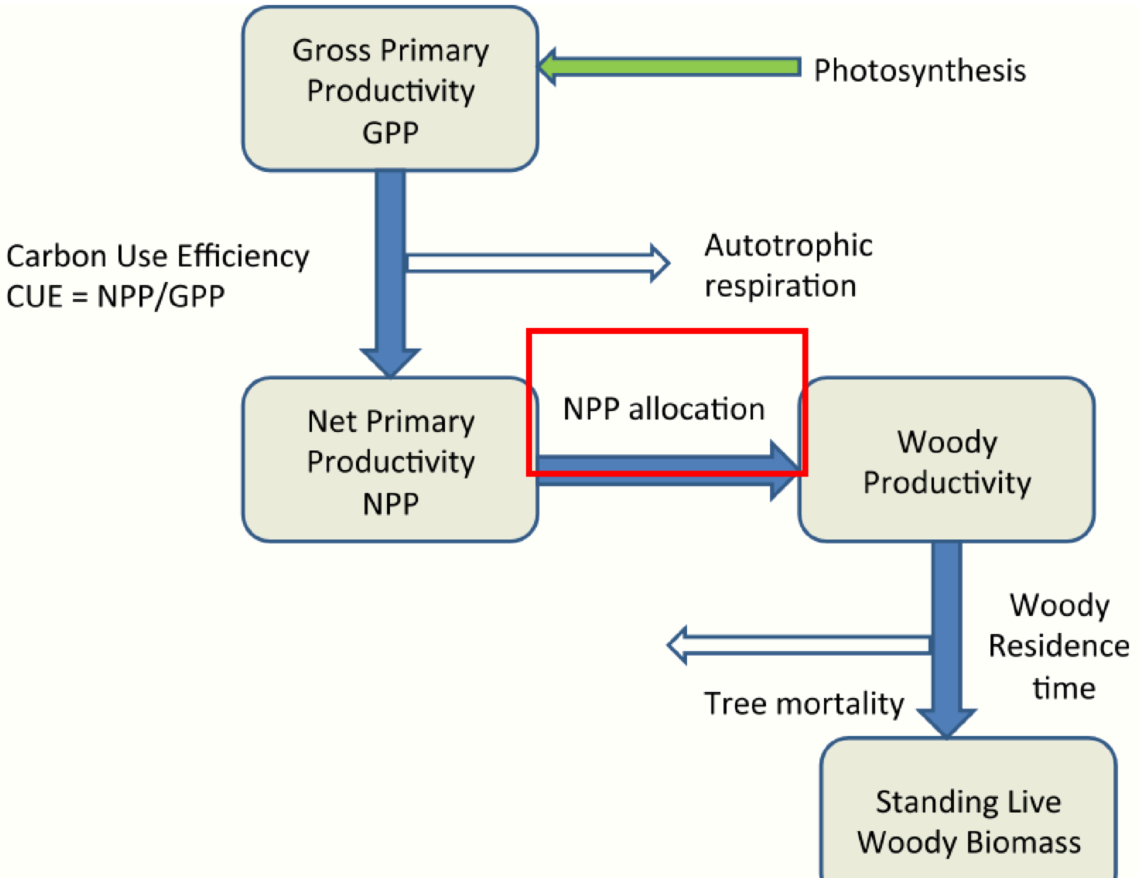
nature COMMUNICATIONS
ARTICLE
https://doi.org/10.1038/s41467-020-14492-w OPEN

Global meta-analysis shows pervasive phosphorus limitation of aboveground plant production in natural terrestrial ecosystems

Enqing Hou[1,2,3★], Yiqi Luo[3], Yuanwen Kuang[1,2], Chengrong Chen[4], Xiankai Lu[1,2], Lifen Jiang[3], Xianzhen Luo[1,2] & Dazhi Wen[1,2★]

Inaccurate/insufficient representation of forest carbon cycle in ESMs

limited the understanding and predictability of the fate of the forests



Malhi et al., 2012

- ❑ Question:
How will plants adjust NPP allocation, particularly to below- vs. above-ground parts, in response to nutrient fertilization in tropical dry forests?

How plants adjust allocation in response to soil nutrient change?

Multiple limitation theory:

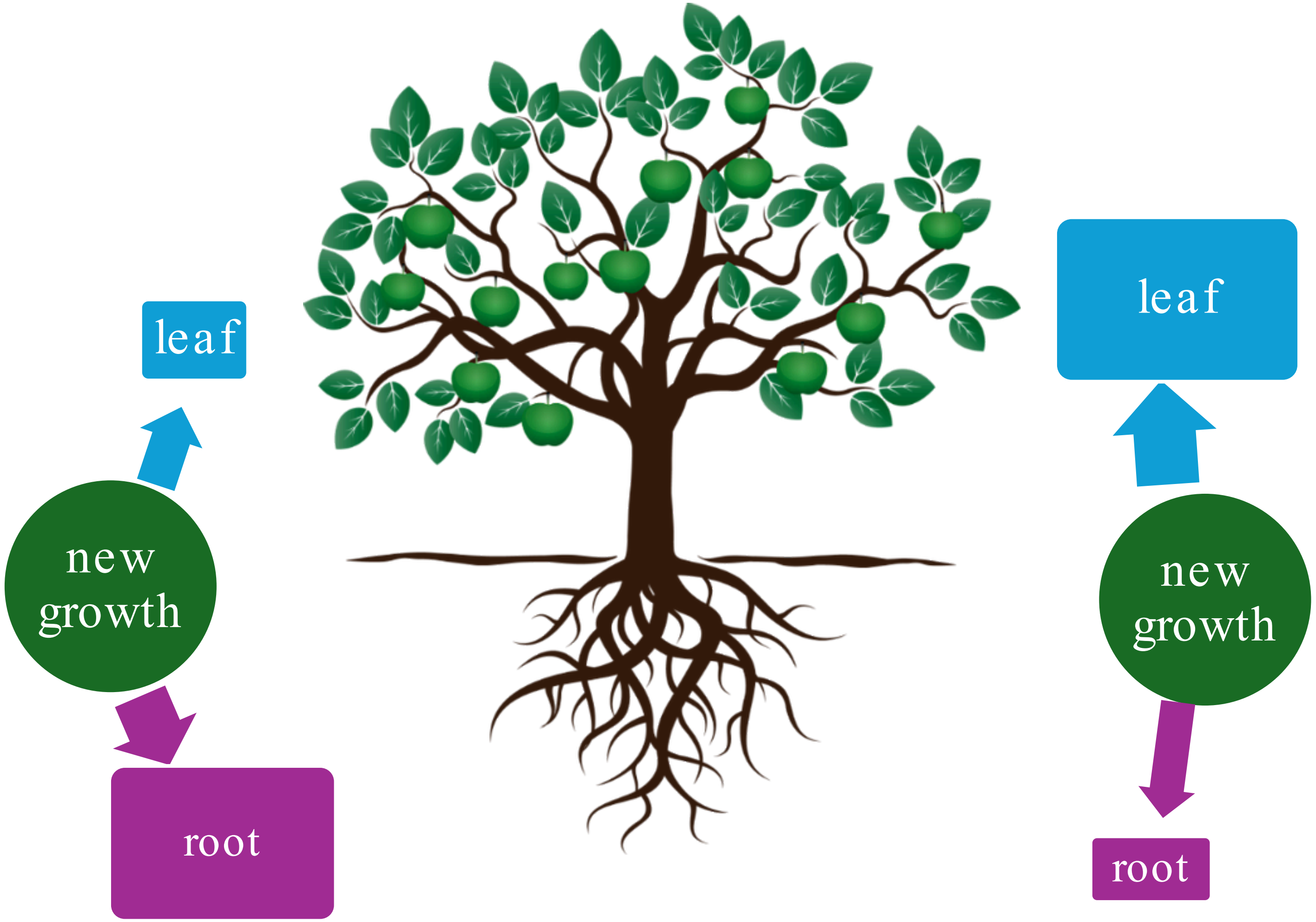
Plants should adjust to their environment so that all essential resources are equally limiting. (Farrior et al. 2013)

We might have expected that:

- when acquisition of a particular nutrient is the most limiting factor for plants, any increases in that nutrient would have resulted in decreased allocation to fine roots.

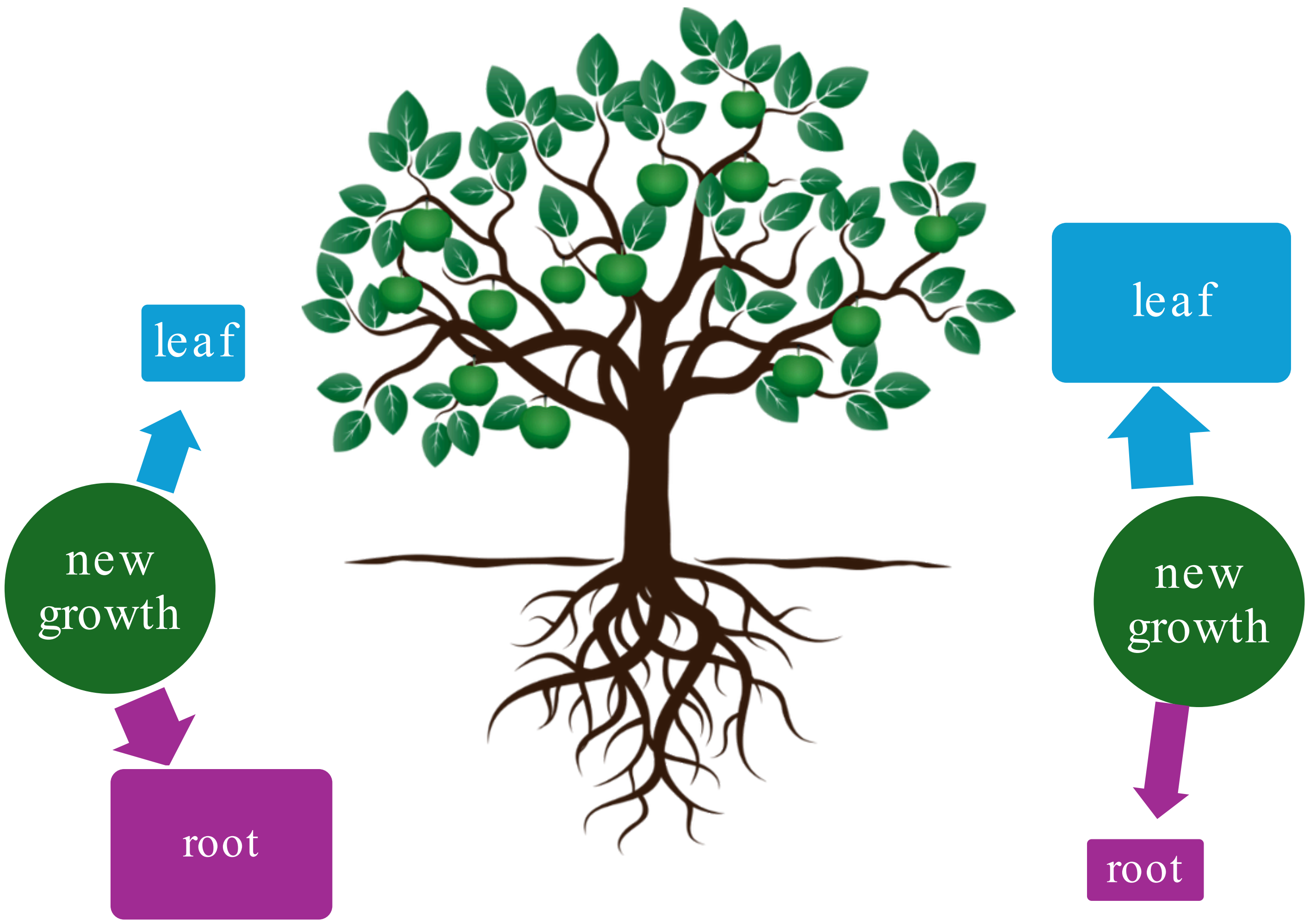
We focused on soil soluble P for our tropical study site.

How plants adjust allocation in response to soil nutrient change?

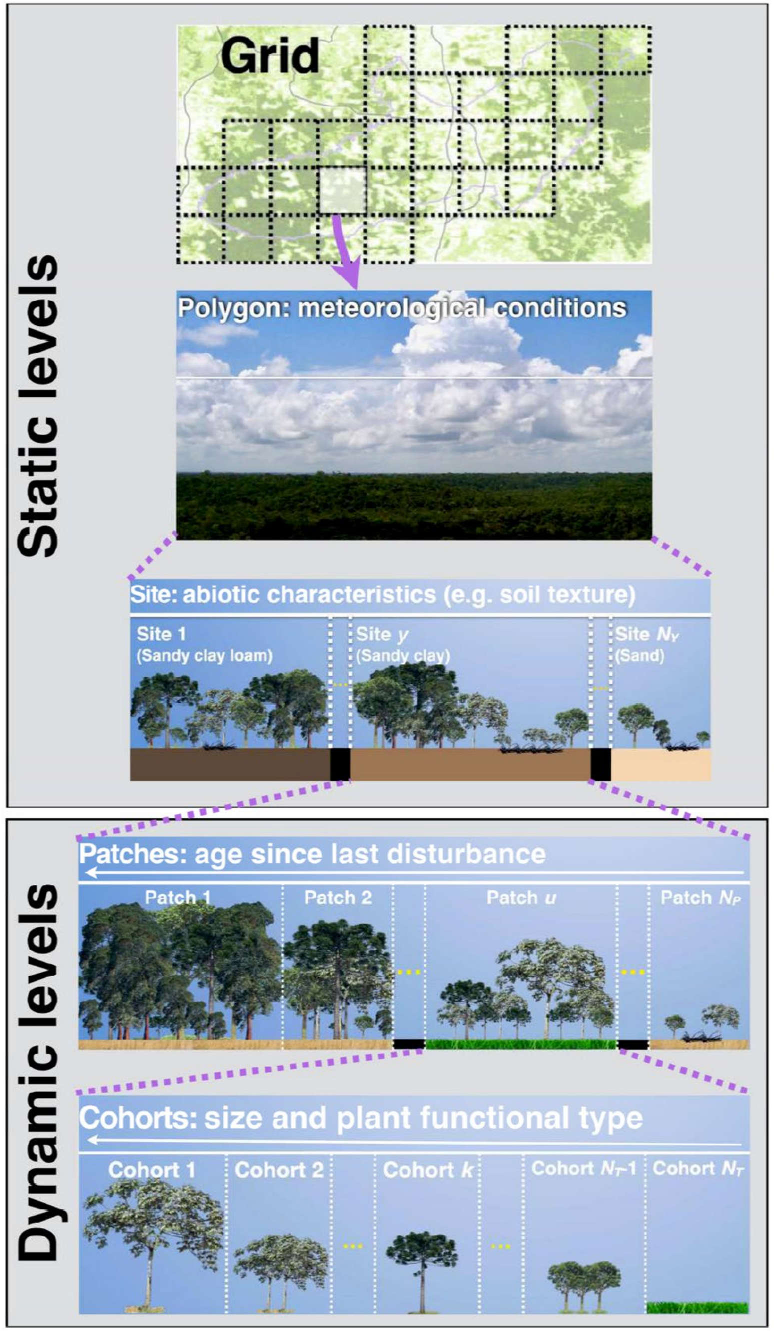


- Observations:
  - Both aboveground and belowground production increases with P addition (Yuan and Chen 2012; Hou et al. 2020)
  - Aboveground production increased more than belowground production with P addition (Li et al. 2016)
  - Increases in fine root production relative to aboveground production with P addition (Cunha et al. 2022)

How plants adjust allocation in response to soil nutrient change?



- Model representation:
  - fixed allocation to fine roots
  - a negative correlation (more soil nutrient, less allocation to roots)
  - a positive correlation (more soil nutrient, more allocation to roots)



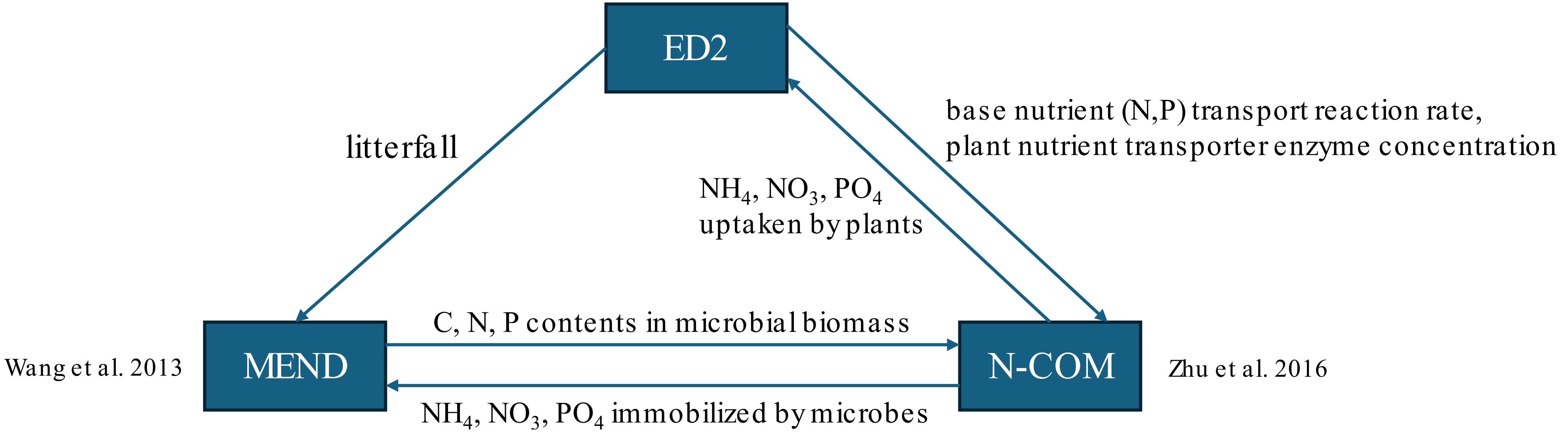
ED2 dynamic vegetation model

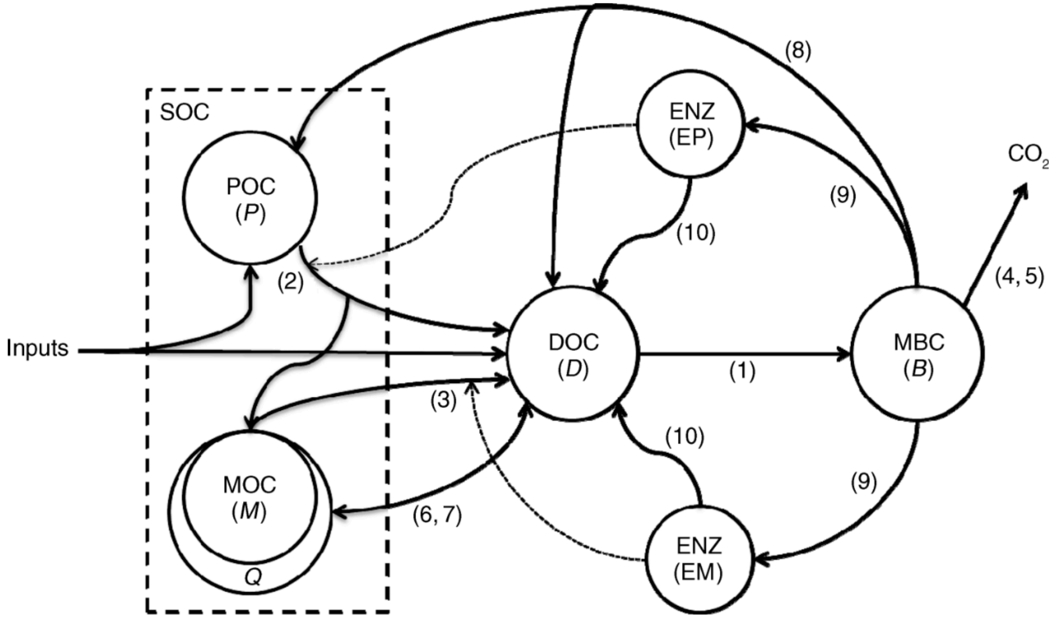
- Principal Inputs:
  - Initial forest state
  - Edaphic conditions
  - Atmospheric forcing
- Principal Outputs:
  - Productivity
  - Carbon allocation
  - Plants recruitment
  - Mortality
  - ……

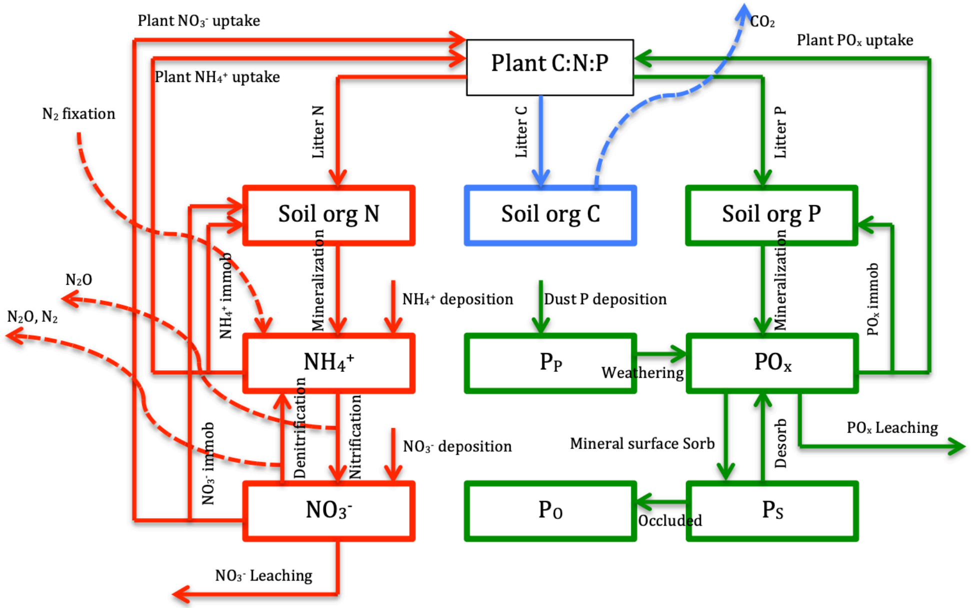
Longo et al. 2019

ED2 with updated nutrient module

Medvigy et al. 2019







(www.isodrones.com)

Methods

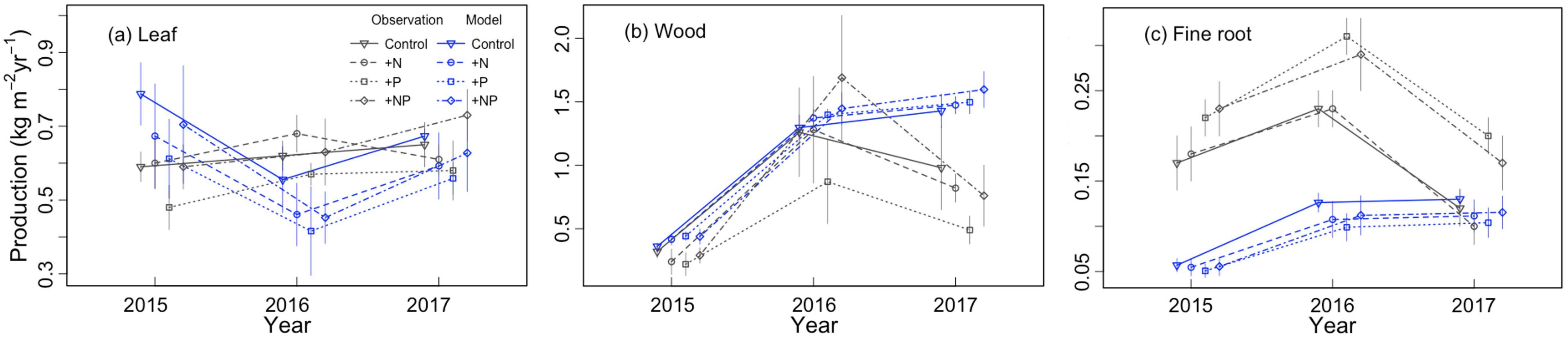
- Field observations (benchmark):
  - Horizontes Meteorological Station in Costa Rica;
  - 2015-2017;
  - 16 experimental sites – 4 controlled, 4 N addition, 4 P addition, 4 N+P addition.

- Initial model parameterization:
  - $\frac{root}{leaf} = 0.3$

- Model simulations:

Simulation set	Number of simulations	Allocation parameterizations	Analysis period	Rationale
Baseline	16, corresponding to 16 plots	$a = 0.3, b = 0$	2015–2017	Validate the baseline model

Baseline



Stem mortality	2015	2016	2017	+NP/others
Observation	10.6 %	6.0 %	4.6 %	1.3–1.8
Baseline model	10.7 %	6.3 %	4.7 %	1.5

- The model simulated reasonable biomass productivity and mortality in baseline settings, with some biases existing.

Methods

- Field observations (benchmark):
  - Horizontes Meteorological Station in Costa Rica;
  - 2015-2017;
  - 16 experimental sites – 4 controlled, 4 N addition, 4 P addition, 4 N+P addition.

- Model modifications:
  - $\frac{root}{leaf} = a + b * soil\ soluble\ P$

- Model simulations:

Simulation set	Number of simulations	Allocation parameterizations	Analysis period	Rationale
Baseline	16, corresponding to 16 plots	$a = 0.3$, $b = 0$	2015–2017	Validate the baseline model
Alternative parameterizations, short-term	16 plots × 63 parameterizations	all combinations of a and b, with $a = 0$, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and $b = -60, -40, -20$, 0, 20, 40, 60.	2015–2017	(1) Determine short-term sensitivity of model to parameterization; (2) validate alternative parameterizations

Alternative parameterizations: 3-year model validation

	a=0	a=0.1	a=0.2	a=0.3	a=0.4	a=0.5	a=0.6	a=0.7	a=0.8
b = -60	W+R	W+R	W+R	W+R	W+R	R	R	R	R
b = -40	W+R	W+R	W+R	W+R	W+R	R	R	R	R
b = -20	W+R	W+R	W+R	W+R	W+R	W+R	R	R	R
b = 0	W+R	W+R	W+R	W+R	W+R	W+R	W+R	R	R
b = 20	W+R	W+R	W+R	R			R	R	R
b = 40	R	R	R			R	R	R	R
b = 60	L+R	L+R	R	R	R	R	R	R	R

$$\frac{root}{leaf} = a + b * soil\ soluble\ P$$

- Only parameterizations assuming a positive relationship between allocation to fine roots and soil P were able to simulate the most realistic overall partitioning of biomass productivity.

Colored entries indicate statistically significant ($p < 0.05$) differences between model simulations and observations in the means of any of control, +N, +P, or +NP plots.

"L" refers to leaf production; "W" refers to wood production; "R" refers to root production.

Methods

- Field observations (benchmark):
  - Horizontes Meteorological Station in Costa Rica;
  - 2015-2017;
  - 16 experimental sites – 4 controlled, 4 N addition, 4 P addition, 4 N+P addition.

- Model modifications:
  - $\frac{root}{leaf} = a + b * soil\ soluble\ P$

- Model simulations:

Simulation set	Number of simulations	Allocation parameterizations	Analysis period	Rationale
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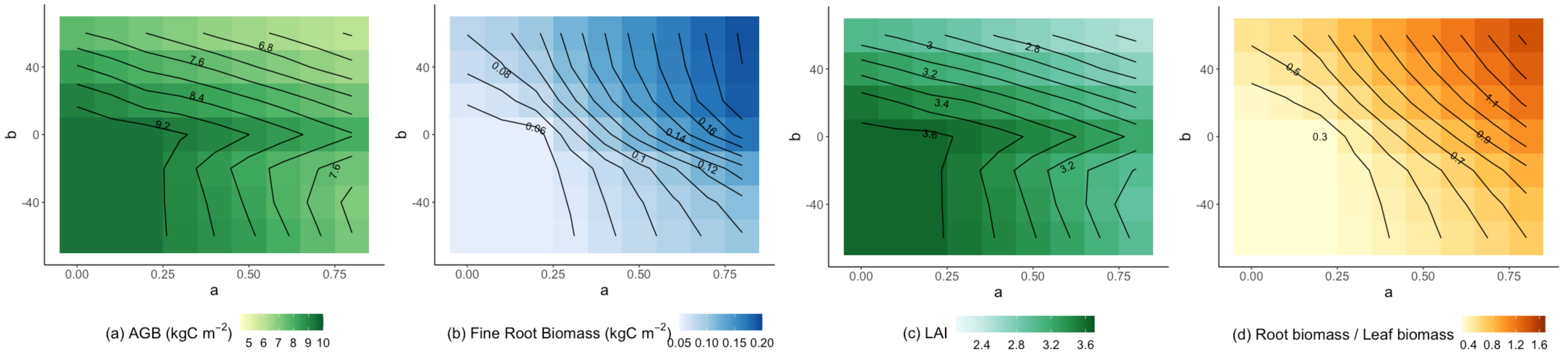
Alternative parameterizations, long-term	16 plots × 63 parameterizations	the same as short-term	30 years	Determine longer-term sensitivity of model to parameterization

Alternative parameterizations: 30-year sensitivity analysis



▶ Strong sensitivity to parameterization:

- capture of aboveground resources ultimately limited production
- potential over-allocation to fine roots

What might explain the success (even short-term) of "pos" parameterizations?

- It could be that soil P supply, not fine root biomass, limited P uptake in the unfertilized plots.
  - In an extreme case, in the complete absence of soil P, P acquisition would be zero regardless of fine root biomass.
  - The optimal amount of fine root biomass (with respect to P acquisition) would be zero in order to avoid construction and maintenance costs.
  - As soil P increases above zero, the optimal amount of fine root biomass would also increase.

- The deciduousness of this forest may be significant.
  - At the beginning of the rainy seasons, trees experience a large P demand to build their P-rich leaves. It may be adaptive for plants to construct these leaves as quickly as possible, and having large fine root production may facilitate that.

- Plants may over-allocate to fine roots in order to maximize their ability to compete with neighbors.

Take home message

- Only parameterizations assuming a positive relationship between relative allocation to fine roots and soil P were able to accurately simulate leaf, wood and fine root production, as well as mortality, at three-year time scale.

- However, this parameterization would over-allocate to fine roots in P-fertilized plots on multidecadal time scales.

- Simultaneous measurements of leaf, wood, and fine root production in nutrient fertilization experiments and longer-term experiments are essential for better simulations of forest carbon balances.