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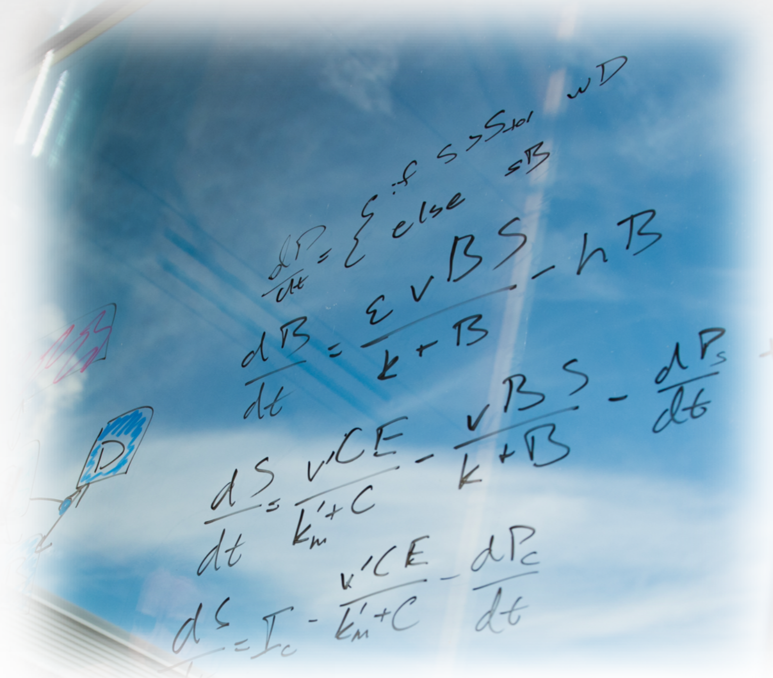
Scaling complexity in soil carbon models



KATHERINE TODD-BROWN

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Pacific Northwest National Laboratory

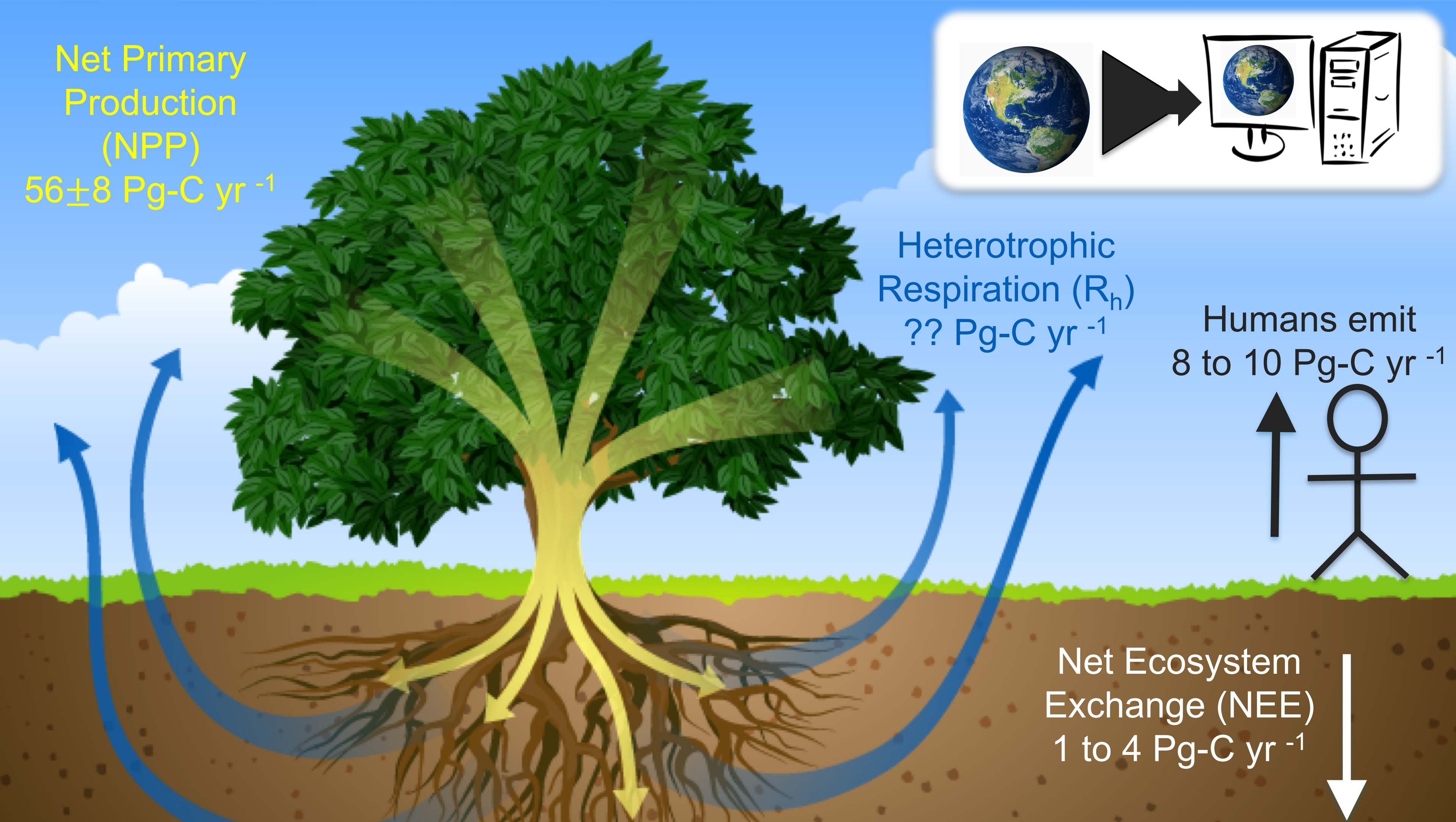
17 March 2018
University of Leicester, UK

@KatheMathBio

katherine.todd-brown@pnnl.gov

U.S. DEPARTMENT OF ENERGY

Why is predicting atmospheric CO_2 levels hard?



Ito, Global Change Biology (2011)
Le Quere, et al. Nature Geoscience (2009)

Change in soil carbon stock over the 21st century are very diverse

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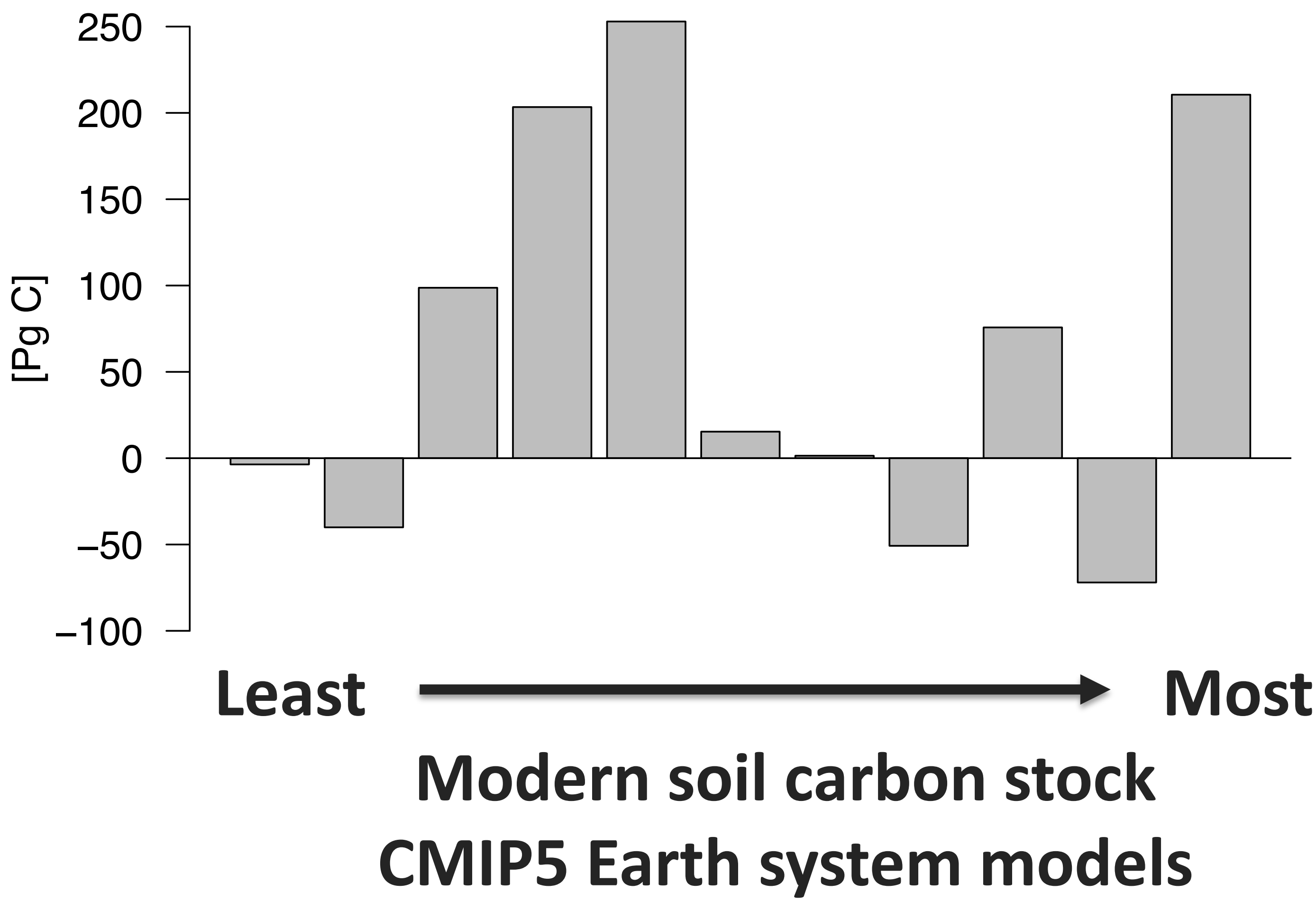
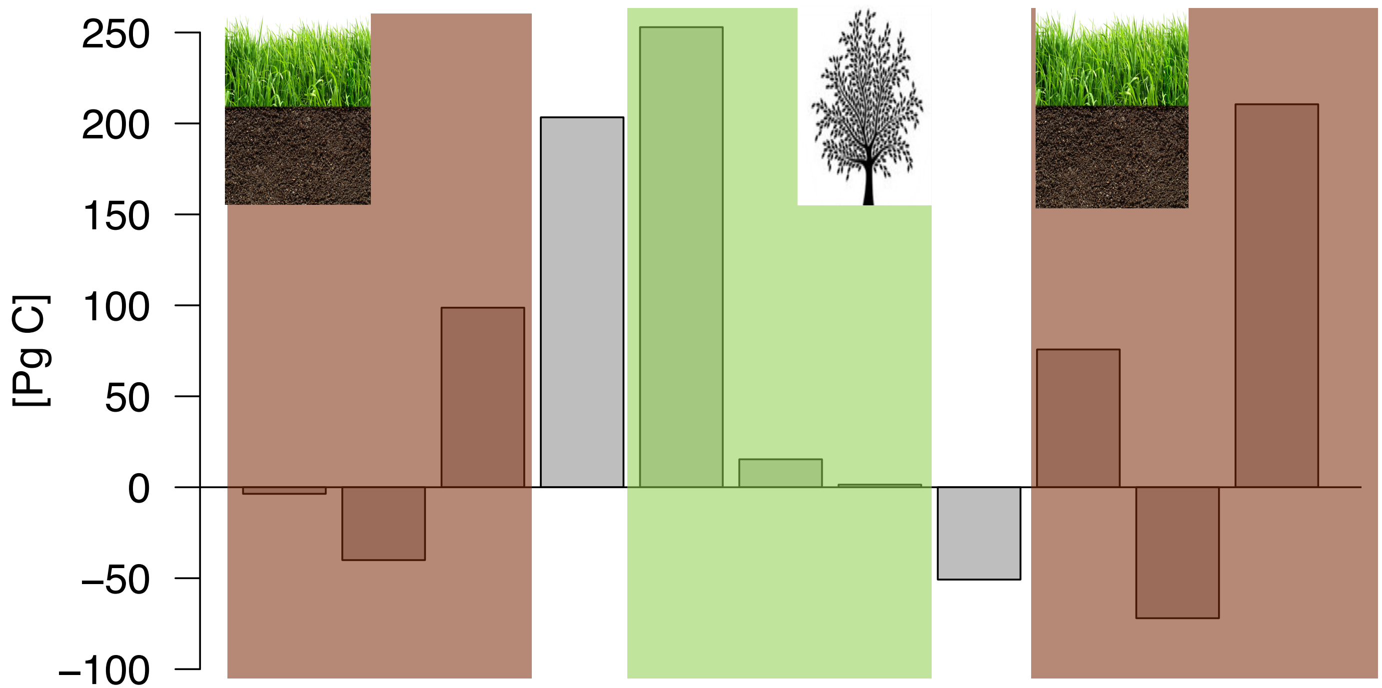


Todd-Brown, et al. *Biogeosciences*. 2014

Modern benchmarks for global soil carbon and NPP do not constrain projections

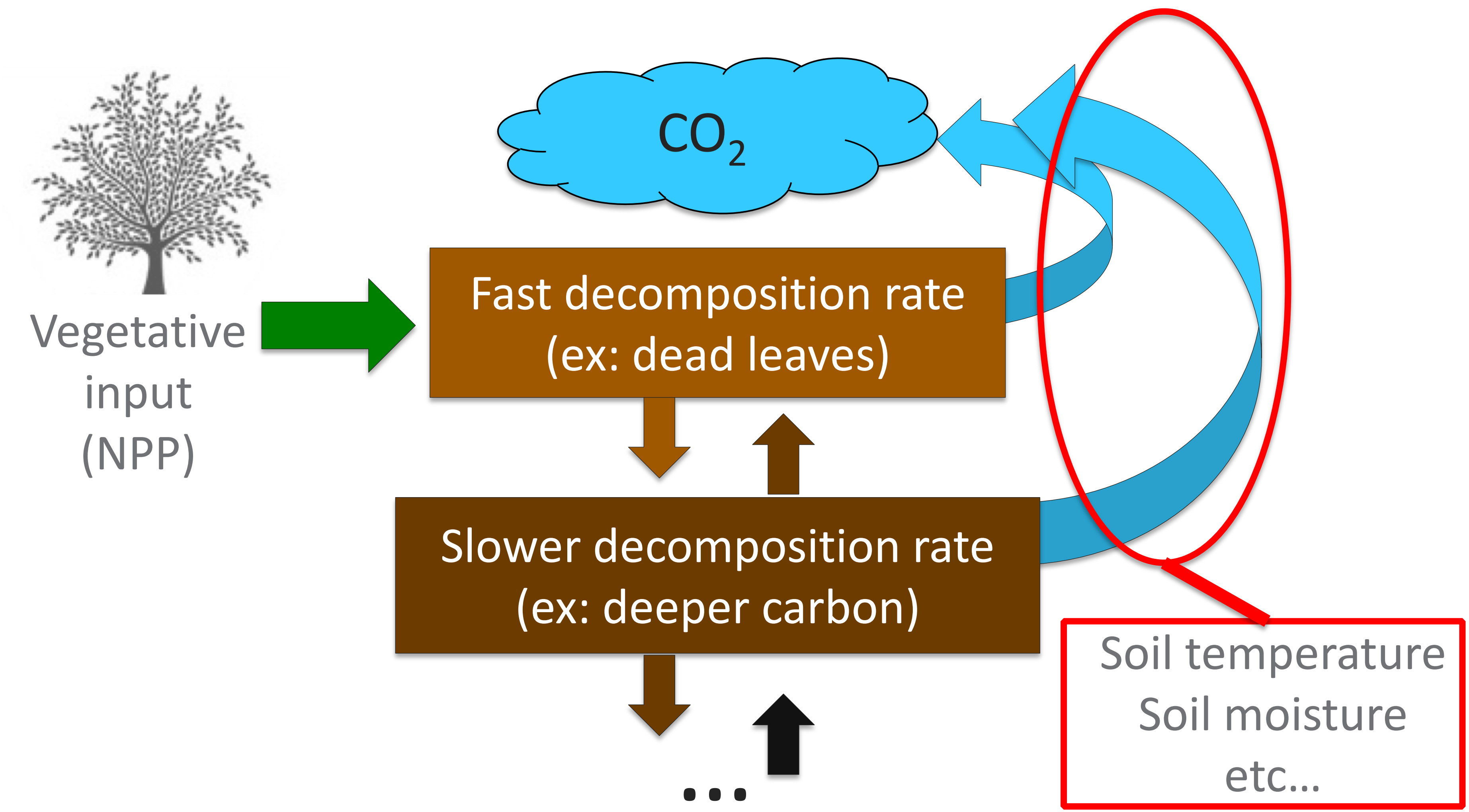


Least → Most

Modern soil carbon stock
CMIP5 Earth system models

Todd-Brown, et al. *Biogeosciences*. 2014

Models can have different inputs, model structure, environmental drivers, and model parameters.



CENTURY: Parton et. al. 1987, 1988, 1992, 1993
CLM: Oleson et. al. *Tech. description of vs 4.0 of CLM 2010*

Shifts in inputs and soil warming are the main drivers of soil carbon shifts.

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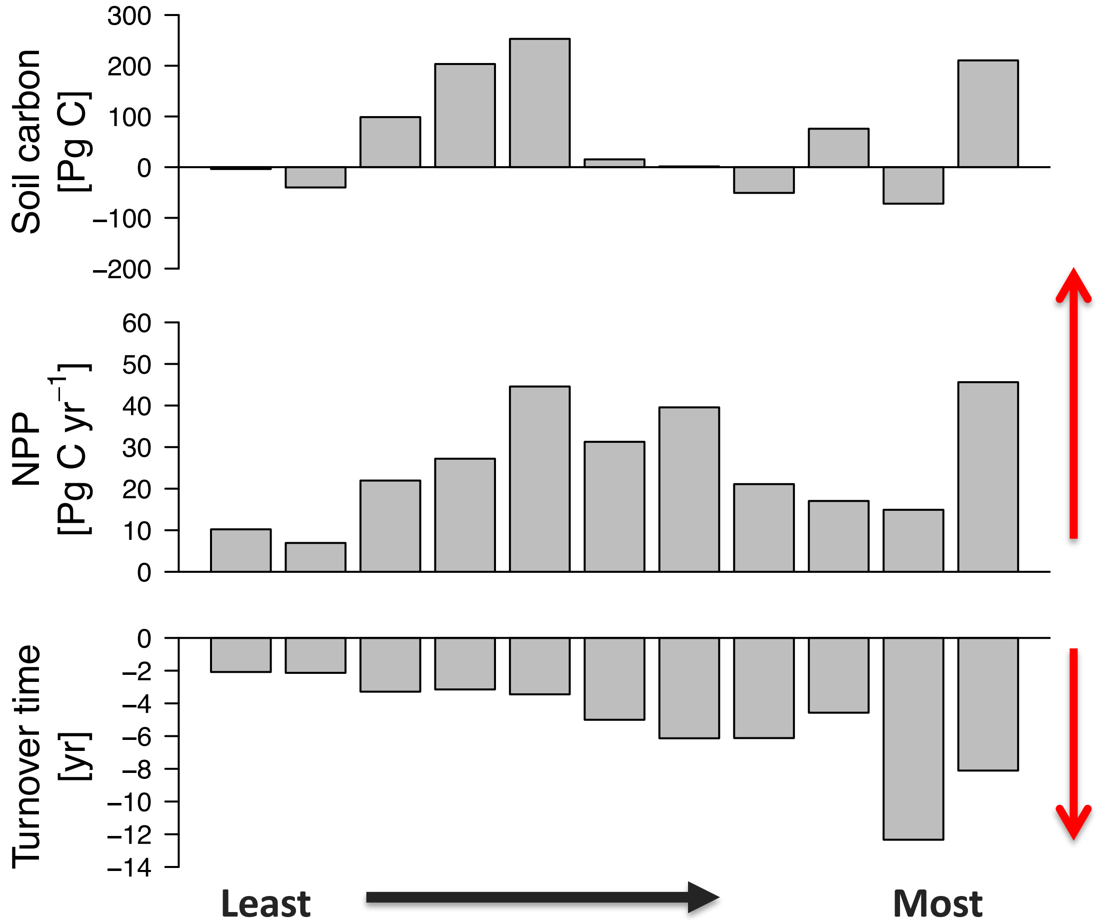

Modern soil carbon stock
CMIP5 Earth system models

CMIP5 RCP 8.5 difference between start and end of 21st century (10yr means)

Todd-Brown, et al. *Biogeosciences*. 2014

Parameterization and temperature explains differences in simulated decomposition rates.

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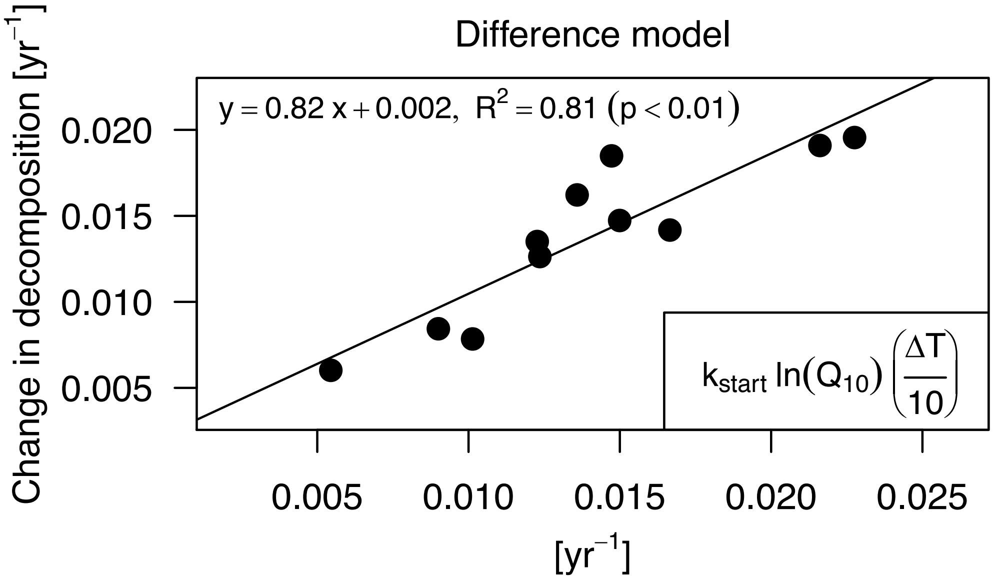
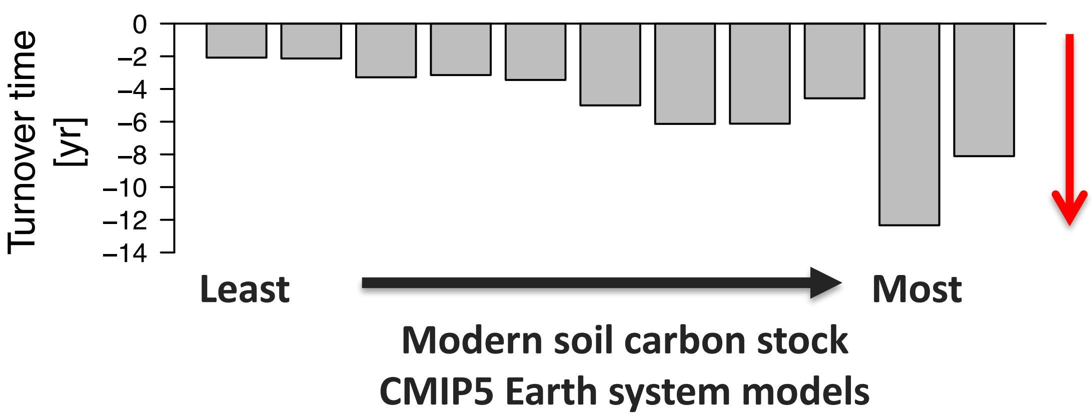
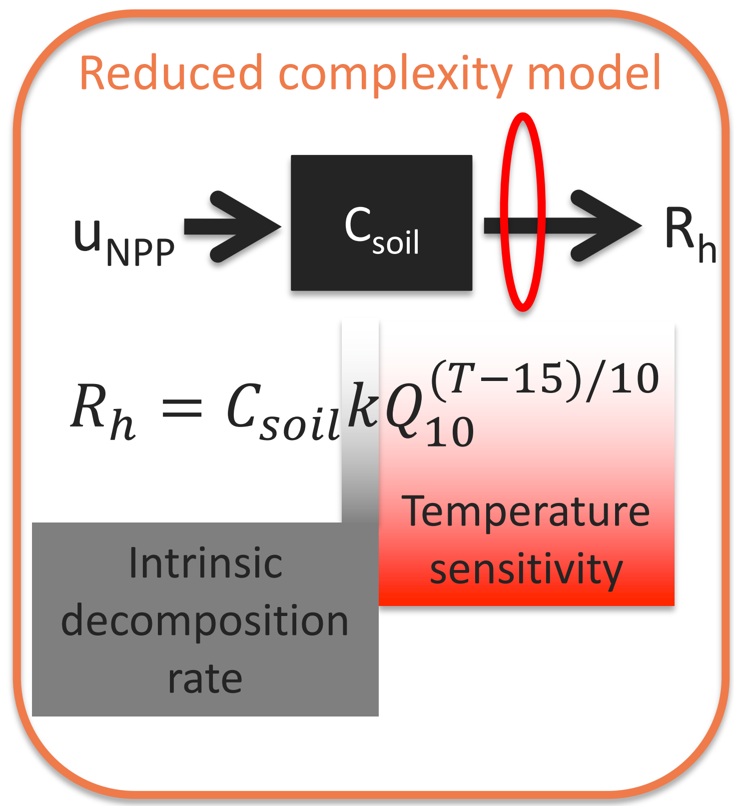
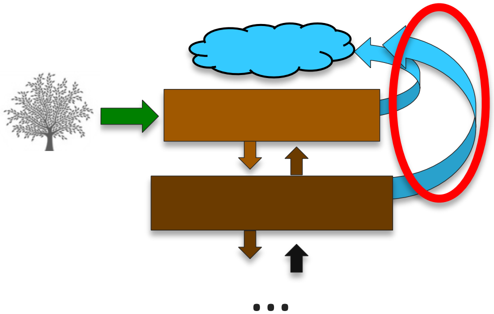




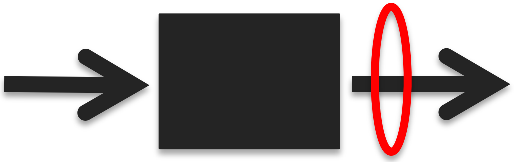
CMIP5 RCP 8.5 difference between start and end of 21st century (10yr means)



Todd-Brown, et al. *Biogeosciences*. 2014

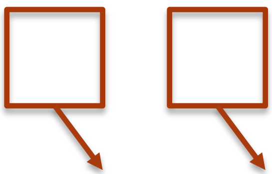


When can you use a one pool model for soils simulations?

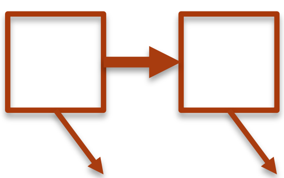


Soil carbon as a one pool model when inputs approximate outputs.

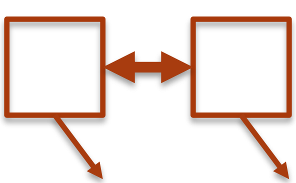
Independent



Cascade



Feedback



$$\frac{d\boldsymbol{C}}{dt} = u(t)\boldsymbol{b} - \boldsymbol{KAC}(t)$$

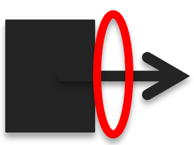
$$\ldots$$

$$u(t) = kC$$

KA is an M-matrix
Input approx. output

Reduced Complexity

One pool



Todd-Brown, Zheng, Crowther, *Biogeosciences* (in review)

Using one pool models to “What If” Earth system model outputs without reruns.

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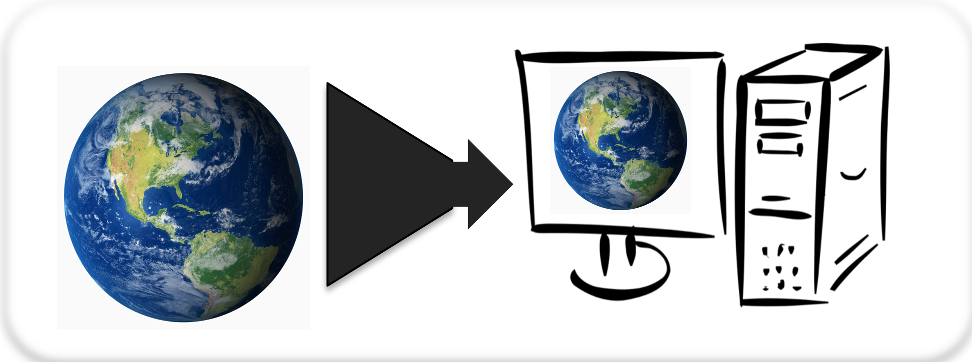
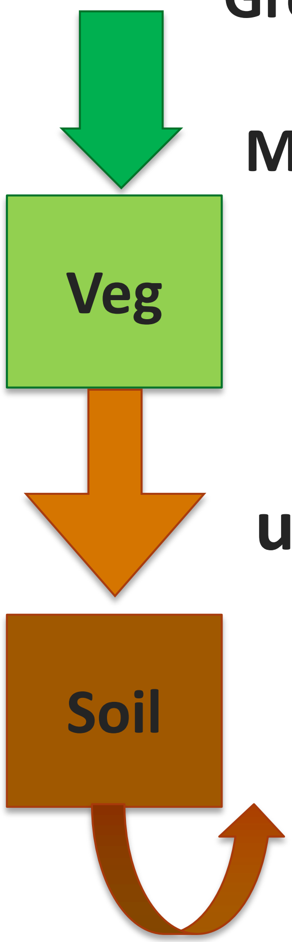


What if…

… plant productivity was limited by C:N:P?

… temperature sensitivity of soil decay was uncertain?

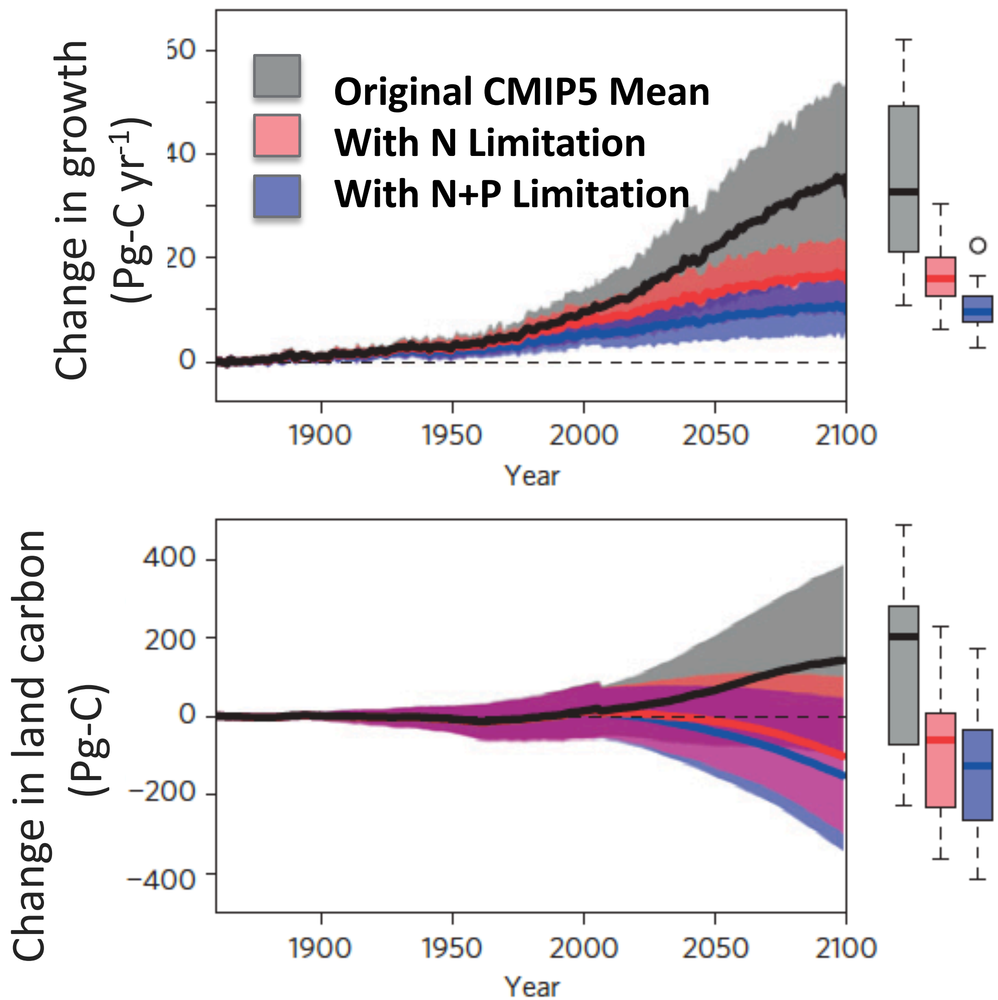
Nutrient limited plants lowers land carbon estimates in Earth system models.



Growth (g) = minimum of Model and C:N:P

$$u_{soil} = u_{org}\, g/g_{org}$$

$$R_h = C_{soil}\, k_{org}$$



Wieder, Cleveland, Smith, and **Todd-Brown**. *Nature Geoscience*, 2015.

Soil carbon uncertainty from temperature response under estimated in Earth system models.

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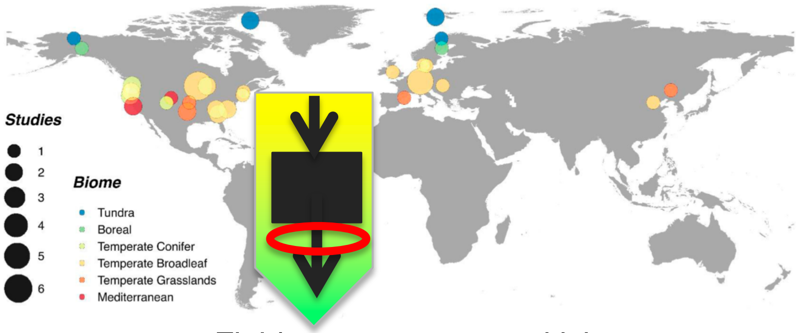
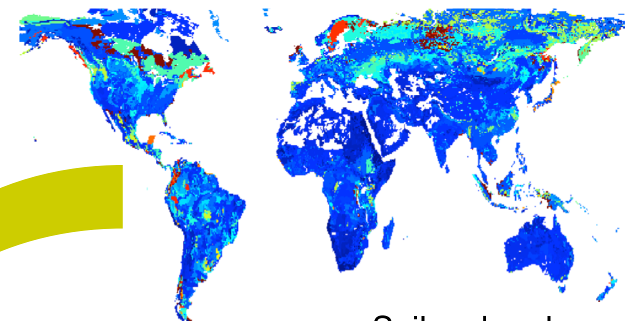
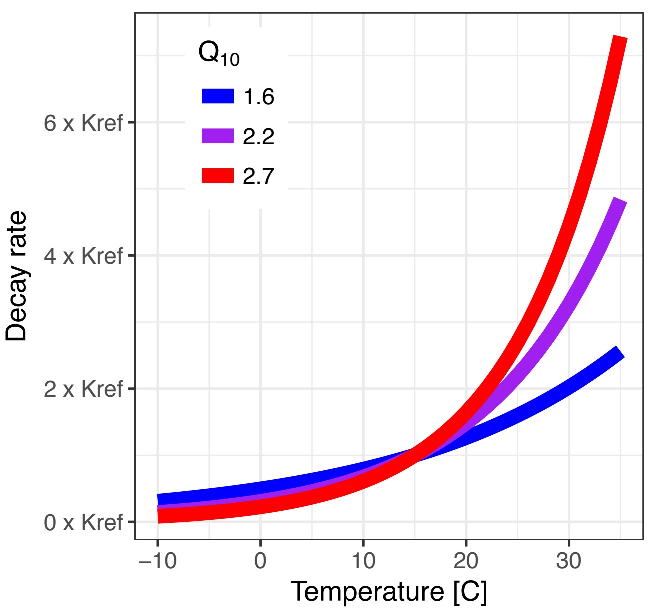
36 field warming experiments

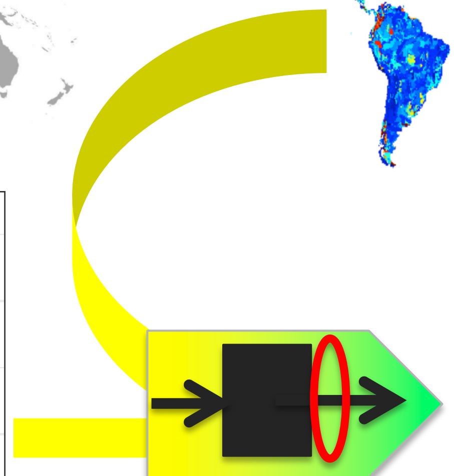


20 Earth system models (CMIP5)

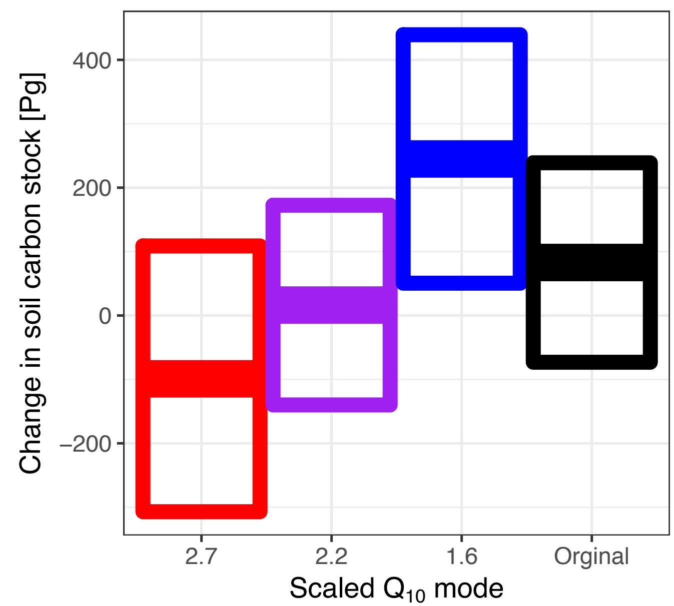


Field temperature sensitivity





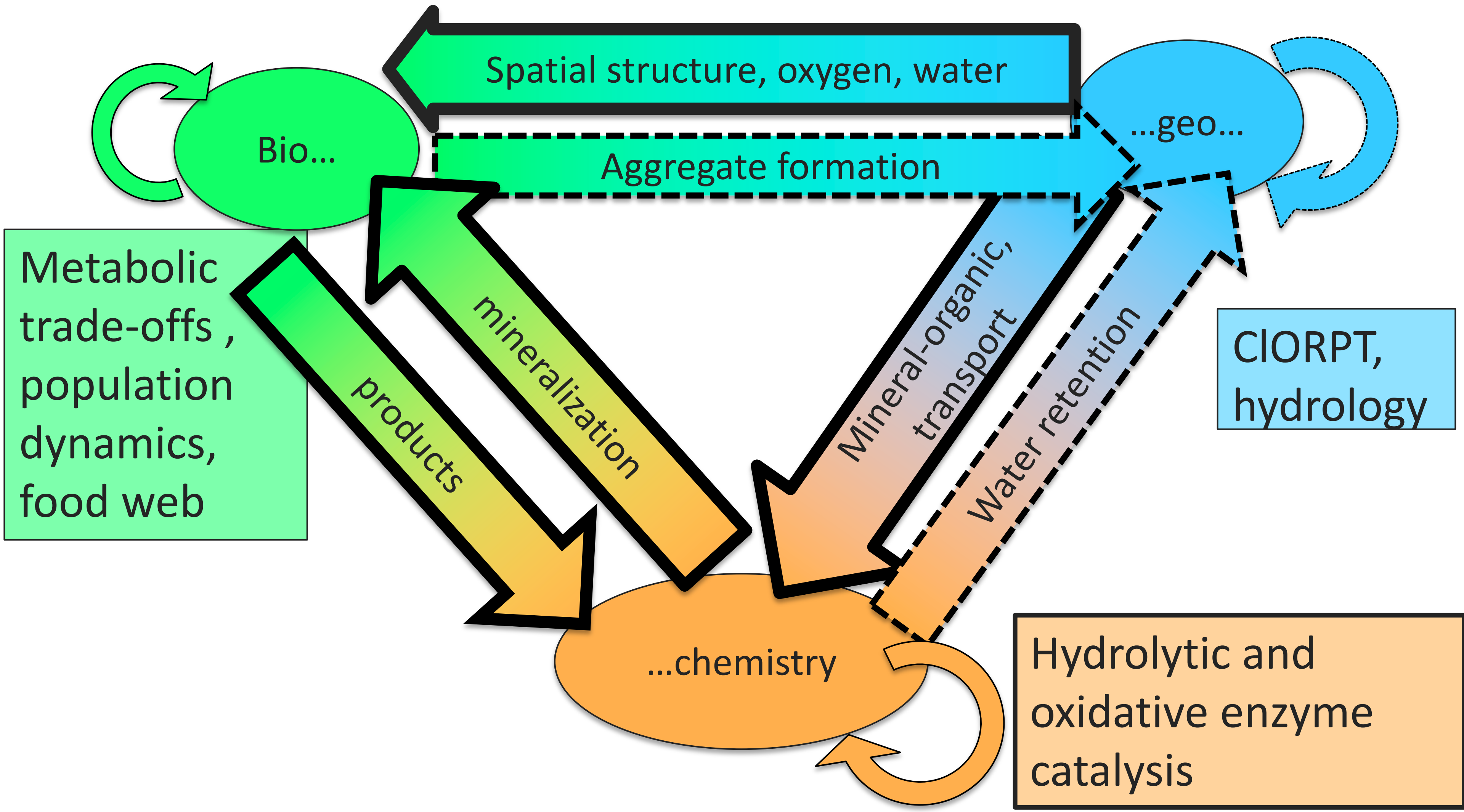
Soil carbon loss with modified Q_{10}



Crowther, **Todd-Brown**, et al. *Nature.* 2017

Todd-Brown, Zheng, Crowther, *Biogeosciences* (in review)

Soil carbon dynamics governed by biological, chemical and geophysical processes.



New models try to capture more explicit process complexity with wider data potential.

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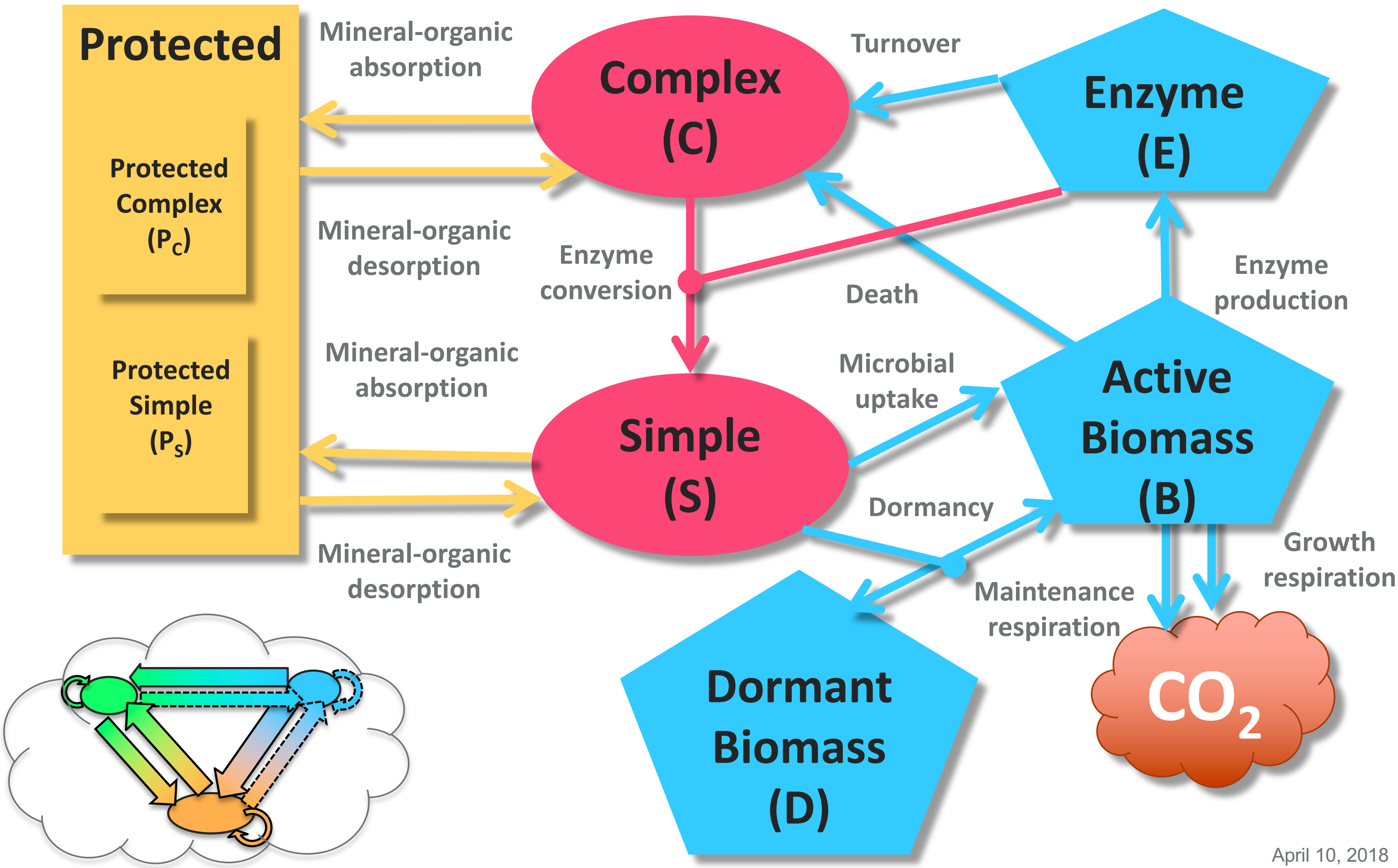
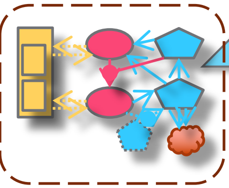
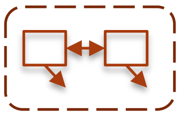
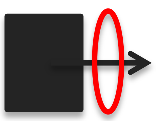


Future work integrating data and models across complexity in soils.







Enriched

Reduced

More processes!

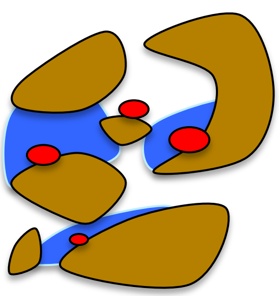
Do process rich models in pore-networks shift community parameters?

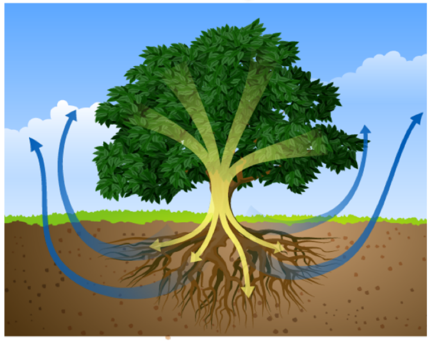
Relative information content – what to measure?

Moisture signal in soils? Field & ESMs

Connect process rich model to a one pool?

Pore → Core → Field → Globe





Mathematical and informatics bridging soil observation and Earth system models at UL

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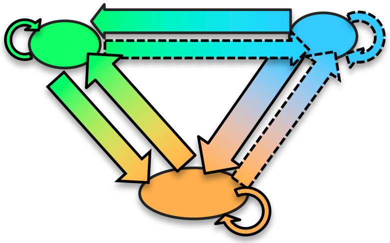
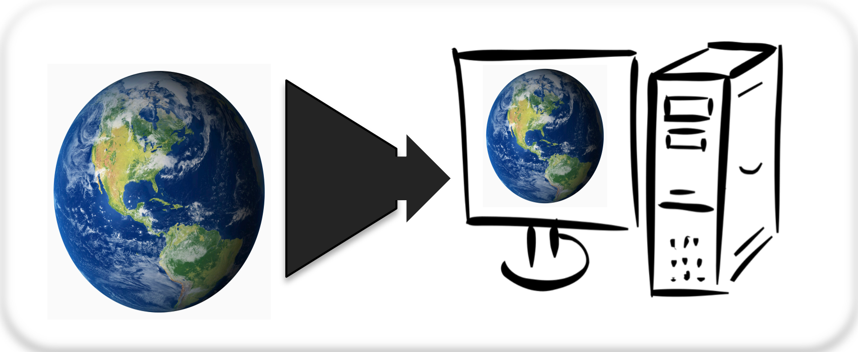
- Undergraduate and graduate research projects
  - Aggregation and harmonization of soil data
  - Model-data integration
  - Model evaluation, comparison, and development



- Coursework offering
  - Data management and informatics
  - Soil biogeochemistry
  - Earth system science
  - Applied model development



- Targeted funders
  - NERC: soil security, critical zone research, math and informatics for ‘omics, Earth system modeling strategy
  - EPSRC: continuum mathematics, mathematical biology, non-linear systems
  - EU-collaborators and US-collaborators (NSF, DOE)

Acknowledgements

- ESM SOC analysis: James Randerson (UCI), Steven Allison (UCI), W. Mac Post (ORNL), Charles Tarnocai (AAFC), E. Ted Schuur (NAU), and CMIP5 modelers (9 institutes)
- ESM post-hoc analysis: Tom Crowther (NIOO), Mark Bradford (Yale), Will Wieder (NCAR), Cory Cleveland (U Montana), Bin Zheng (PNNL), and data providers (40 institutes)
- Process explicit models: Vanessa Bailey (PNNL), Nancy Hess (PNNL), Tim Scheibe (PNNL), Jeremy Zucker (PNNL), Peyton Smith (PNNL), Matthew Smith (Microsoft), Josh Schimel (UCSB), Melanie Mayes (ORNL), Julie Jastrow (ANL), Stefano Manzoni (Stockholm U), Jennifer Talbot (BU)

Linus Pauling Postdoctoral Fellowship, Pacific Northwest National Lab

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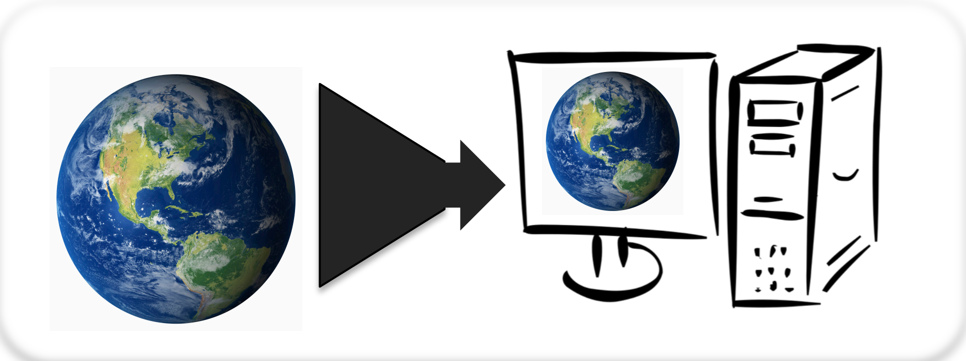
Scaling complexity in soil carbon models

Predictions of future soil carbon stock in Earth system models



Reducing model complexity

- Mathematical cleverness
- Model-data integration

Enriching model complexity

- Refine assumptions
- New experimental opportunities

Complexity in space-time

Soil carbon as a one pool model when inputs approximate outputs or (in some cases) single timescale.

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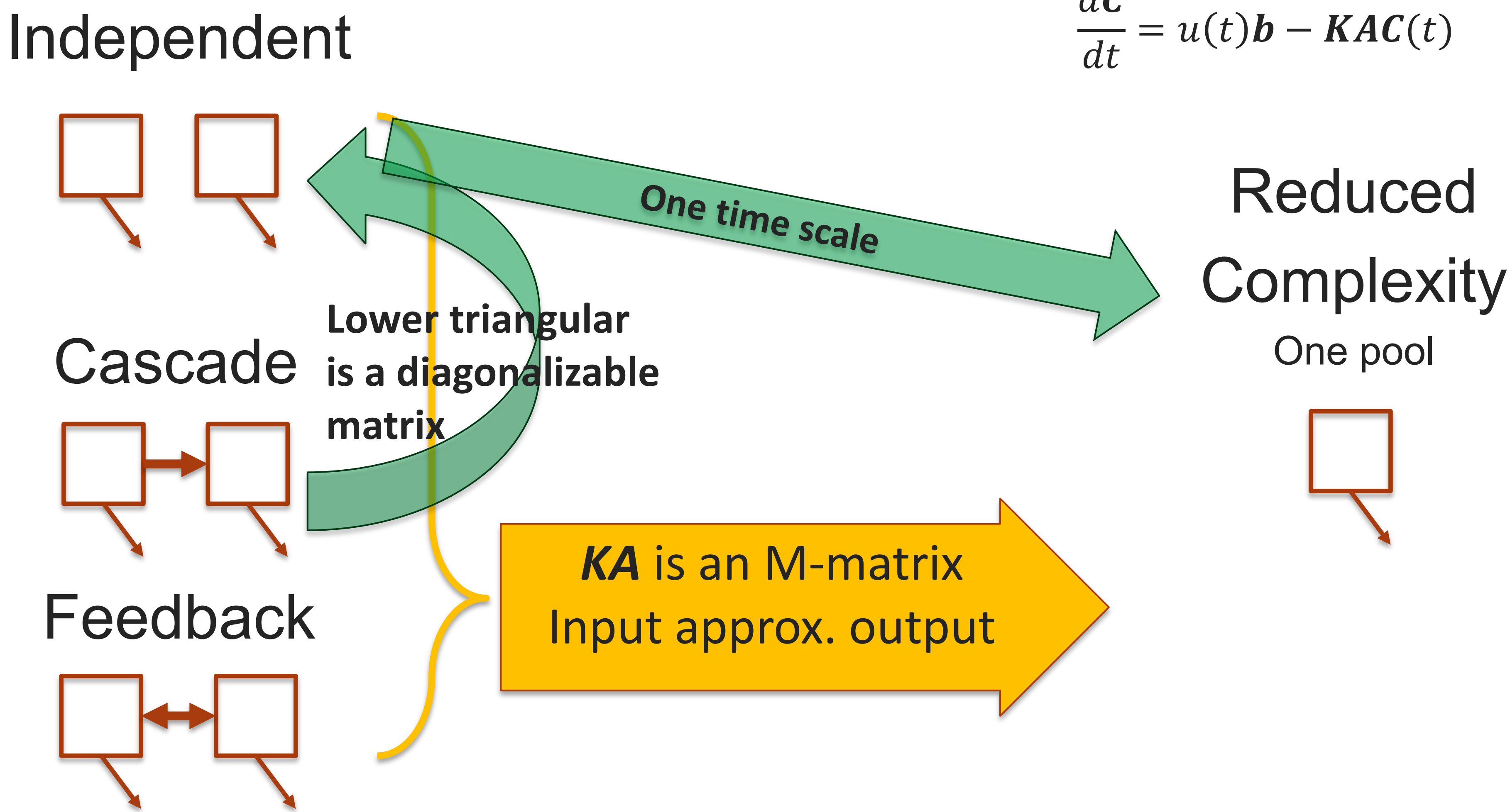
$$\frac{d\boldsymbol{C}}{dt} = u(t)\boldsymbol{b} - \boldsymbol{KAC}(t)$$

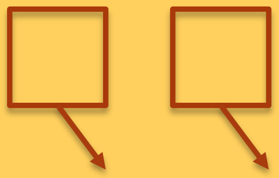


Todd-Brown, Zheng, Crowther, *Biogeosciences* (in submission)

Soil carbon models fall into three classes; independent, cascade, and feedback.

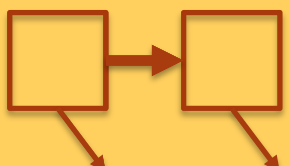
Independent

Diagonal matrix



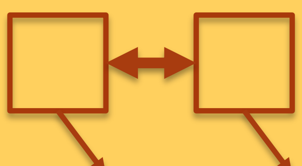
Cascade

Lower triangular matrix



Feedback

Dense matrix



$$\frac{d\boldsymbol{C}}{dt} = u(t)\boldsymbol{b} - \boldsymbol{K}\boldsymbol{A}\boldsymbol{C}(t)$$

Todd-Brown, Zheng, Crowther, *Biogeosciences* (in review)

Derive field Q_{10} from soil carbon, shift ESM Q_{10}, and recalculate new SOC shift.

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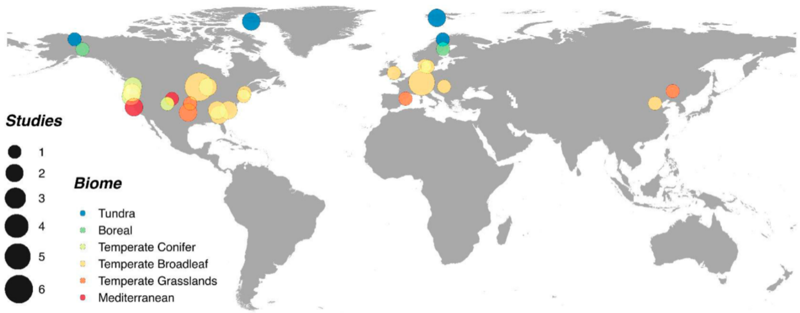
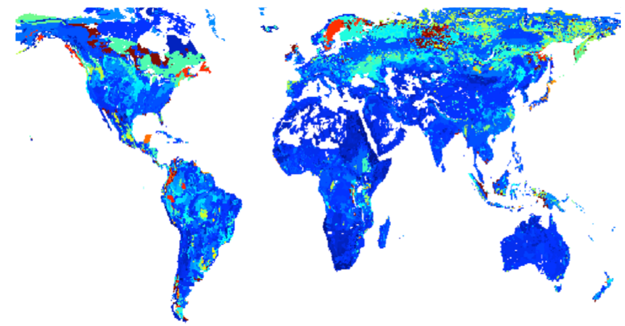
36 field warming experiments



Crowther, Todd-Brown, et al. *Nature.* 2017

20 Earth system models (CMIP5)



Reduced complexity model at quasi-steady state

$$u_{in} \rightarrow \boxed{C_{soil}} \rightarrow R_h$$

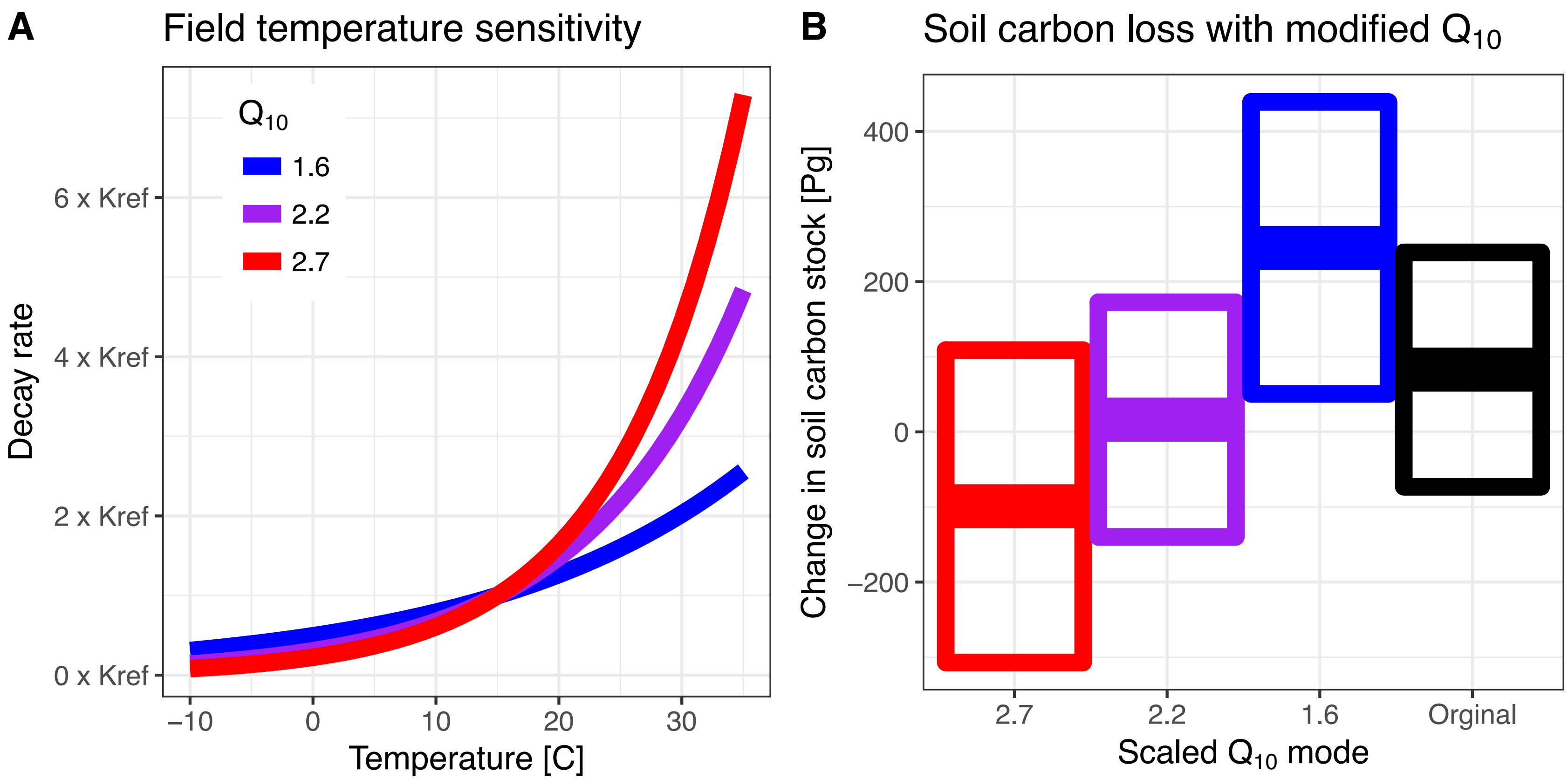
$$u_{in} = C_{soil} k Q_{10}^{(T-15)/10}$$

Intrinsic decomposition rate

Temperature sensitivity

Todd-Brown, Zheng, Crowther, *Biogeosciences* (in submission)

Data-Q_{10} uncertainty led to high ESM-dSOC variation.



Todd-Brown, Zheng, Crowther, *Biogeosciences* (in submission)

A reasonable set of assumptions linking process-rich and reduced complexity:

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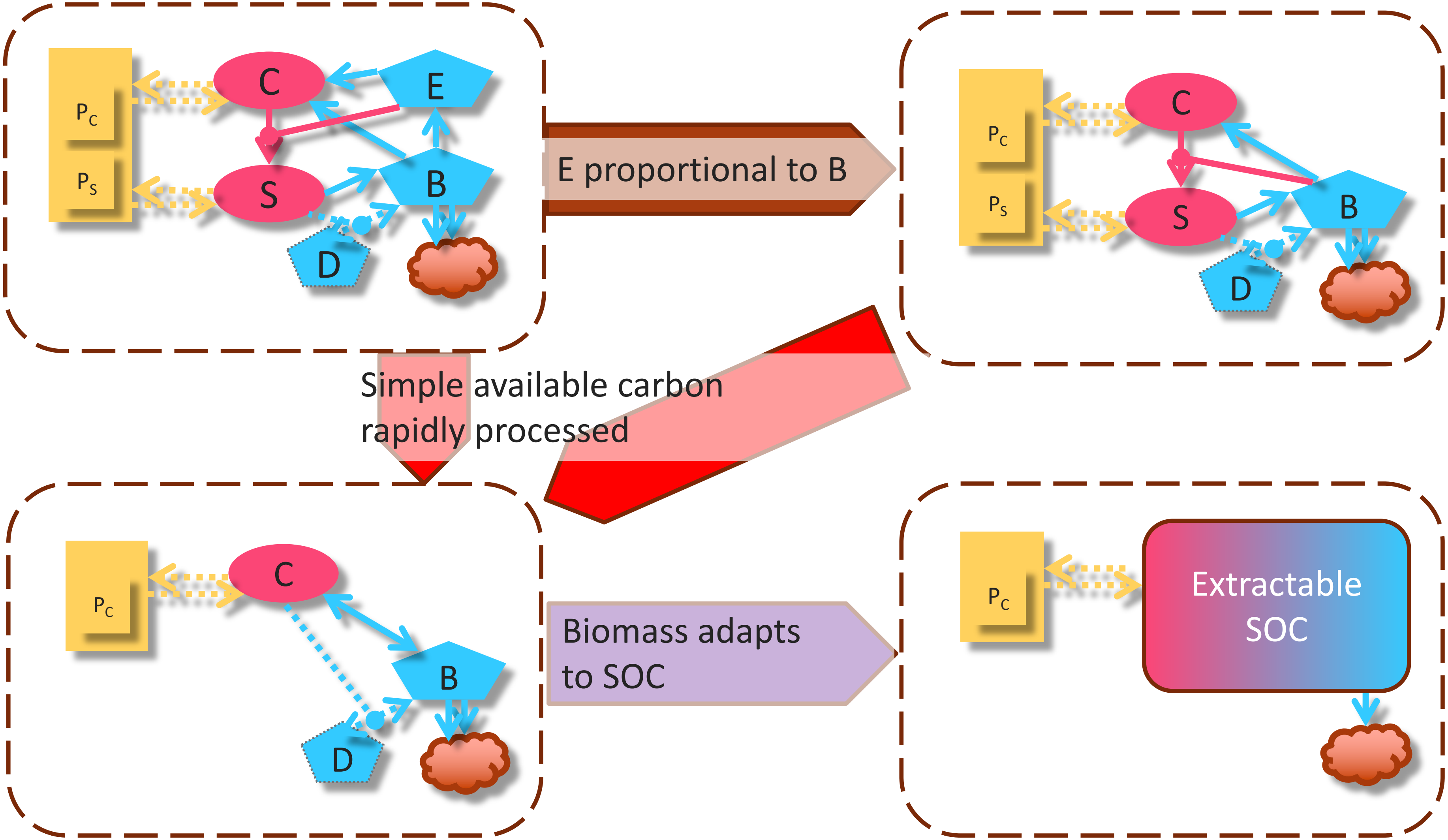
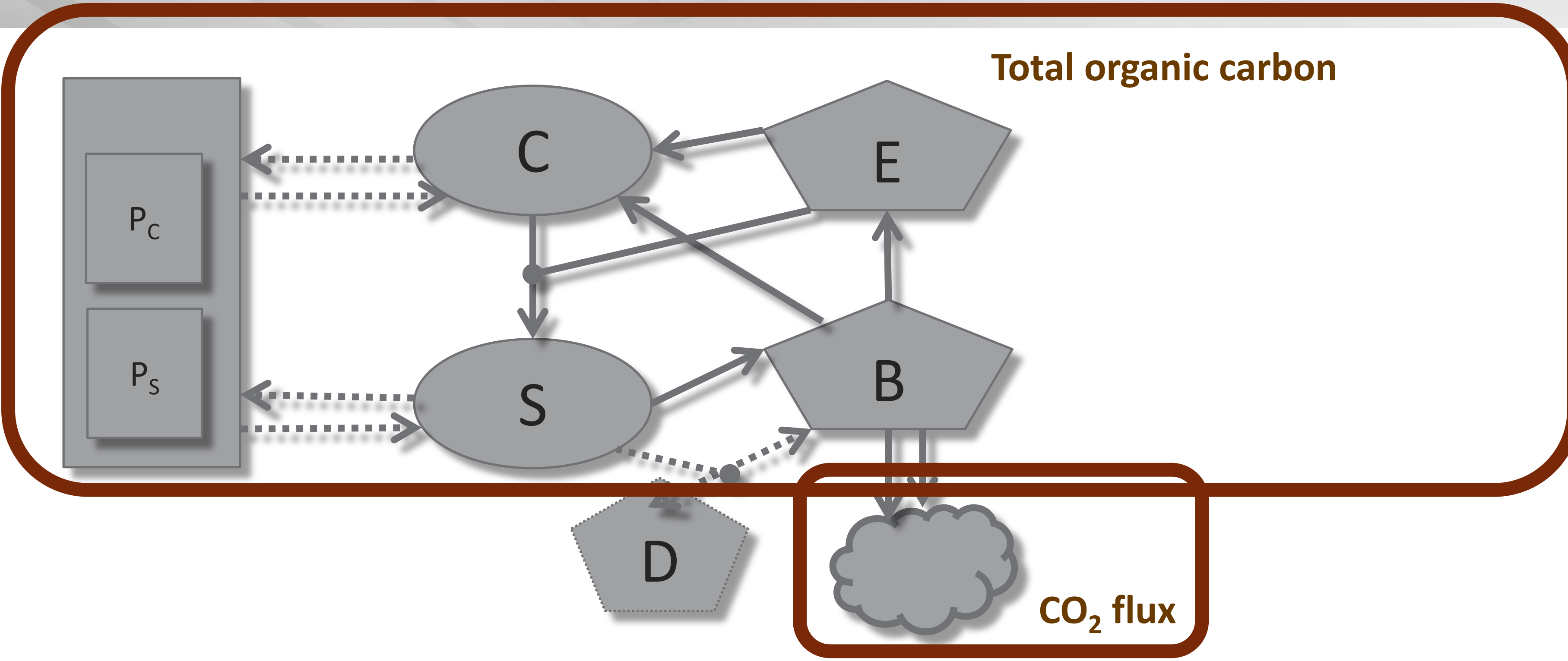


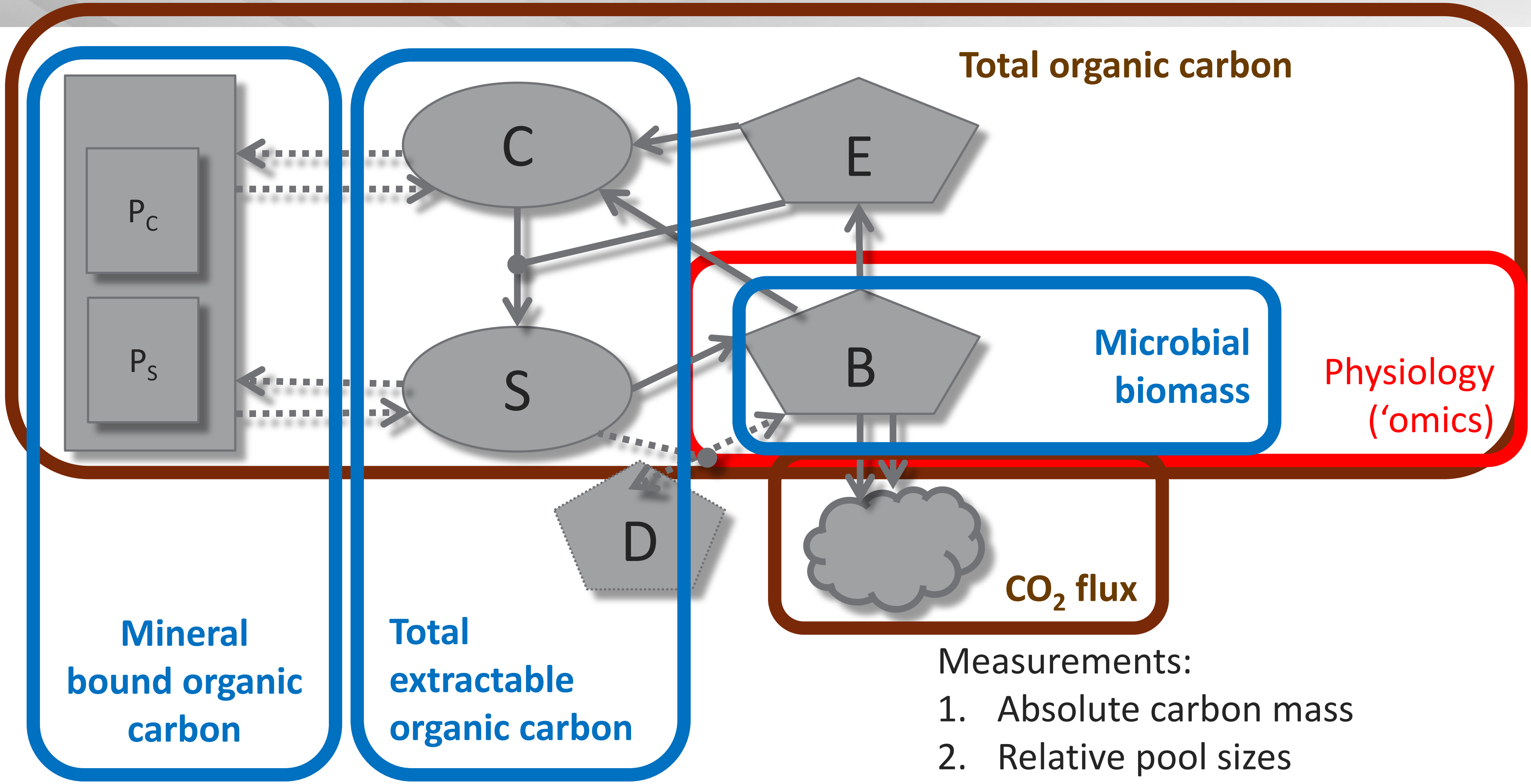
The promise of data integration in process-rich models.



Measurements:

1. Absolute carbon mass
2.
3.
4. Carbon pool age
5.

The promise of data integration in process-rich models.



Measurements:

1. Absolute carbon mass
2. Relative pool sizes
3. Relative pool change
4. Carbon pool age
5. Theoretical parameter values

The promise of data integration in process-rich models.

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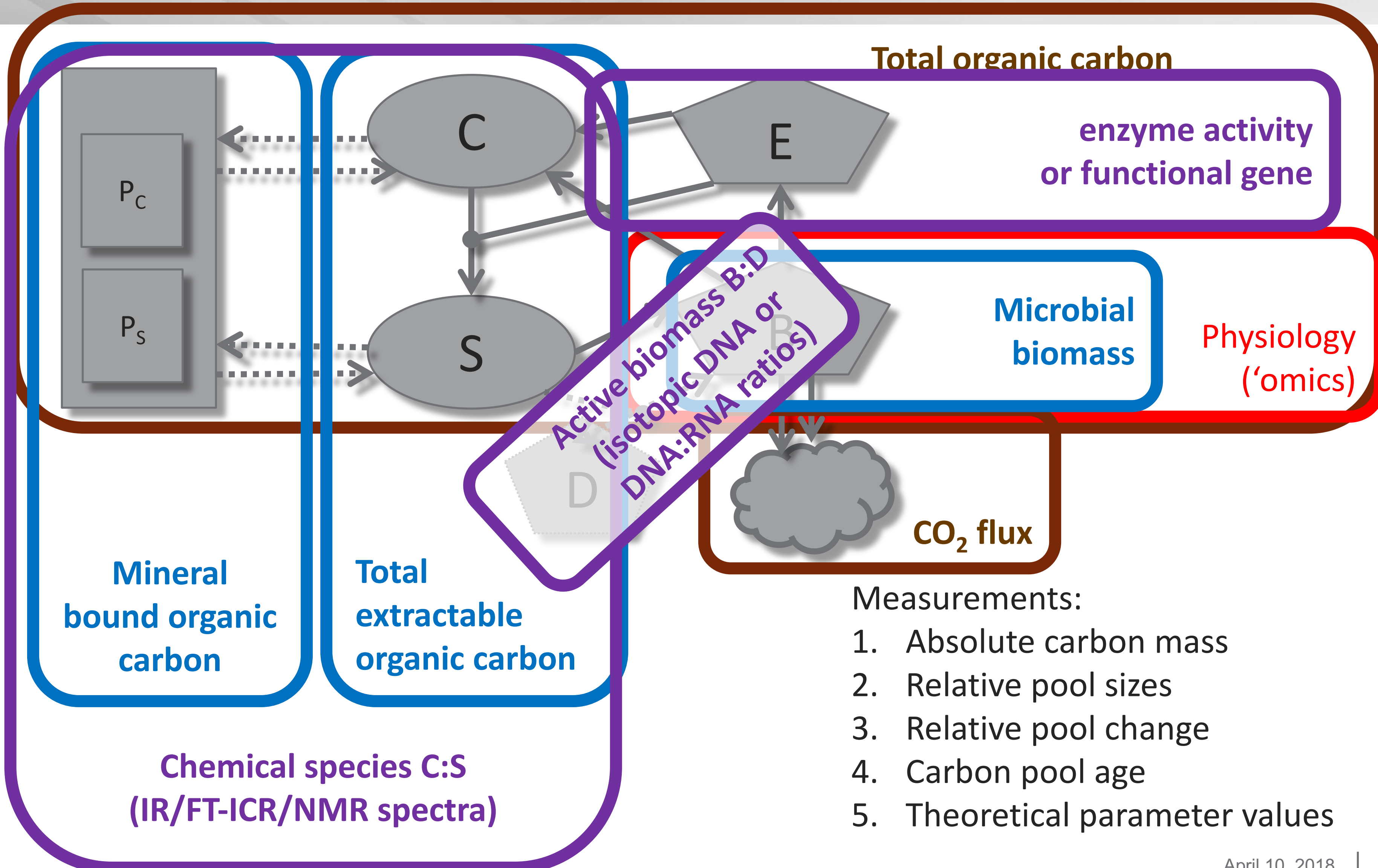
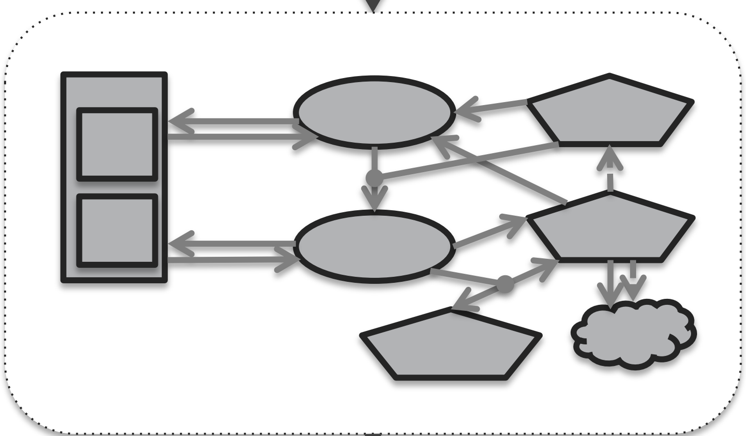


Measurements:

1. Absolute carbon mass
2. Relative pool sizes
3. Relative pool change
4. Carbon pool age
5. Theoretical parameter values

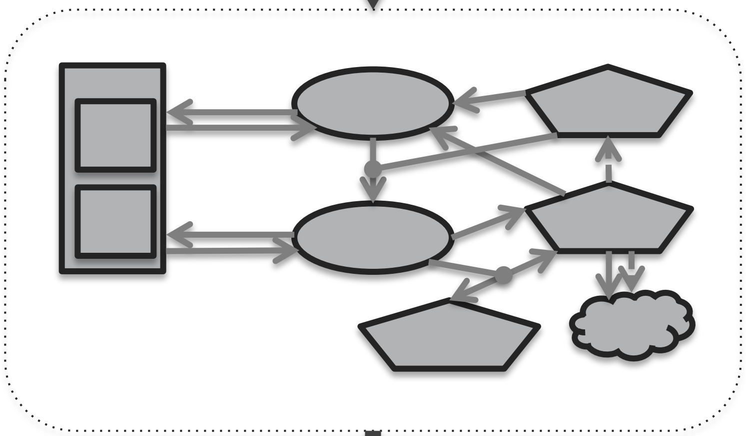
Well-mixed vs aggregated isolated pores simulations…

Randomly sample parameter set → Calculate mean parameter set



Isolated cumulative CO_2

Aggregated mean CO_2



Well-mixed CO_2

Measuring means is not enough, parameter distribution also matters.

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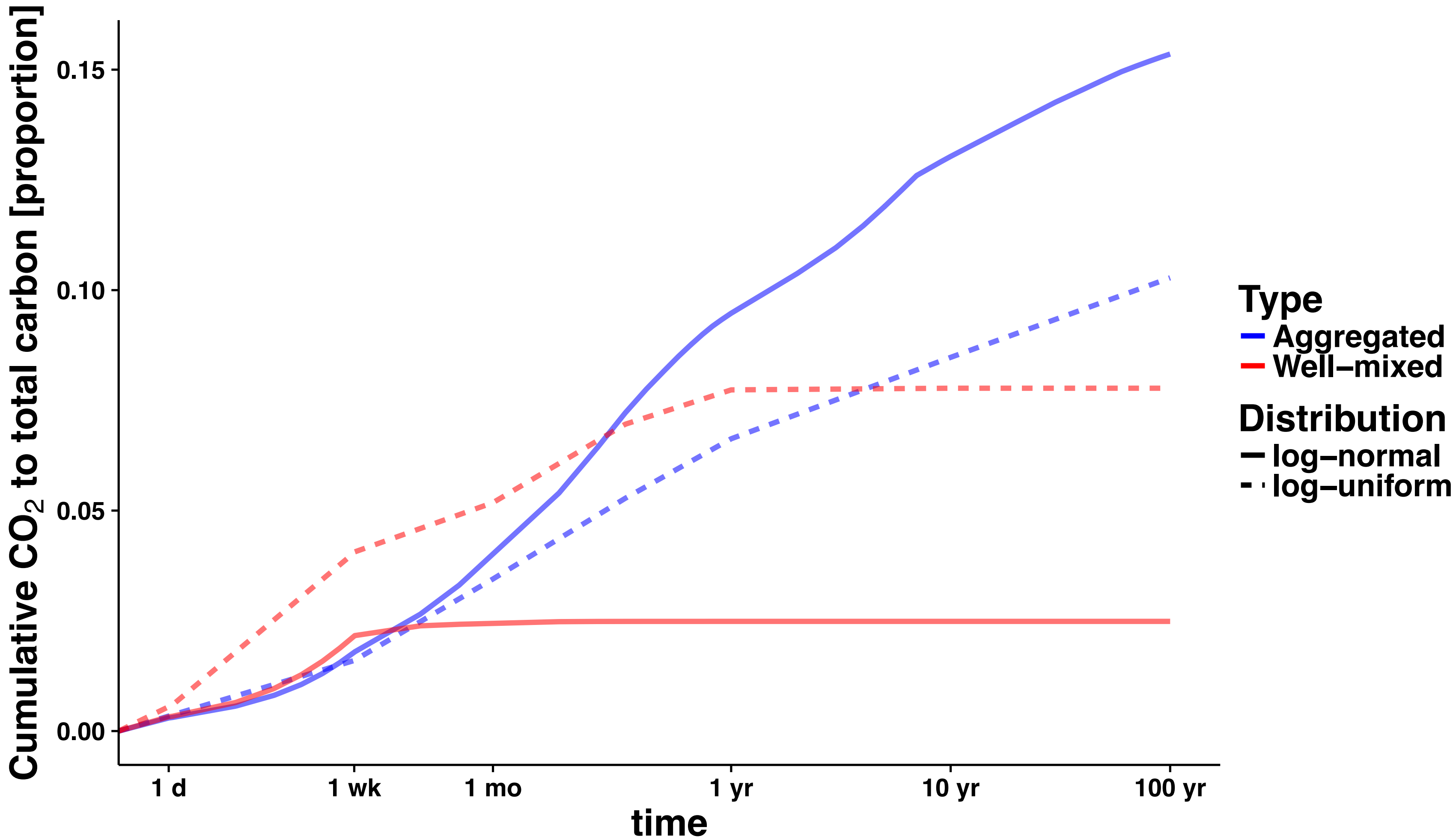

Just Another Microbial (JAM) model integrates biotic and abiotic processes

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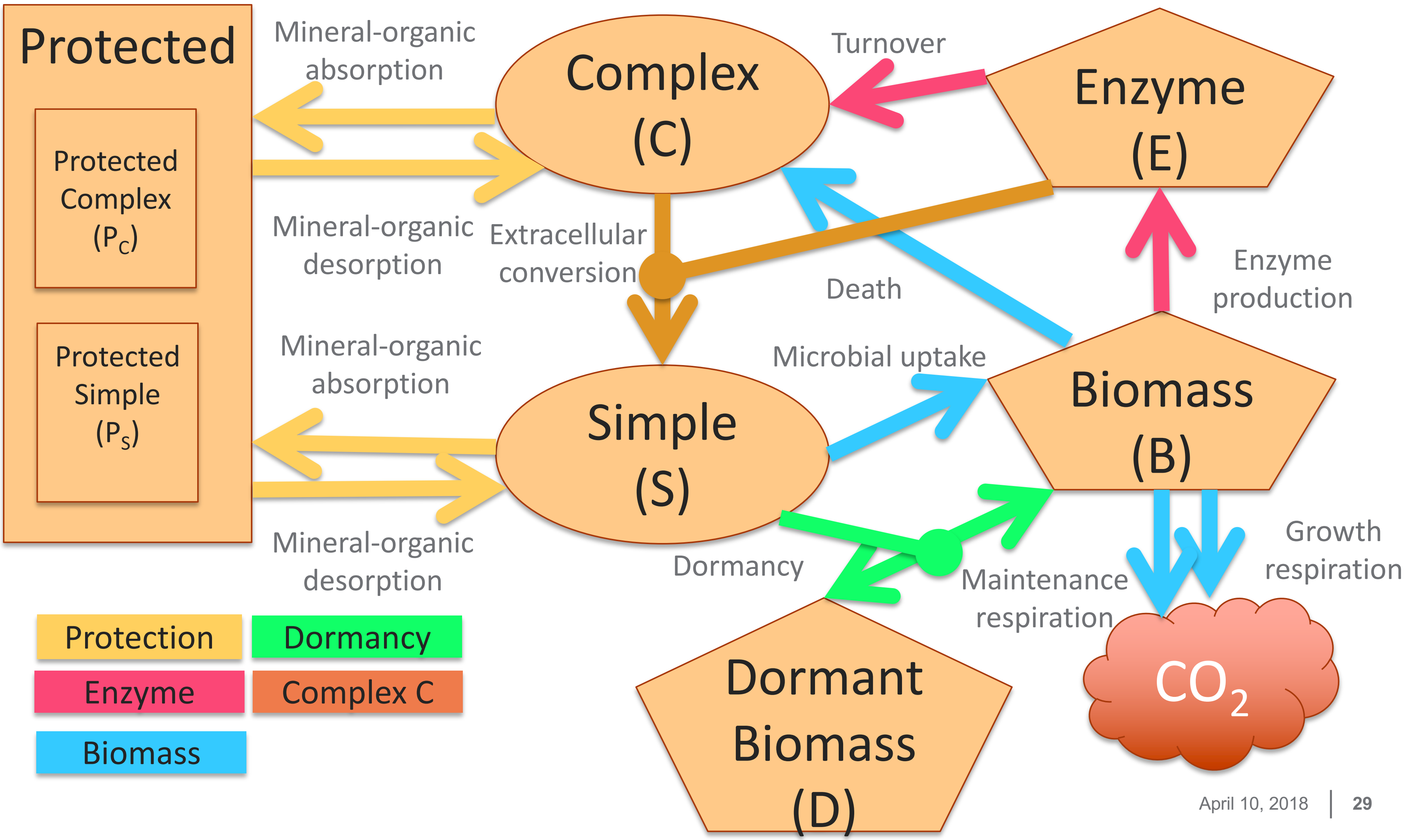
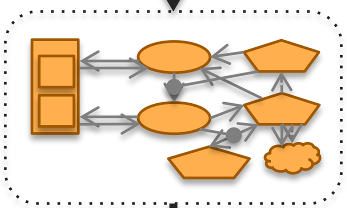


Sensitivity of cumulative CO_2 to parameter perturbations…

Perturbed parameter set

$p_i = (p_1+\varepsilon, \ldots, p_{23})$

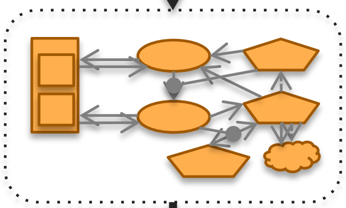


$CO_2(p_i)$

\-

Parameter set

$p_k = (p_1, \ldots, p_{23})$



$CO_2(p_k)$

=

CO_2 response to perturbation

$$\frac{dCO_2}{dp_1} = \frac{\left[C_{CO2}(p_i) - C_{CO2}(p_k)\right] \Big/ \sum_i C_i}{\varepsilon \big/ p_{1\ range}}$$

1 unit = a parameter shift over the parameter range drives 100% increase in cumulative CO_2

Direction of effect of parameter on CO_2 depends on other parameters (e.g. CUE).

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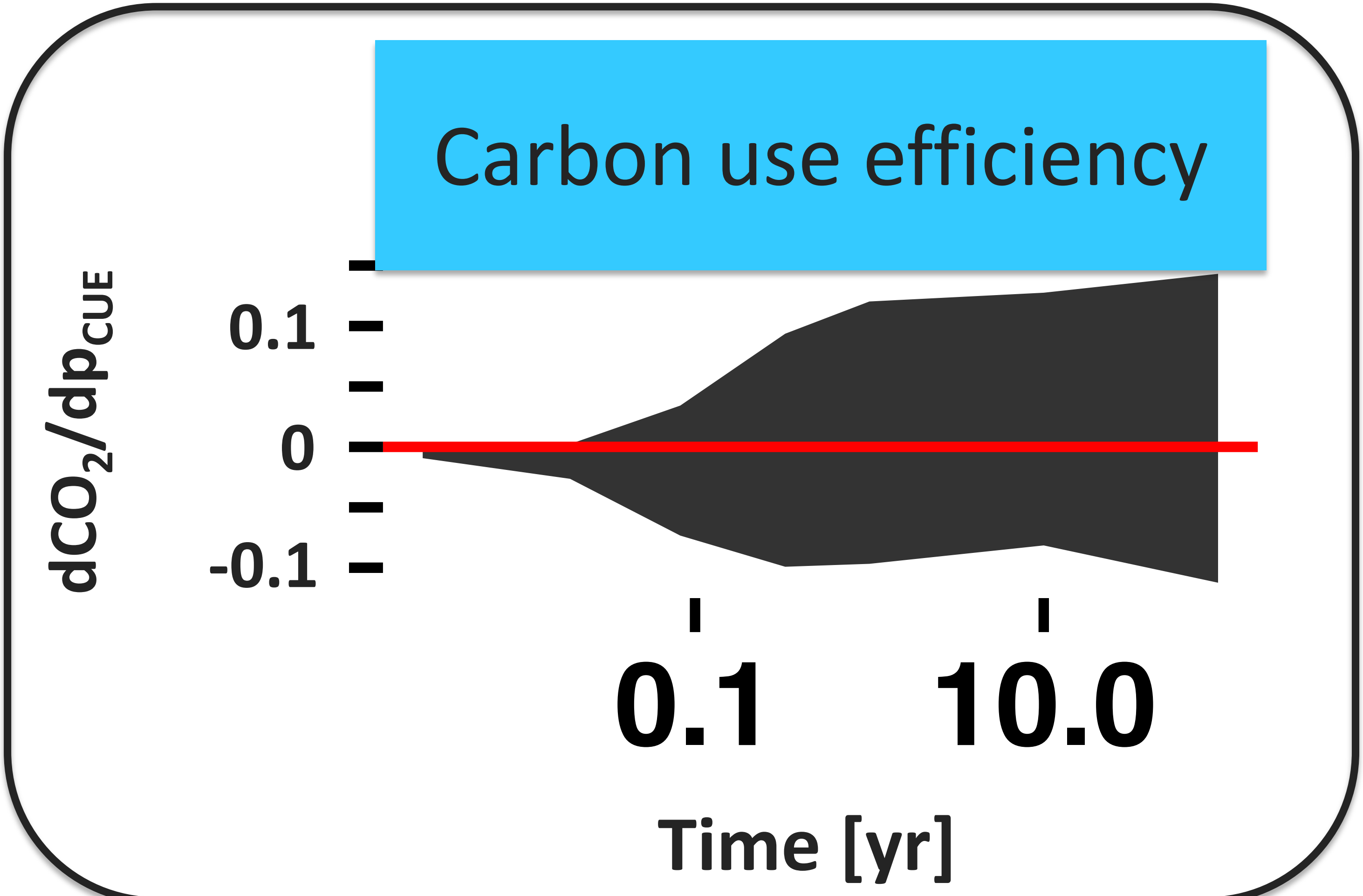
Sensitivity of cumulative CO_2 to parameter perturbation (95% CI)



Biological parameters are good targets for ‘easy’ model improvements.

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Sensitivity of cumulative CO_2 to parameter perturbation (95% CI)