Data and Model Synthesis for Process-Level Understanding of Terrestrial Ecosystems

Anthony Walker

Martin De Kauwe, Belinda Medlyn, Sönke Zaehle,
Alistair Rogers, Shawn Serbin,
Dan Lu, Ming Ye

ORNL is managed by UT-Battelle
for the US Department of Energy

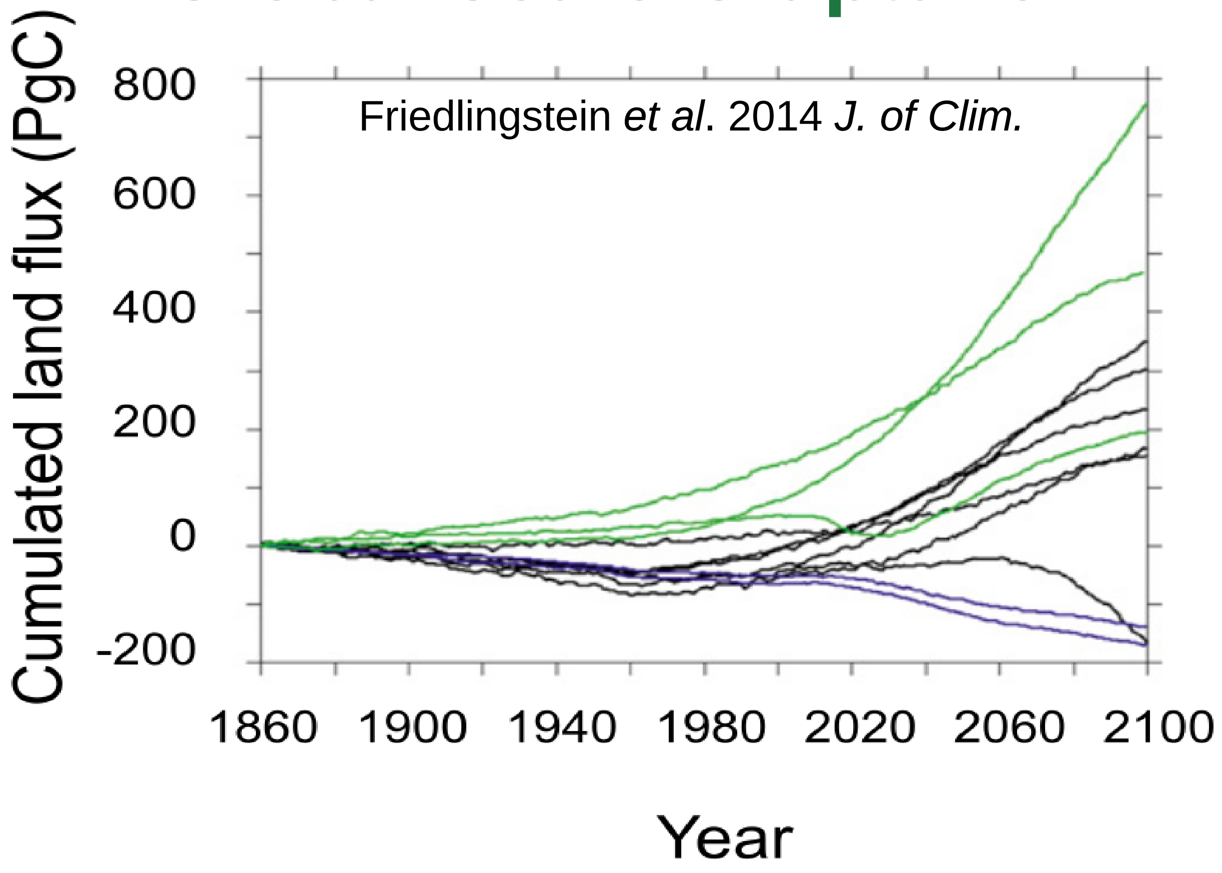
OAK RIDGE
National Laboratory

Talk Outline

- Intro
- FACE Model Data Synthesis – 10 yr forest biomass responses to elevated CO_2
- Multi-assumption modelling (MAAT)
- Model GPP evaluation against GPP proxies using PCA

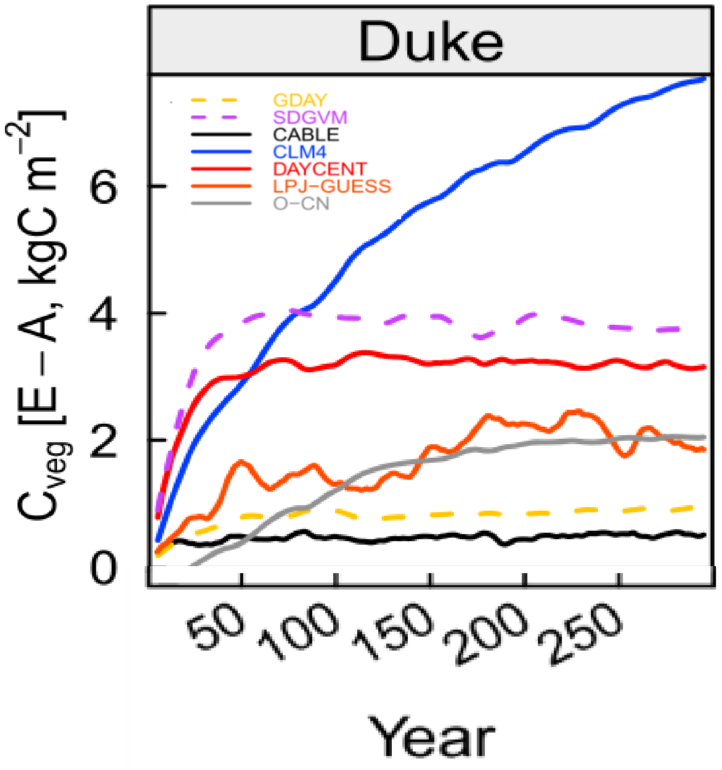
Inherent uncertainty in ecosystem models precludes predictive understanding

Global scale C uptake



Forest stand scale C uptake

Walker *et al*. 2015 *Biogeochem. Cycles*

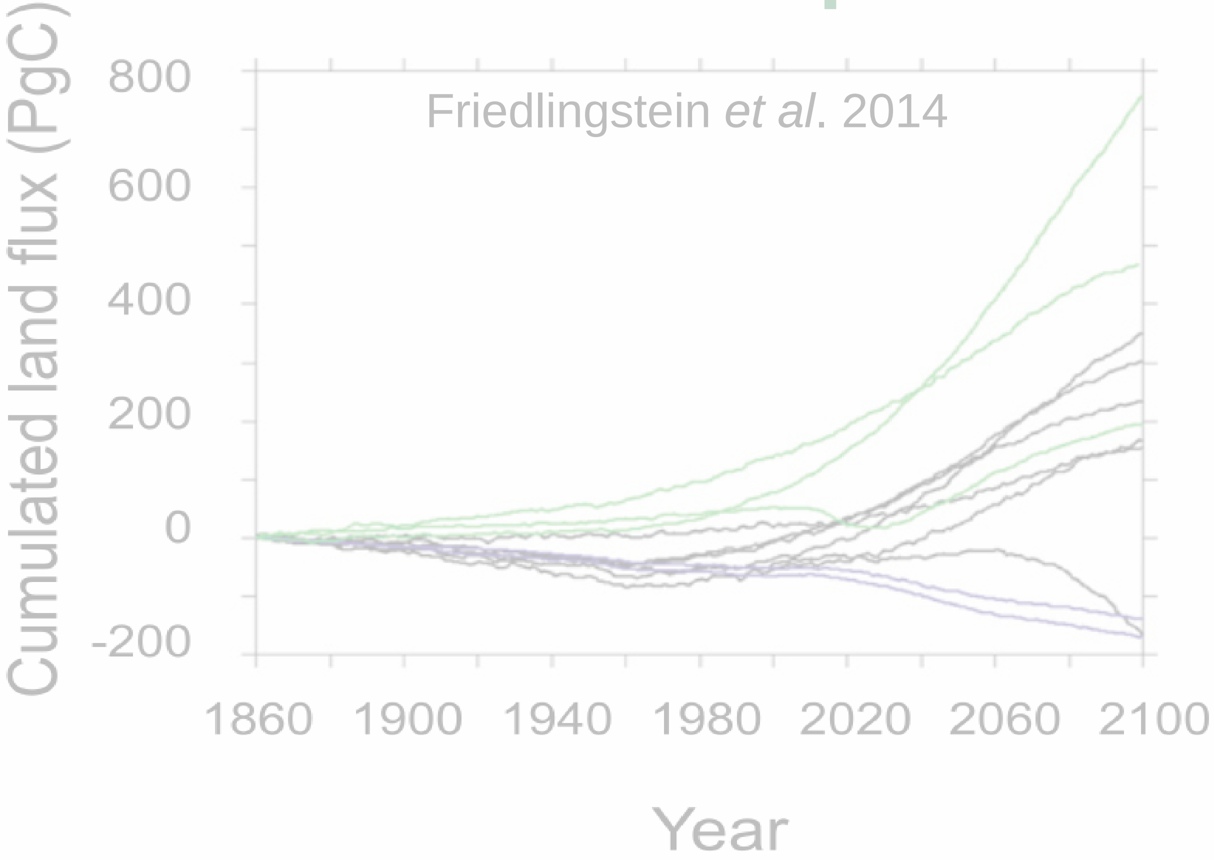


OAK RIDGE National Laboratory

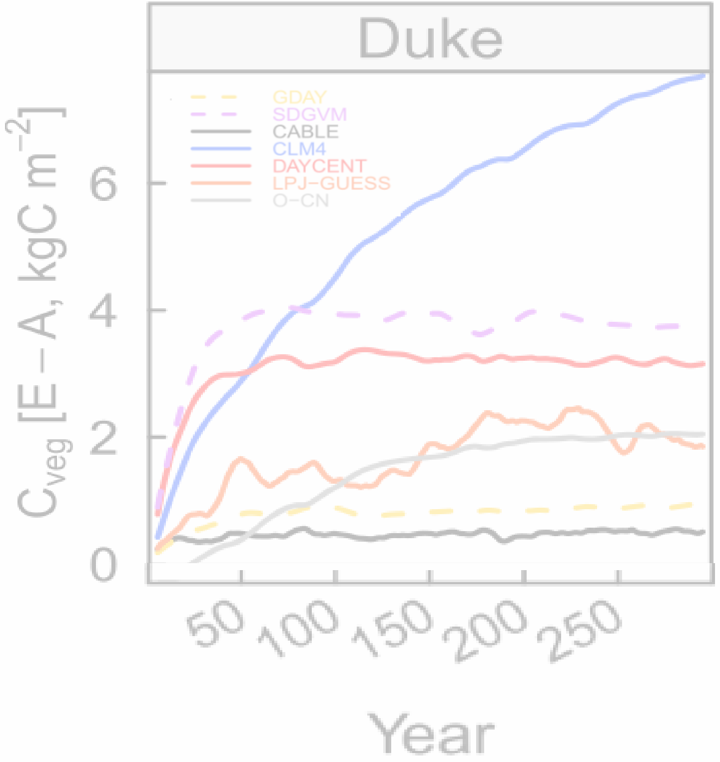
The first step towards predictive understanding is to properly characterise uncertainty and identify its sources

Forest stand scale C uptake

Global scale C uptake



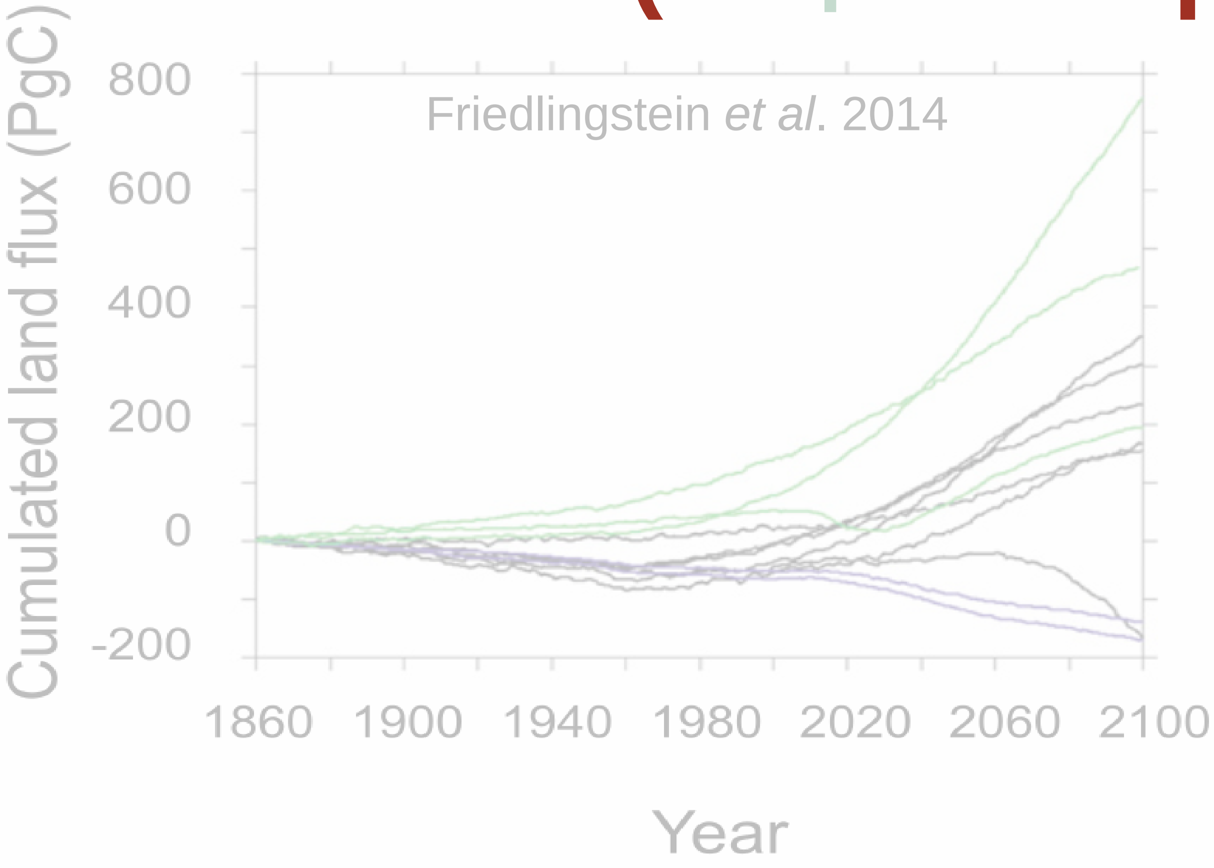
Walker *et al*. 2015



The first step towards predictive understanding is to properly characterise uncertainty and identify its sources

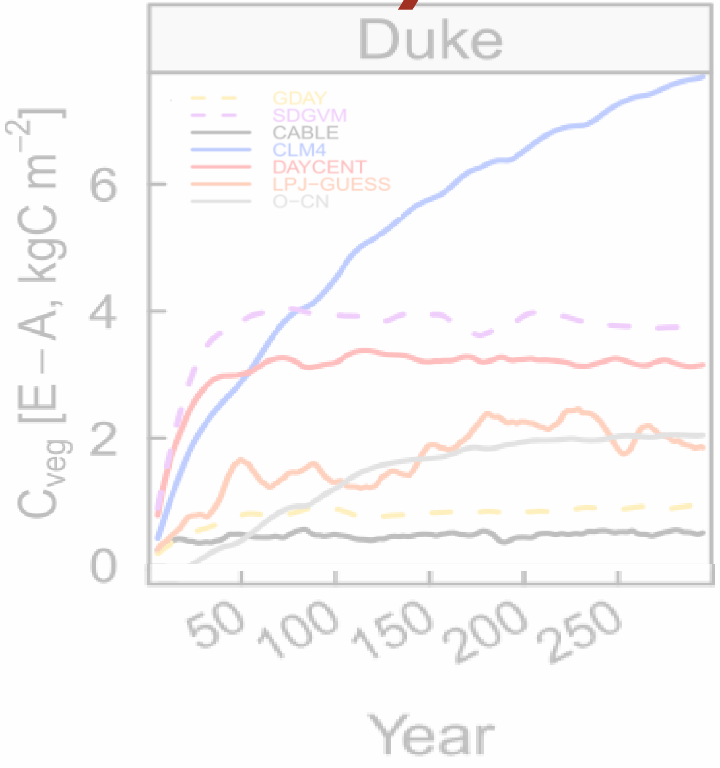
- **Alternative trait values (uncertain parameters)**

Global scale C uptake



Forest stand scale C uptake

Walker et al. 2015

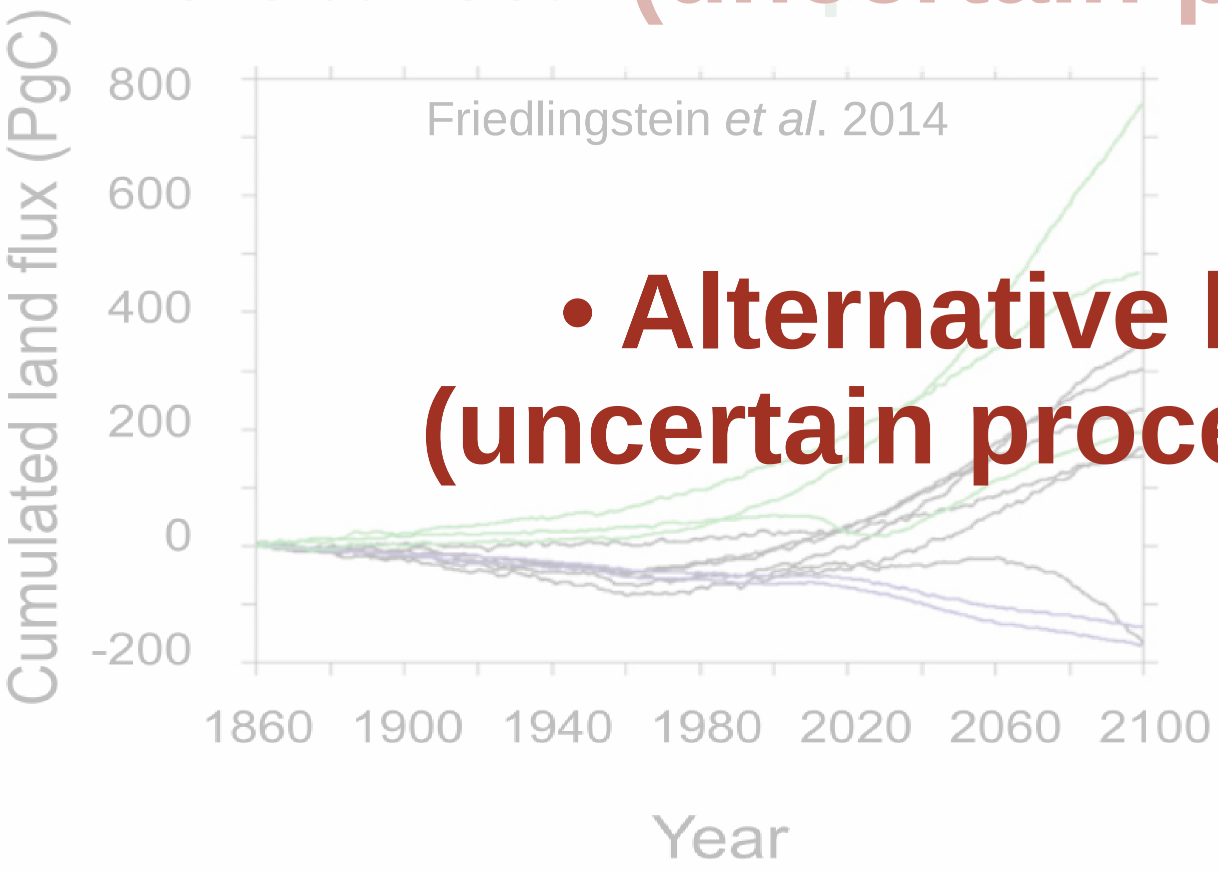


Oak Ridge National Laboratory

The first step towards predictive understanding is to properly characterise uncertainty and identify its sources

- **Alternative trait values (uncertain parameters)**

Global scale C uptake



Forest stand scale C uptake

Walker *et al*. 2015

- **Alternative hypotheses (uncertain process knowledge)**

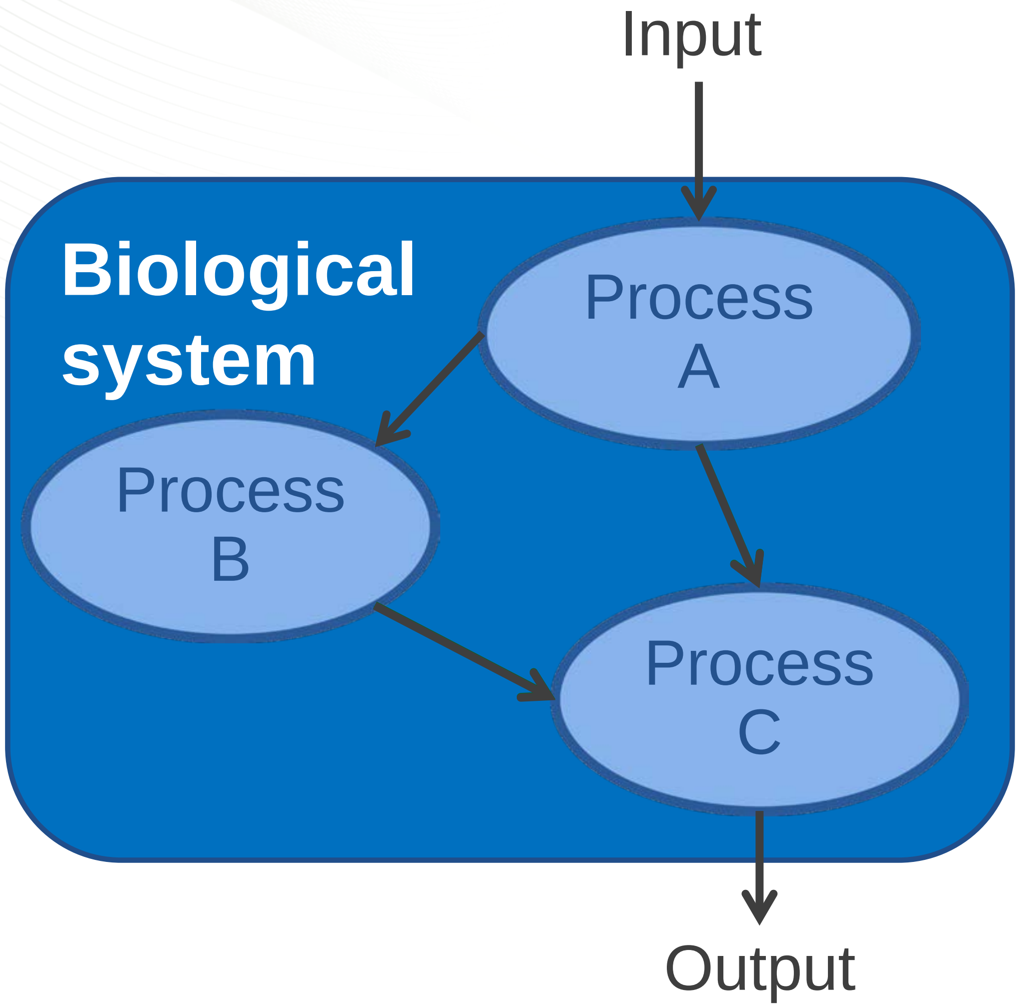
Hypothesis

A mechanistic description of how a process works.

synonyms:

- process representation
- model structure
- assumption (not exactly)

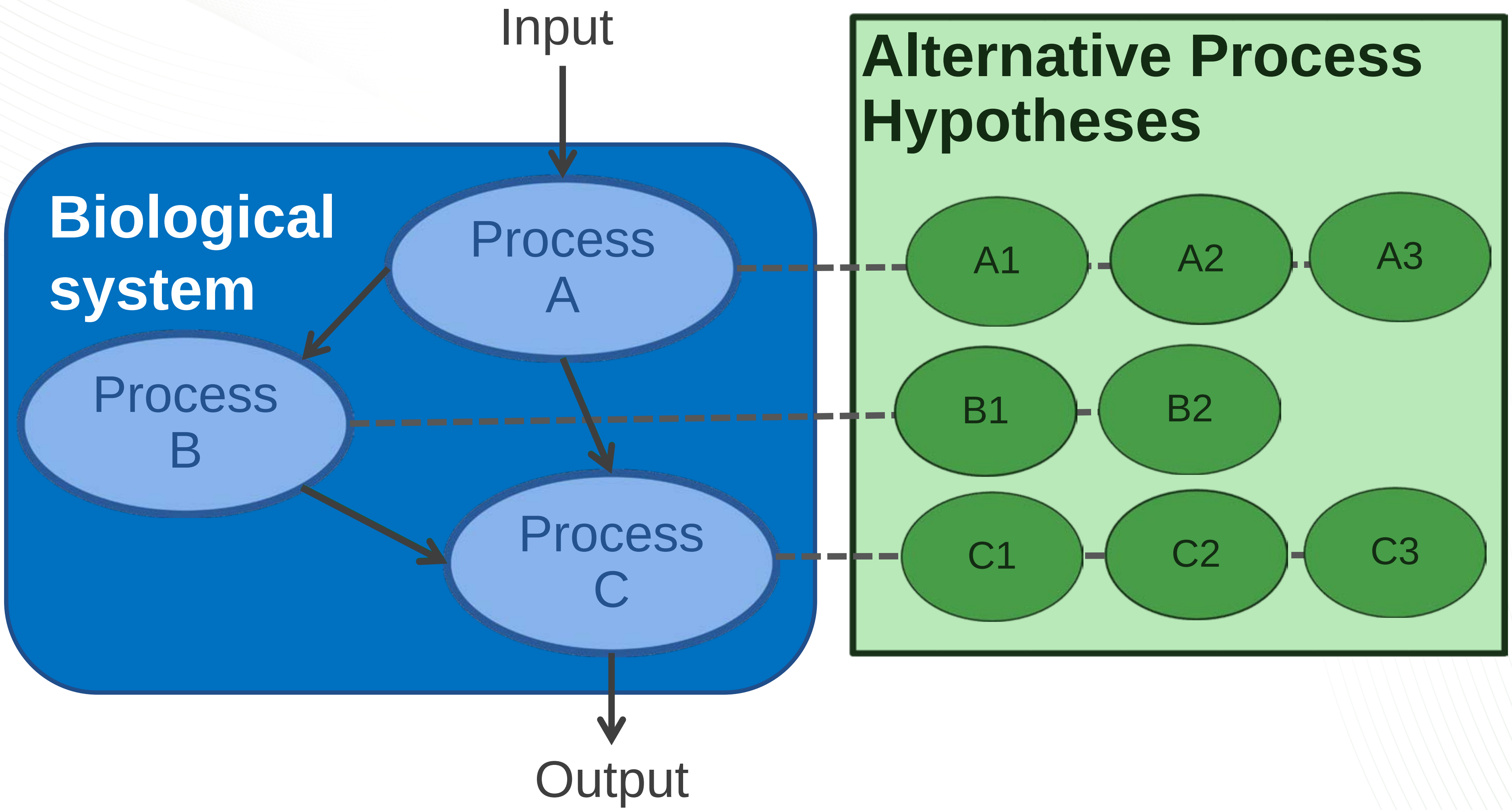
Systems are composed of multiple processes



OAK RIDGE National Laboratory

Systems are composed of multiple processes

Competing hypotheses can exist for each process

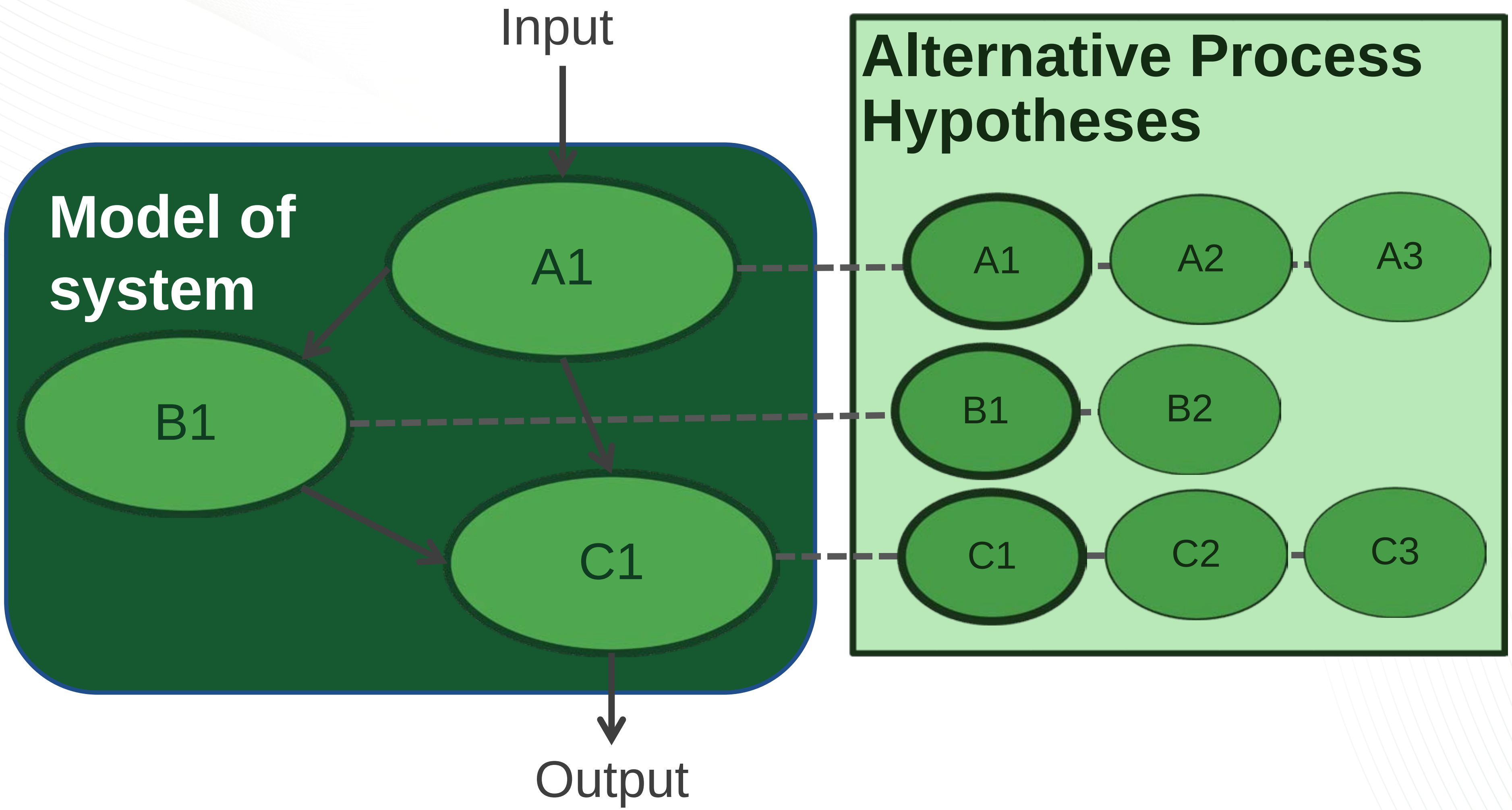


Oak Ridge National Laboratory

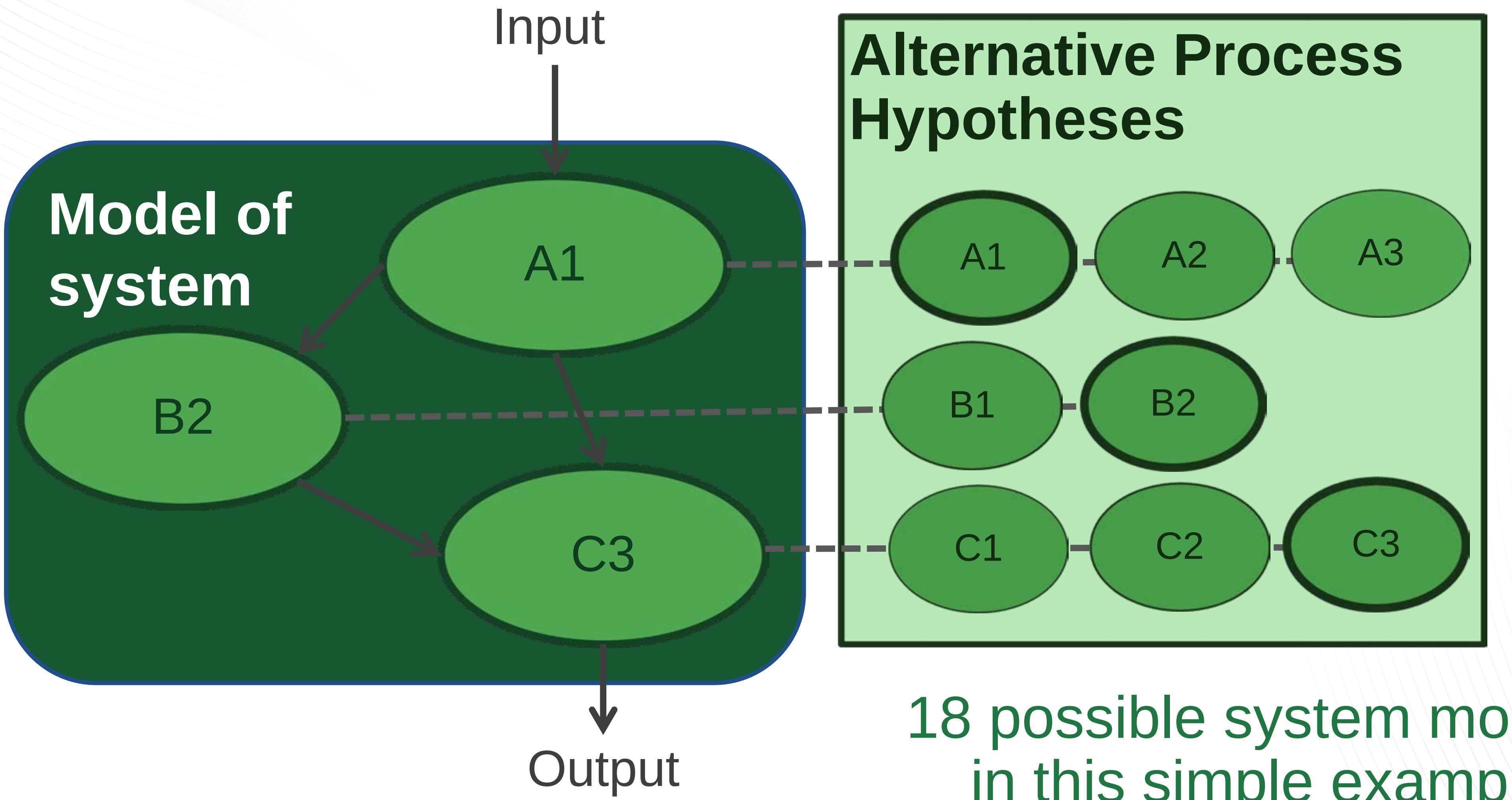
Systems are composed of multiple processes

Competing hypotheses can exist for each process

Resulting in multiple possible models of the system



Systems are composed of multiple processes
Competing hypotheses can exist for each process
… but alternative models are possible



18 possible system models in this simple example

Oak Ridge National Laboratory

FACE Model Data Synthesis

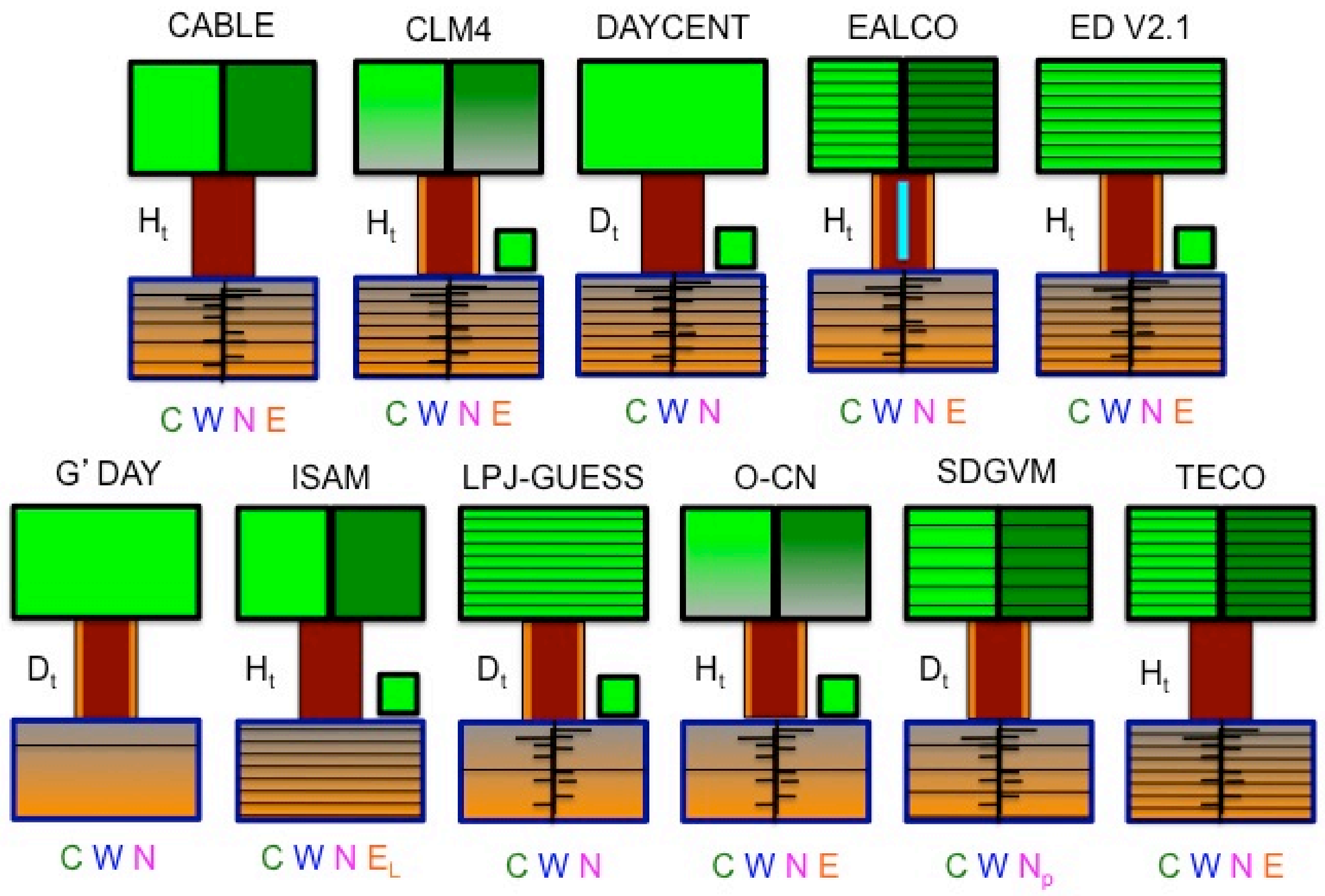
A model inter-comparison evaluated against FACE data

Biomass responses to eCO_2

	Rhinelander	ORNL	Duke	KSC
MAT [°C]	6.0 (0.8)	14.8 (0.9)	14.8 (0.6)	22.1 (0.4)
MAP [mm]	662 (122)	1221 (218)	1081 (168)	1094 (207)
MAPET [mm]	1187 (178)	1483 (78)	1494 (53)	2391 (156)
MI	0.57 (0.15)	0.74 (0.17)	0.65 (0.14)	0.46 (0.10)

MAT – mean annual temperature, MAP – mean annual precipitation, MAPET – mean annual potential evapotranspiration calculated using the Penman-Monteith equation assuming zero canopy resistance. MI – Moisture index (MAP/MAPET). Standard deviation in parentheses.

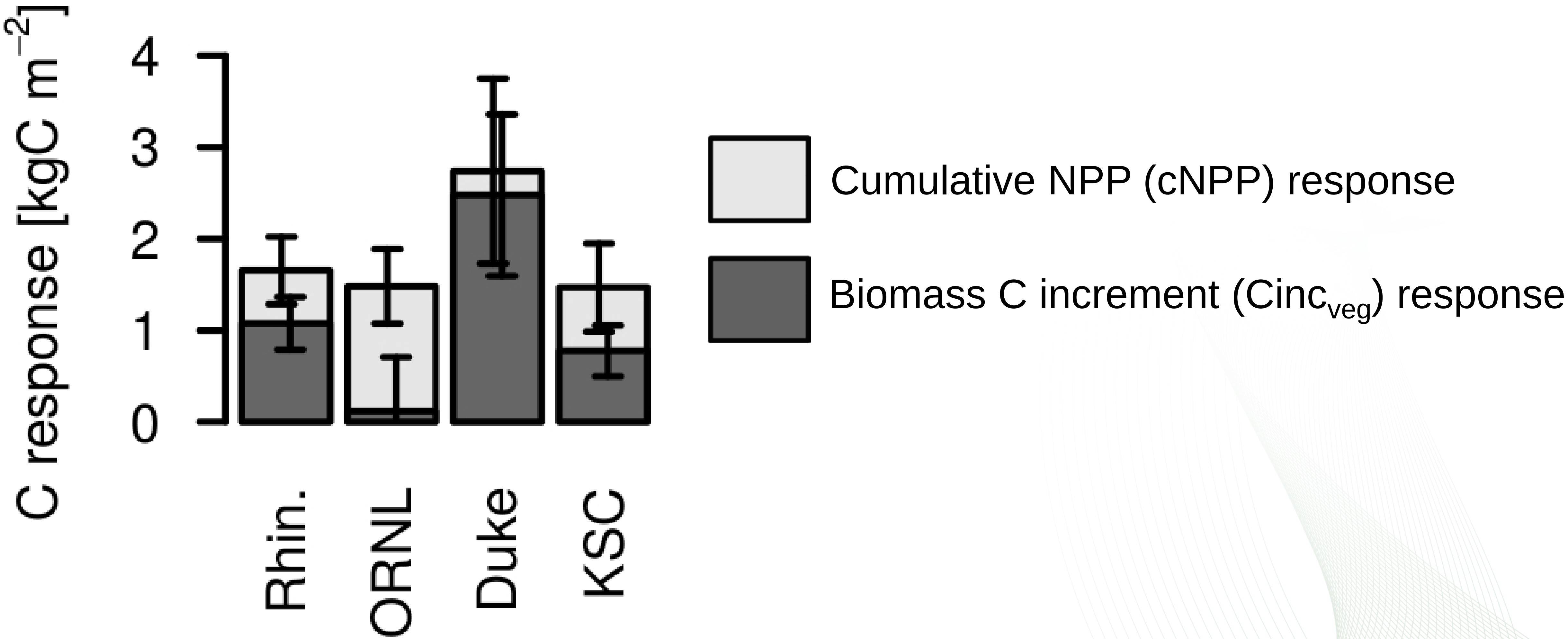
Models



Schematic of the 11 models of the first phase of the FACE Model Data Synthesis project showing common processes but different ways in which those processes are represented

Walker *et al*. 2014 *JGR Biogeosci.*

10 year response of NPP and Biomass C increment to eCO_2



Walker *et al. In Review*

Meta-analysis using mixed-effects regression models

					Random effects		
model	response	Fixed effect	parameter	SEM	re.site	re.Intercept	re.slope
1	NPP	Intercept	0.723	0.133	Rhin.	0.516 (0.481–0.556)	-
		eCO_2	0.164	0.031	ORNL	0.814 (0.773–0.849)	-
					Duke	1.050 (1.003–1.086)	-
					KSC	0.511 (0.486–0.540)	-
2	$Cinc_{veg}$	Intercept	3.616	1.156	Rhin.	3.320 (2.995–3.652)	-
		eCO_2	1.045	0.258	ORNL	4.047 (3.698–4.376)	-
					Duke	6.294 (5.913–6.585)	-
					KSC	0.801 (0.825–0.614)	-

Walker *et al*. *In Review*

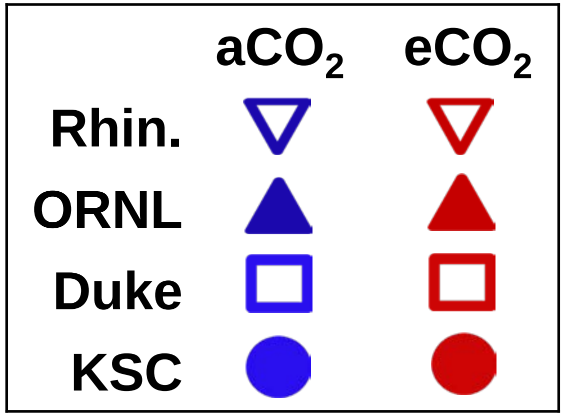
Meta-analysis using mixed-effects regression models

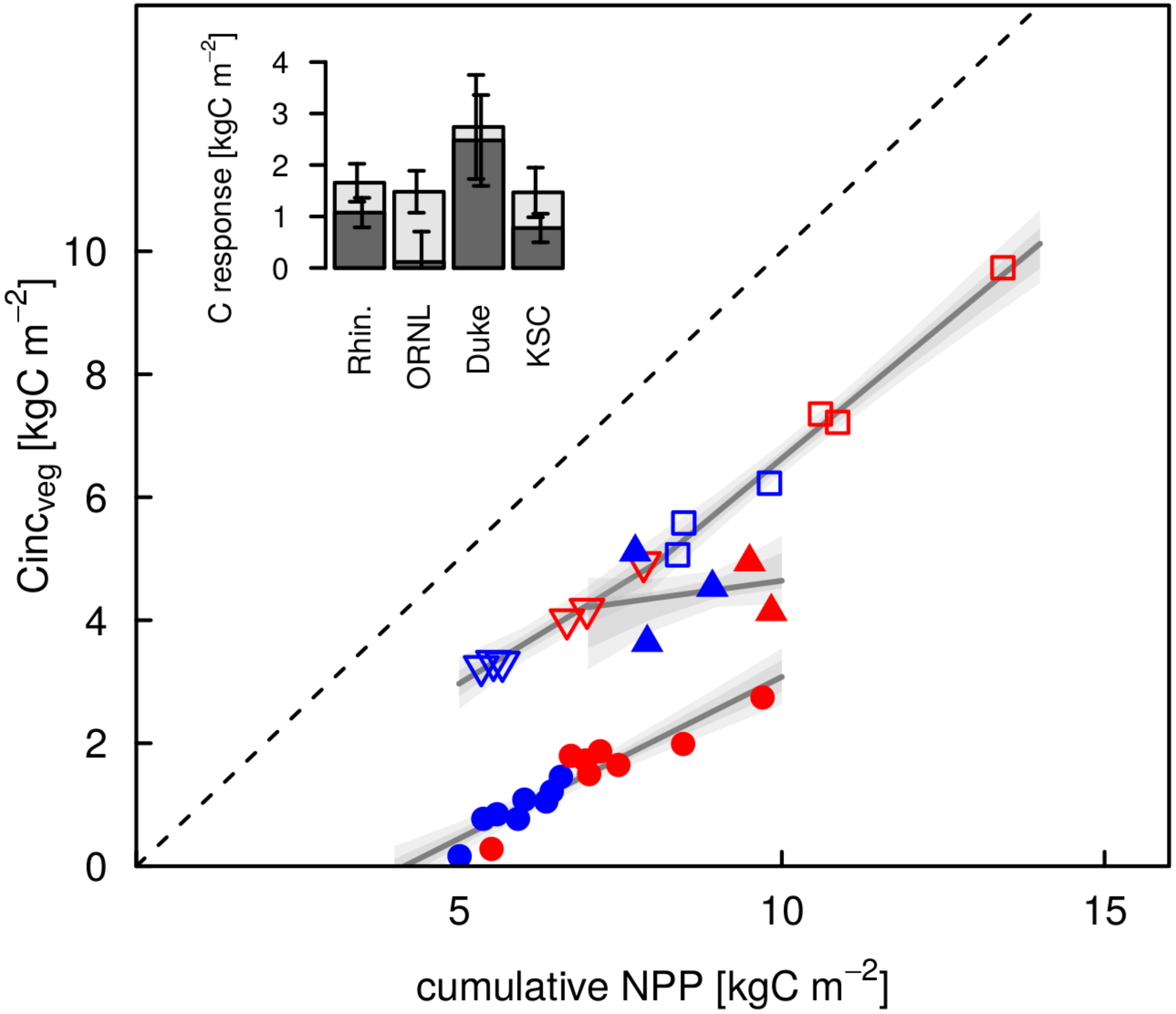
model	response	Fixed effect	parameter	SEM	Random effects: re.site	re.Intercept	re.slope
1	NPP	Intercept	0.723	0.133	Rhin.	0.516 (0.481–0.556)	-
		eCO_2	0.164	0.031	ORNL	0.814 (0.773–0.849)	-
					Duke	1.050 (1.003–1.086)	-
					KSC	0.511 (0.486–0.540)	-
2	$Cinc_{veg}$	Intercept	3.616	1.156	Rhin.	3.320 (2.995–3.652)	-
		eCO_2	1.045	0.258	ORNL	4.047 (3.698–4.376)	-
					Duke	6.294 (5.913–6.585)	-
					KSC	0.801 (0.825–0.614)	-
3	$Cinc_{veg}$	Intercept	-0.332	1.422	Rhin.	-0.245 (-1.055–0.627)	0.642† (0.504–0.764)
		cNPP	0.546†	0.173	ORNL	3.205 (-0.436–3.849)	0.144† (0.070–0.553)
					Duke	-2.103 (-2.704– -0.985)	0.873† (0.767–0.933)
					KSC	-2.183 (-2.640– -1.720)	0.526† (0.460–0.594)

† Indicates the biomass production rate, i.e. the slope of the assumed linear relationship between $Cinc_{veg}$ and cNPP.

Walker *et al. In Review*

Plot level relationship of $Cinc_{veg}$ to cNPP





Walker *et al*. *In Review*

Meta-analysis using mixed-effects regression models

model	response	Fixed effect	parameter	SEM	Random effects: re.site	re.Intercept	re.slope
1	NPP	Intercept	0.723	0.133	Rhin.	0.516 (0.481–0.556)	-
		eCO_2	0.164	0.031	ORNL	0.814 (0.773–0.849)	-
					Duke	1.050 (1.003–1.086)	-
					KSC	0.511 (0.486–0.540)	-
2	$Cinc_{veg}$	Intercept	3.616	1.156	Rhin.	3.320 (2.995–3.652)	-
		eCO_2	1.045	0.258	ORNL	4.047 (3.698–4.376)	-
					Duke	6.294 (5.913–6.585)	-
					KSC	0.801 (0.825–0.614)	-
3	$Cinc_{veg}$	Intercept	-0.332	1.422	Rhin.	-0.245 (-1.055–0.627)	0.642† (0.504–0.764)
		cNPP	0.546†	0.173	ORNL	3.205 (-0.436–3.849)	0.144† (0.070–0.553)
					Duke	-2.103 (-2.704– -0.985)	0.873† (0.767–0.933)
					KSC	-2.183 (-2.640– -1.720)	0.526† (0.460–0.594)

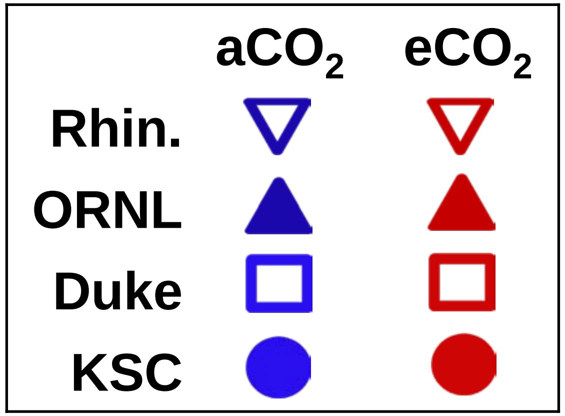
No direct CO_2 effect on $Cinc_{veg}$!

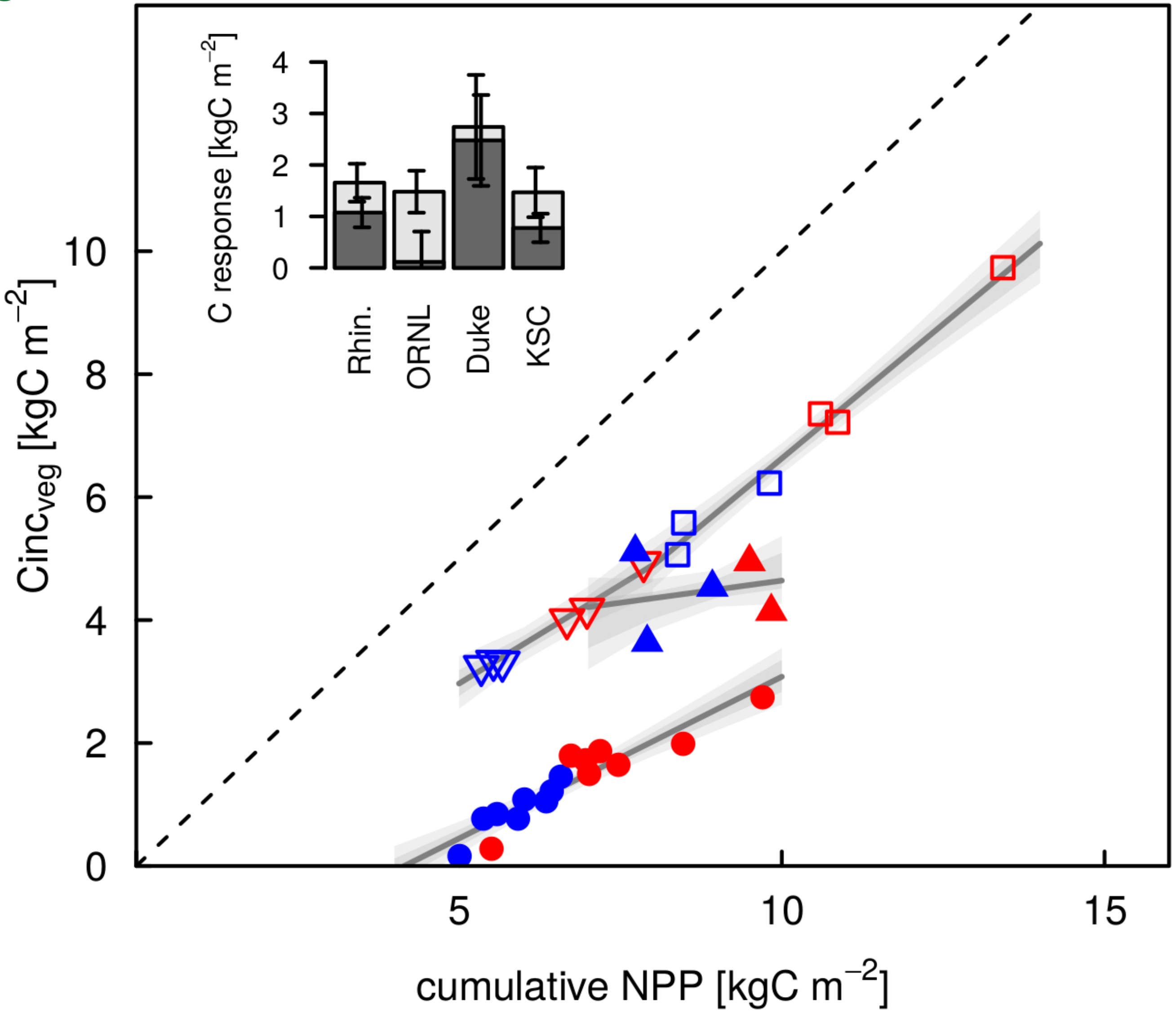
† Indicates the biomass production rate, i.e. the slope of the assumed linear relationship between $Cinc_{veg}$ and cNPP.

Walker *et al*. *In Review*

Cinc_{veg} response can be predicted by cNPP response and slope of the relationship

$$Cinc_{veg} = \Delta cNPP . \frac{dCinc_{veg}}{dcNPP}$$





Walker *et al.* *In Review*

Meta-analysis using mixed-effects regression models

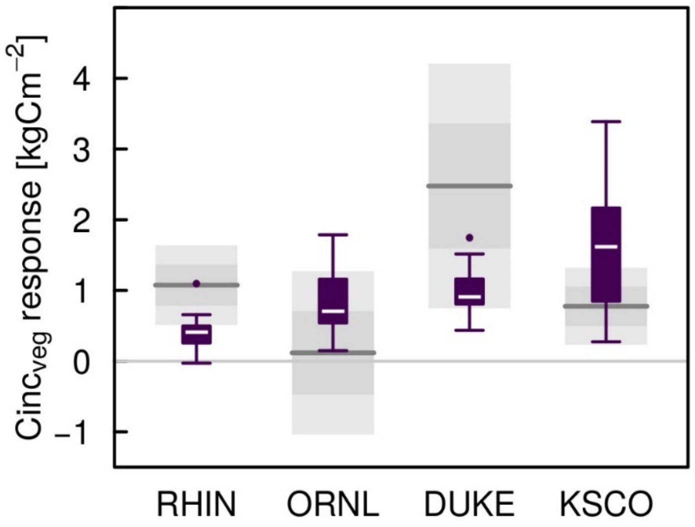
model	response	Fixed effect	parameter	SEM	Random effects: re.site	re.Intercept	re.slope
1	NPP	Intercept	0.723	0.133	Rhin.	0.516 (0.481–0.556)	-
		eCO_2	0.164	0.031	ORNL	0.814 (0.773–0.849)	-
					Duke	1.050 (1.003–1.086)	-
					KSC	0.511 (0.486–0.540)	-
2	$Cinc_{veg}$	Intercept	3.616	1.156	Rhin.	3.320 (2.995–3.652)	-
		eCO_2	1.045	0.258	ORNL	4.047 (3.698–4.376)	-
					Duke	6.294 (5.913–6.585)	-
					KSC	0.801 (0.825–0.614)	-
3	$Cinc_{veg}$	Intercept	-0.332	1.422	Rhin.	-0.245 (-1.055–0.627)	0.642† (0.504–0.764)
		cNPP	0.546†	0.173	ORNL	3.205 (-0.436–3.849)	0.144† (0.070–0.553)
					Duke	-2.103 (-2.704– -0.985)	0.873† (0.767–0.933)
					KSC	-2.183 (-2.640– -1.720)	0.526† (0.460–0.594)
4	fW	Intercept	0.365	0.121	Rhin.	0.476 (0.435–0.507)	-
		cNPP	0.020	0.005	Duke	0.480 (0.417–0.529)	-
					KSC	0.139 (0.101–0.172)	-

Walker *et al*. *In Review*

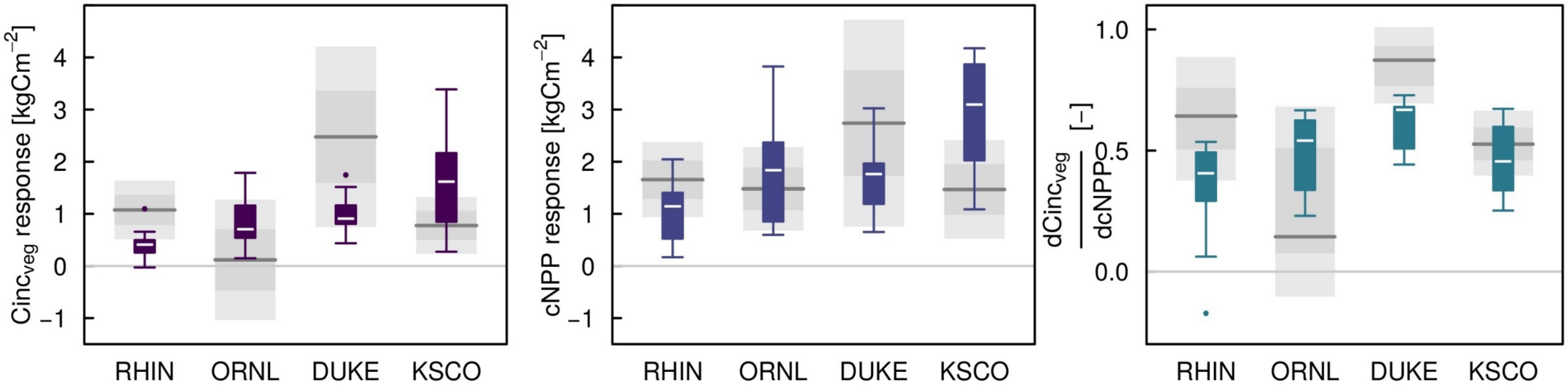
Assuming wood allocation dominates veg turnover, biomass production rate can be calculated:

$$\frac{dCinc_{veg}}{dcNPP} = fW_a + 2\frac{dfW}{dcNPP}cNPP$$

Model ensemble $Cinc_{veg}$ response



Model ensemble $Cinc_{veg}$ response

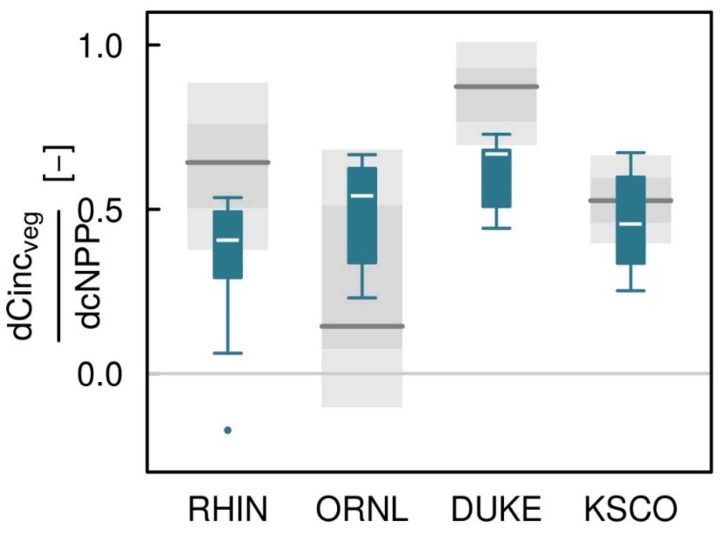


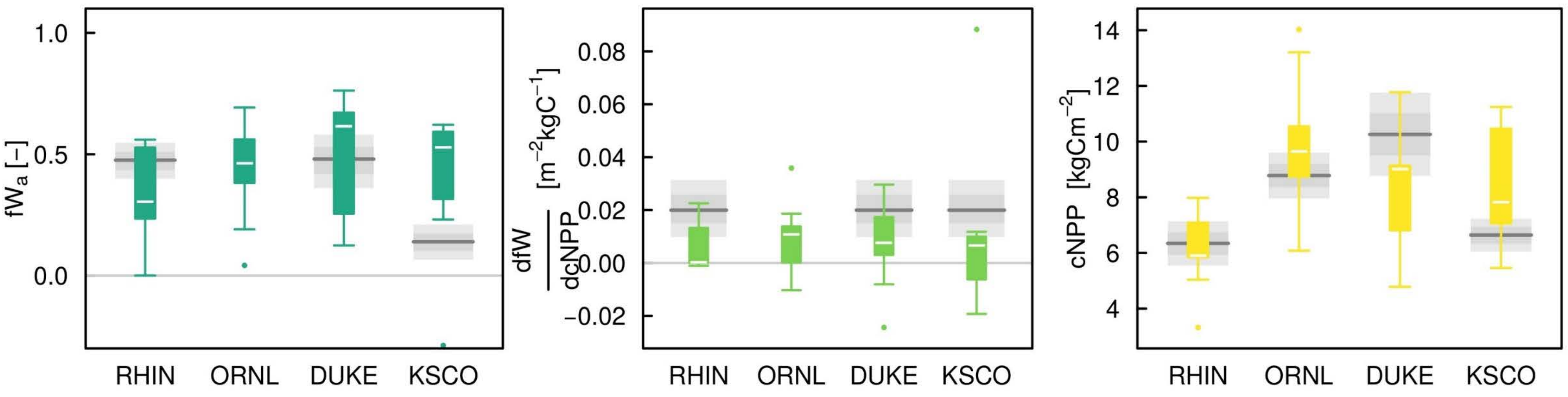
$$Cinc_{veg} = \Delta cNPP.\frac{dCinc_{veg}}{dcNPP}$$

Oak Ridge National Laboratory

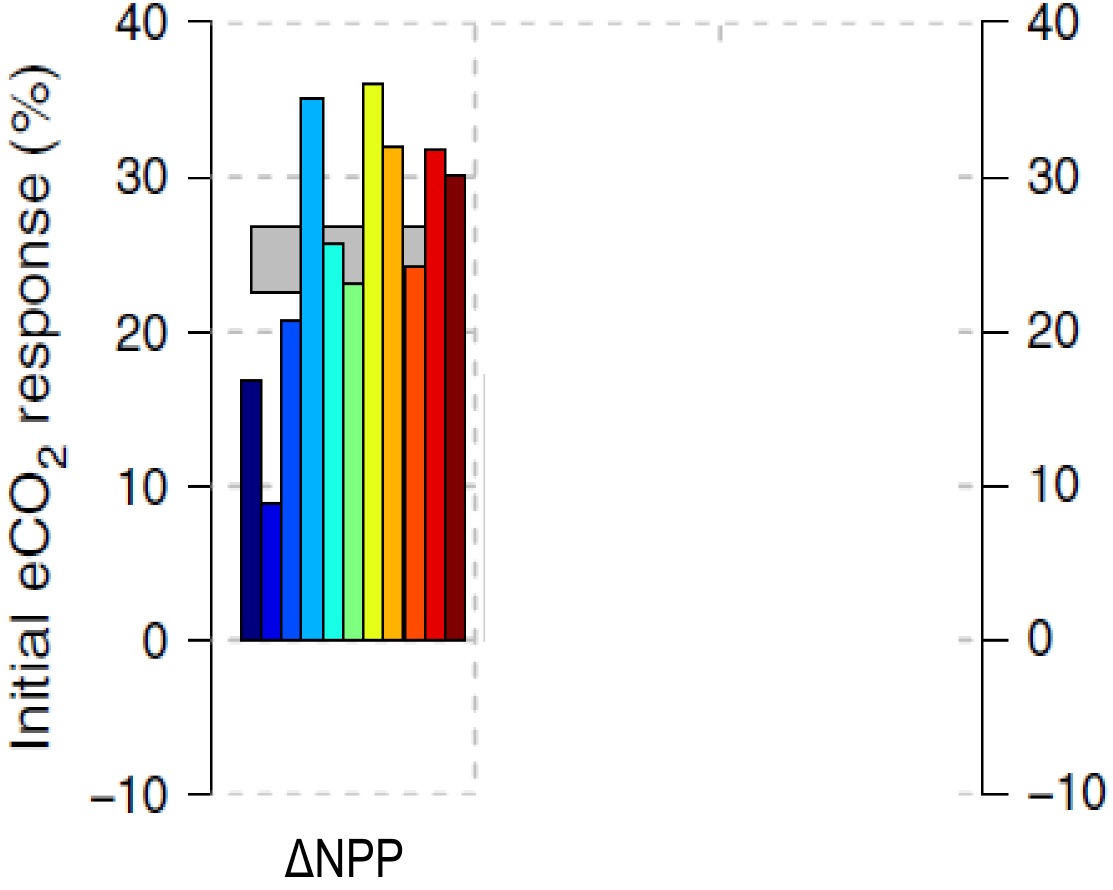
Model ensemble $Cinc_{veg}$ response

$$\frac{dCinc_{veg}}{dcNPP} = fW_a + 2\frac{dfW}{dcNPP}cNPP$$





NPP & N response to eCO_2, Duke

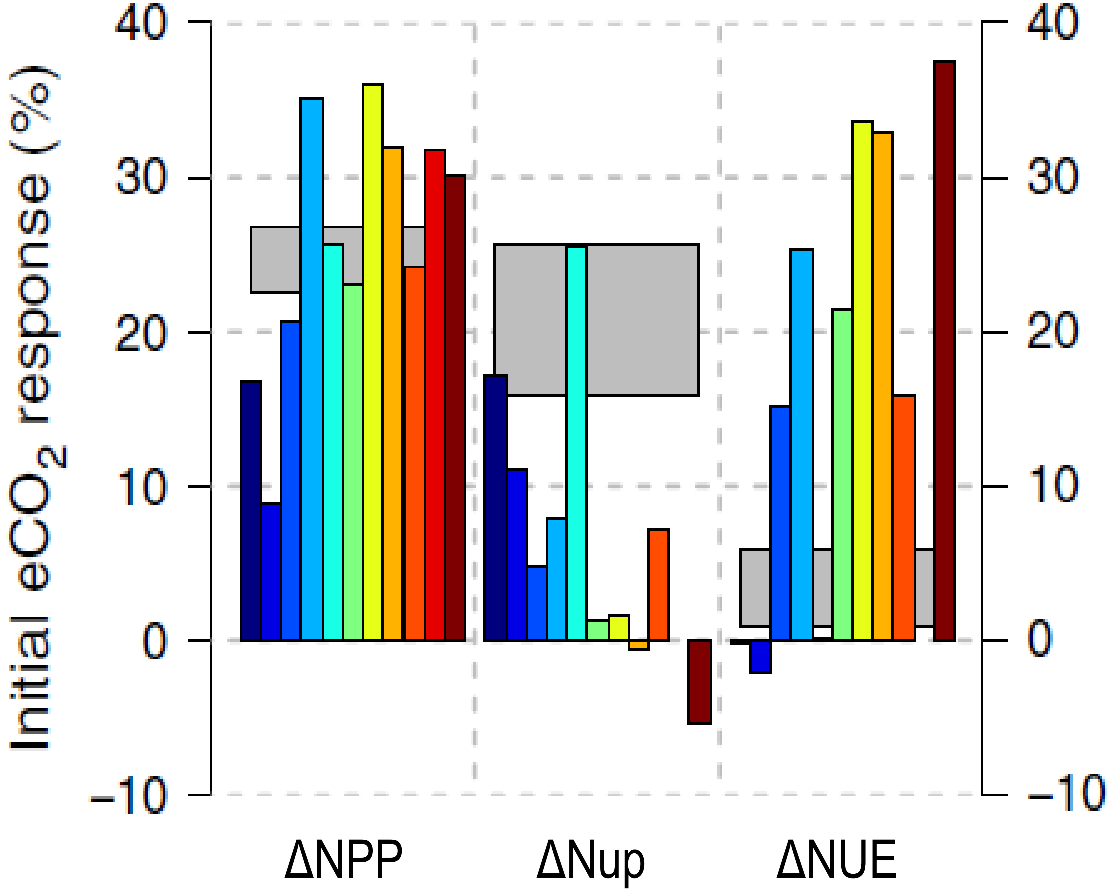


NPP = Nup x NUE

ΔNPP = ΔNup x ΔNUE

Zaehle *et. al.* 2014 *New Phyt.*

NPP & N response to eCO_2, Duke

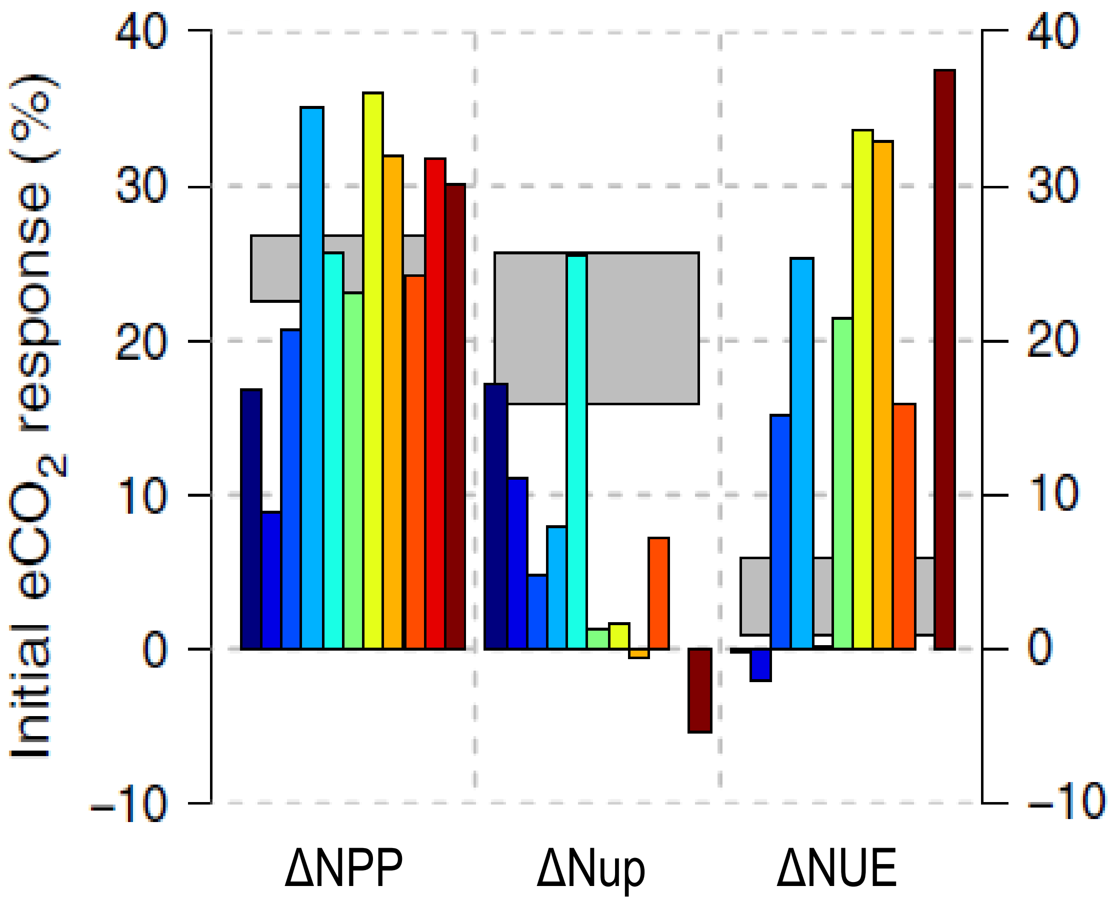


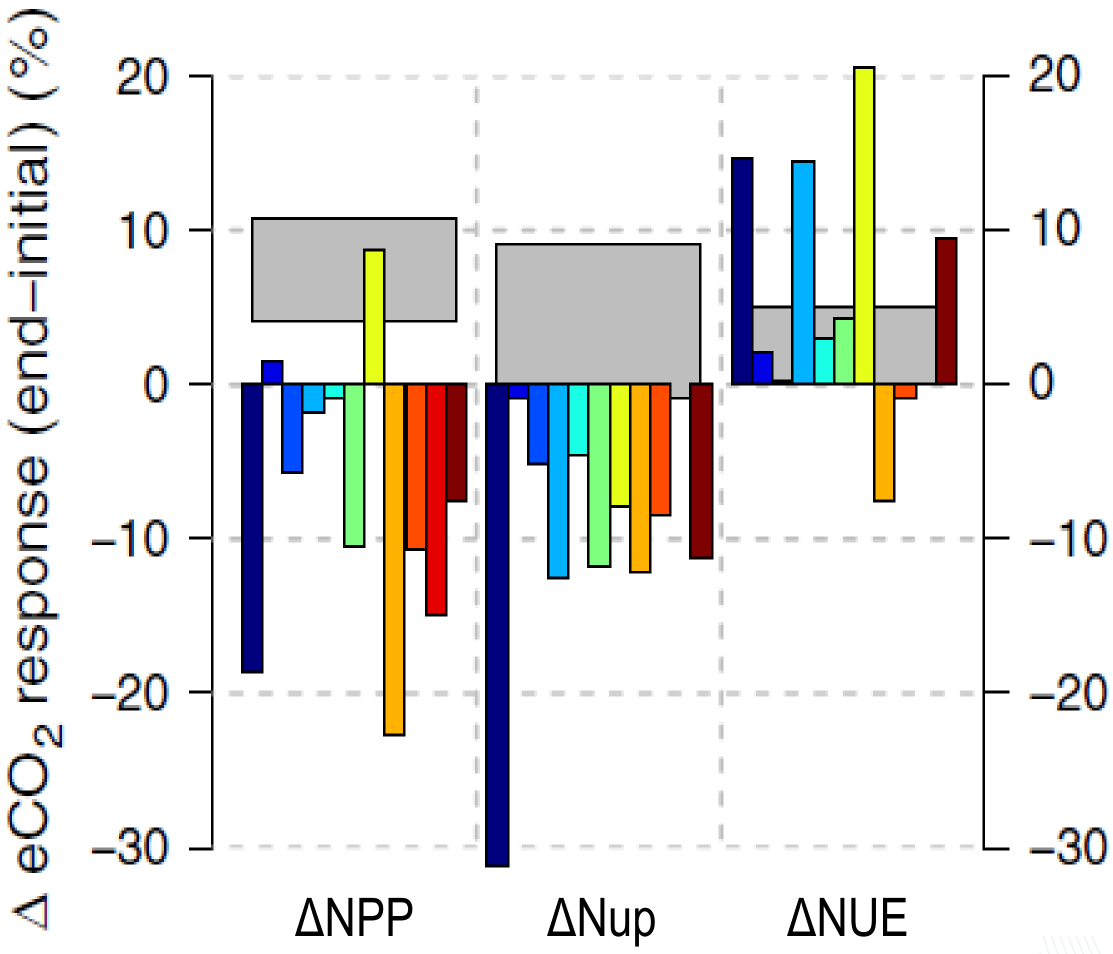
NPP = Nup x NUE

Models generally captured the initial NPP response response but confounded the Nup response with the NUE response.

Zaehle *et. al.* 2014 *New Phyt.*

NPP & N response to eCO_2, Duke

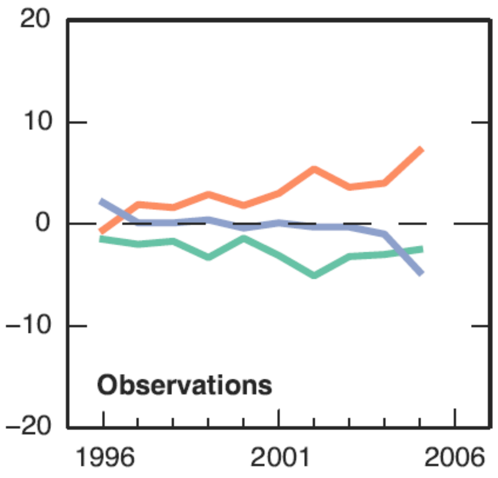


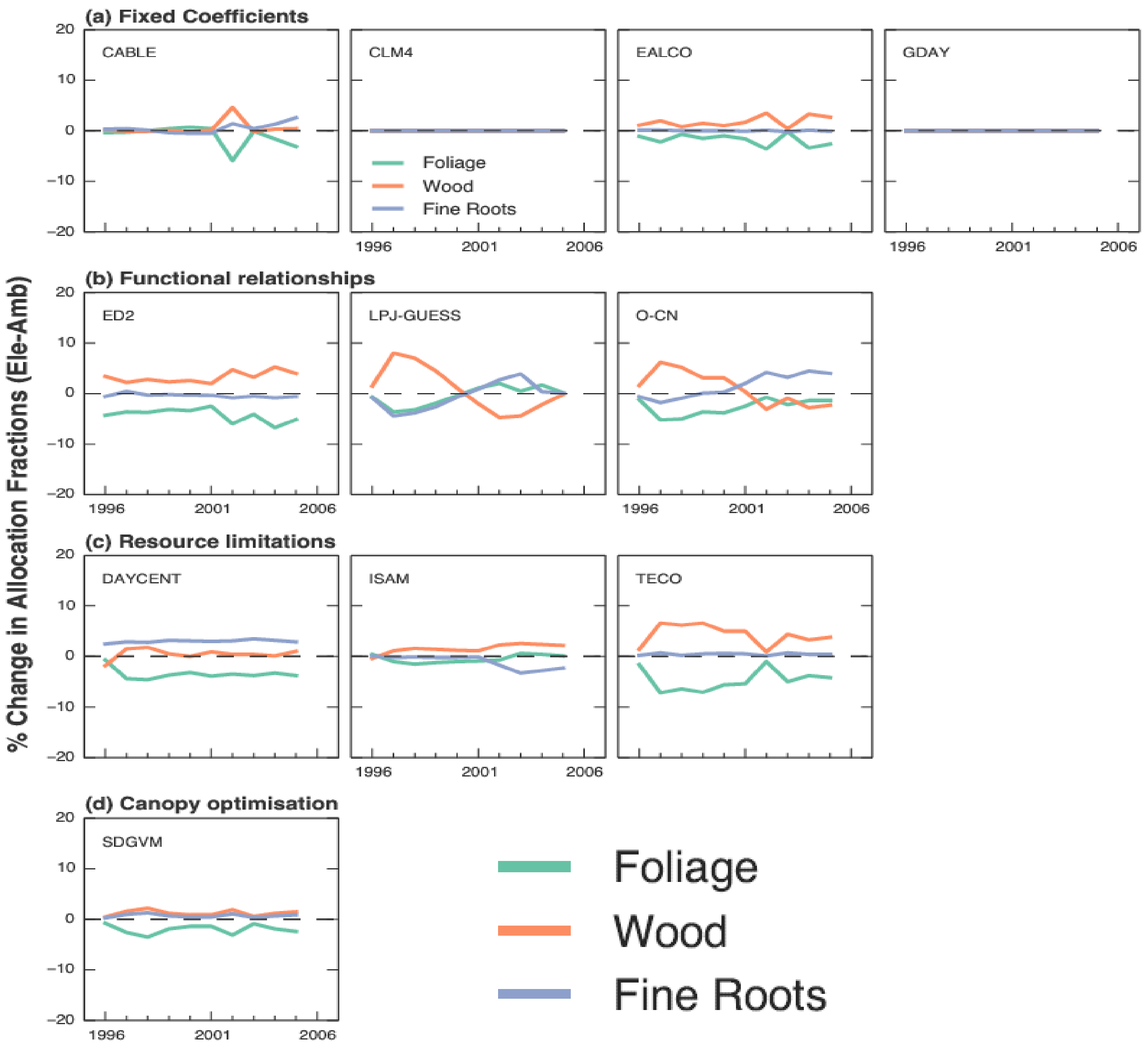


NPP increased by the end of the experiment, all but one model predicted a decrease. Increased Nup was not sustained by the models

Zaehle *et. al.* 2014 *New Phyt.*

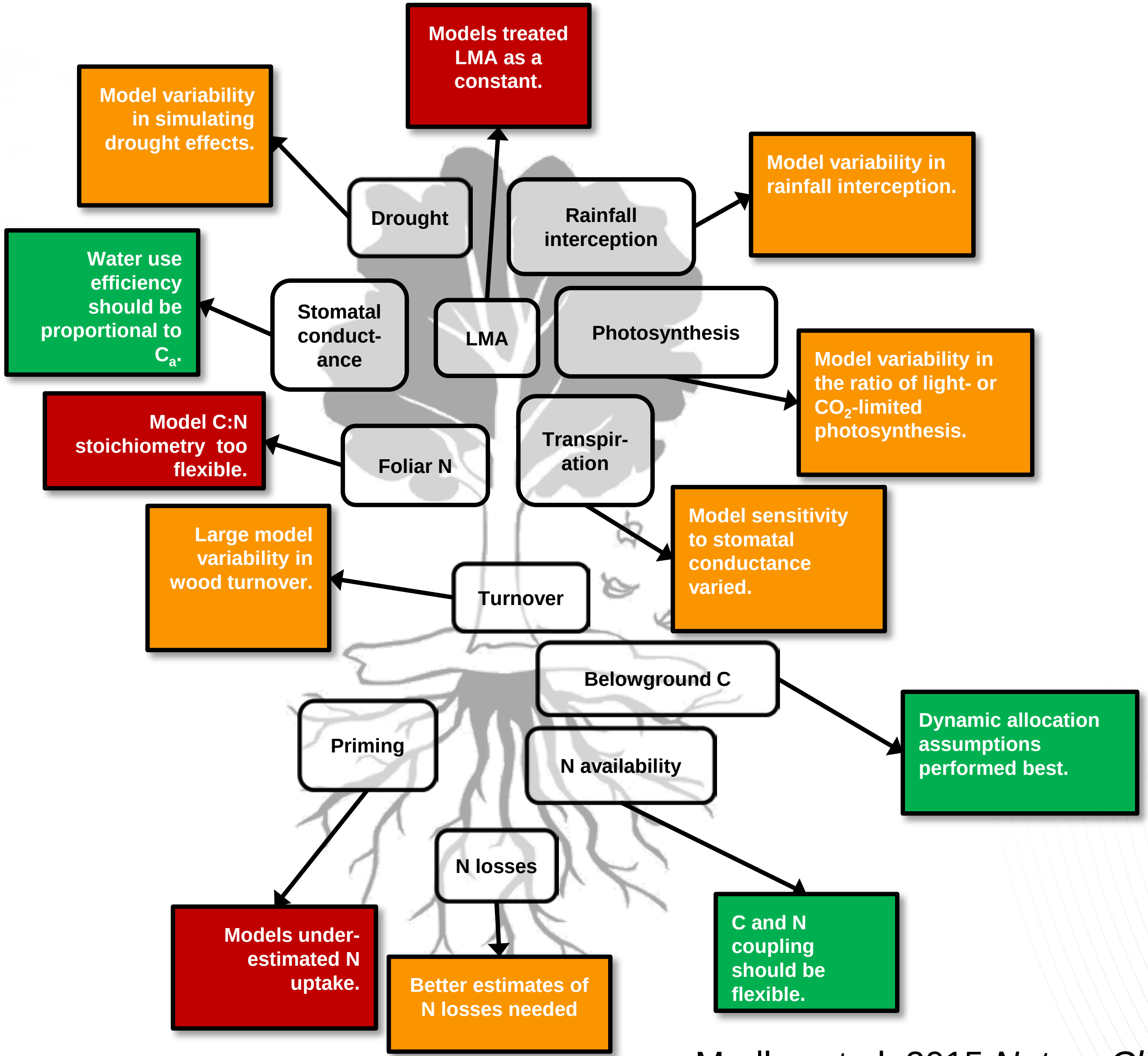
Changes in C allocation in response to eCO_2, Duke





De Kauwe *et. al.* 2015 *New Phyt.*

FACE-MDS Phase-1 Summary



Medlyn et al. 2015 *Nature Clim. Change*

FACE-MDS 10 yr Biomass Summary

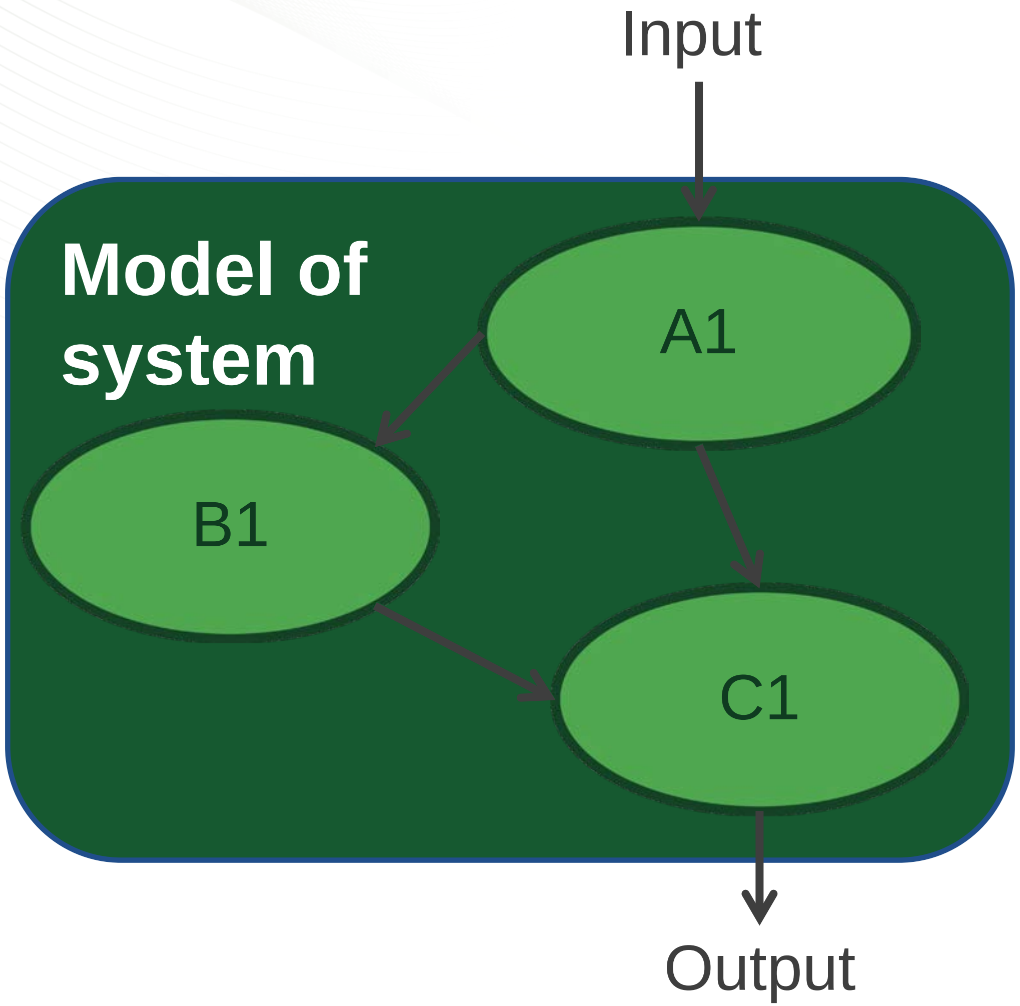
- A sustained long-term stimulation of forest biomass in response to CO_2 concentrations predicted for the middle of the century was clearly demonstrated.
- Modelling this is site specific:
  - At ORNL uncertainty was too high in 10 year biomass response
  - At KSC the temperature by CO_2 interaction was not observed
  - At Rhin and Duke NPP was under-predicted due to inability to increase N uptake AND allocation response to CO_2 was too low

MAAT & multi-hypothesis modeling

Systems are composed of multiple processes

Competing hypotheses can exist for each process

Traditional models use only single hypotheses

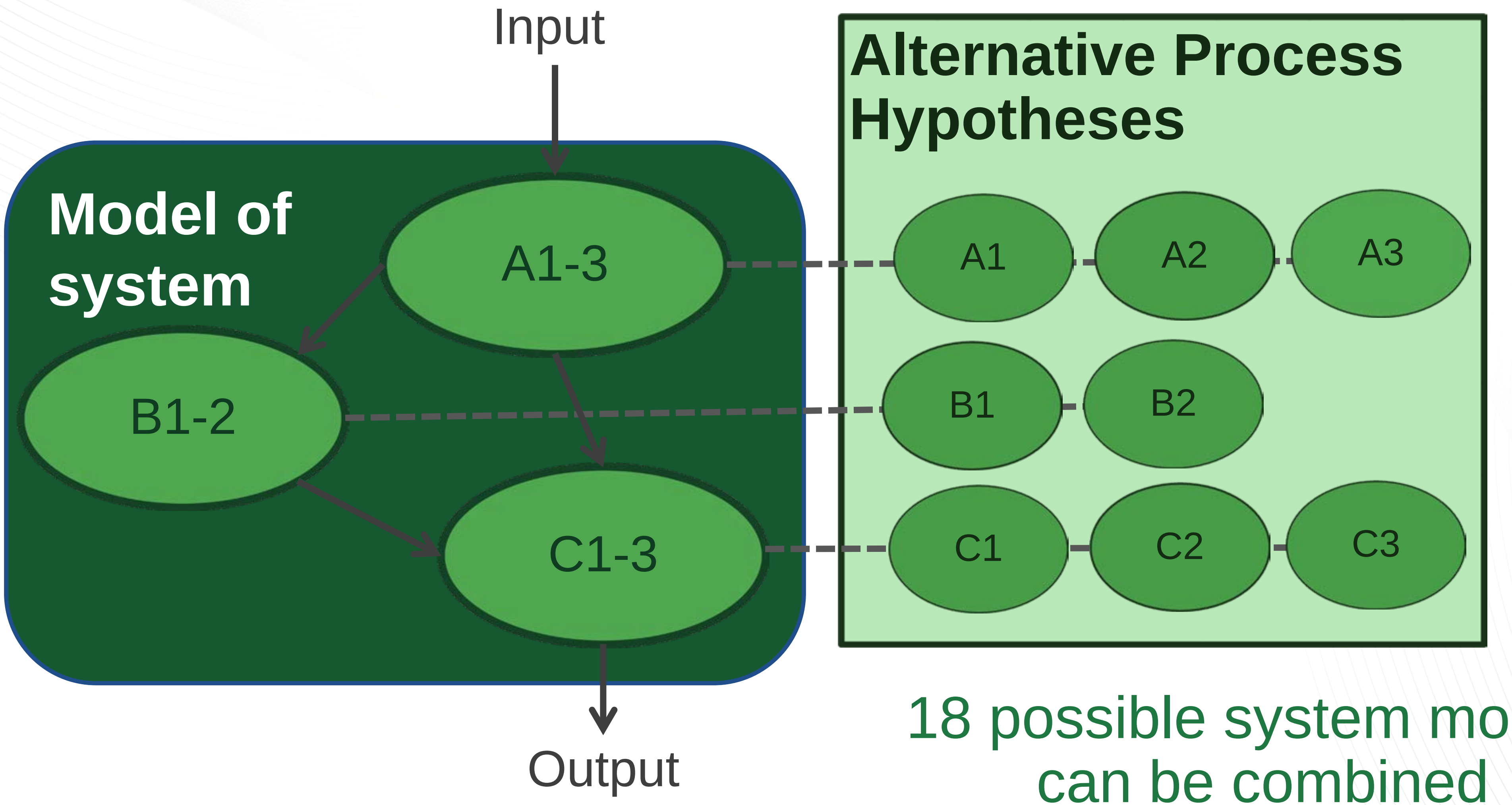


OAK RIDGE National Laboratory

Systems are composed of multiple processes

Competing hypotheses can exist for each process

Multi-hypothesis modeling



18 possible system models can be combined

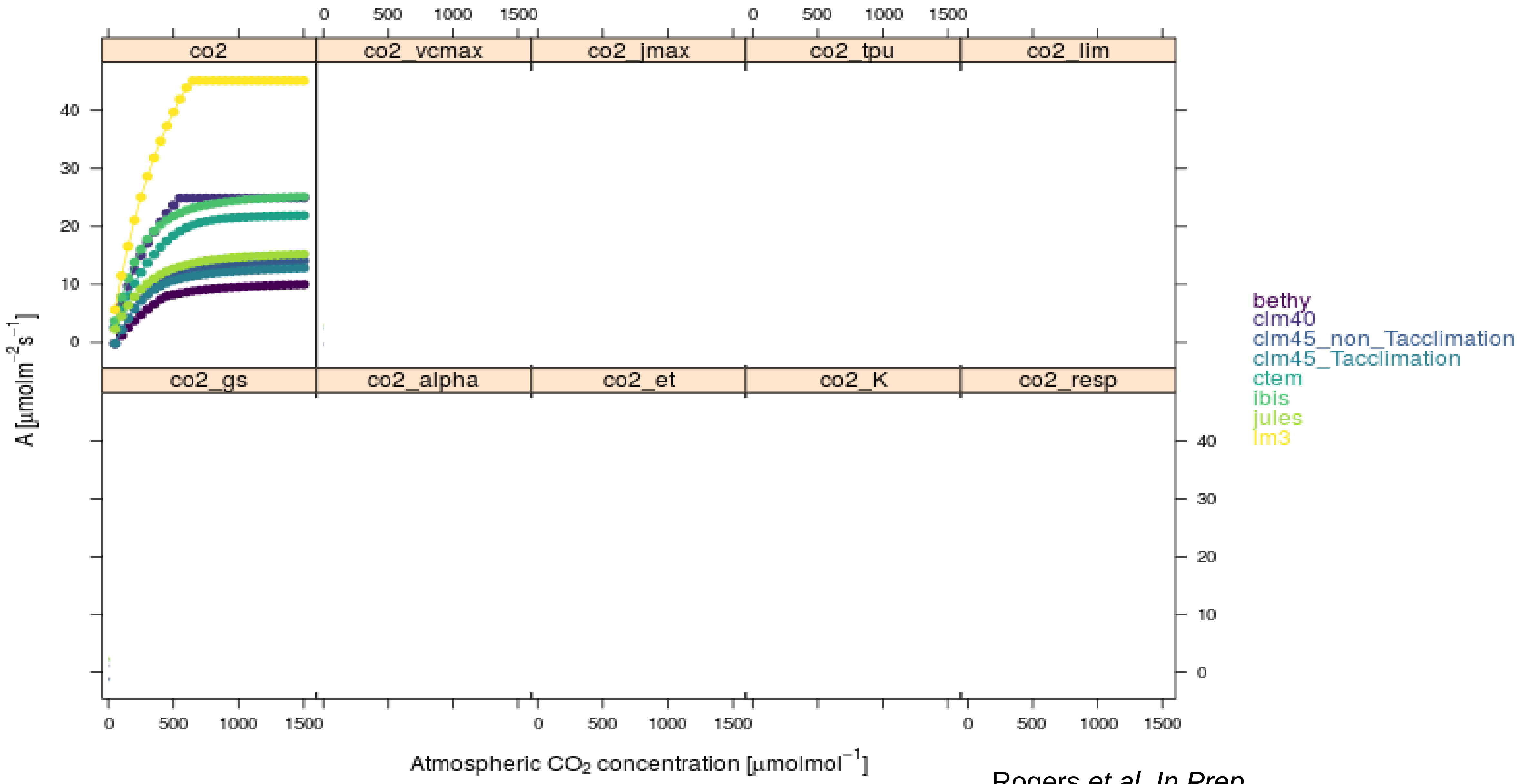
Multi-Assumption Architecture & Testbed (MAAT)

- A multi-hypothesis software framework developed to allow system model configuration with process hypotheses, parameters (traits), and boundary conditions on-the-fly during runtime
- Designed to analyze the variation in system model outputs caused when multiple competing hypotheses exist for multiple processes (considers parameter variability)
- Framework is general and not system specific
- Currently applied to modelling leaf-scale photosynthesis
- Can mimic ALM, CLM, LM3, JULES, BETHY, + others … or can create and run all possible model combinations
- Employs a novel algorithm for process-level global sensitivity analysis (Dai, *et al.* 2017 *WRR*), as well as for global parameter sensitivity analysis (Saltelli *et al.*, 2010)

Walker *et al. In Prep*

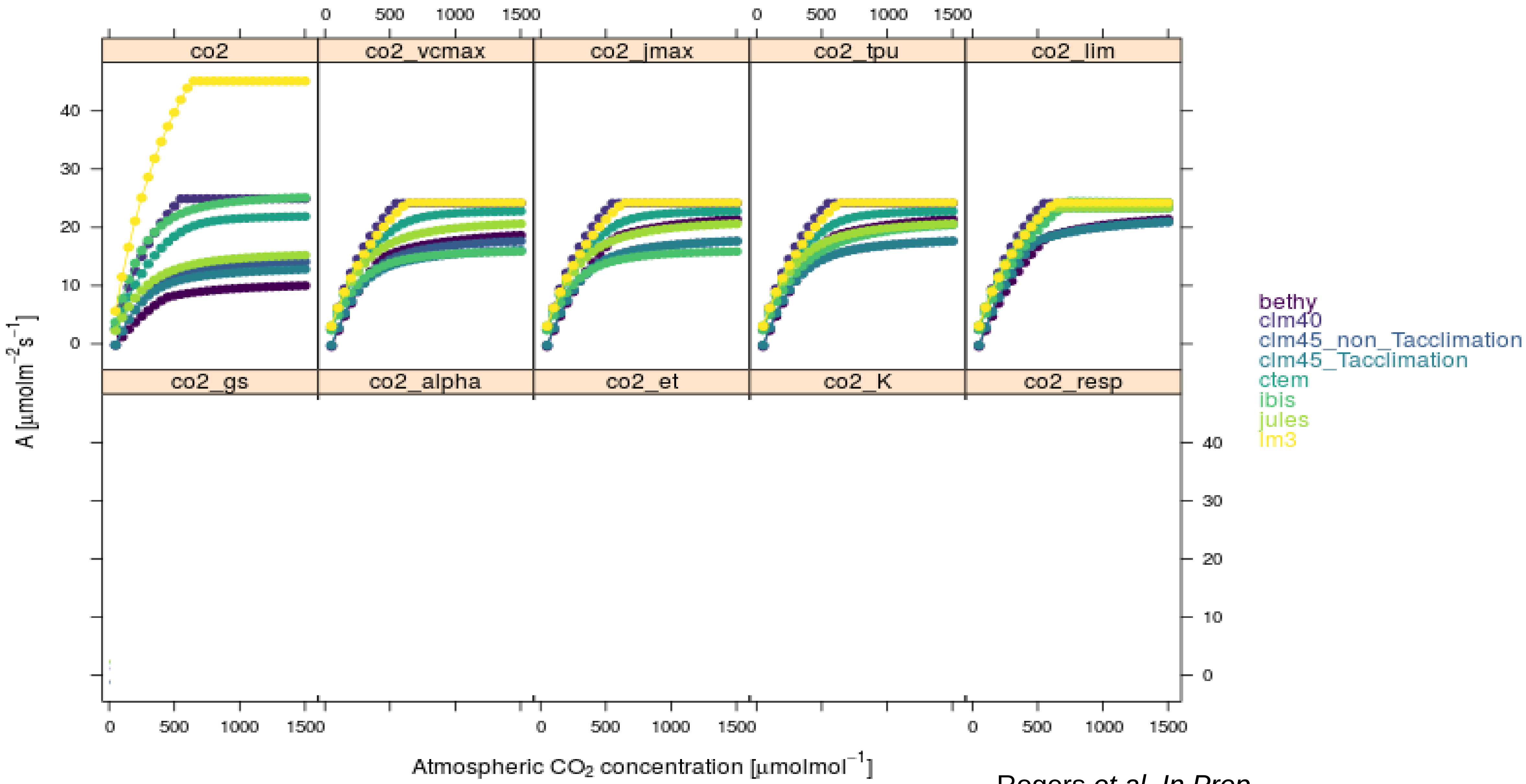
OAK RIDGE National Laboratory

Mimicking & unifying CMIP5 models



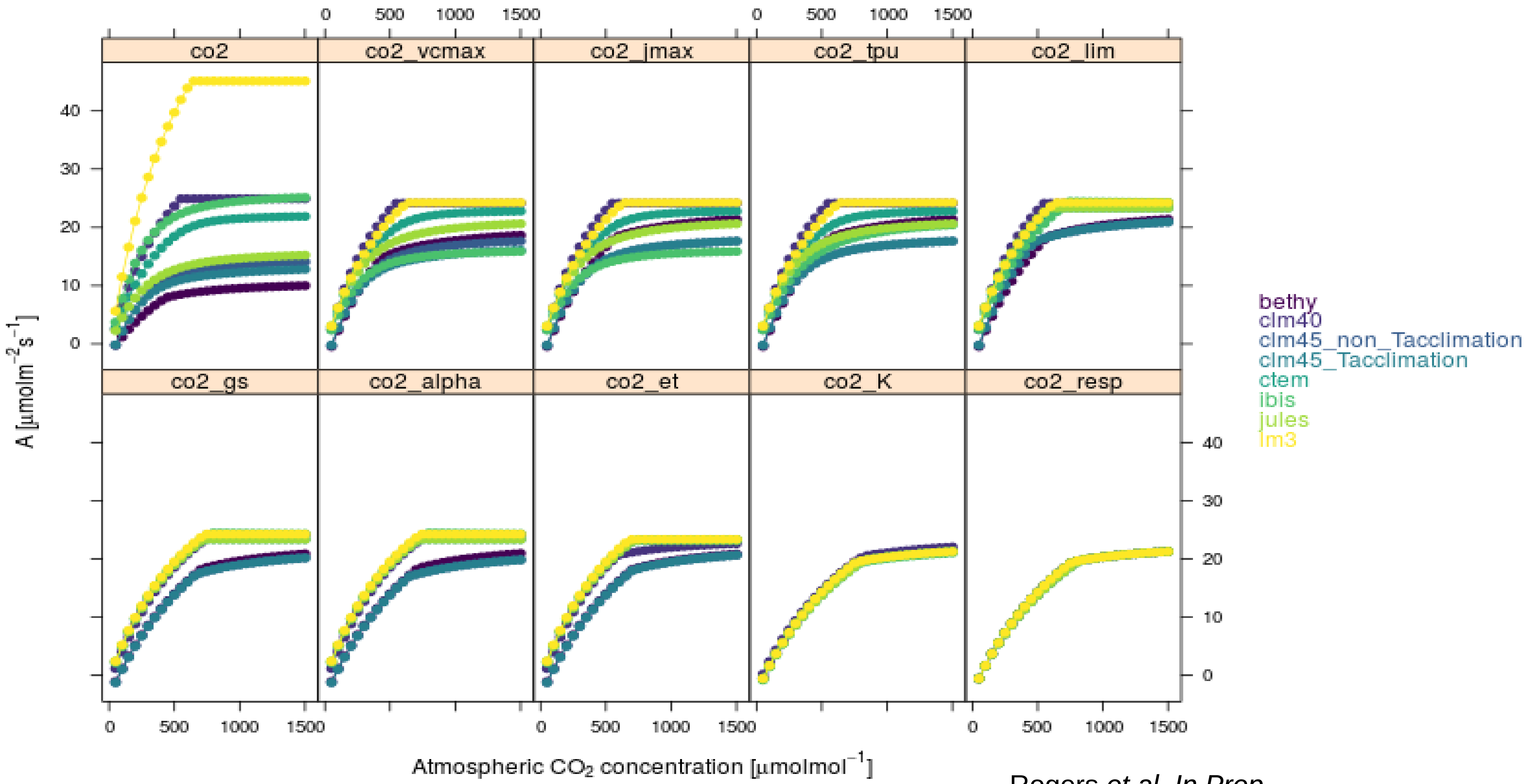
Rogers *et al. In Prep*

Mimicking & unifying CMIP5 models



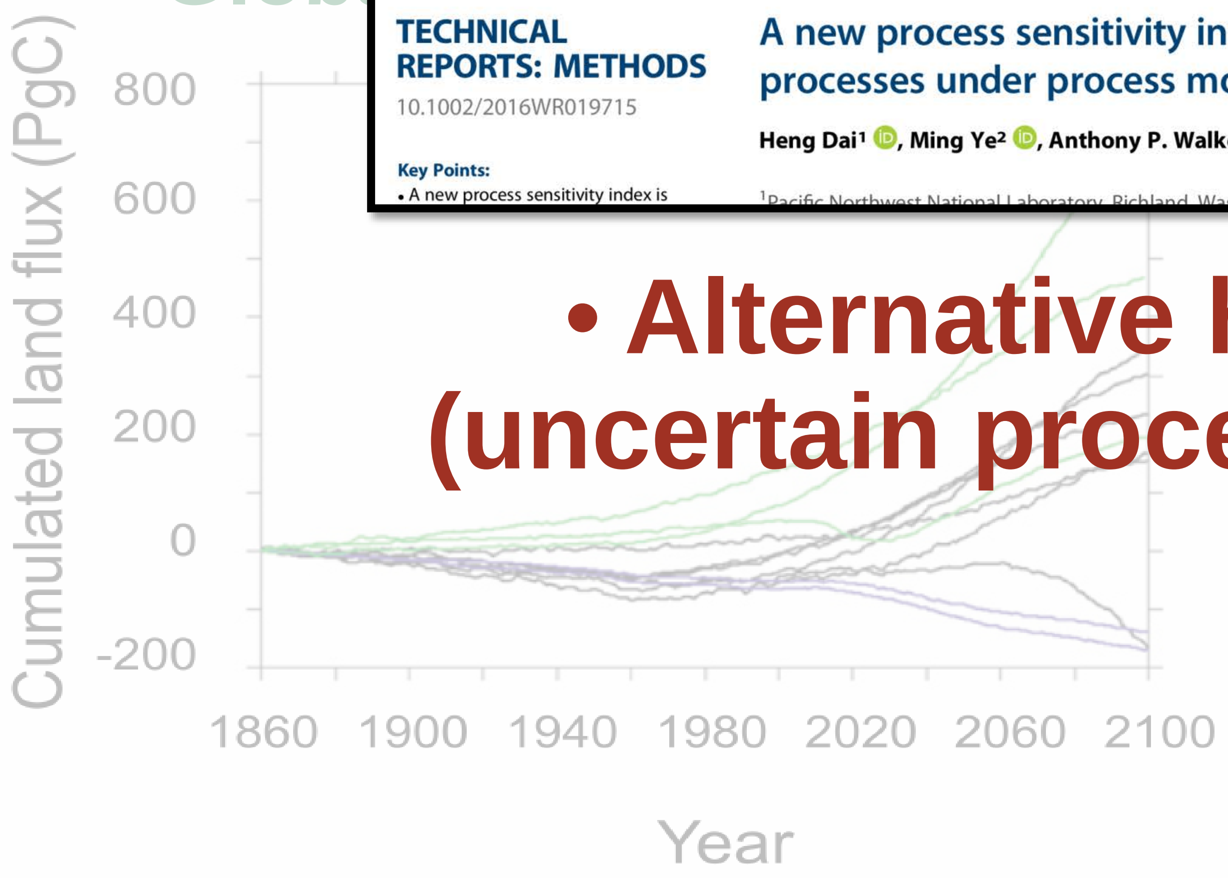
Rogers *et al. In Prep*

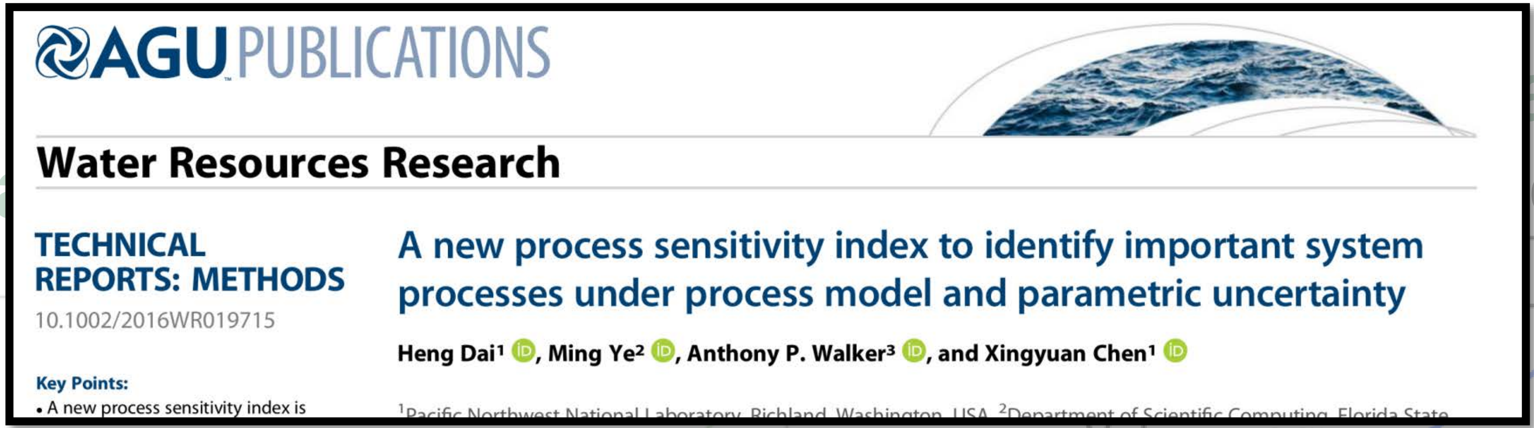
Mimicking & unifying CMIP5 models



Rogers *et al. In Prep*

The first step towards predictive understanding is to properly characterise uncertainty and identify its sources




AGU PUBLICATIONS

Water Resources Research

TECHNICAL REPORTS: METHODS

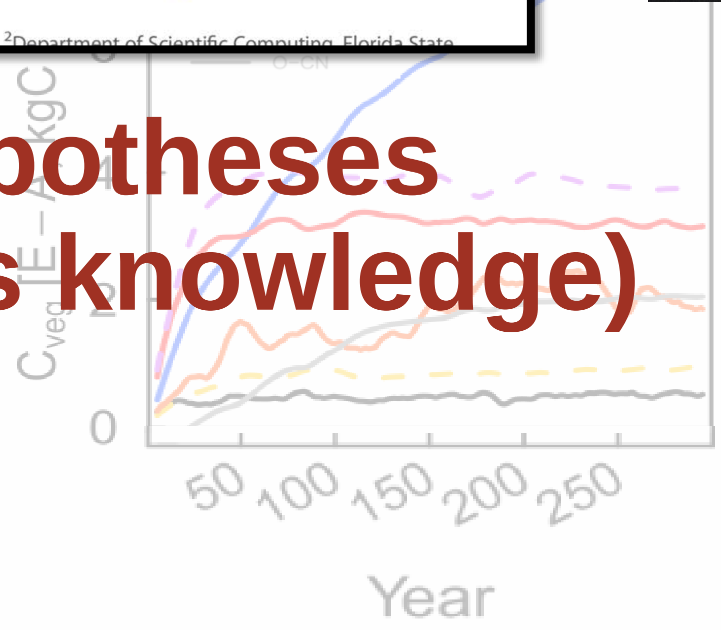
10.1002/2016WR019715

A new process sensitivity index to identify important system processes under process model and parametric uncertainty

Heng Dai[1], Ming Ye[2], Anthony P. Walker[3], and Xingyuan Chen[1]

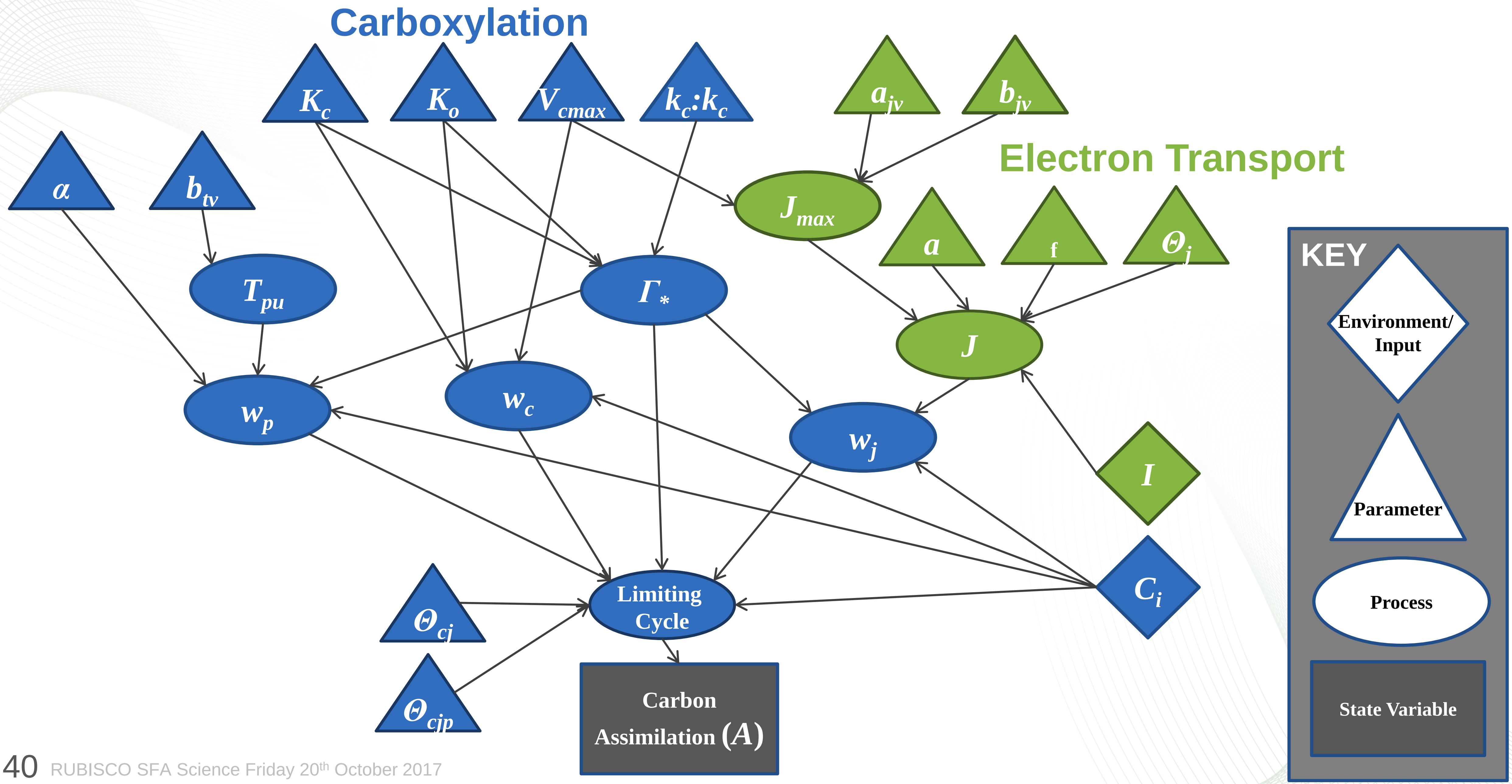
Key Points:

- A new process sensitivity index is

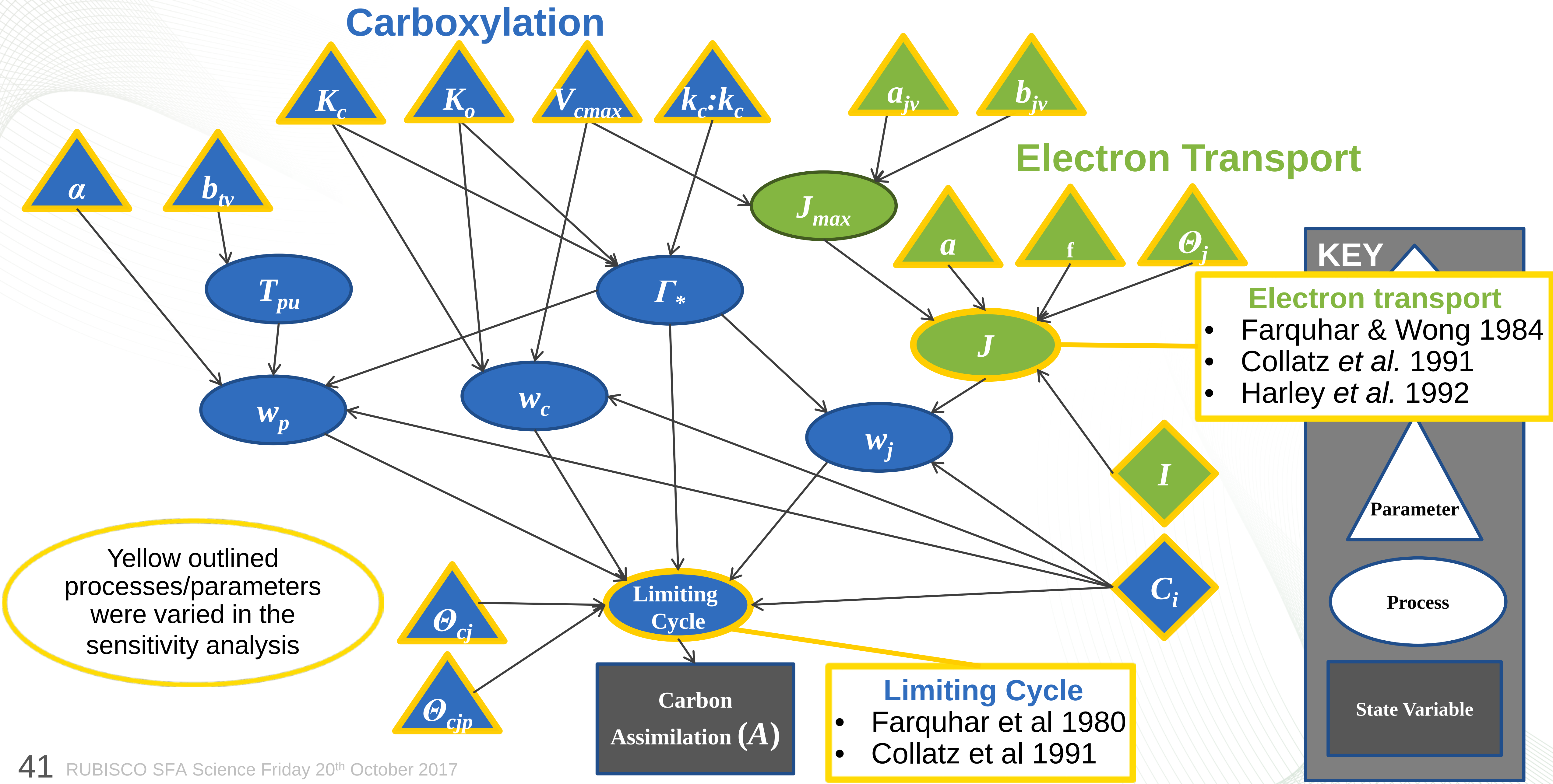


- **Alternative hypotheses (uncertain process knowledge)**

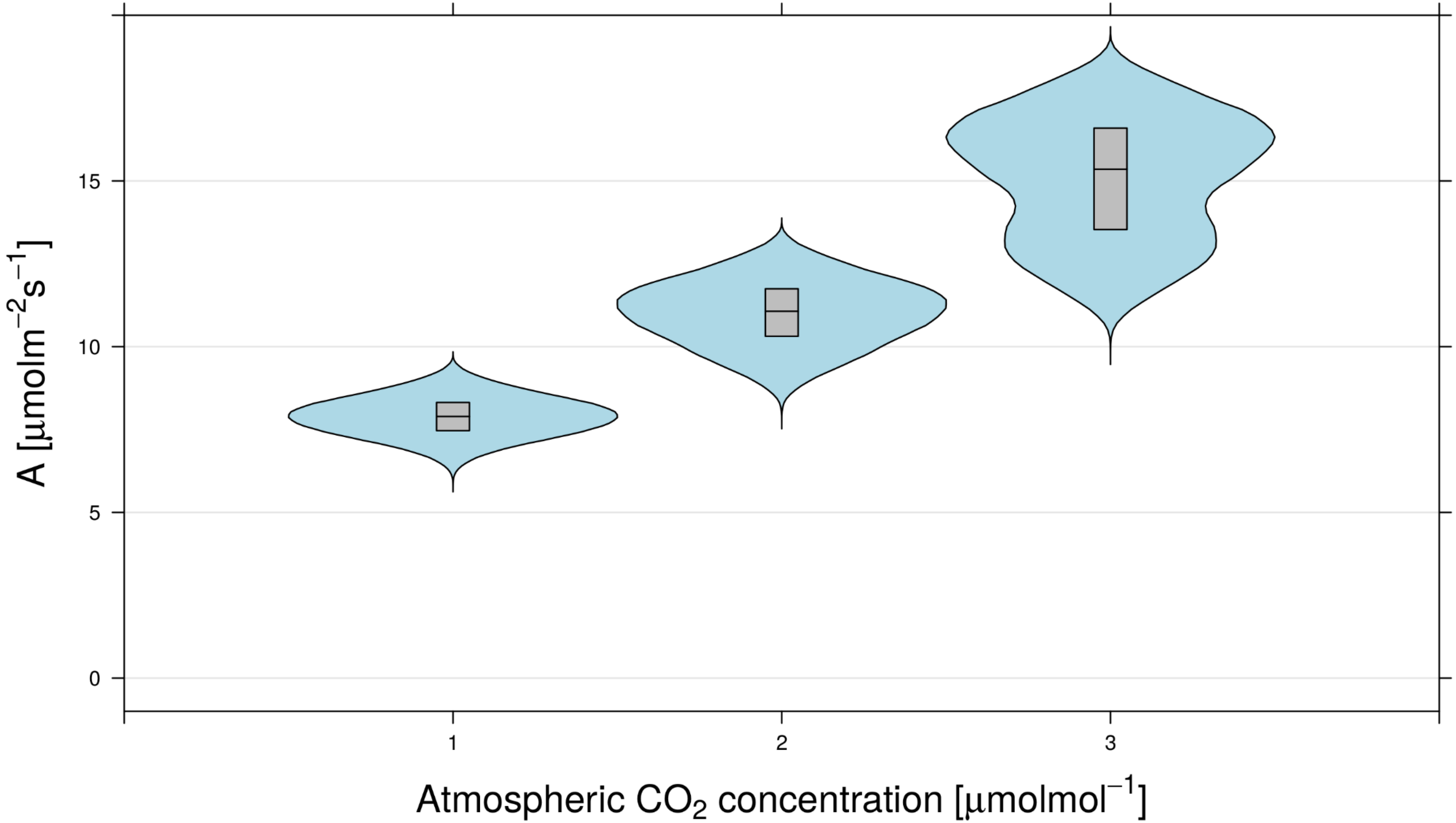
Graph of the enzyme kinetic model of C3 photosynthesis:



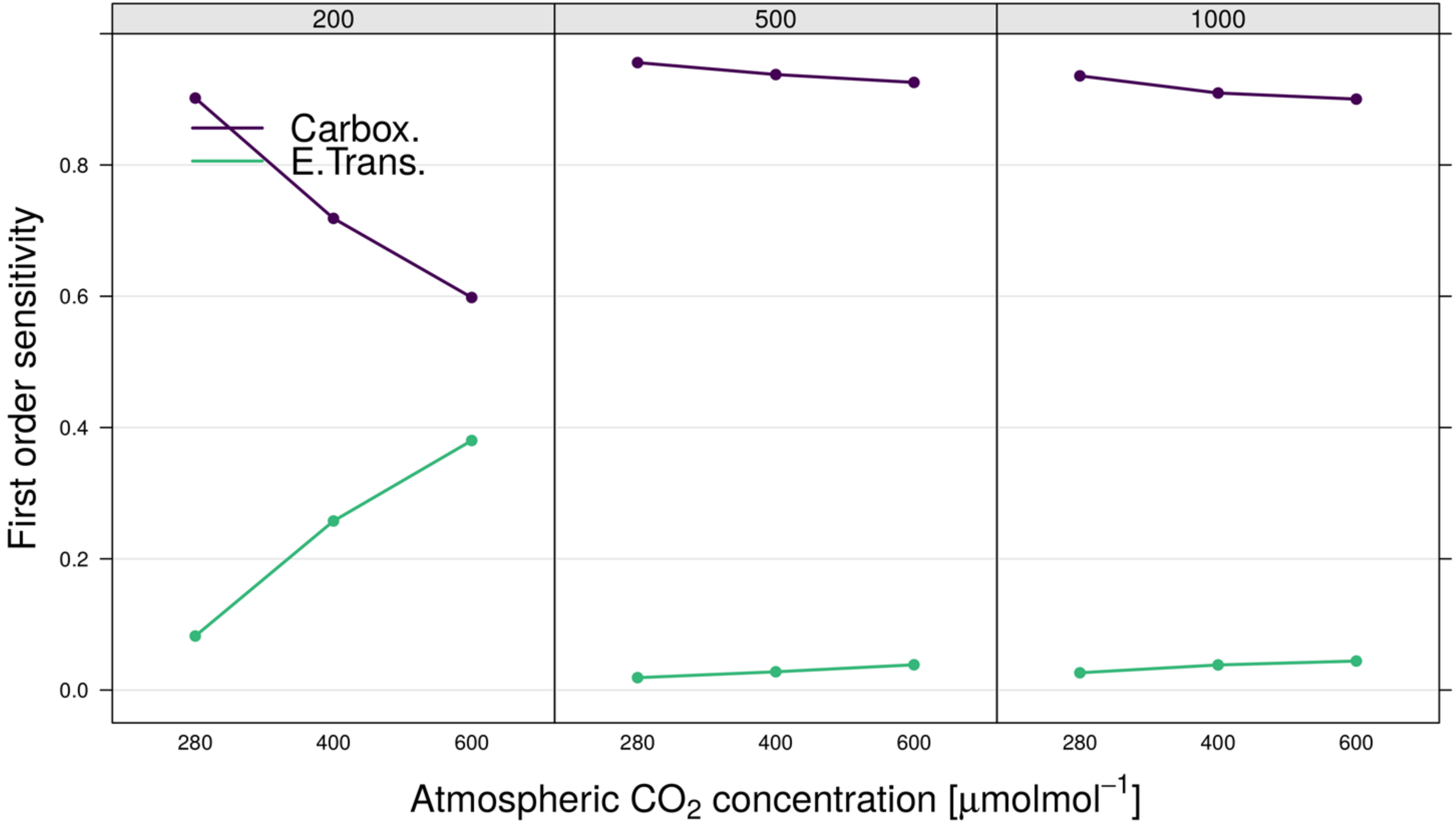
Graph of the enzyme kinetic model of C3 photosynthesis:



Variability in carbon assimilation

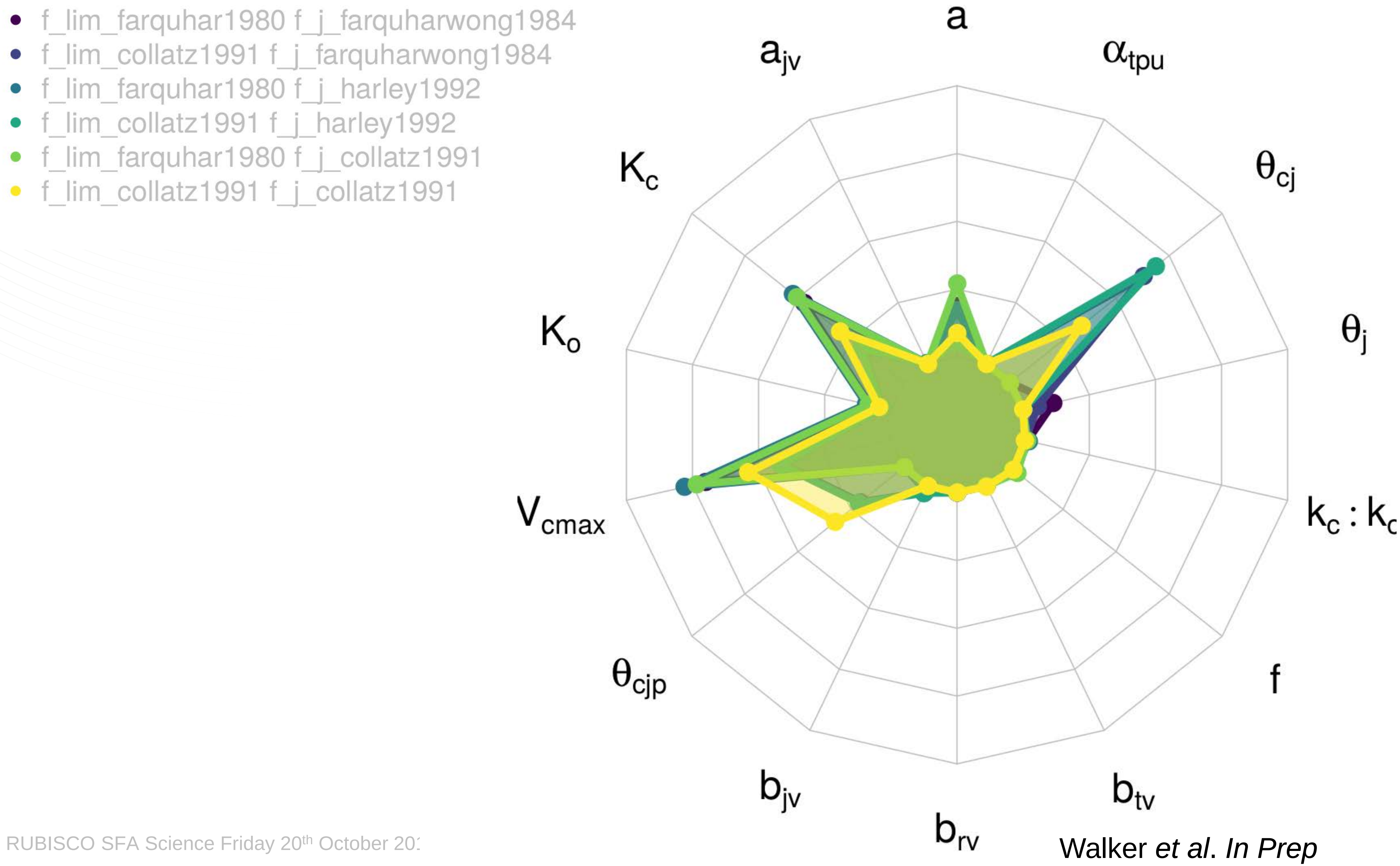


Process Sensitivity Index against CO_2



Walker et al. *in prep*

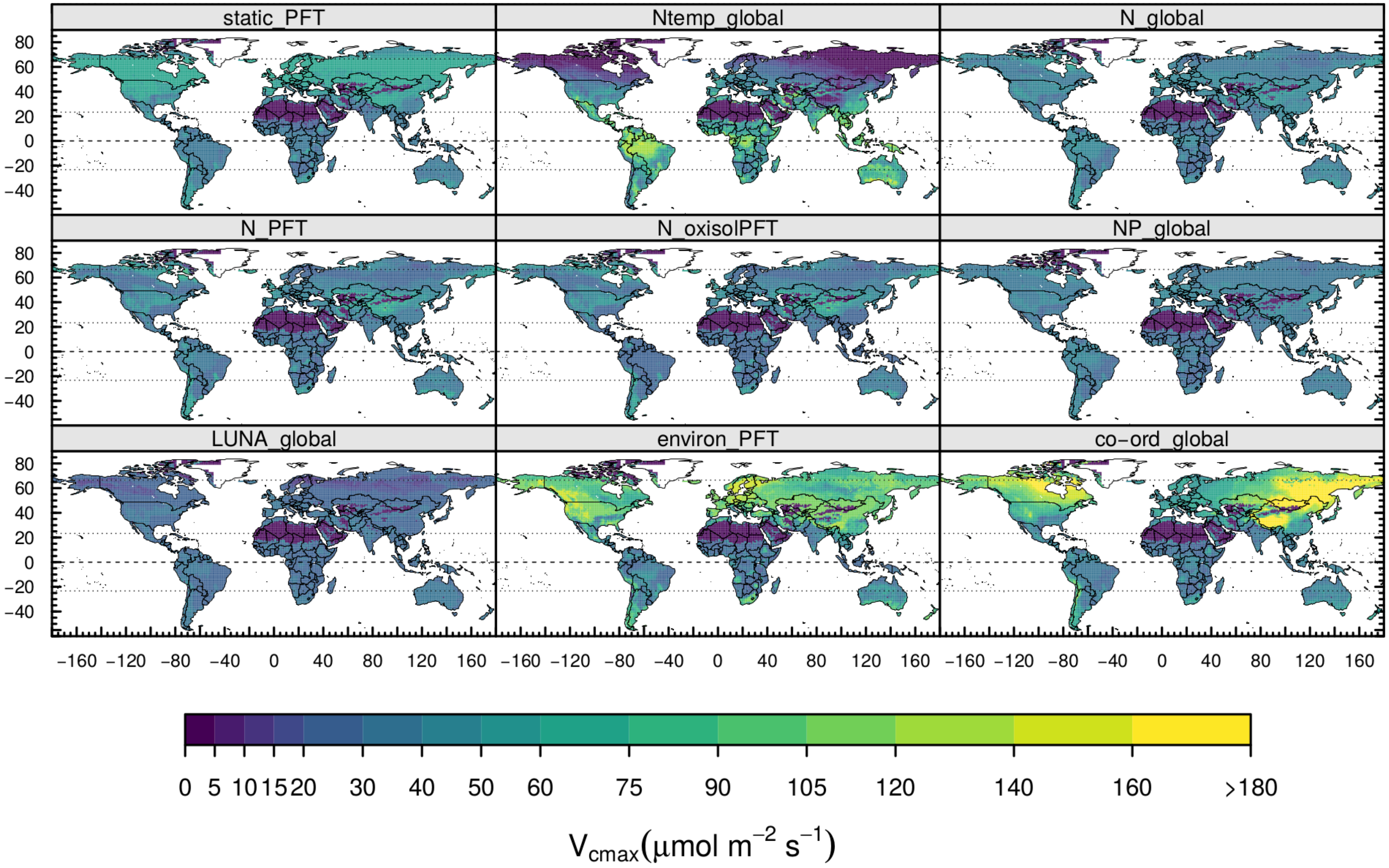
Parameter Sensitivity Index



Walker *et al*. *In Prep*

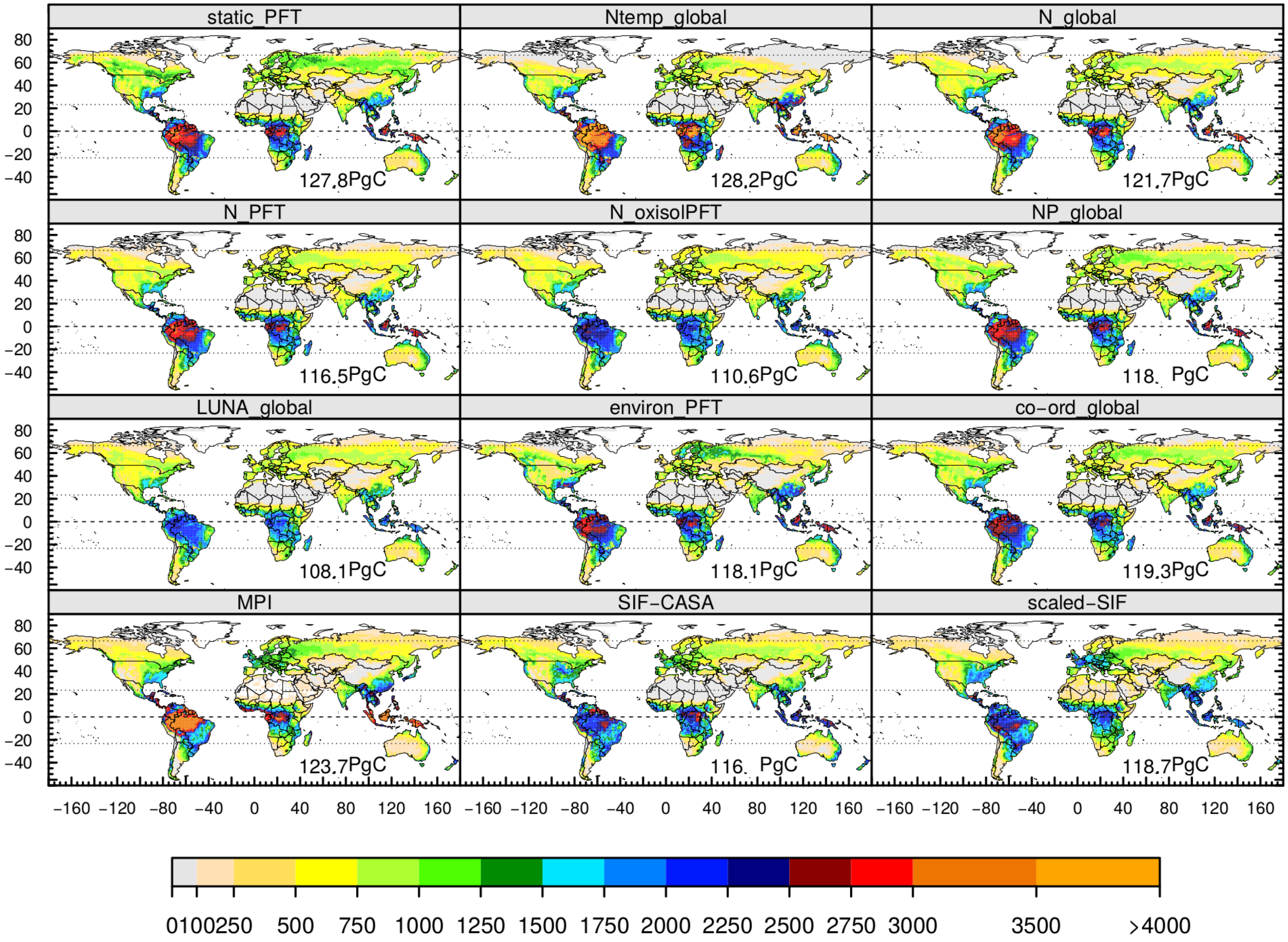
AK RIDGE
tional Laboratory

Evaluation of global GPP



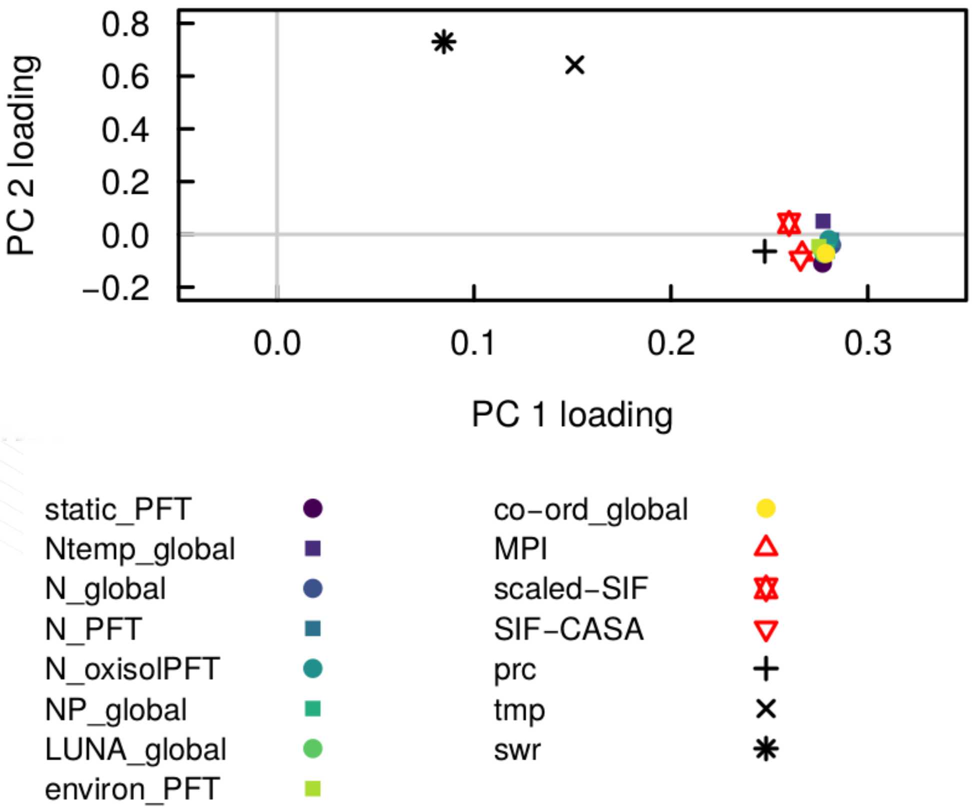
Walker *et al*. (2017) *New Phyt.*

GPP



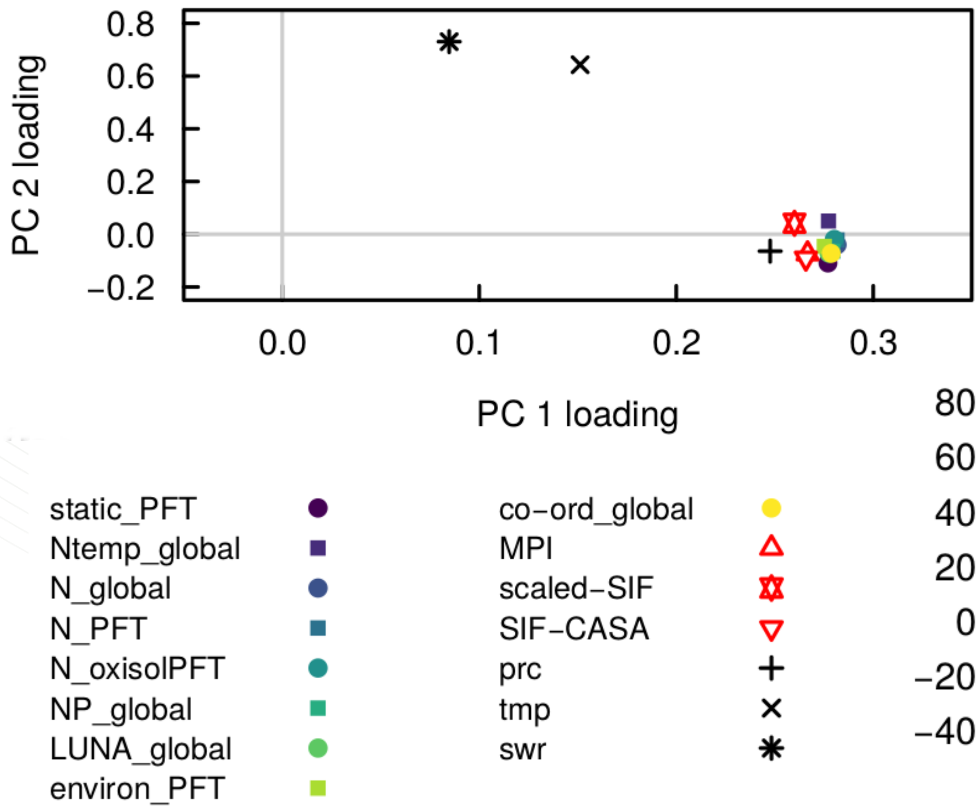
OAK RIDGE National Laboratory

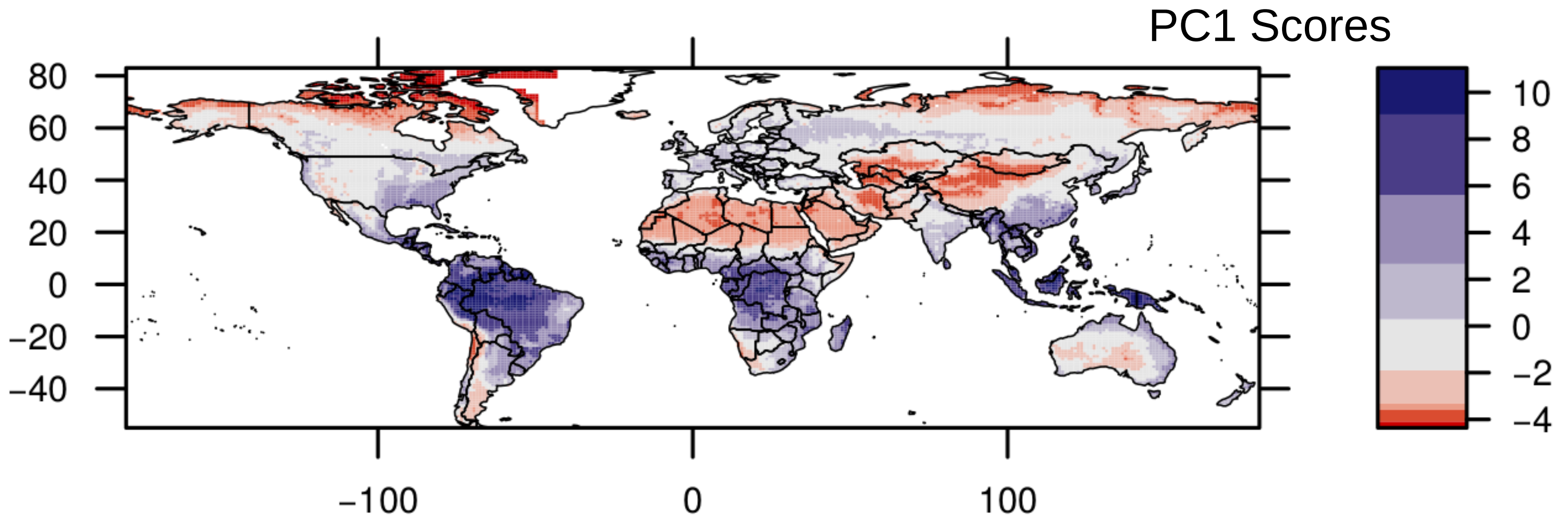
PCA as a model evaluation tool

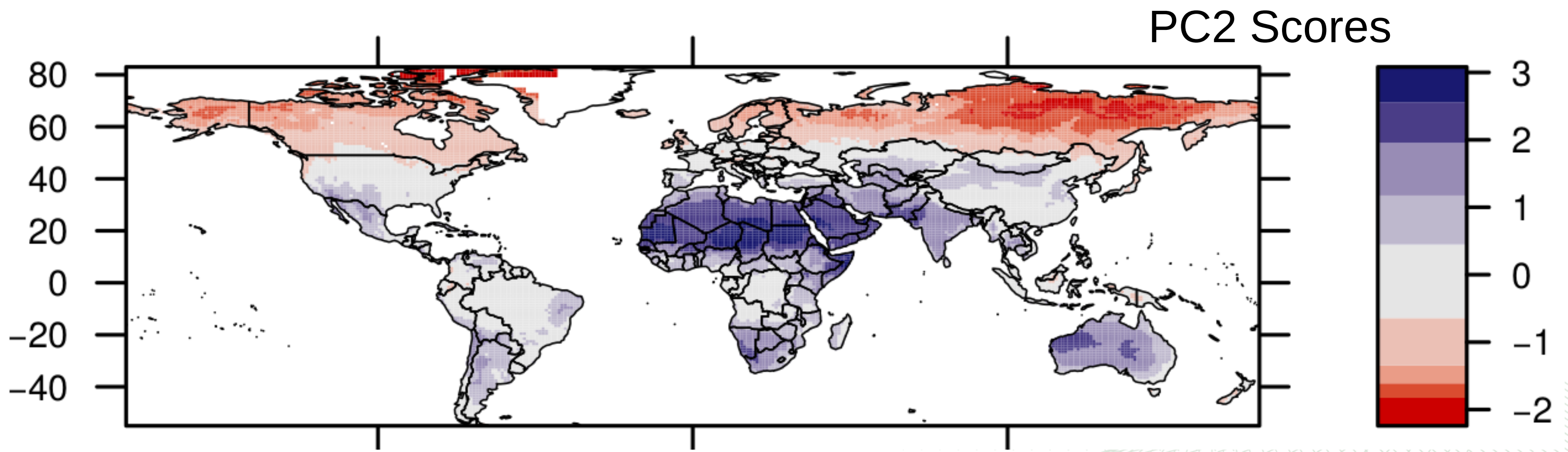


Walker *et al*. (2017) *New Phyt.*

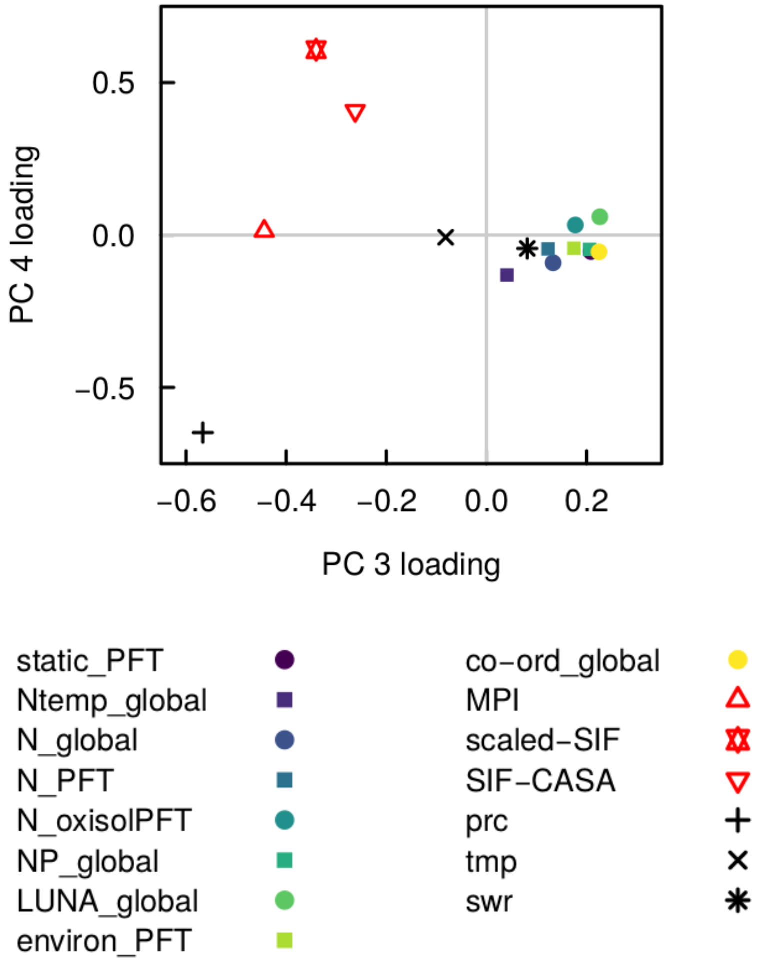
PCA suggests the first mode of spatial GPP variability is driven by precipitation





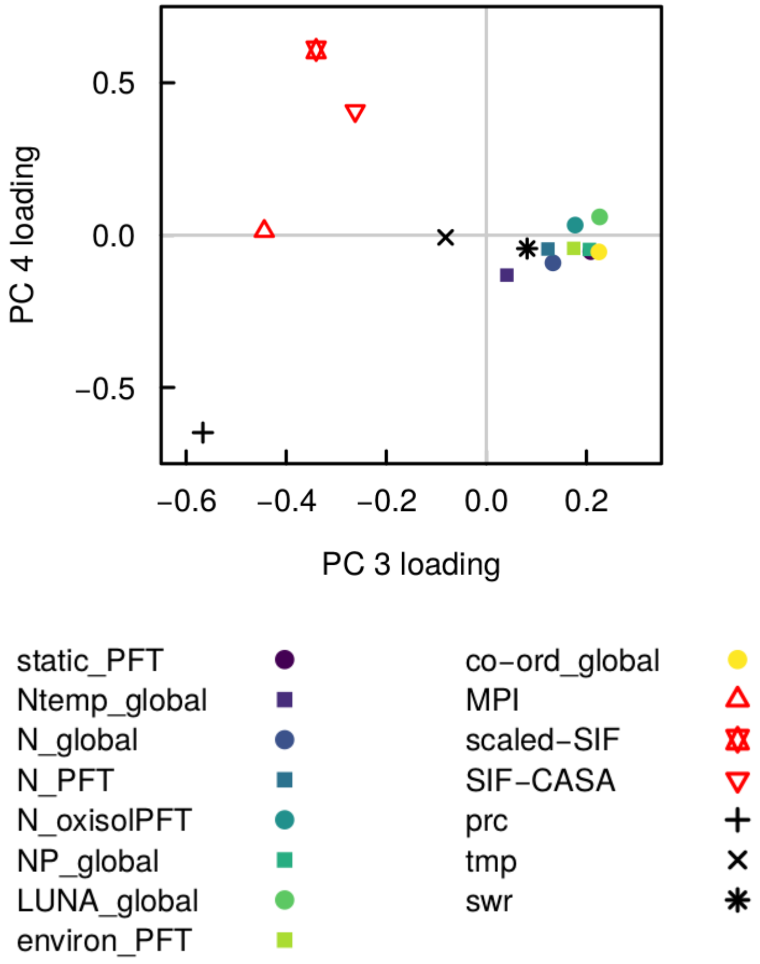


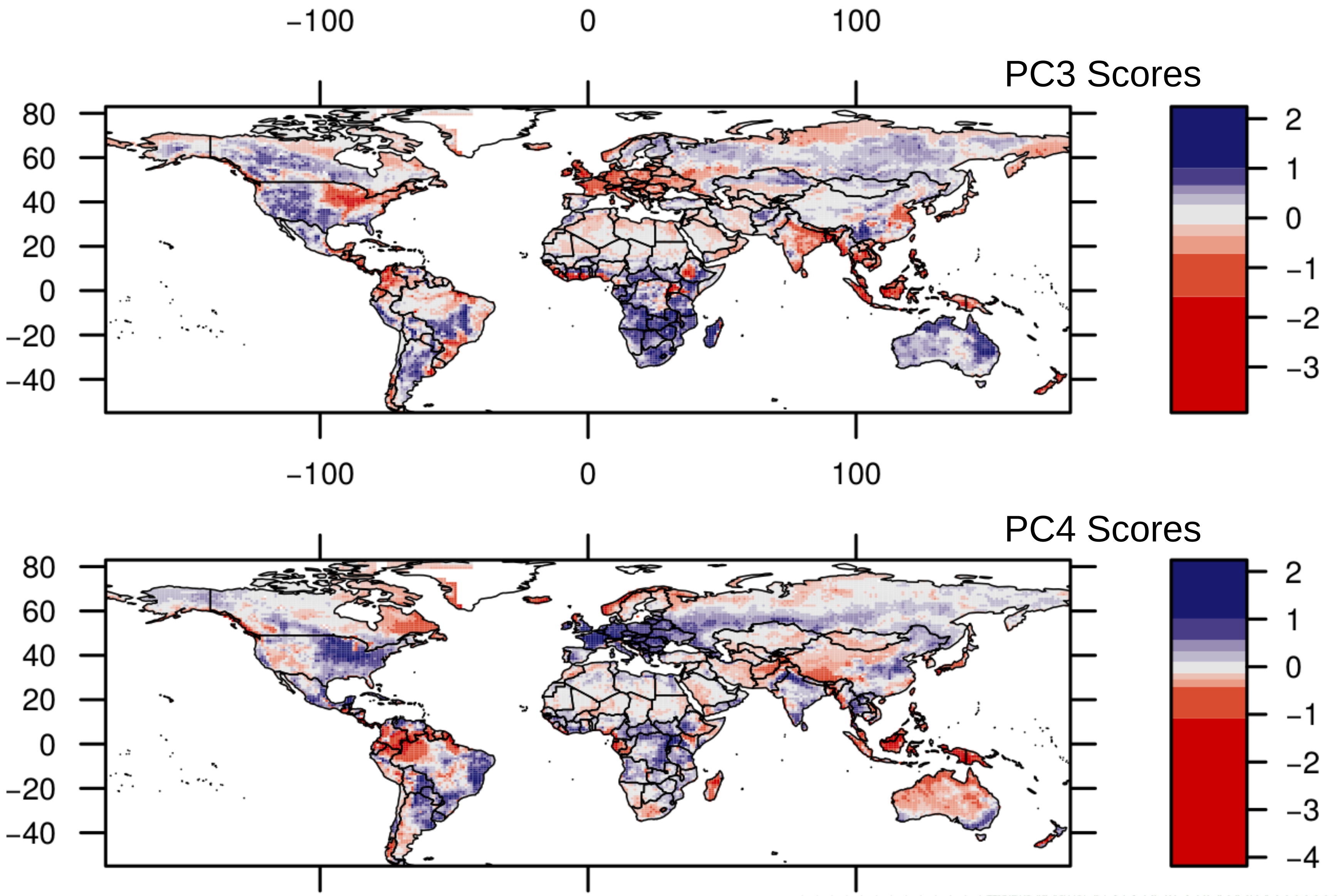
PC4 segregates SIF based GPP from precipitation



Walker *et al*. (2017) *New Phyt.*

PC4 segregates SIF based GPP from precipitation





Quick Summary

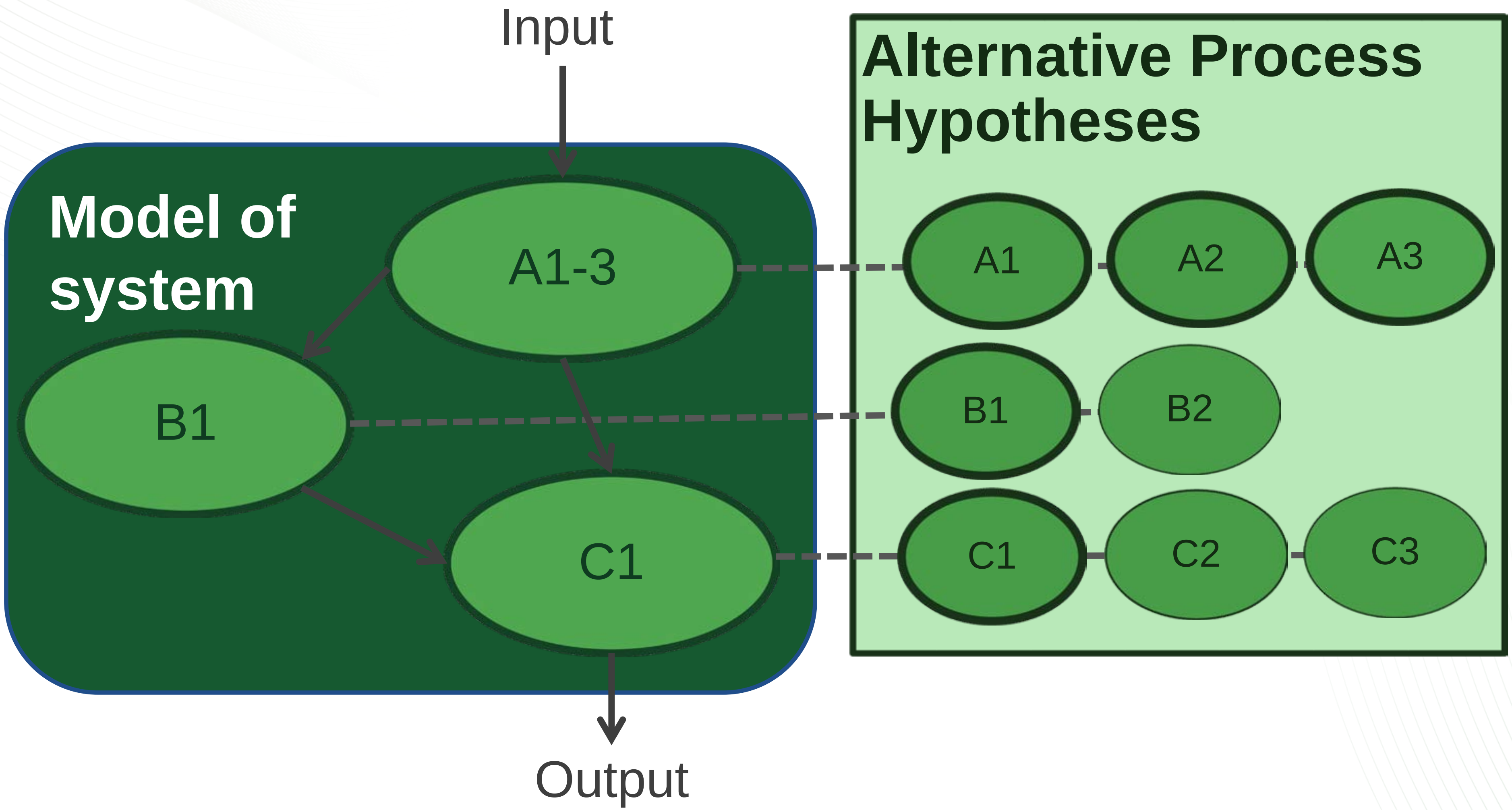
- Process based model analysis is useful and interesting
- A number of methods are out there including:
  - Variable decomposition
  - Comparison against simple models
    (not shown, but used in FACE-MDS)
  - Multi-assumption modelling
  - PCA (not strictly process based, but can be used to observed patterns and support process based hypotheses)

Thanks to you, collaborators, and sponsors

Systems are composed of multiple processes

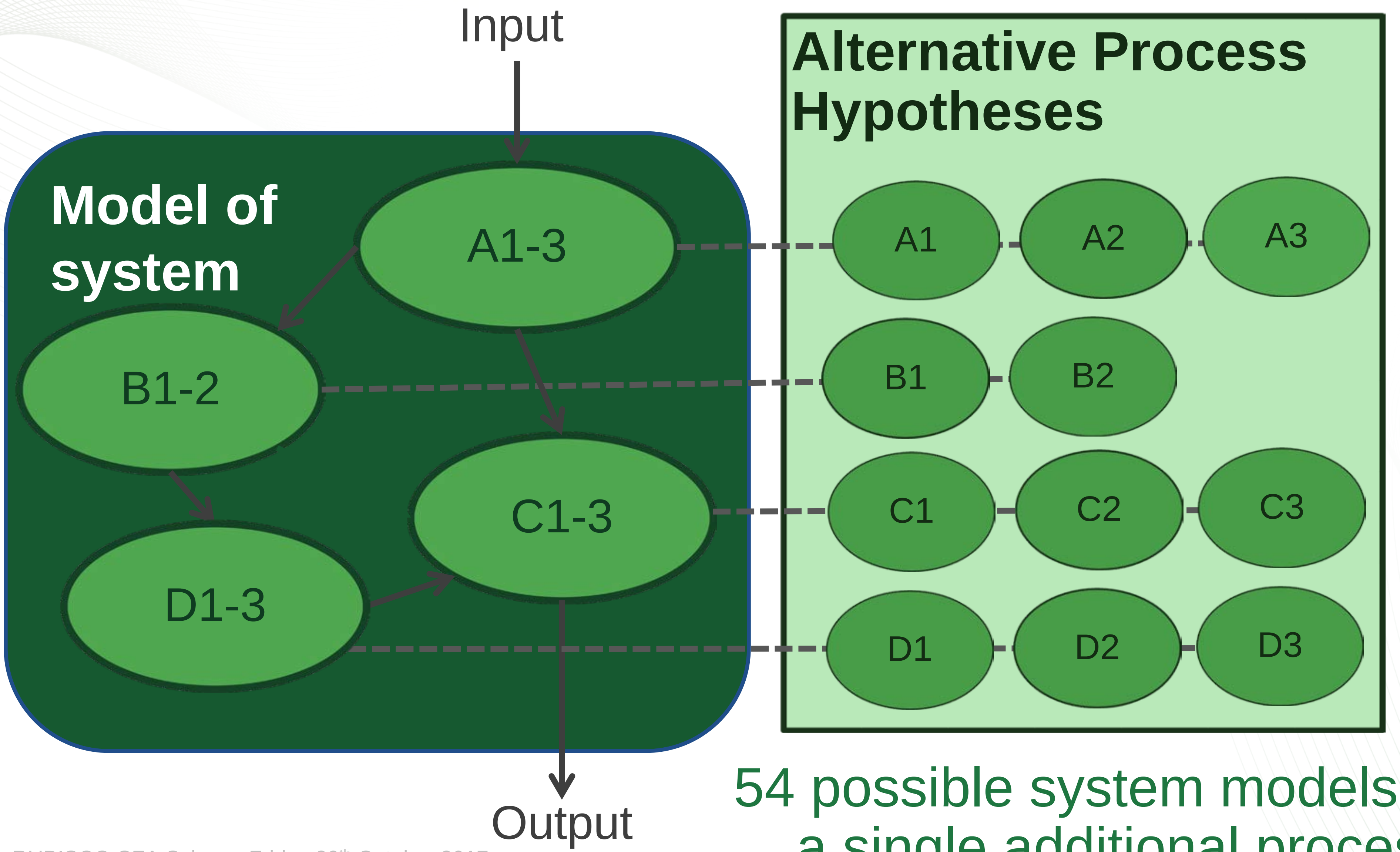
Competing hypotheses can exist for each process

Single process multi-hypothesis modeling



OAK RIDGE National Laboratory

… but additional processes come with the cost of additional uncertainty & model complexity



54 possible system models with a single additional process