Towards a better representation of crop growth and management in the Community Earth System Model

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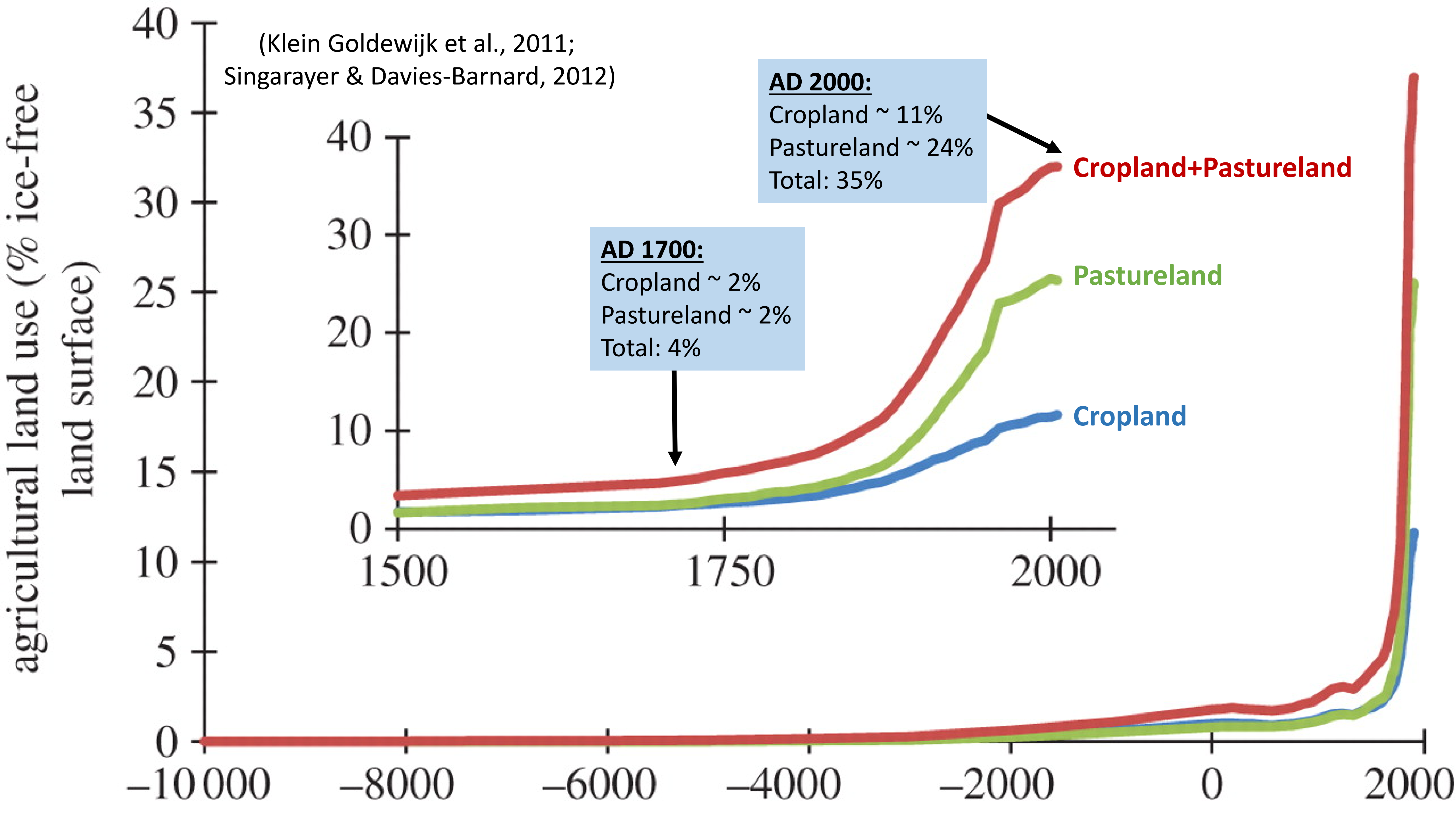
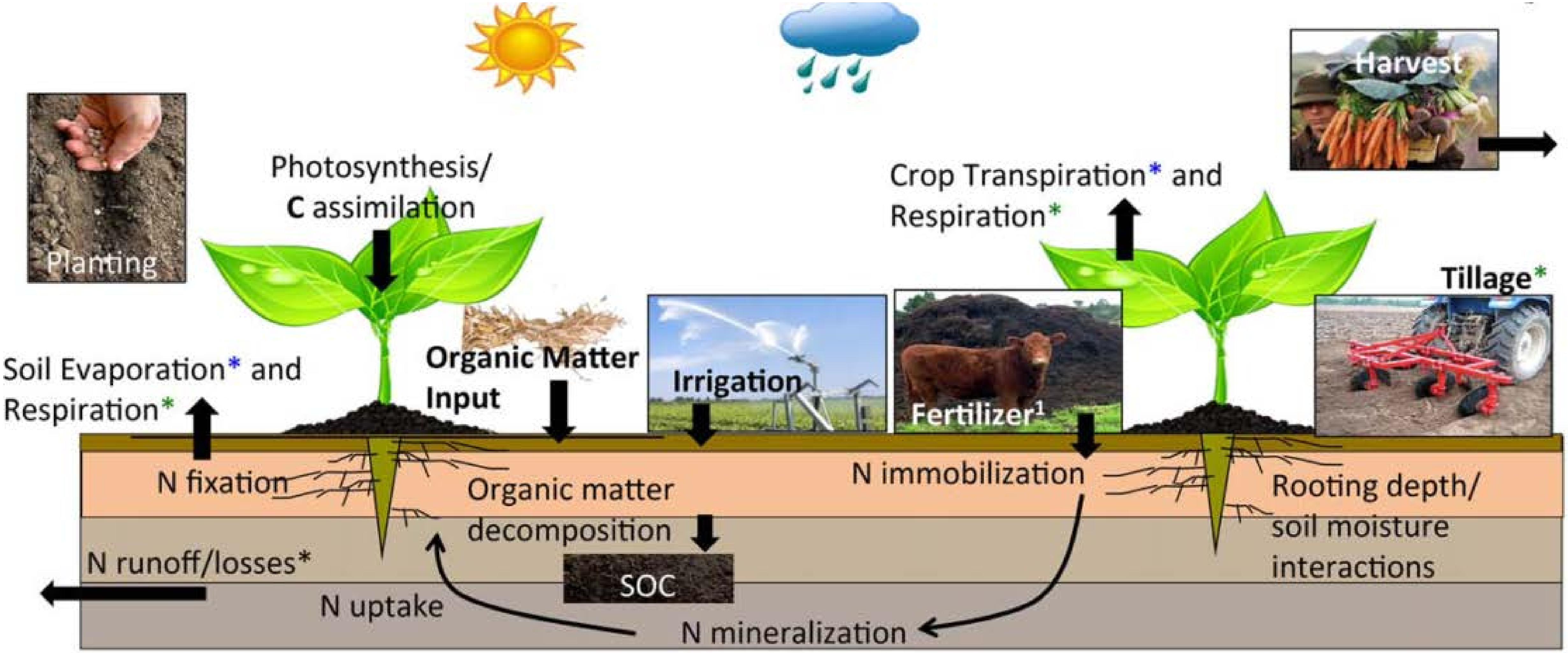
PNNL: Min Chen, **Stanford**: Zhenong Jin

LMWG meeting, Feb. 2018, NCAR Mesa Lab, Boulder, CO



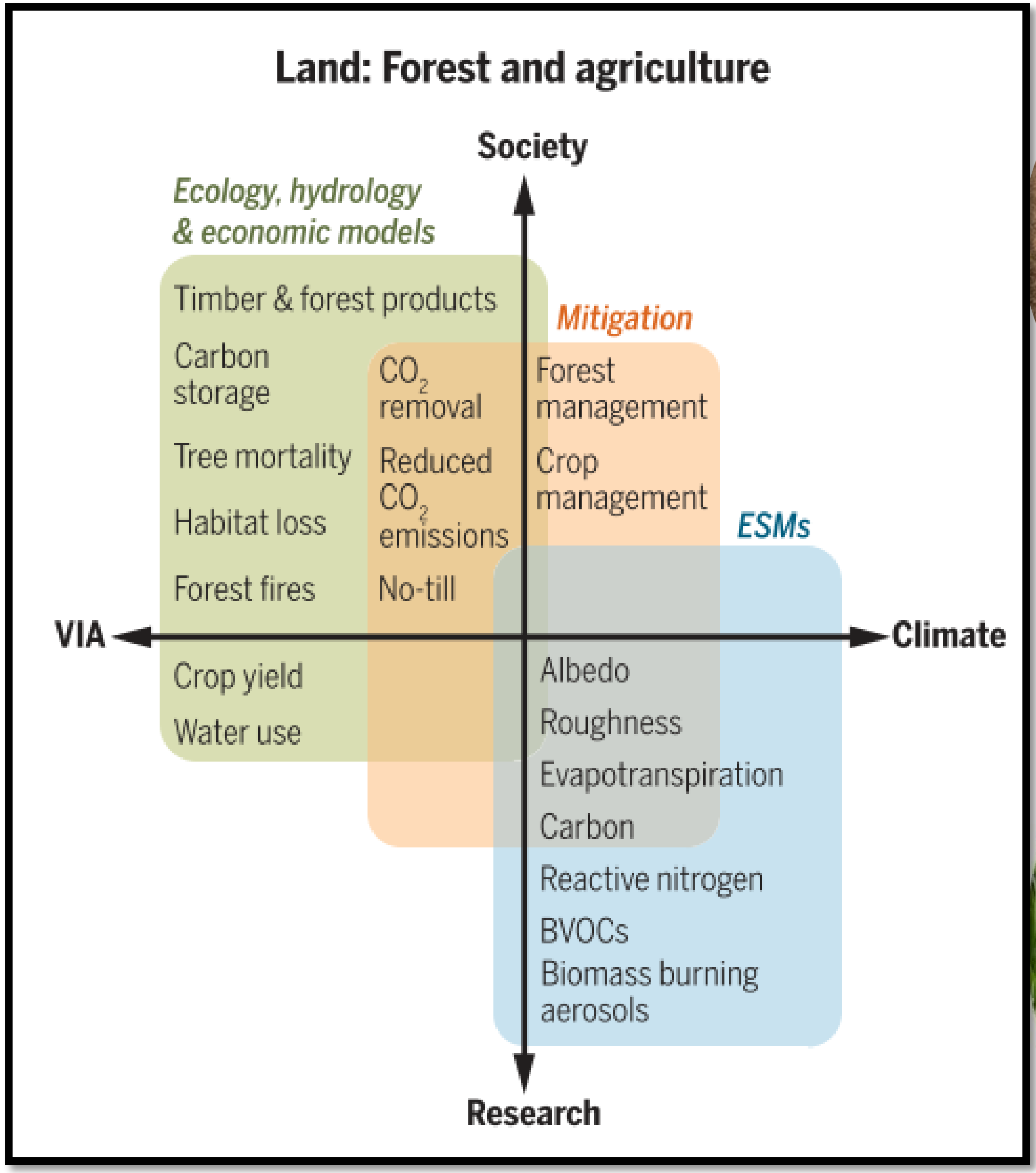
(Klein Goldewijk et al., 2011;
Singarayer & Davies-Barnard, 2012)
AD 2000:
Cropland ~ 11%
Pastureland ~ 24%
Total: 35%
AD 1700:
Cropland ~ 2%
Pastureland ~ 2%
Total: 4%
Cropland+Pastureland
Pastureland
Cropland
agricultural land use (% ice-free land surface)
0
5
10
15
20
25
30
35
40
−10 000
−8000
−6000
−4000
−2000
0
2000
1500
1750
2000

Agriculture in the Dynamic Earth System



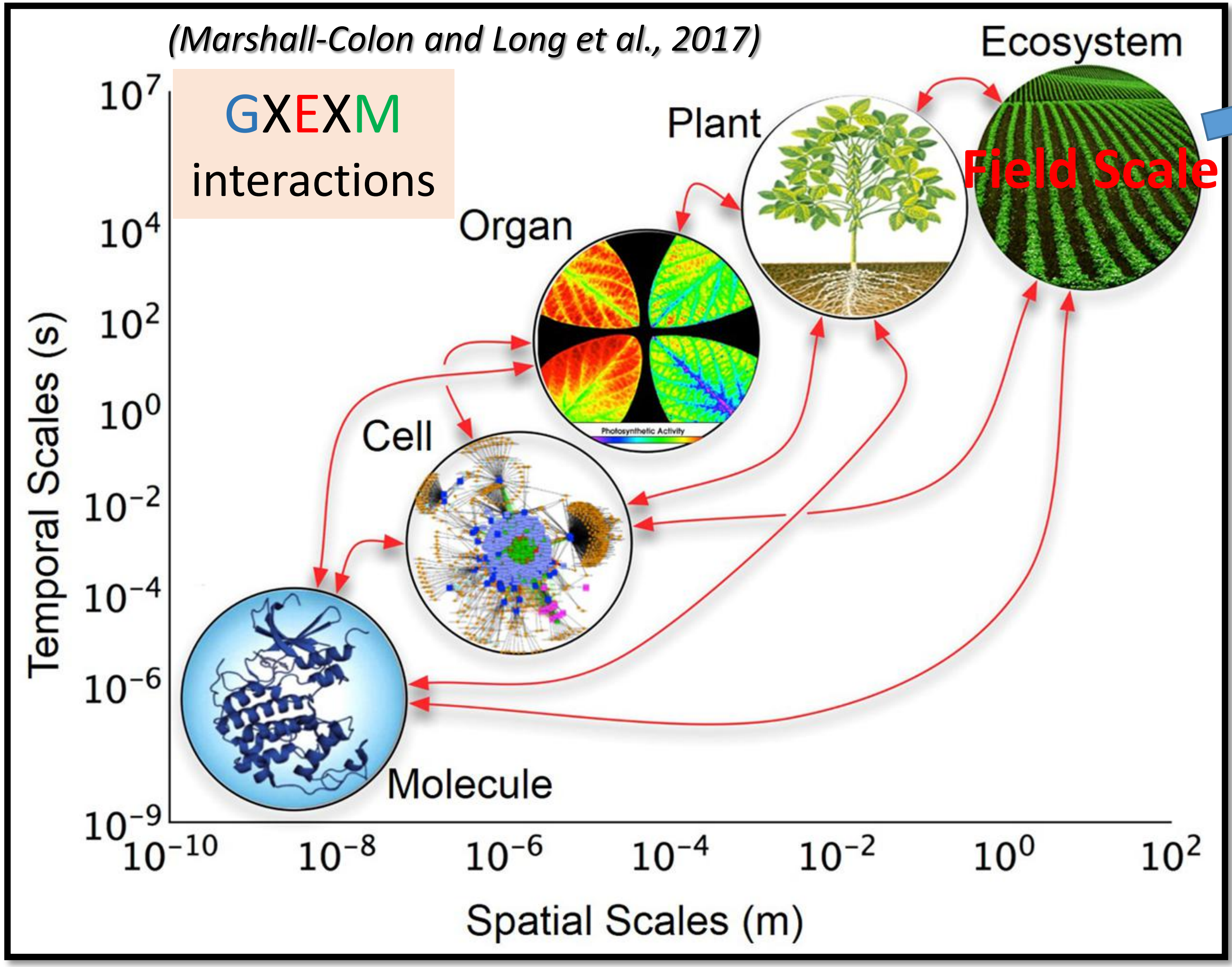
McDermid et al. (JAMES, 2017)

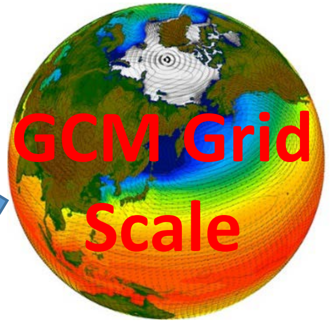
Agriculture in the Dynamic Earth System



Bonan and Doney (Science, 2018)

Crop Modeling across Multi-scales





Agronomy

Plant physiology

Plant system biology

Genetics/genomics

Where are we now in crop modeling?

1. Generic model with no reference to species
2. Species-specific model with no reference to genotype/cultivars
3. Genetic differences represented by cultivar specific parameters
4. Genetic differences represented by gene actions modeled through their effects on model parameters(Gene-to-Phenotype, G2P)
5. Genetic differences represented by genotypes, with gene action explicitly simulated based on knowledge of regulation of gene expression and effects of gene products
6. Genetic differences represented by genotypes, with the gene action simulated at the level of interactions of regulators, gene products, and other metabolites

White and Hoogenboom (2003)

Where are we now in crop modeling?
(Agronomy Community)

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Where are we now in crop modeling?
(Earth System Modeling Community)

1. **Generic model with no reference to species**
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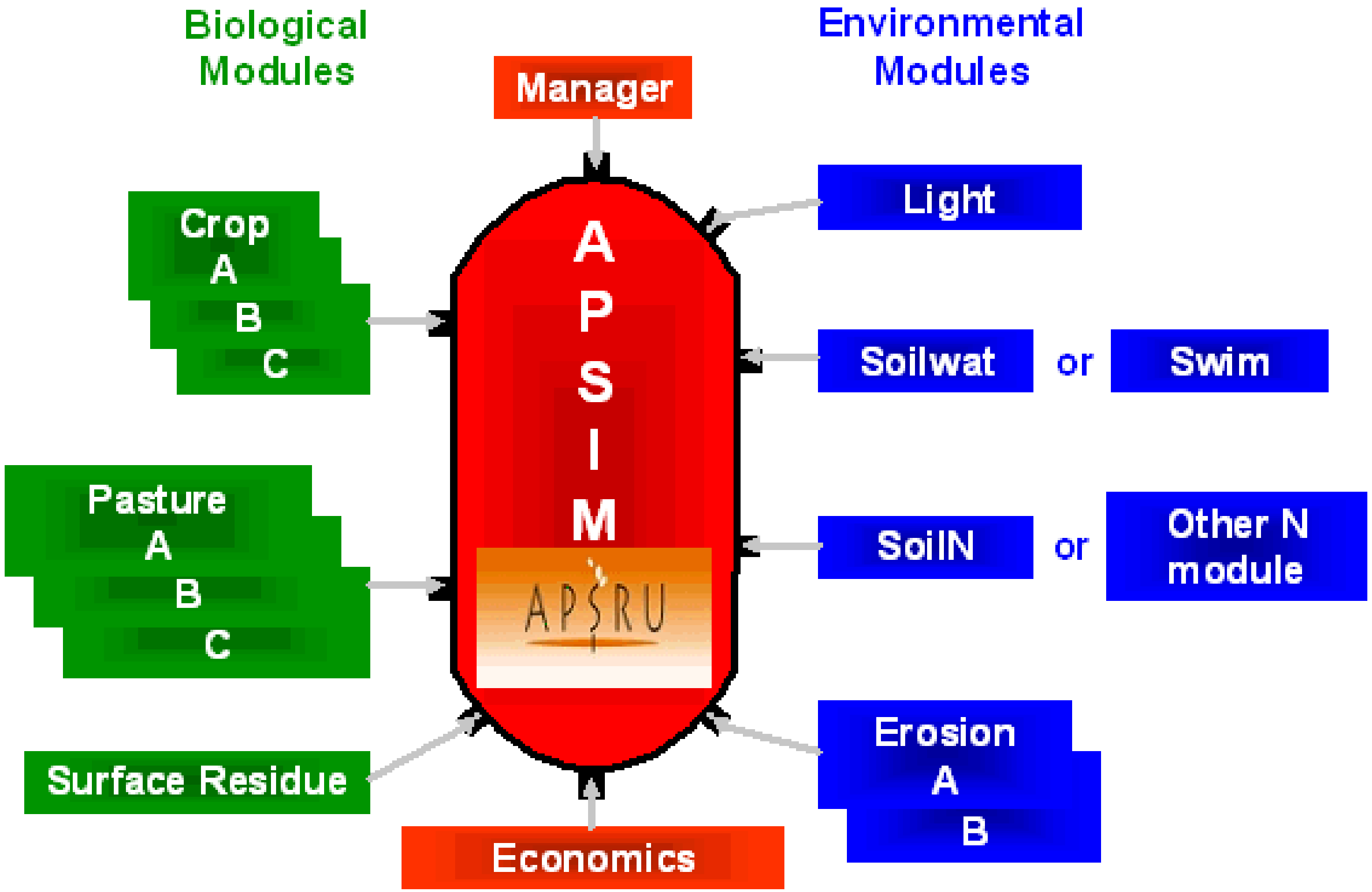
White and Hoogenboom (2003)

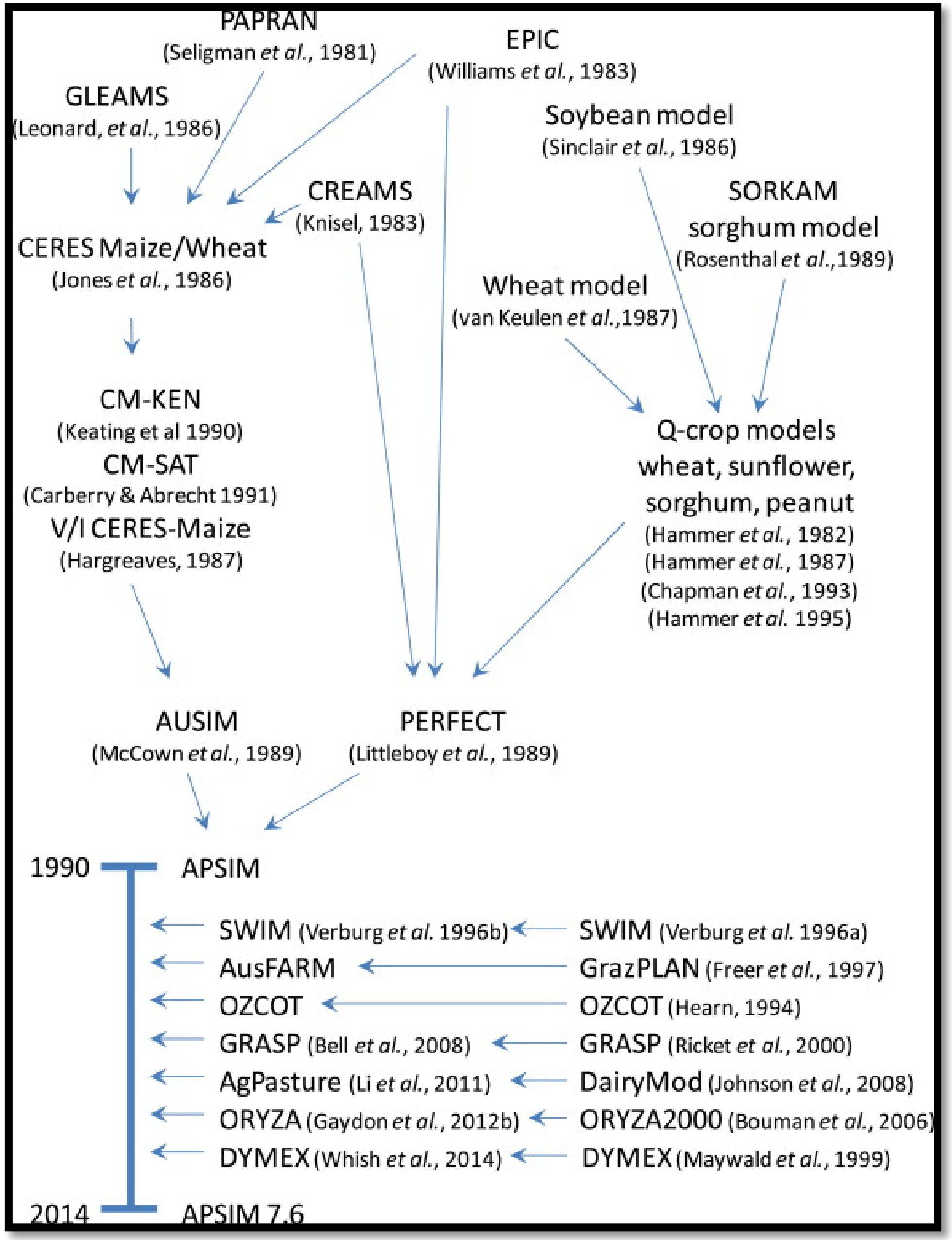
ESM-based versus agronomy-based crop models

Model	Strength	Weakness
CLM4.5	• Sophisticated soil and canopy hydrology • Two-stream approximation of canopy radiative transfer • Physical-based stomatal conductance, photosynthesis, and respiration • Explicit calculation of canopy temperature • More process-driven CO_2 fertilization effects • Can be coupled in climate model (CESM)	• Missing critical crop phenology stages (e.g. flowering) and reproductive processes (e.g. grain number formation) • Lack of stage-dependent stress simulation • Linear accumulation of thermal time (Peng et al., 2018)
APSIM	• More detailed crop phenology stages • Stage-dependent stress simulation • Piece-wise linear response of thermal time • More detailed management practices	• RUE-based calculation of NPP and no explicit simulation of photosynthesis and respiration • Lack of resolving energy balance • Simplified soil hydrology

Our simple idea is to combine the strengths of these two types of crop models (CLM-APSIM)!

Why APSIM?





(Cox et al., 2001; Holzworth et al., 2014)

Towards a generic crop template-the APSIM approach

- **Generic Crop template (GCROP)** (Wang et al., 2002): 26 crop types including cereals horticultural crops, vines, pastures and weeds
- **Generic legume model** (Robertson and Carberry, 1998; Robertson et al., 2002; Turpin et al., 2003): chickpea, mungbean, peanut, and lucerne
- **Generic Plant template**=GCROP+generic legume model
- **Plant Modelling Framework** (Brown et al., 2014): all crops species

<u>These generic templates are also favored by the earth system modeling community</u>

Agricultural and Forest Meteorology 249 (2018) xxx–xxx

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Agricultural and Forest Meteorology

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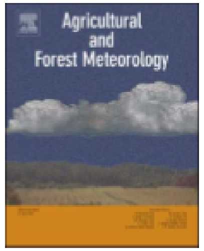

Research paper

Improving maize growth processes in the community land model: Implementation and evaluation

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Peng et al., 2018, AFM

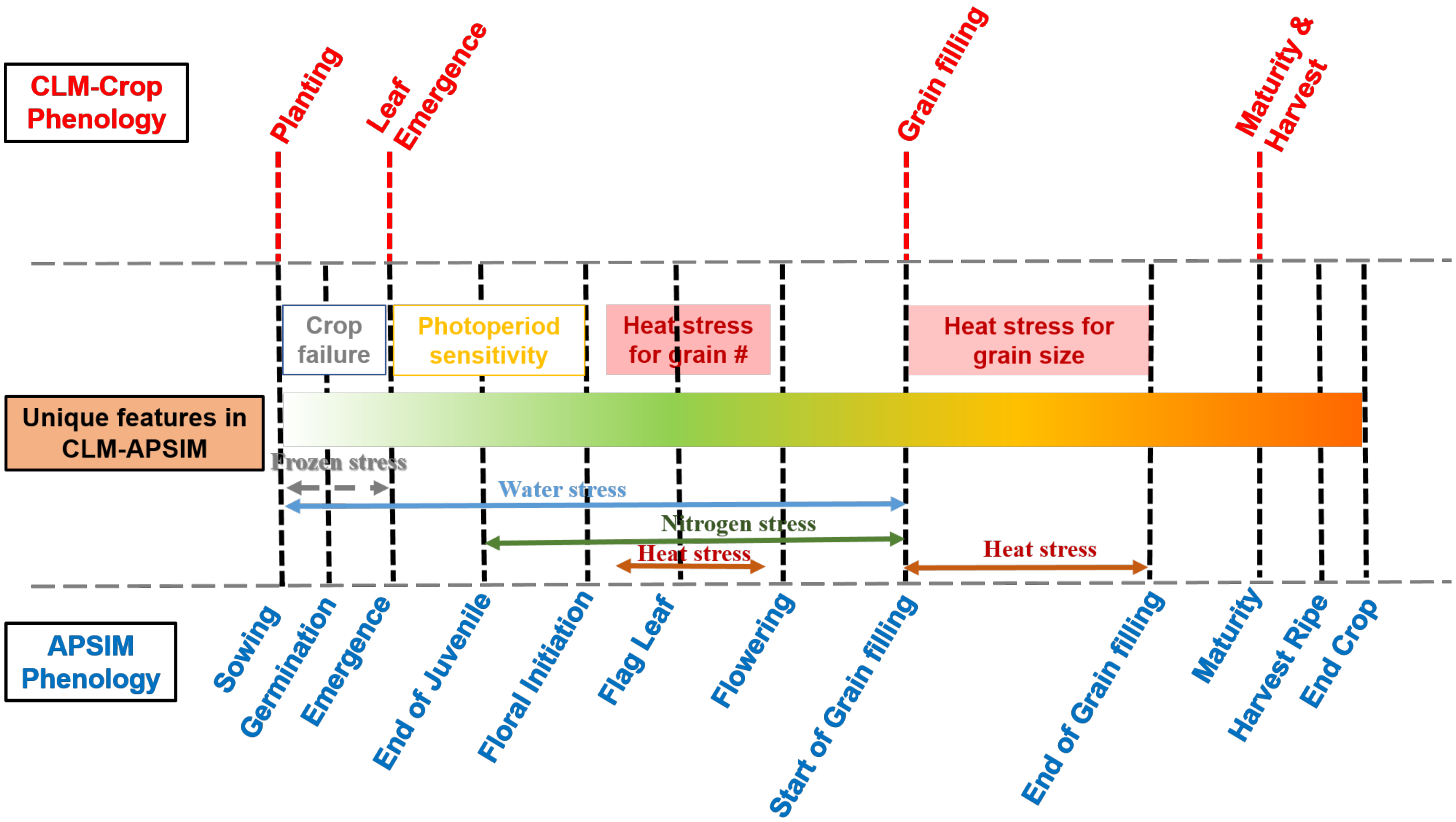
ARTICLE INFO

Keywords:
Maize
Community land model
APSIM
Phenology
Carbon allocation
Yield
Stress

ABSTRACT

Earth system models (ESMs) are essential tools to study the impacts of historical and future climate on regional and global food production, as well as to assess the effectiveness of possible adaptations and their potential feedback to climate. Several current ESMs have the capabilities to simulate crop growth. However, some critical crop growth processes (e.g. flowering and other reproductive processes) and their responses to environmental extremes (e.g. heat stress) are not yet represented in most of these models. In this paper, an improved maize growth model was implemented in the Community Land Model version 4.5 (CLM4.5) by modifying the maize planting scheme, incorporating the phenology scheme adopted from the APSIM model (Agricultural Production Systems sIMulator), adding a new carbon allocation scheme into CLM4.5, and improving the estimation of canopy structure parameters including leaf area index (LAI) and canopy height. Unique features of the new model (CLM-APSIM) include more detailed phenology stages, an explicit implementation of the impacts of

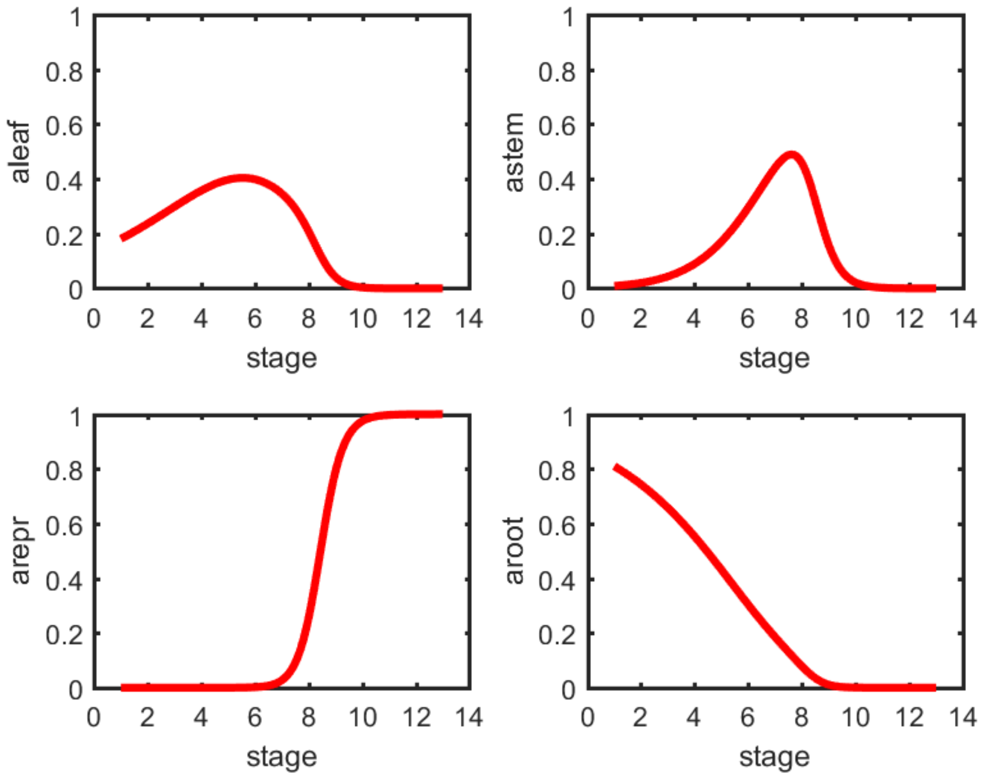
CLM-APSIM maize model

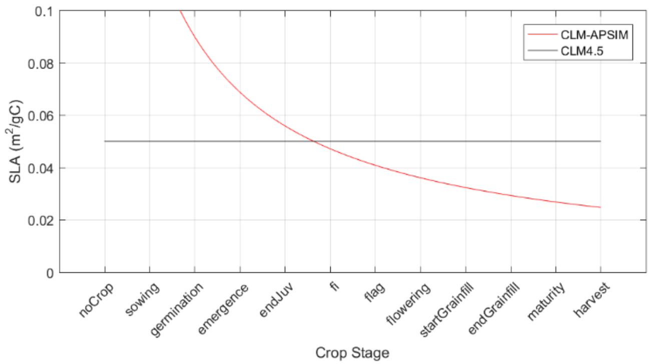


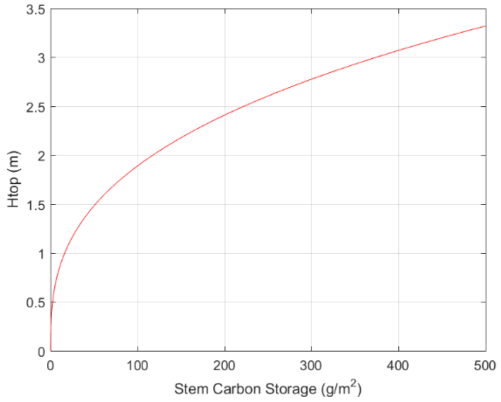
CLM-APSIM maize model

❑ Other features in CLM-APSIM:

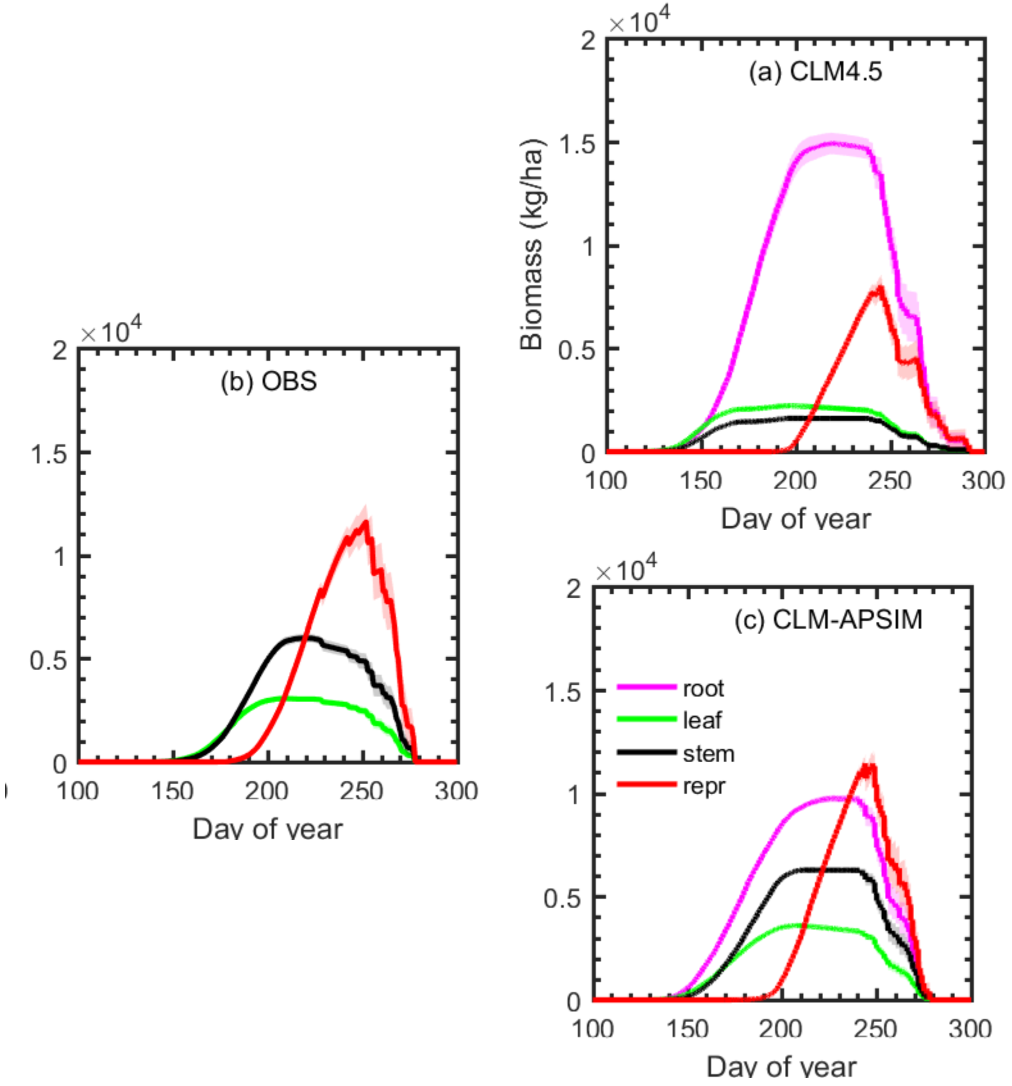
- Hydrology and photosynthesis follow CLM4.5 (Collatz, 1991 and 1992; Ball et al., 1987; Ball 1988);
- New carbon allocation scheme
- Dynamic Specific Leaf Area
- Estimating canopy height from stem carbon pool size, instead of LAI

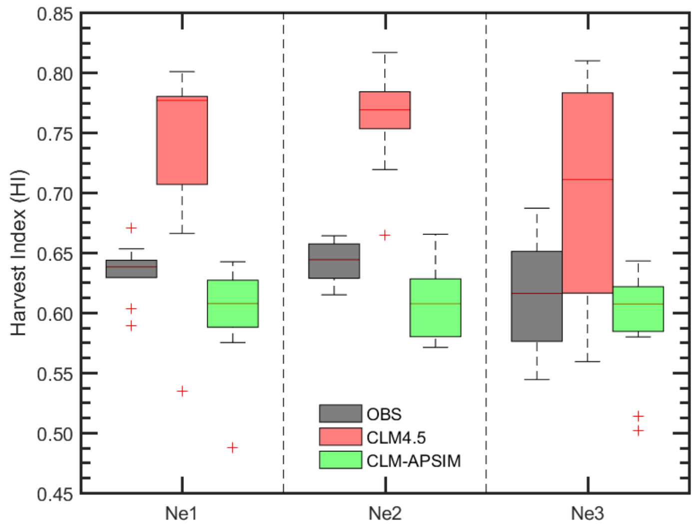


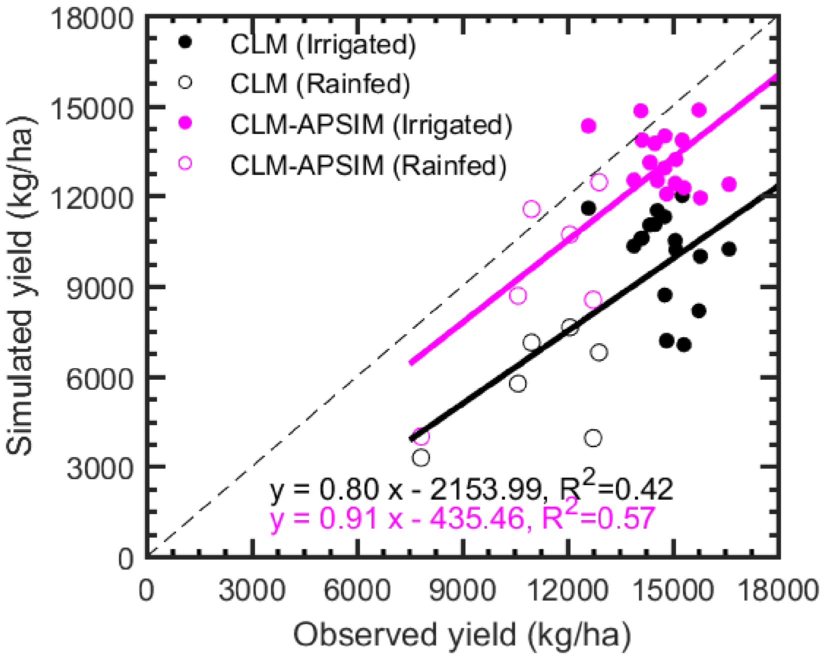




Site-level evaluation of CLM-APSIM







(Peng et al., 2018, AFM)

Define the parameter space

- We selected 129 parameters in CLM-APSIM, categorized into 11 classes:
- (1) radiative transfer (RAD)
- (2) aerodynamics (AD)
- (3) soil thermodynamics (ST)
- (4) canopy interception (CI)
- (5) surface runoff (SR)
- (6) Soil water (SW)
- (7) photosynthetic (PSN)
- (8) Carbon-Nitrogen allocation (CNA)
- (9) External nitrogen cycle (EN)
- (10) CLM4.5 Maize (CM)
- (11) CLM-APSIM Maize (CAM)

- Parameter ranges: default*(1.0±20%)
- Uniform distribution
- Morris for qualitative parameter screening
- Sobol for quantitative sensitivity analysis

Parameter screening: Morris method

- One trajectory: starting from a reference point, change One-parameter-at-A-Time (OAT) until all parameters are changed (D+1)
- Repeat trajectories: r repetitions.
- Total samples: N=r*(D+1)
- Sensitivity measures: elementary effect (EE)

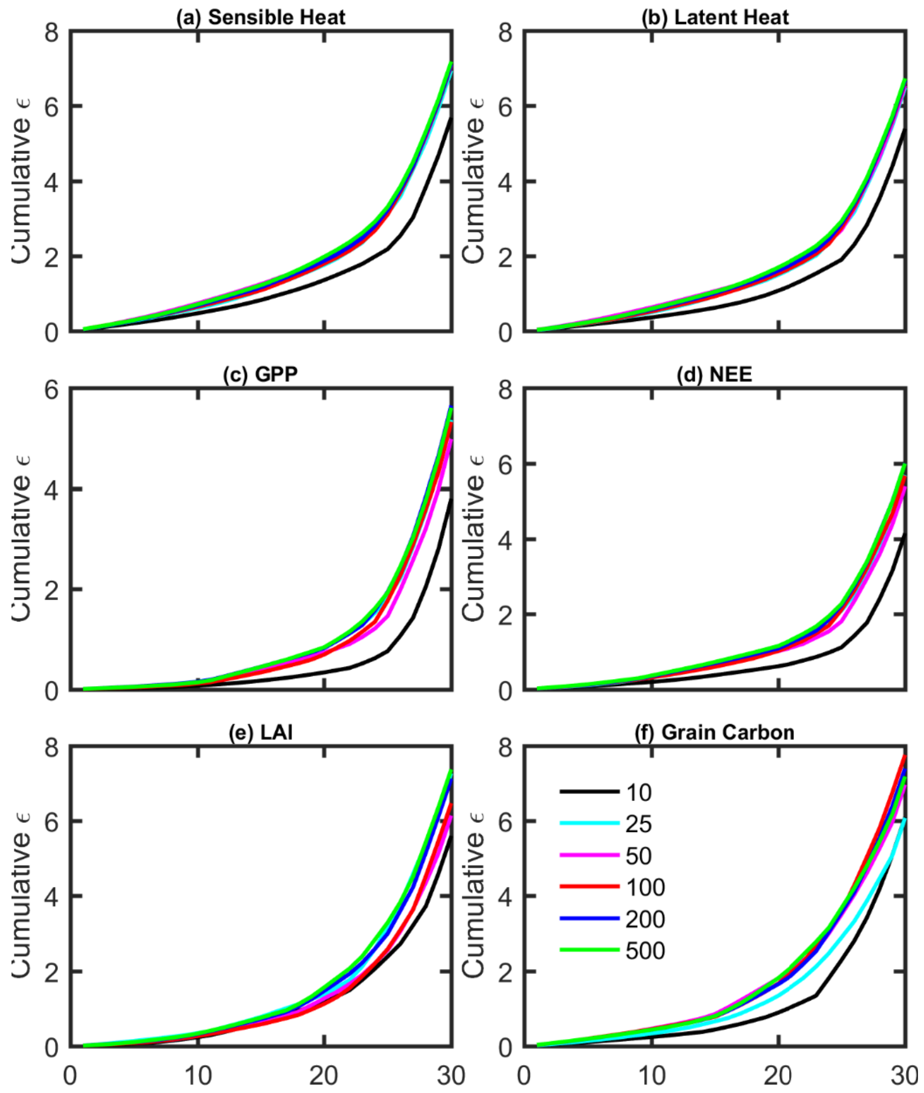
$$d_i(X) = \frac{y(x_1, \cdots, x_{i-1}, x_i + \Delta, x_{i+1}, x_k) - y(X)}{\Delta}$$

$$\mu_i = E\langle d_i(X) \rangle$$

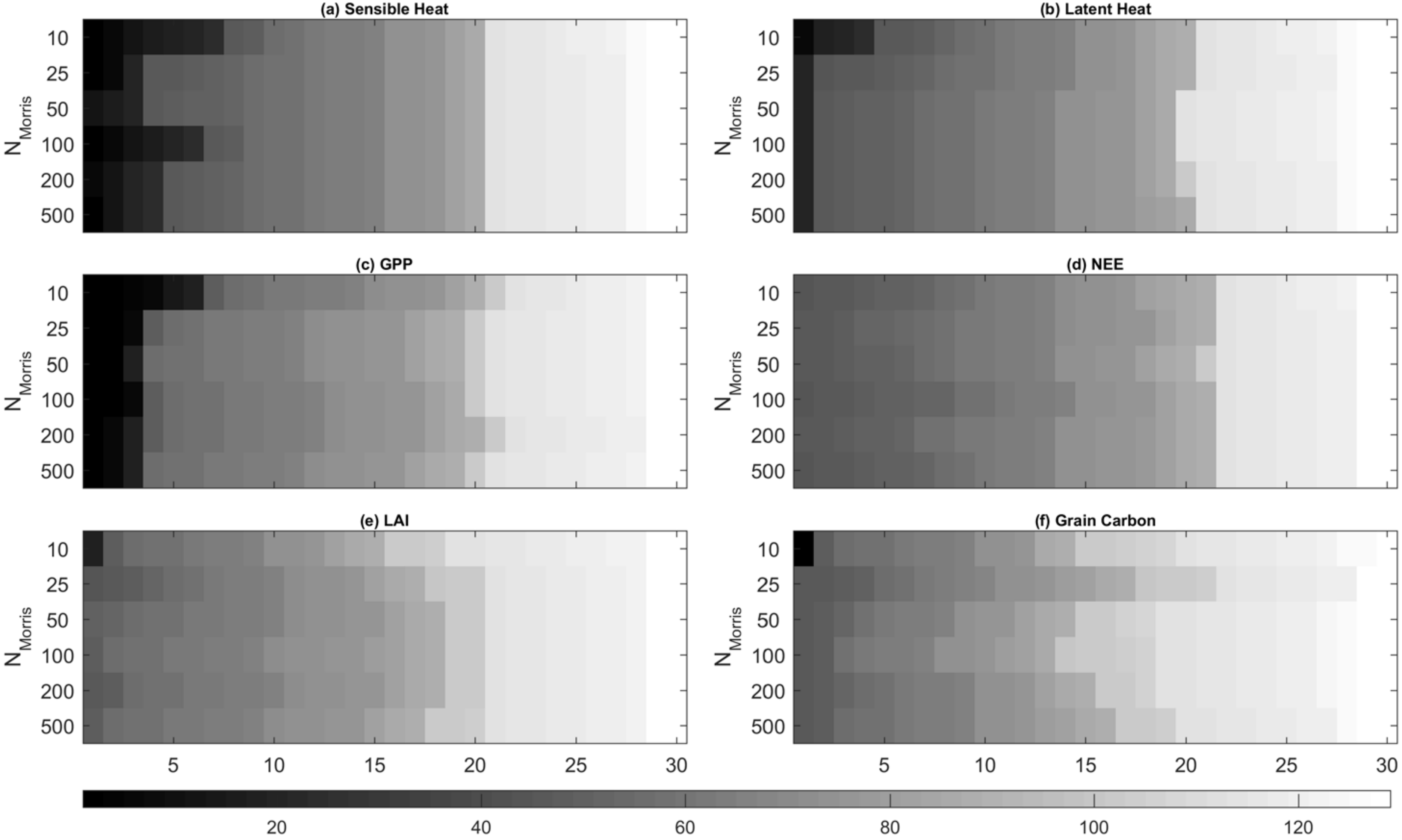
$$\sigma_i = E\langle [d_i(X) - \mu]^2 \rangle$$

$$\mu_i^* = E\langle |d_i(X)| \rangle$$

$$\varepsilon = \sqrt{\mu^{*2} + \sigma^2}$$

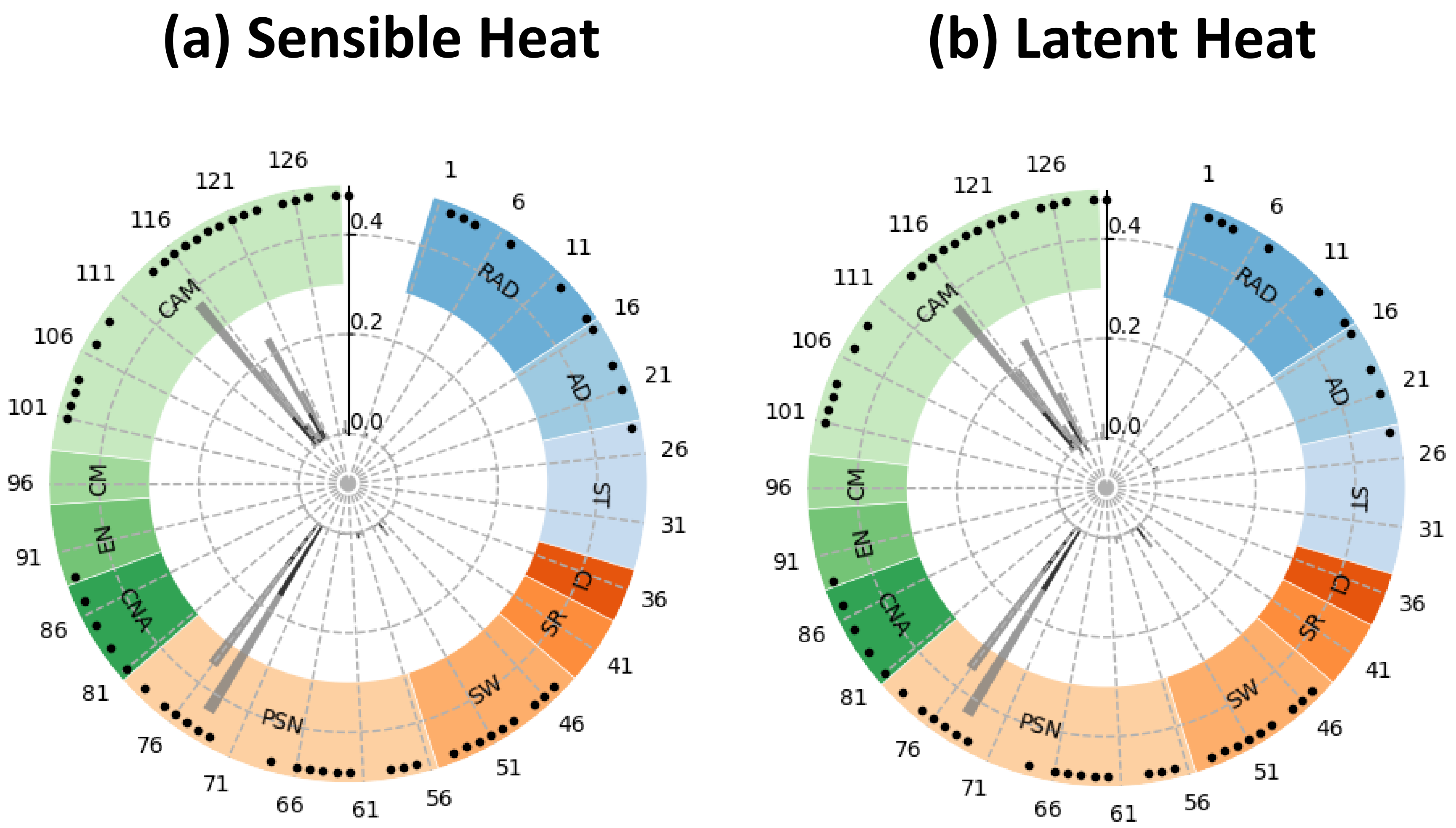


Parameter screening: Morris method



60 parameters emerged in this figure and will be used for quantitative SA

Quantitative Parameter SA: Sobol' method



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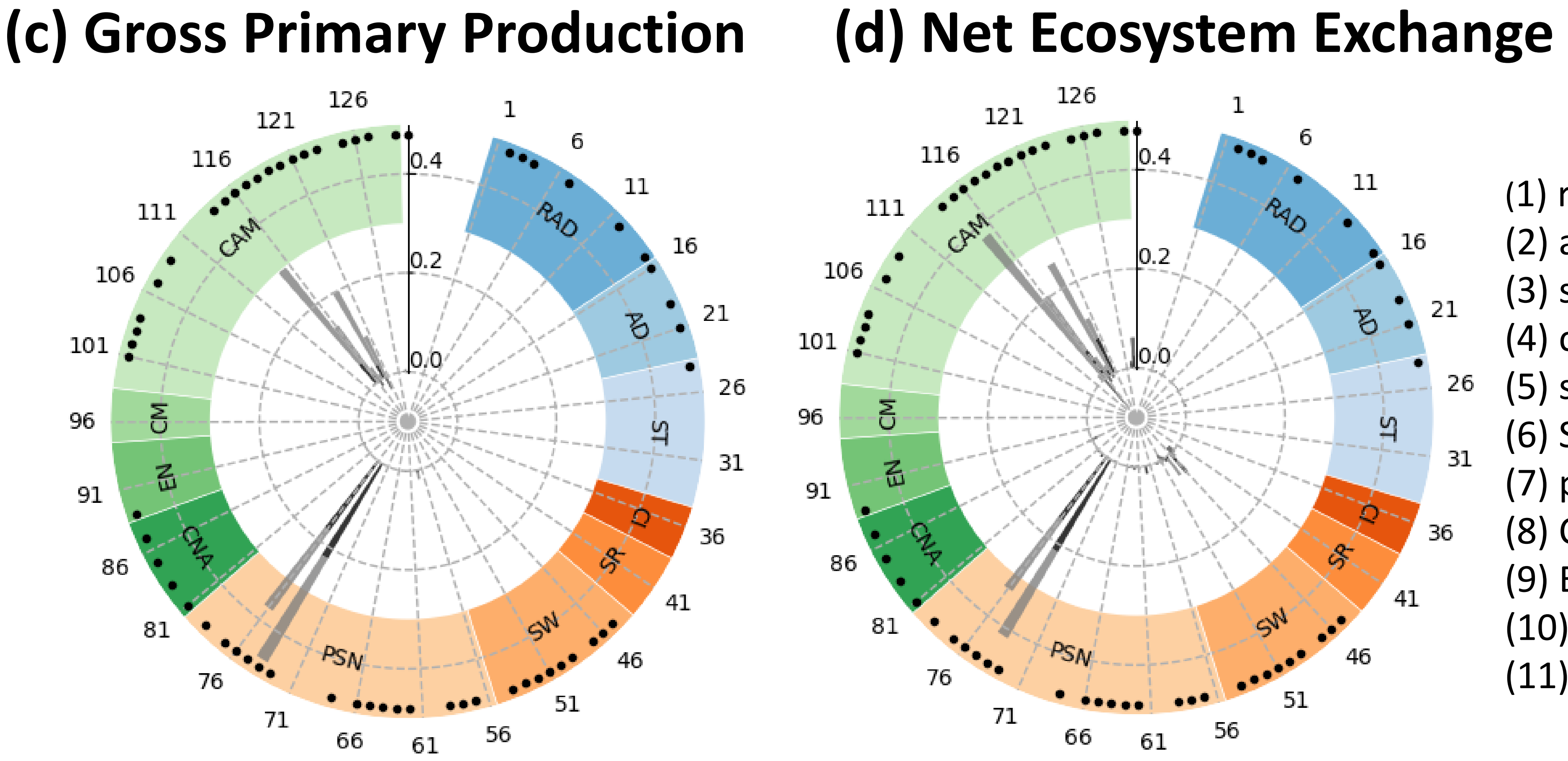

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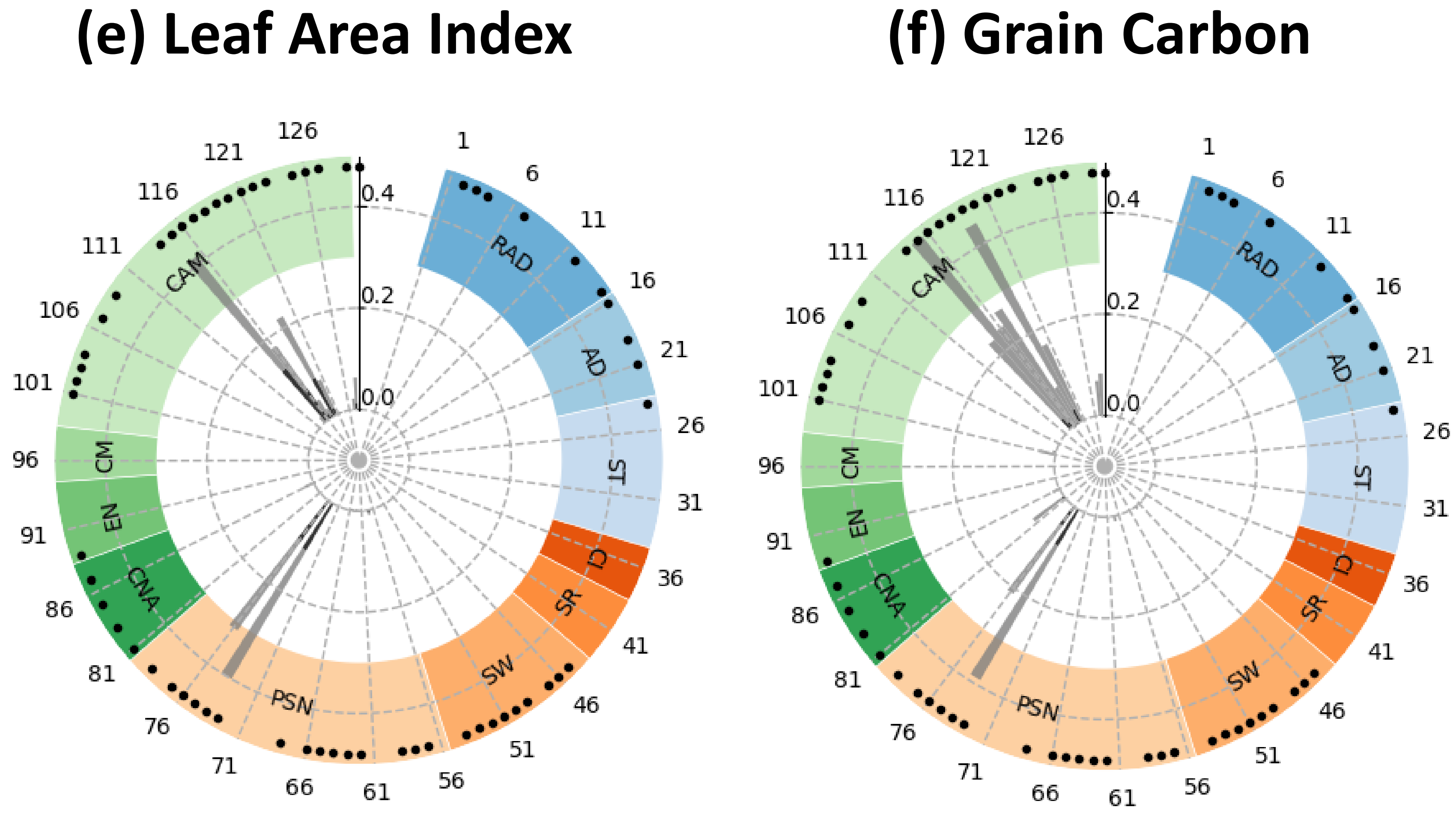

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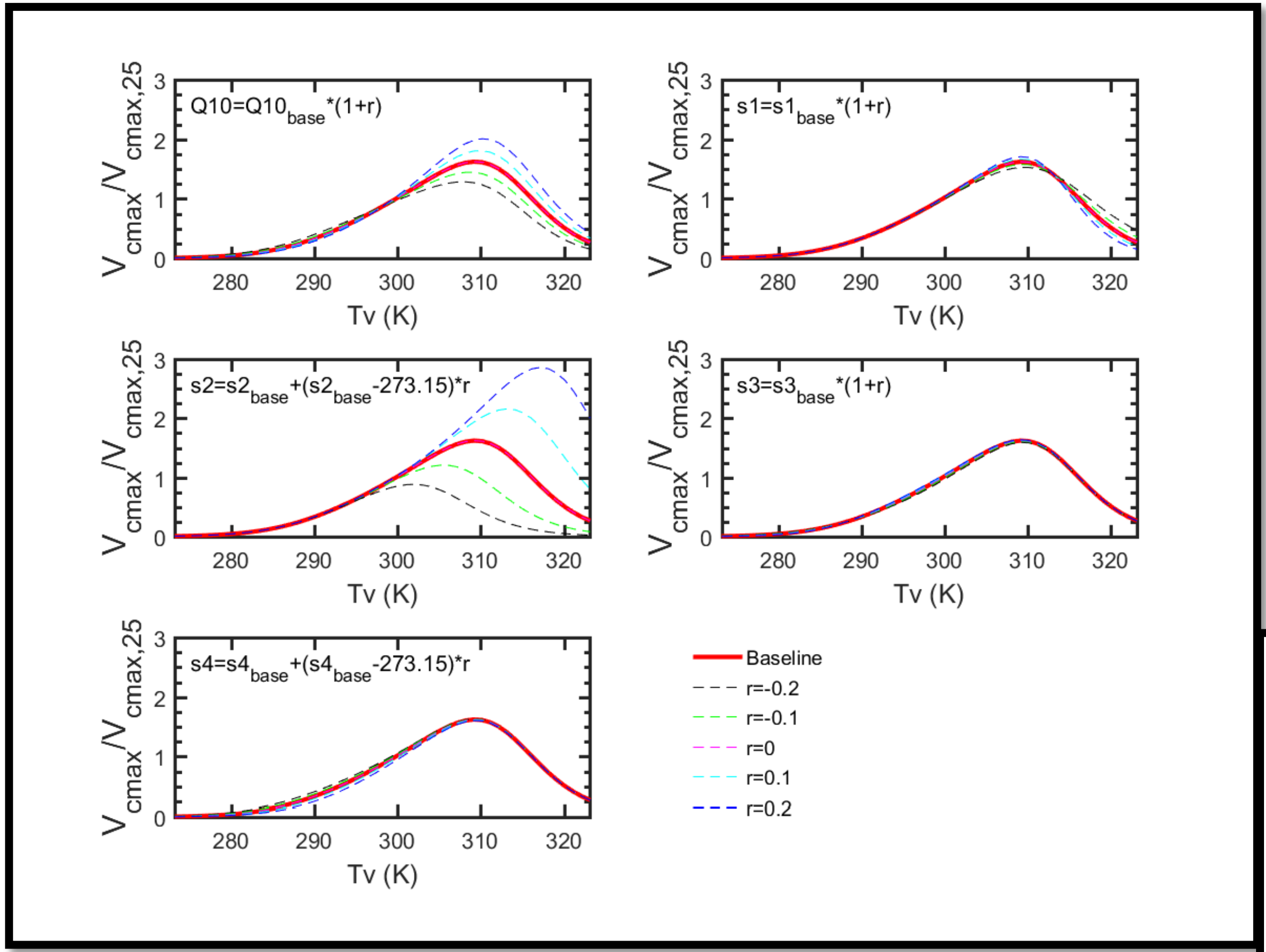
What are the most sensitive parameters?

Category	ID	Parameters	Sensitive responses
Soil Water (SW)	46	**parameter for porosity of the mineral soil**	SH, LH, NEE
	48	**parameter for saturated matric potential of the mineral soil**	SH, LH, NEE
Photosynthesis (PSN)	74	**S2 in Vcmax**	SH, LH, GPP, NEE, LAI, Yield
	76	**S4 in Vcmax**	SH, LH, GPP, NEE, LAI, Yield
Carbon-Nitrogen allocation (CAN)	82	**leaf C:N in vegetative stage**	Yield
CLM-APSIM Maize model (CAM)	114	**Total Thermal Time for reproductive stages**	Yield
	115	**alpha for leaf**	SH, LH, GPP, NEE, LAI, Yield
	116	**beta for leaf**	SH, LH, GPP, NEE, LAI, Yield
	117	**alpha for stem**	SH, LH, GPP, NEE, LAI, Yield
	118	**beta for stem**	SH, LH, GPP, NEE, LAI, Yield
	119	**alpha for root**	SH, LH, GPP, NEE, LAI, Yield
	120	**beta for root**	SH, LH, GPP, NEE, LAI, Yield
	128	**kappa for dynamic SLA**	NEE, LAI, Yield
	129	**lambda for dynamic SLA**	NEE, LAI, Yield

What are the most sensitive parameter?



For C4 plants,

$$V_{c\max} = V_{c\max 25}\left[\frac{Q_{10}^{(T_v-298.15)/10}}{f_H(T_v)\,f_L(T_v)}\right]$$

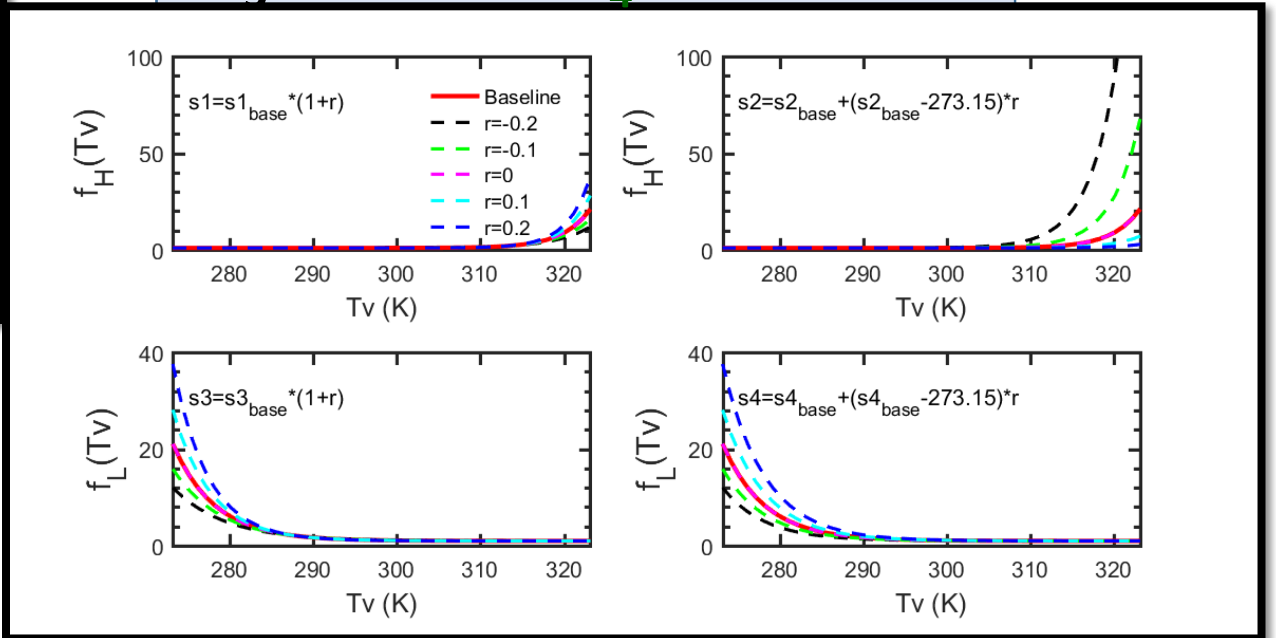
$$f_H(T_v) = 1+\exp\left[s_1(T_v - s_2)\right]$$

$$f_L(T_v) = 1+\exp\left[s_3(s_4 - T_v)\right]$$

with $Q_{10} = 2$,

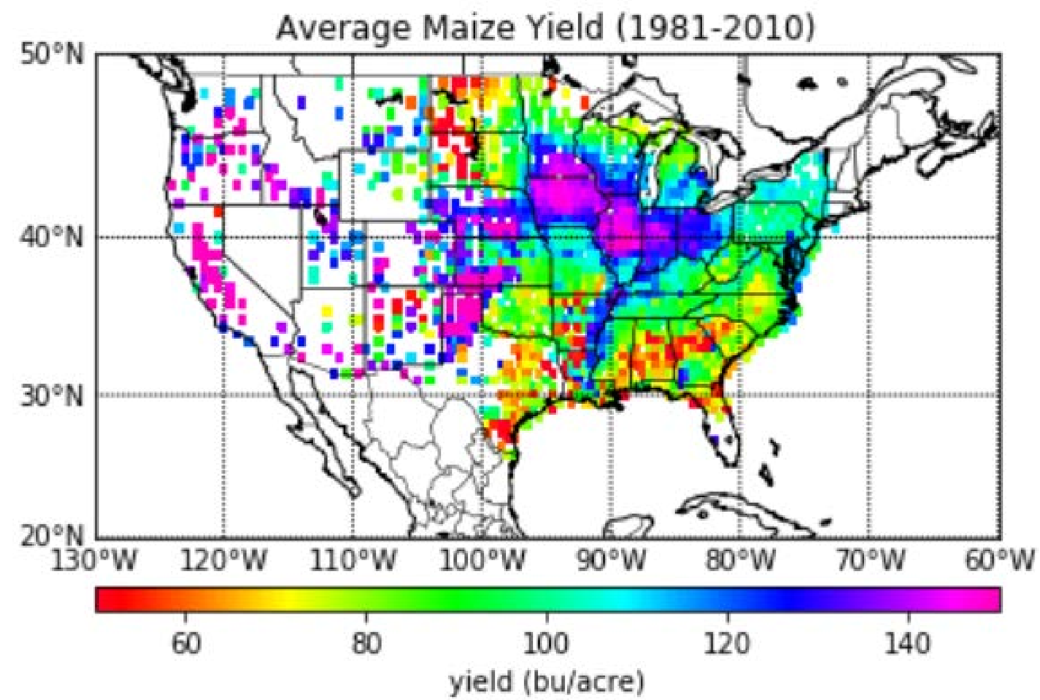
$S_1 = 0.3\ K^{-1}$, $S_2 = 313.15\ K$,

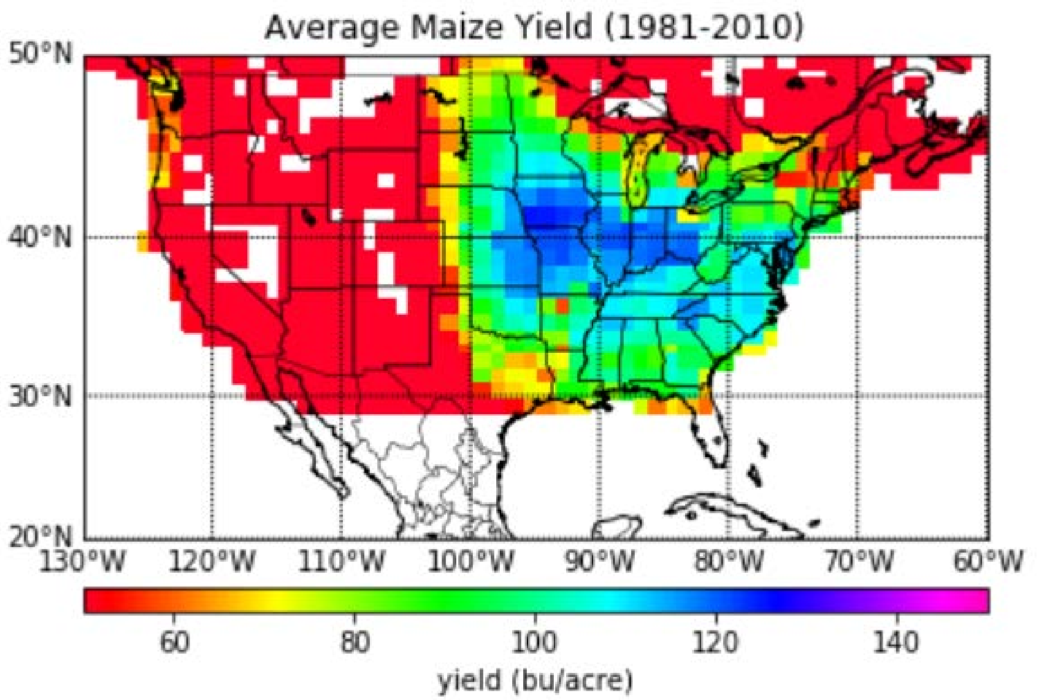
$S_3 = 0.2\ K^{-1}$, $S_4 = 288.15\ K$.

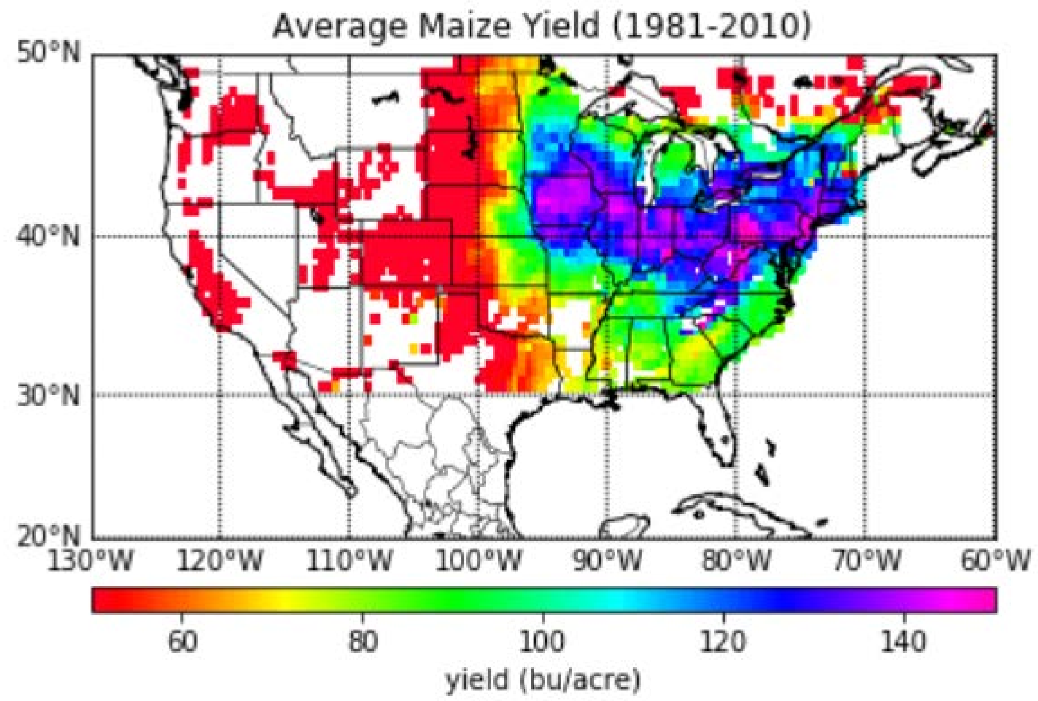


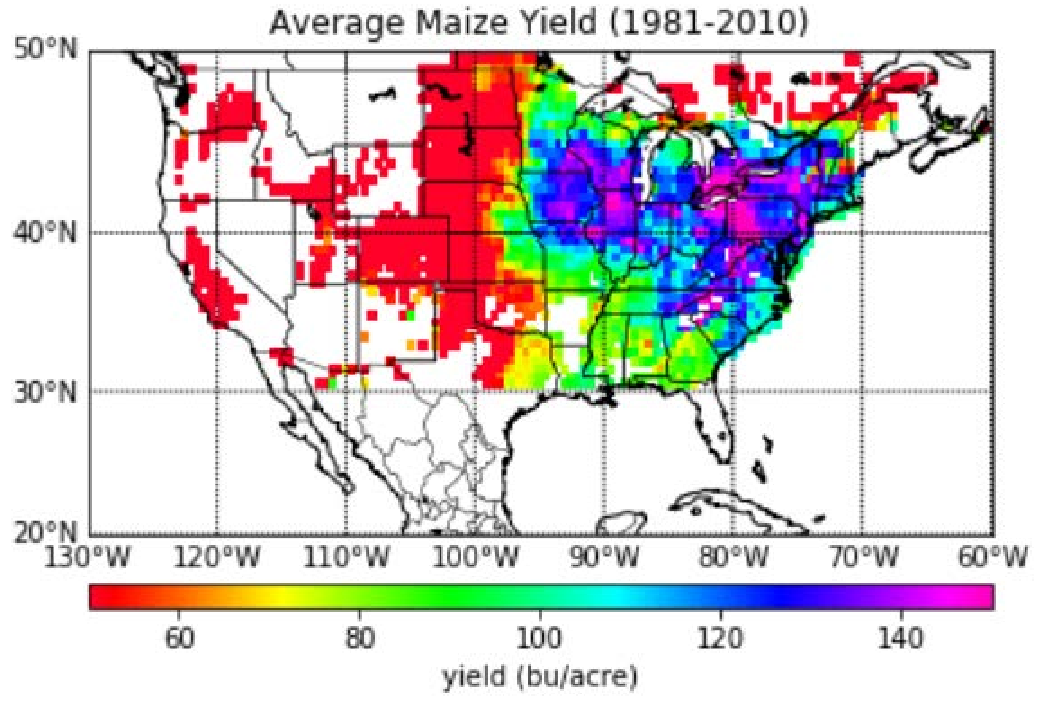
Impact of model structures

NASS	CLM5.0
CLM4.5	CLM-APSIM

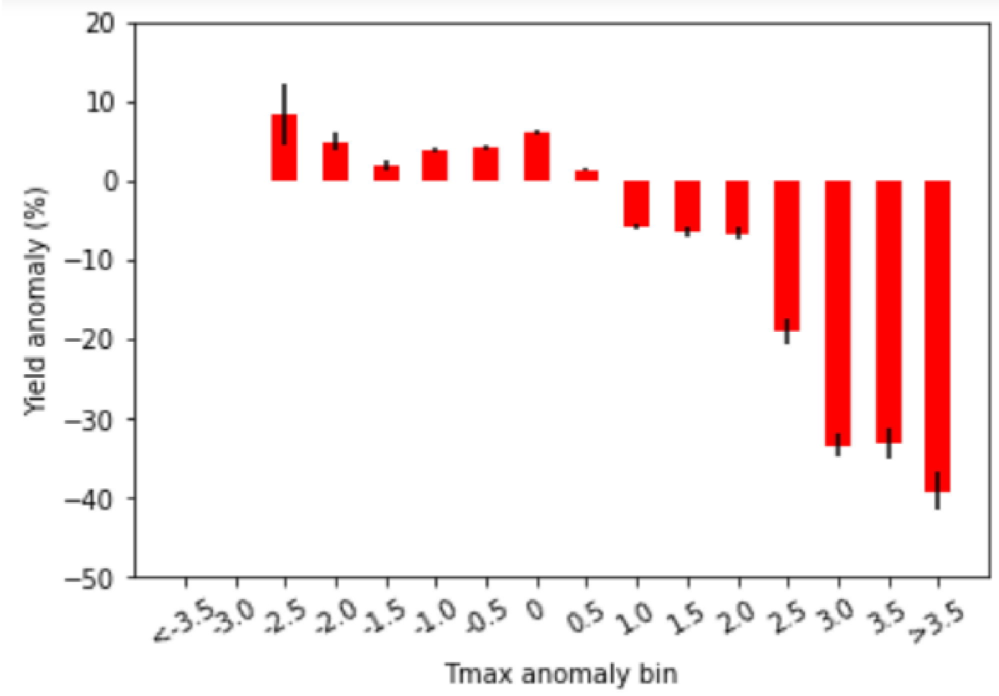


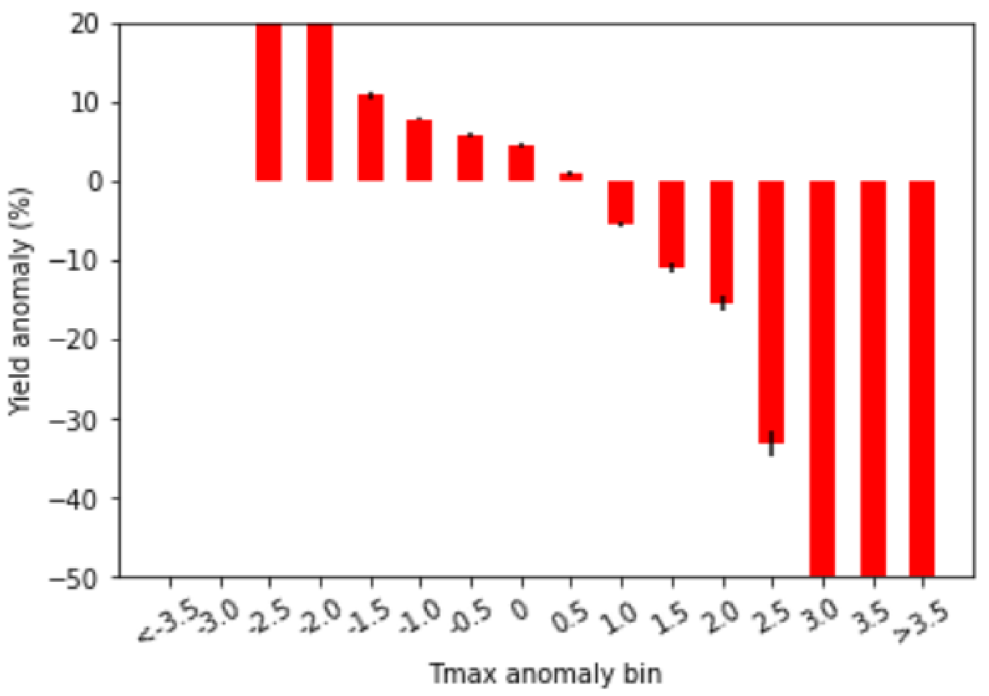




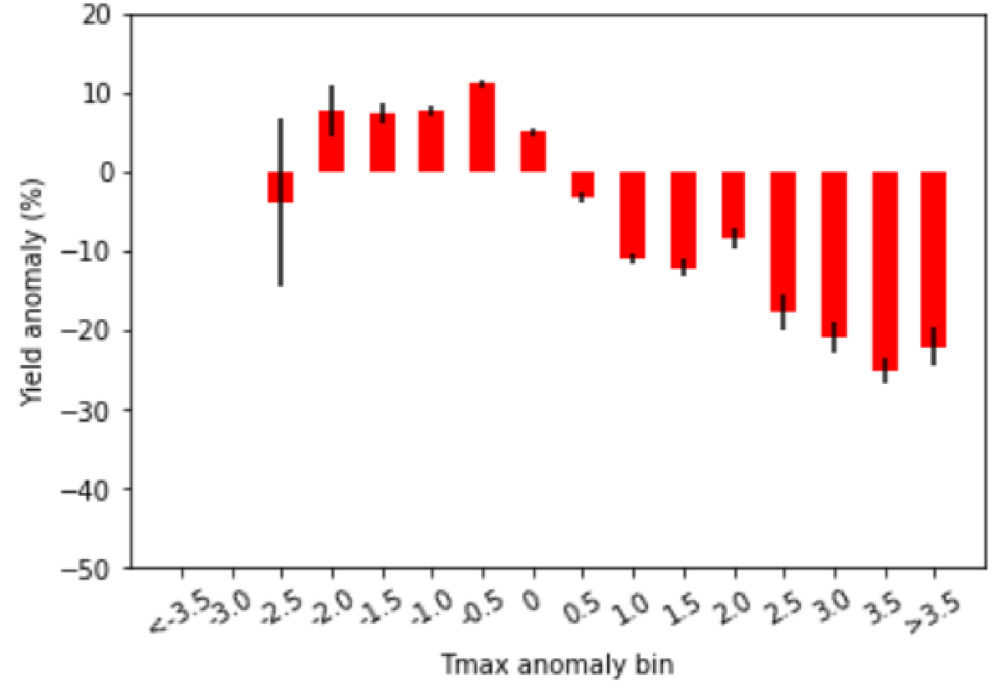


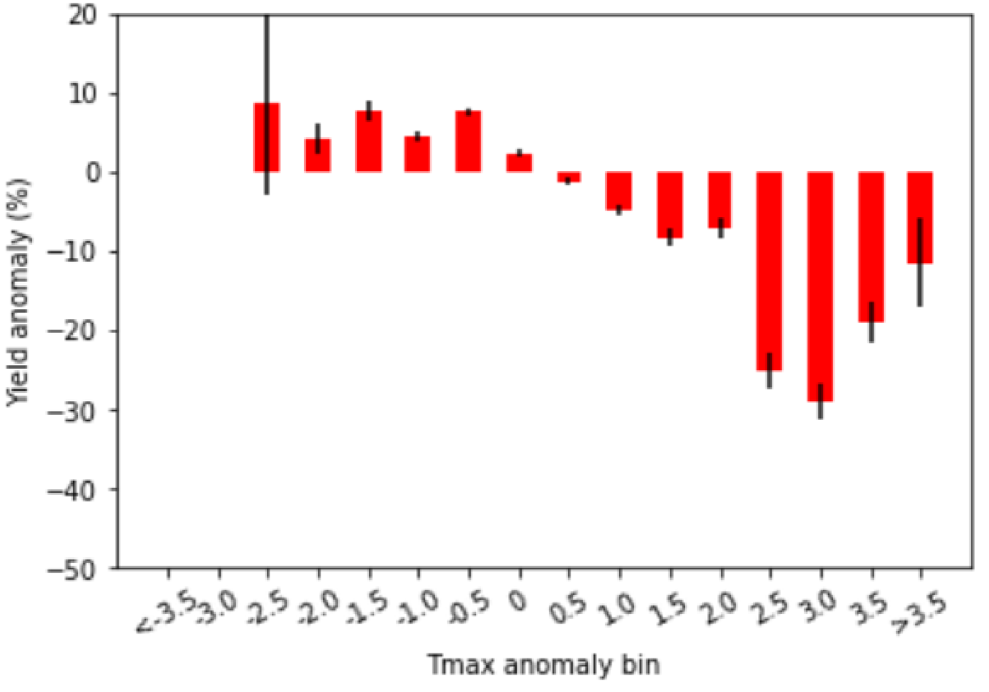
Impact of model structures



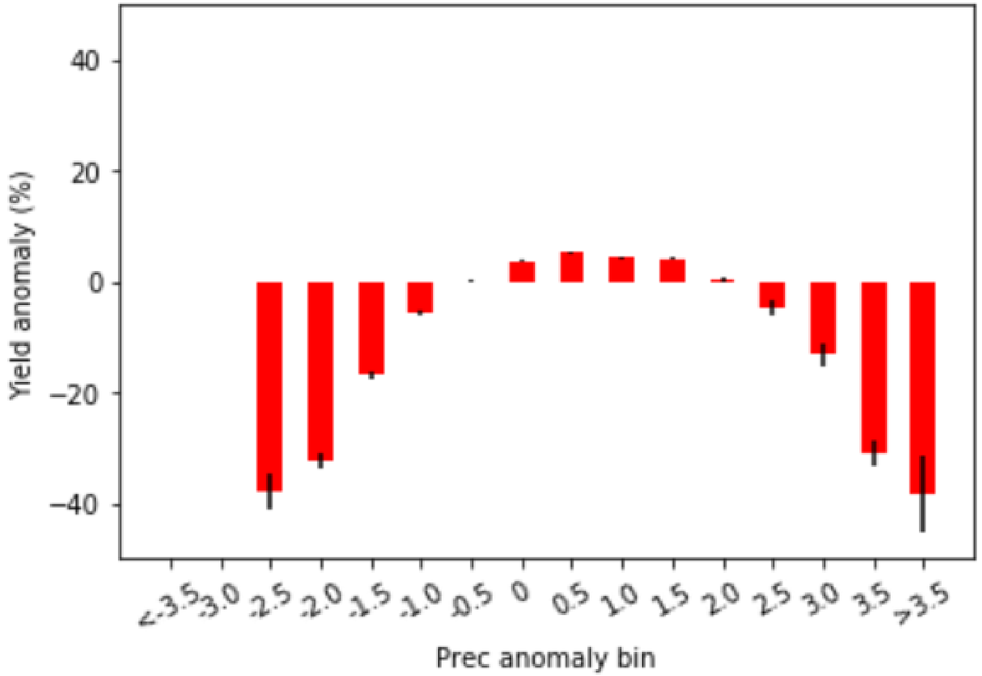


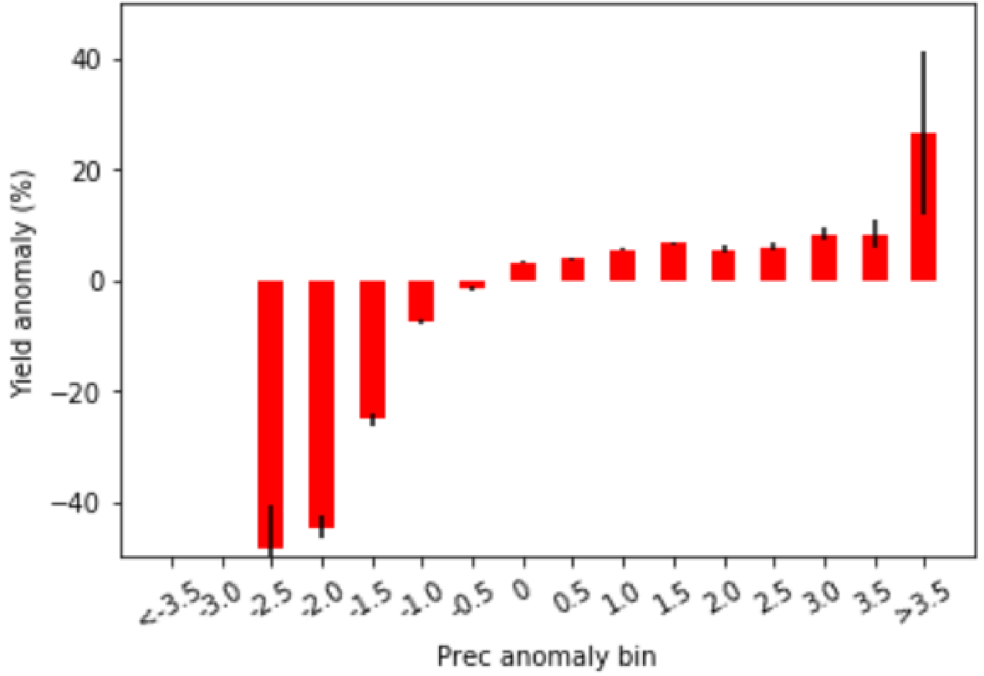
NASS	CLM5.0
CLM4.5	CLM-APSIM





Impact of model structures





NASS	CLM5.0
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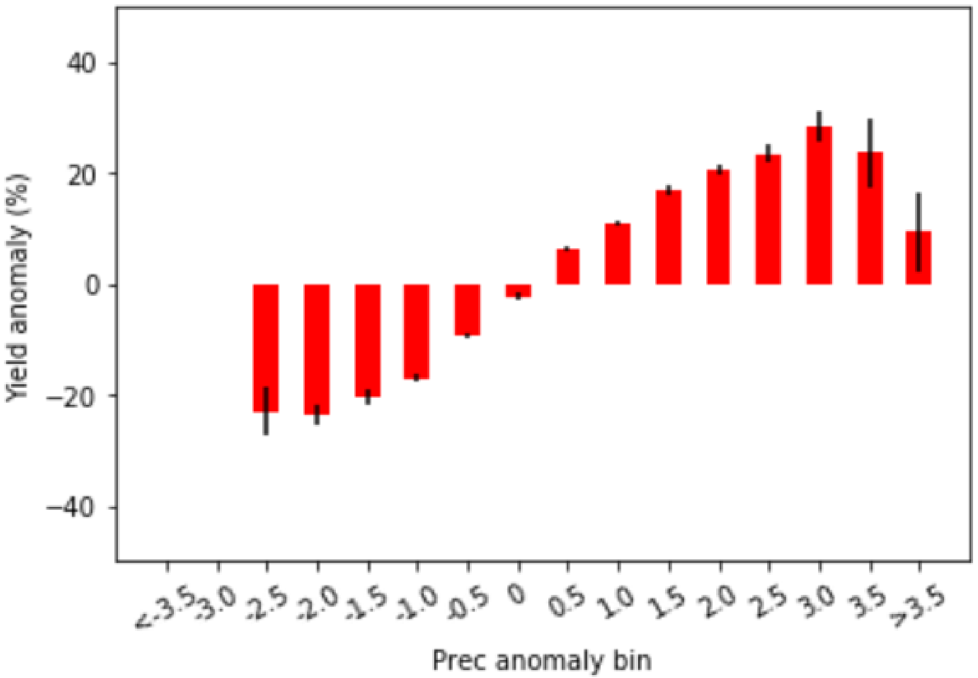
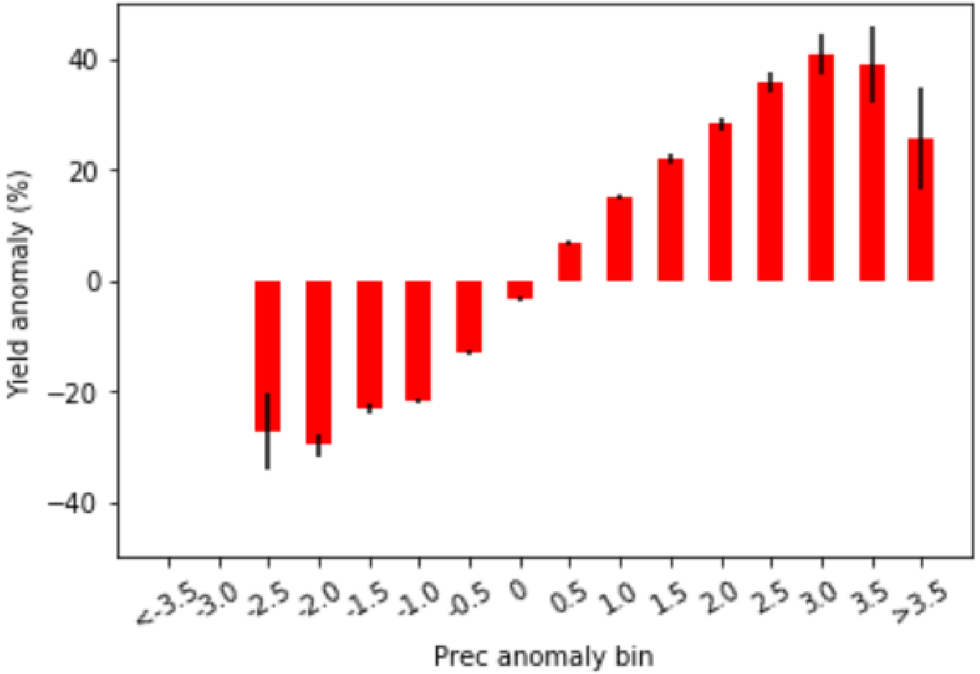
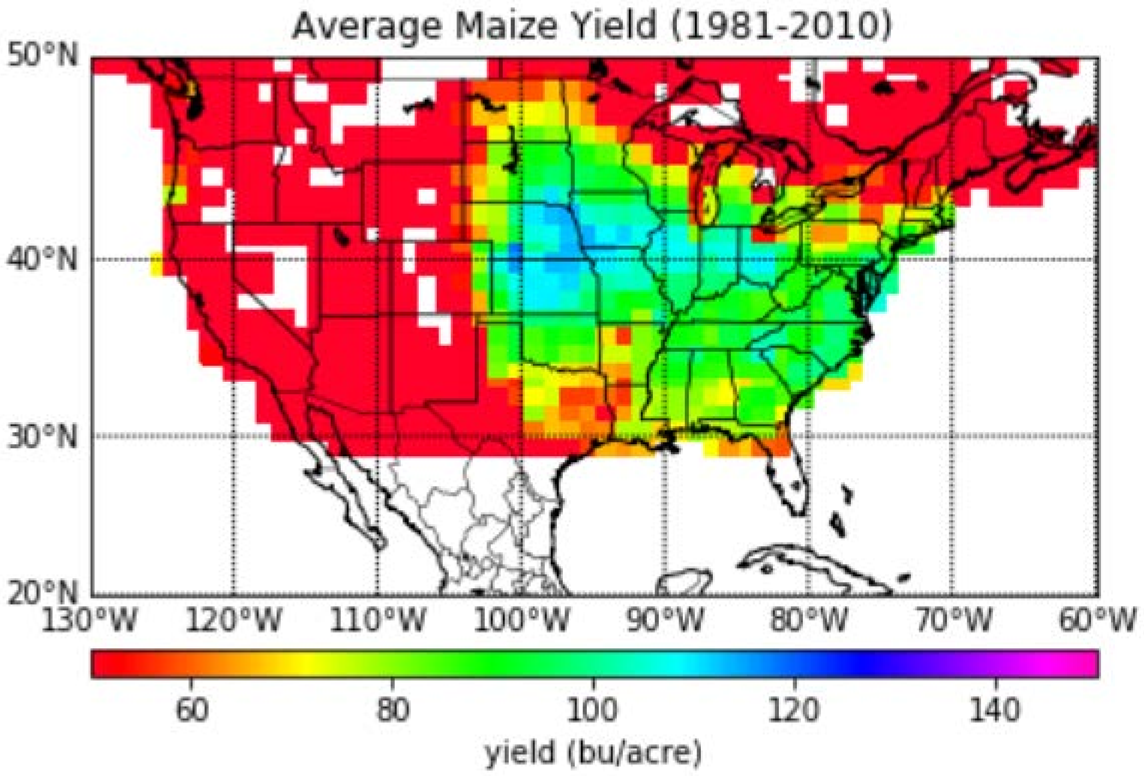
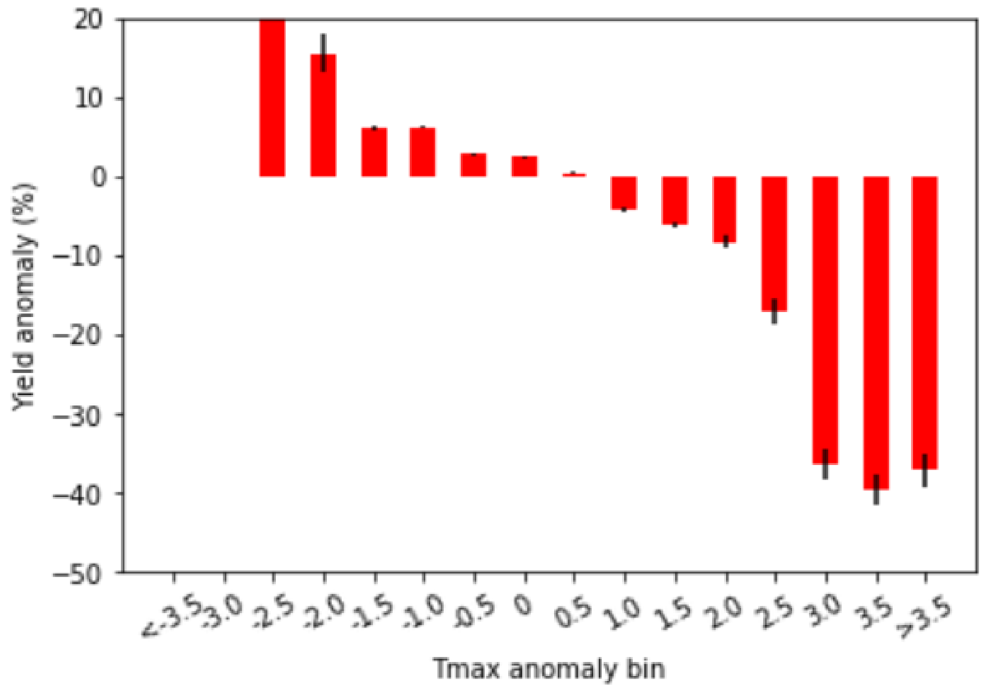


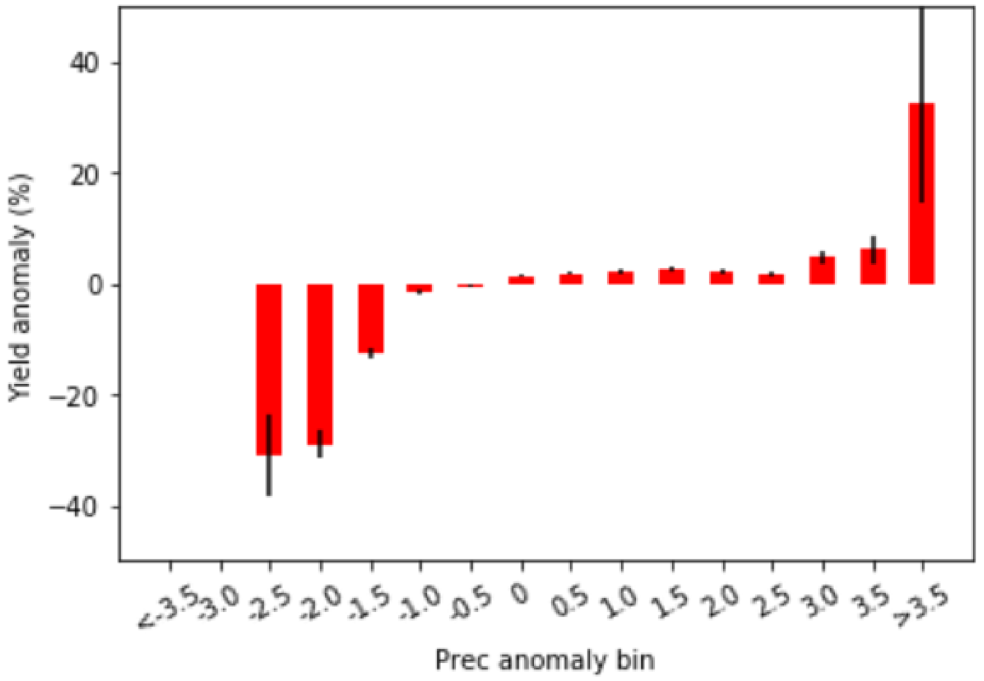


Impact of forcing dataset

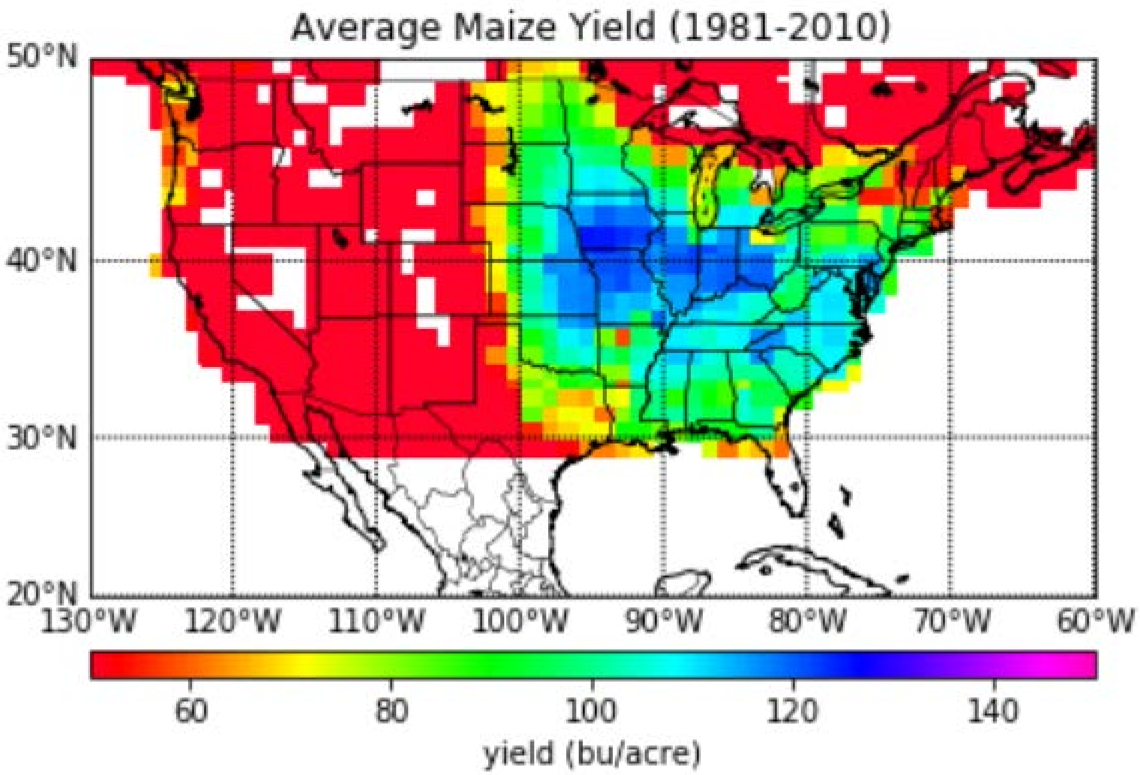


CLM5.0 with GSWP3V1 forcing

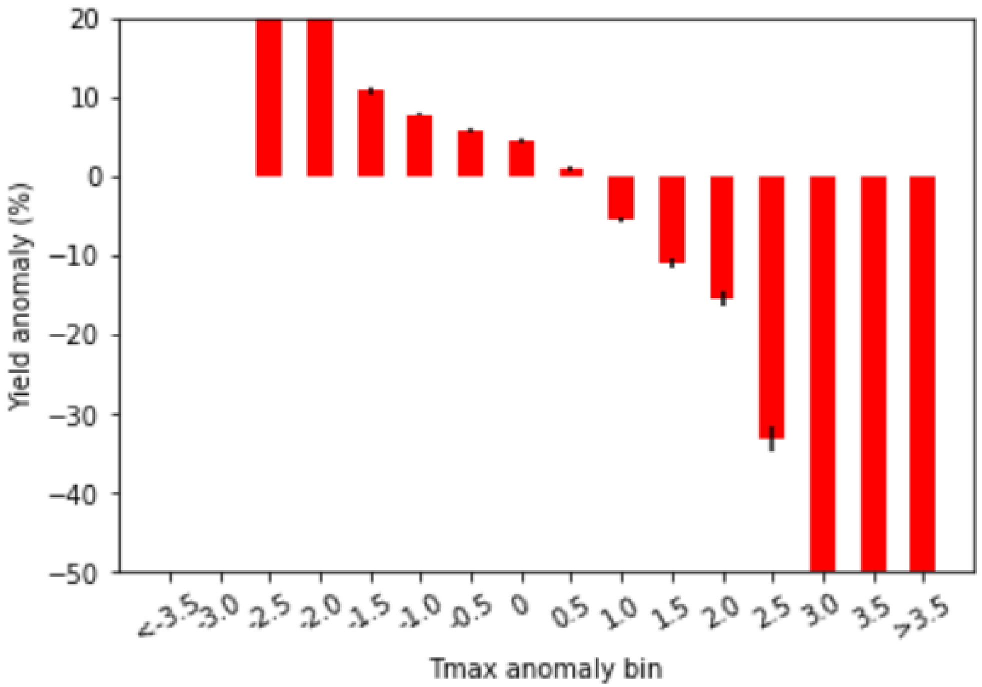


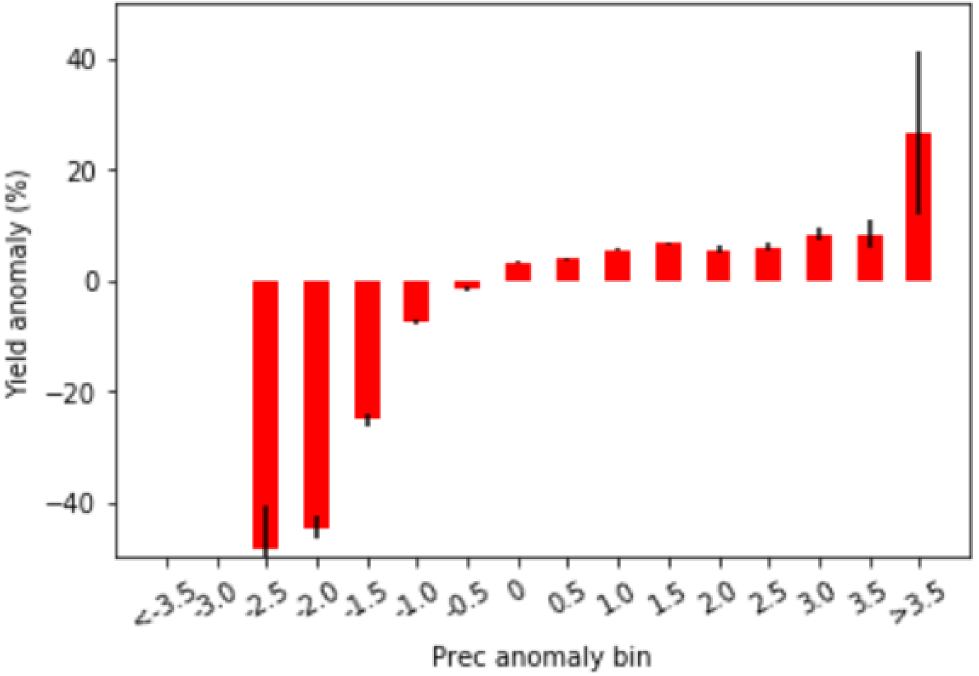


Impact of forcing dataset



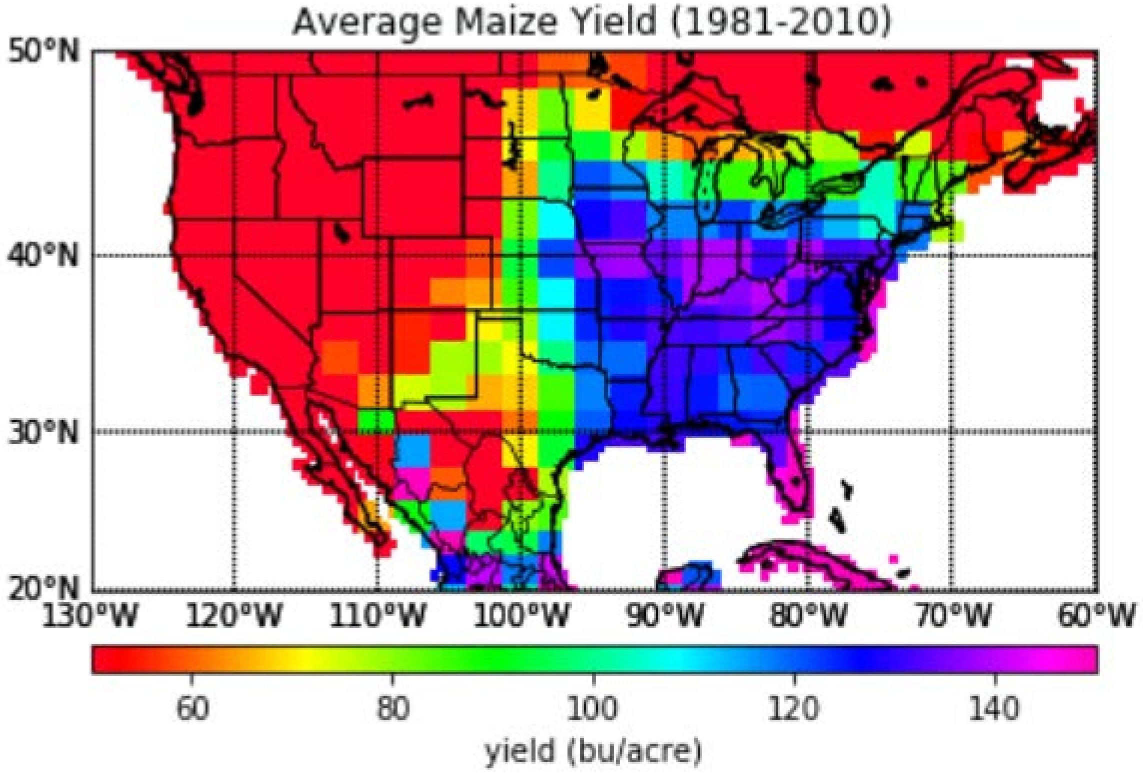
CLM5.0 with CRUNCEPV7 forcing

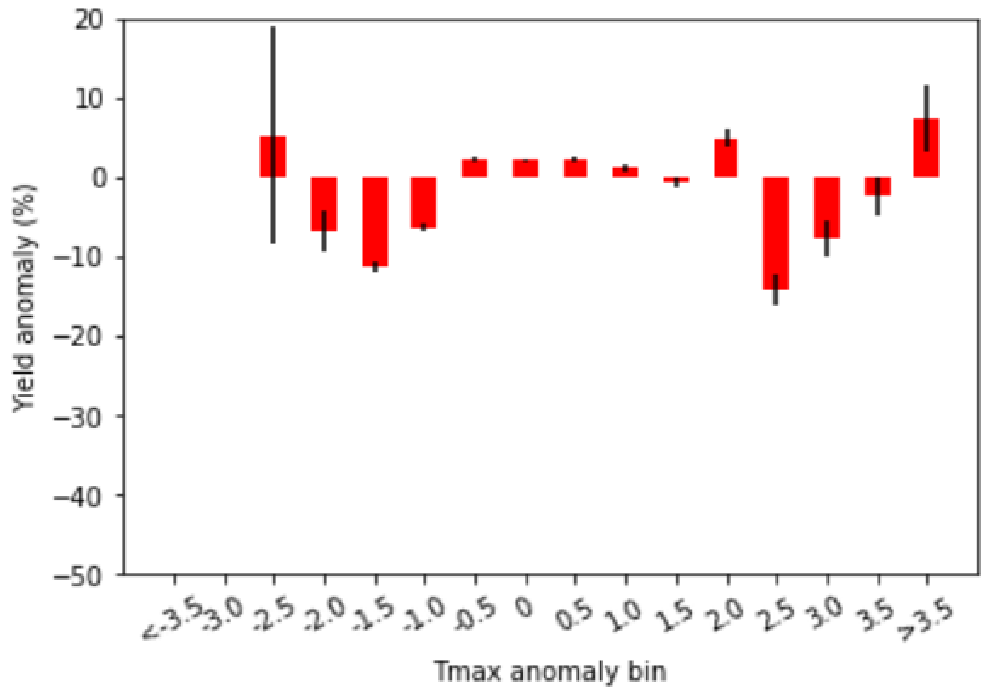


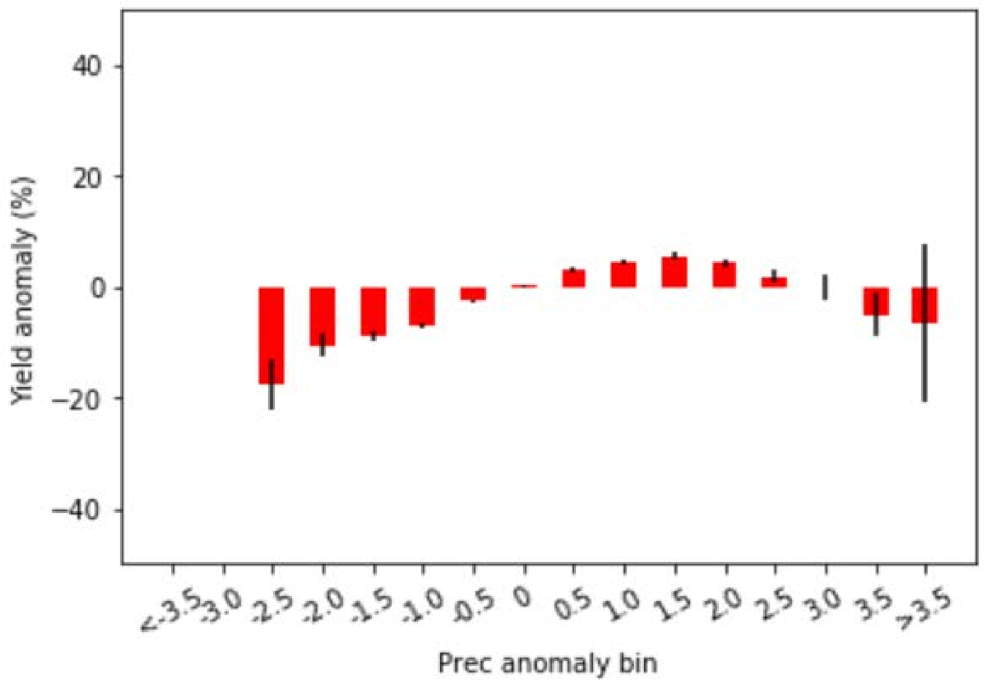


Impact of forcing dataset

AGMIP GGCMI simulation



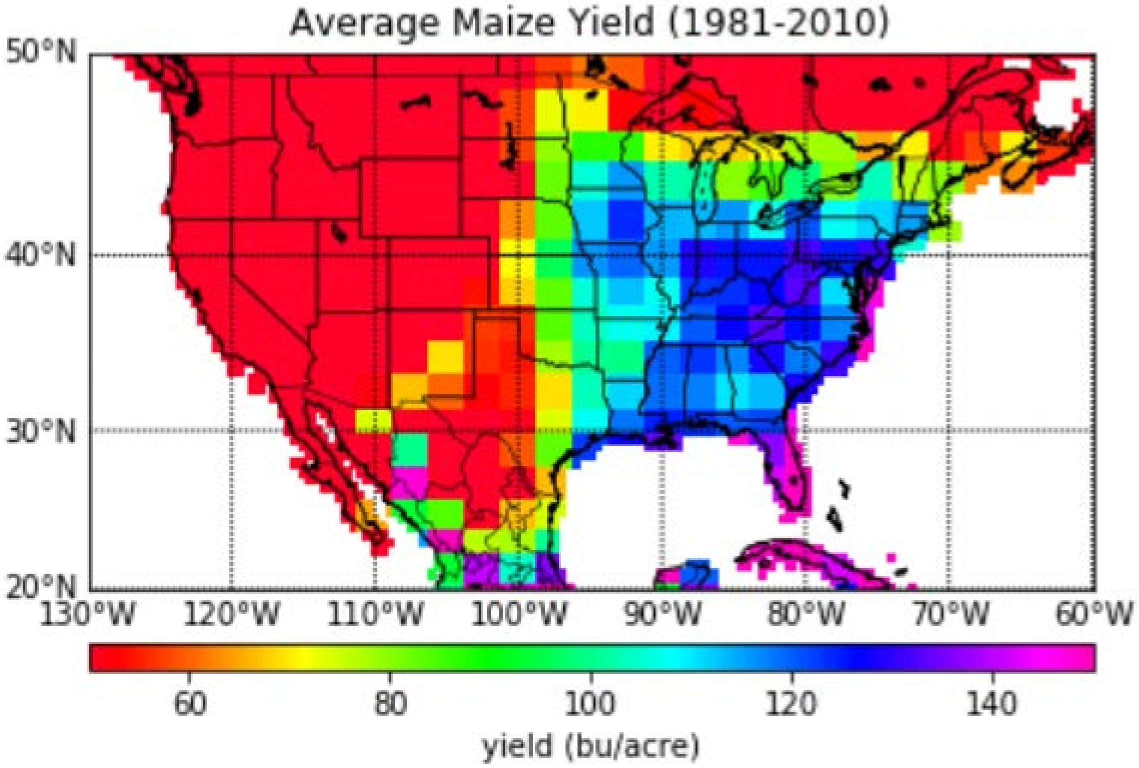


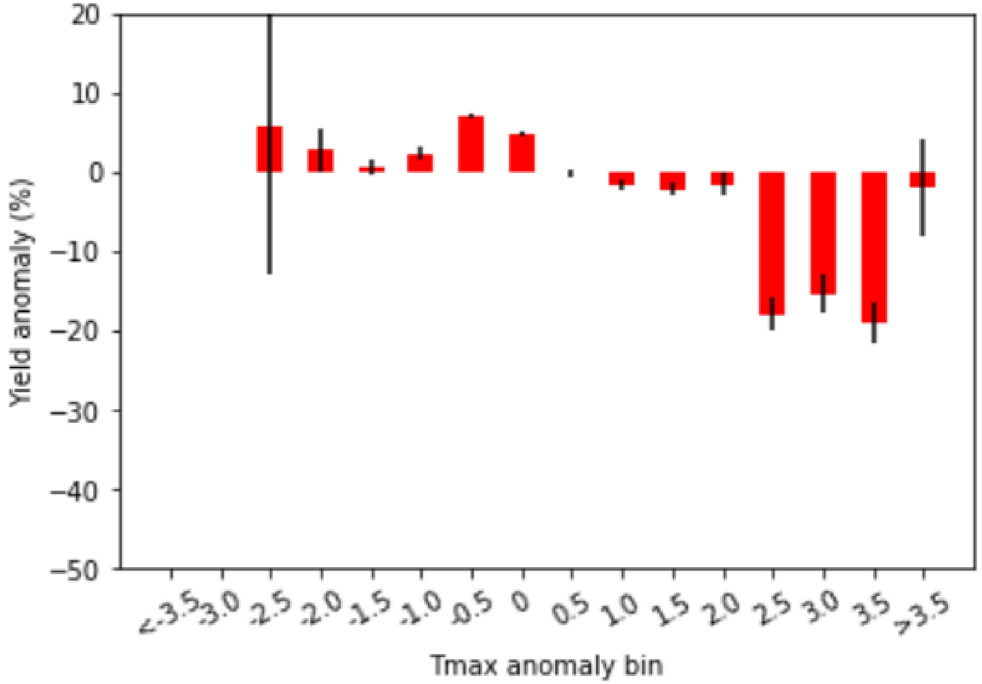


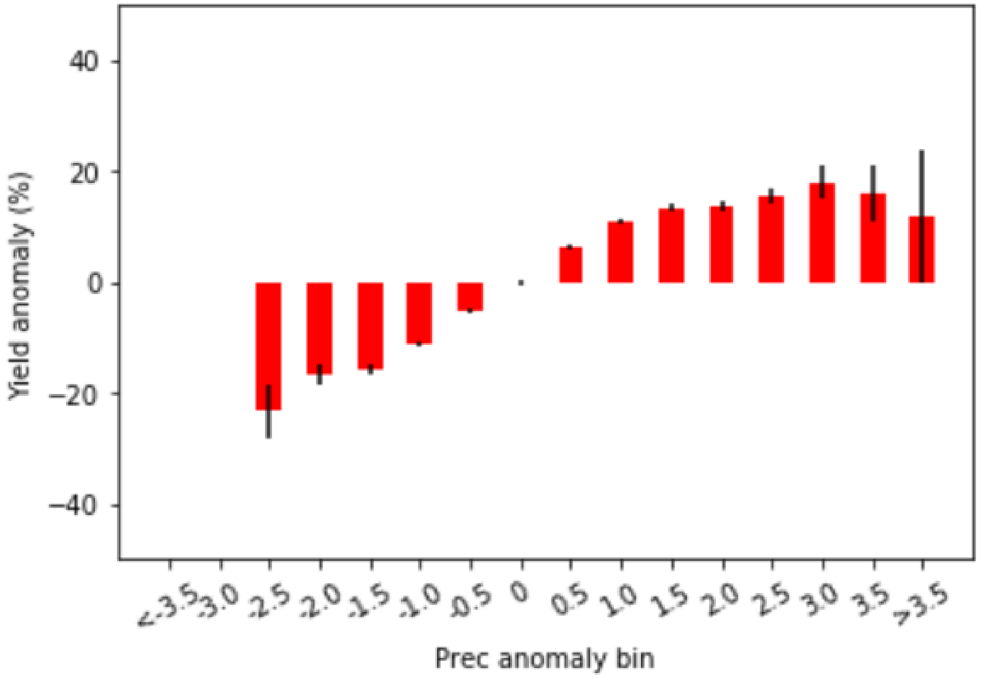
CLM-Crop in AGMIP-GGCMI with AgMERRA forcing (default_noirr experiment)

Impact of forcing dataset

AGMIP GGCMI simulation







CLM-Crop in AgMIP-GGCMI with WFDEI.GPCC forcing (default_noirr experiment)

Summaries

- We implemented a new maize model by combining CLM4.5 and APSIM models in CESM
- Site-level evaluation results show good performance of the new model
- The parameters controlling temperature dependences of photosynthetic capacity and carbon allocation are most sensitive in surface flux and yield simulation
- At regional scale, there is large uncertainties from both model structures and forcing datasets in the crop yield response to climate variability

Ongoing work and future plans

- Multi-objective Bayesian parameter calibration
- Confronting both the CLM4.5 and CLM-APSIM models with FACE and T-FACE experimental data from the SoyFACE facility at Illinois
- Extending the CLM-APSIM to Soybean, Wheat and Rice
- Global simulation experiments and more management options

Thanks!