Advancing crop modeling from field to regional scales to assess agroecosystem productivity, sustainability, and climate adaptations

Prof. Kaiyu Guan (kaiyug@Illinois.edu) & Dr. Bin Peng (binpeng@Illinois.edu)

Nature Resources and Environmental Sciences
National Center for Supercomputing Applications
University of Illinois at Urbana-Champaign
(Website: http://faculty.nres.illinois.edu/~kaiyuguan/)

ILLINOIS

E3SM All-Hands Webinar Apr 28, 2020

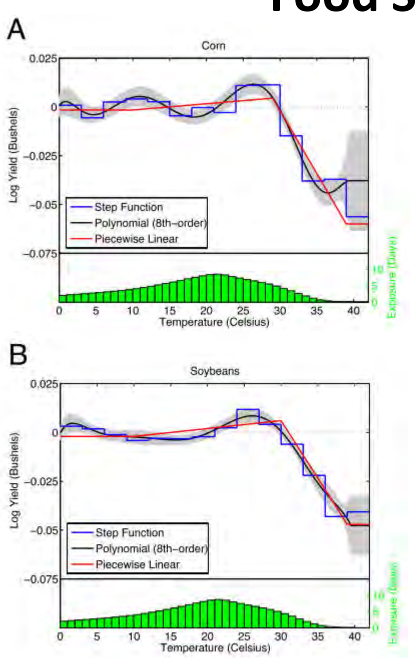
NCSA

1

Food Security

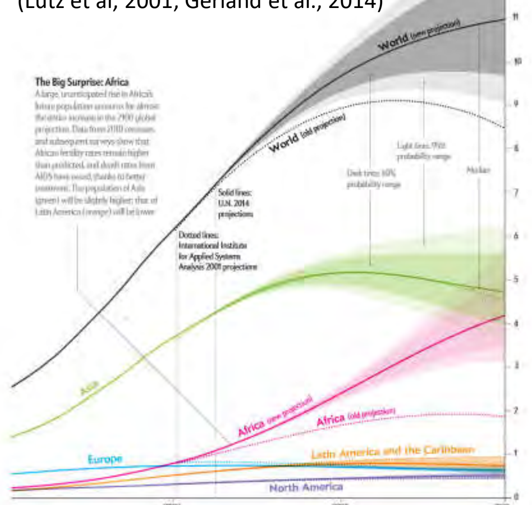
Risk in the food supply due to climate change

(Schlenker and Roberts, 2009)



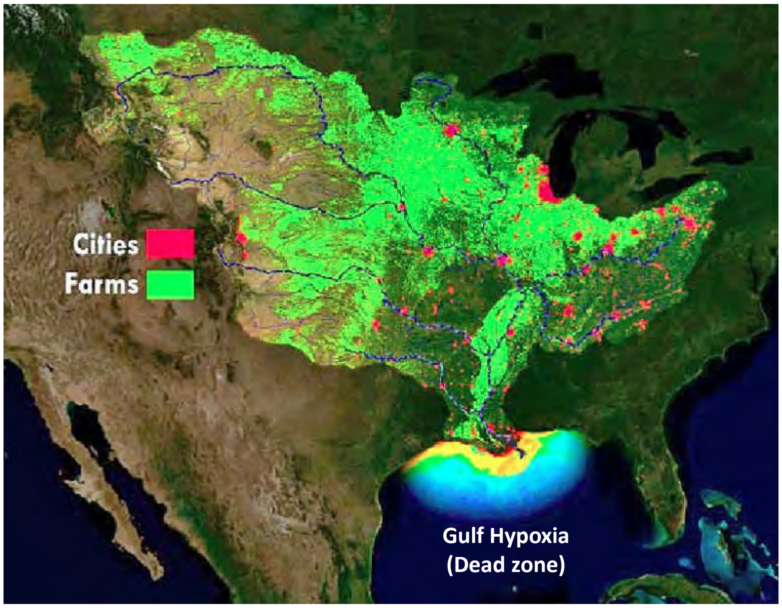
Increased food demand due to Population explosion

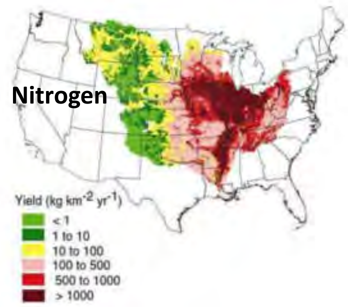
(Lutz et al, 2001; Gerland et al., 2014)

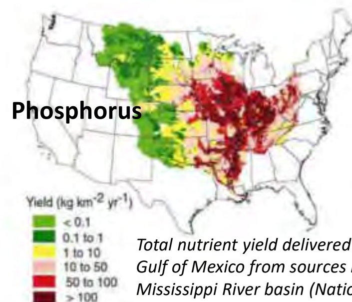


2

Environmental Sustainability







Total nutrient yield delivered to the Gulf of Mexico from sources in the Mississippi River basin (National Research Council, 2009)

3

Overarching Science Questions and Approaches

❑Science questions: Could the US Midwest remain as the global food basket in the next 100 years? How can we ensure co-sustainability of food production and environmental quality in this landscape?

✓How do environment (e.g. climate, soil) and human management affect hydrological cycle, nutrient cycle, and their interaction in the US Midwest agroecosystems?

✓How does management practices (winter cover crops, soil tillage, tile drainage, fertilization) affect nutrient cycle and their downstream impacts?

❑Approaches: We are developing an **integrative framework of modeling and monitoring**, which can capture field-scale processes and also their integrated impacts at larger scales (watershed, basin, and even regional to global)

4

Topics in this talk:

(1) A multiscale crop modeling framework for climate change adaptation assessment
(2) Improving the crop growth representation in earth system model by developing CLM-AgSys
(3) Towards model-data integration: New T-FACE field experiments for model benchmarking
(4) Towards model-data integration: Multi-source remote sensing observations
(5) Modeling sustainability from field to watershed scales in the Midwest agroecosystems

5

5

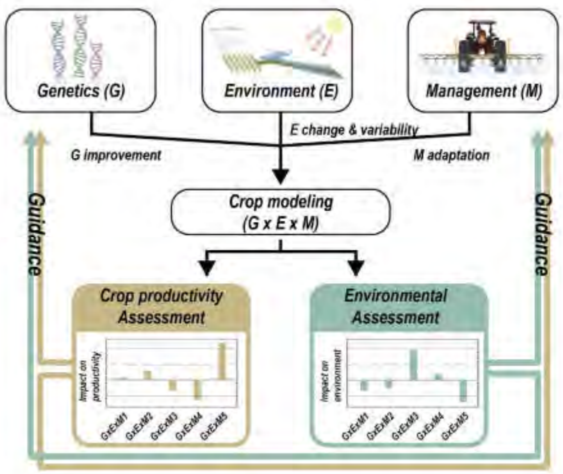
Topics in this talk:

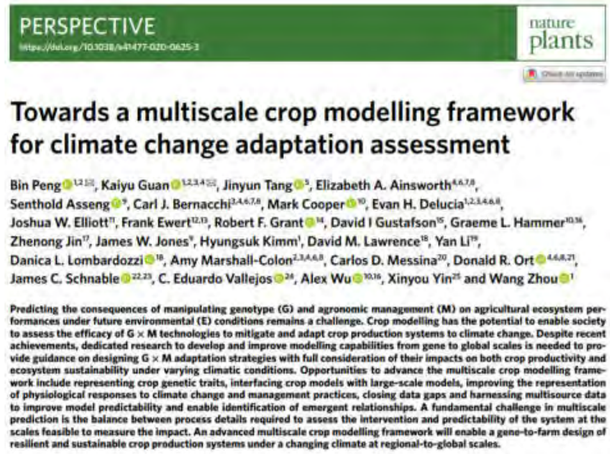
(1) A multiscale crop modeling framework for climate change adaptation assessment
(2) Improving the crop growth representation in earth system model by developing CLM-AgSys
(3) Towards model-data integration: New T-FACE field experiments for model benchmarking
(4) Towards model-data integration: Multi-source remote sensing observations
(5) Modeling sustainability from field to watershed scales in the Midwest agroecosystems

6

6

Agricultural Adaptations to Climate Change





PERSPECTIVE

https://doi.org/10.1038/s41477-020-0625-3

nature plants

Towards a multiscale crop modelling framework for climate change adaptation assessment

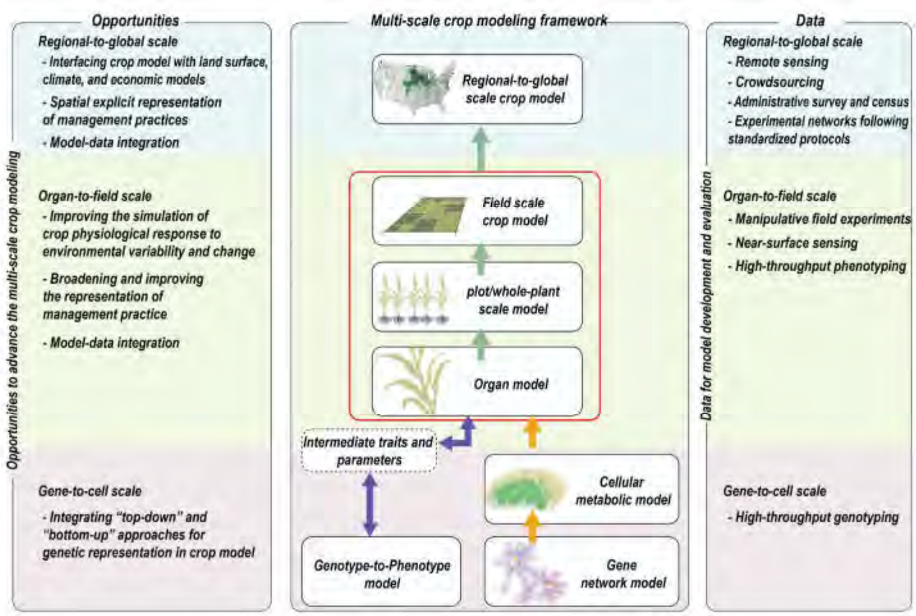
Bin Peng[1,2], Kaiyu Guan[1,2,3,4], Jinyun Tang[5], Elizabeth A. Ainsworth[4,6,7,8], Senthold Asseng[9], Carl J. Bernacchi[3,4,6,7,8], Mark Cooper[10], Evan H. Delucia[1,2,3,4,6,8], Joshua W. Elliott[11], Frank Ewert[12,13], Robert F. Grant[14], David I Gustafson[15], Graeme L. Hammer[10,16], Zhenong Jin[17], James W. Jones[9], Hyungsuk Kimm[1], David M. Lawrence[18], Yan Li[19], Danica L. Lombardozzi[18], Amy Marshall-Colon[2,3,4,6,8], Carlos D. Messina[20], Donald R. Ort[4,6,8,21], James C. Schnable[22,23], C. Eduardo Vallejos[24], Alex Wu[10,16], Xinyou Yin[25] and Wang Zhou[1]

Predicting the consequences of manipulating genotype (G) and agronomic management (M) on agricultural ecosystem performances under future environmental (E) conditions remains a challenge. Crop modelling has the potential to enable society to assess the efficacy of G × M technologies to mitigate and adapt crop production systems to climate change. Despite recent achievements, dedicated research to develop and improve modelling capabilities from gene to global scales is needed to provide guidance on designing G × M adaptation strategies with full consideration of their impacts on both crop productivity and ecosystem sustainability under varying climatic conditions. Opportunities to advance the multiscale crop modelling framework include representing crop genetic traits, interfacing crop models with large-scale models, improving the representation of physiological responses to climate change and management practices, closing data gaps and harnessing multisource data to improve model predictability and enable identification of emergent relationships. A fundamental challenge in multiscale prediction is the balance between process details required to assess the intervention and predictability of the system at the scales feasible to measure the impact. An advanced multiscale crop modelling framework will enable a gene-to-farm design of resilient and sustainable crop production systems under a changing climate at regional-to-global scales.

(Peng, Guan, et al., 2020, Nature Plants)

7

Multi-scale crop modeling framework



(Peng, Guan et al., 2020, Nature Plants)

8

Towards a multi-scale crop modelling framework for climate change adaptation assessment

Table 1. A summary of recommended actions to advance multi-scale crop modeling

Directions/Opportunities	Recommended actions	P	M	D
Going to gene scale	**A1.** Comparing "top-down" and "bottom-up" approaches for genotype-to-phenotype simulation	X	X	X
	A2. Integrating "top-down" and "bottom-up" approaches to represent genetic traits in CMs		X	X
Going to global scale	**A3.** Interfacing CMs with large-scale land surface, climate and economic models		X	
	A4. Scaling the surface heterogeneity from field to regional/global scale	X	X	X
Simulating the physiological responses to CC	**A5.** Simulating coupled soil–root–canopy-atmosphere water transfer driven by energy balances	X	X	
	A6. Improving the stomatal and intra-leaf diffusional conductance models	X	X	
	A7. Improving the simulation of responses of carbon/nitrogen source-sink relationship to stresses	X	X	
	A8. Developing mechanistic models for ozone stress	X	X	
	A9. Simulating the root growth and metabolism under oxygen deficiency	X	X	
Representing the impacts of crop management practices	**A10.** Simulating coupled Carbon-Nitrogen-Phosphorus cycles in CMs	X	X	X
	A11. Simulating microbe-root interaction in CMs	X	X	X
	A12. Representing more management practices in large-scale CMs		X	X
	A13. Simulating stresses from crop pests and diseases as well as weed competition on crop growth	X	X	X
	A14. Improving simulation of fate and transport of pesticide across landscape	X	X	X
Closing the data gaps	**A15.** Collecting more site-level experimental data following standardized protocols			X
	A16. Conducting multi-dose experiments for observed crop responses to CC factors			X
	A17. Collecting more soil profile data to improve the gridded soil products			X
	A18. Enriching management data through working with farmers and government agencies and using crowdsourcing and remote sensing			X
Model-data integration	**A19.** Evaluating CMs using eddy-covariance flux data		X	X
	A20. Evaluating CMs in simulating the emergent relationships from data		X	X
	A21. Spatial-explicitly calibrating CMs using remote sensing data as constraints		X	X

***P** for process understanding; **M** for model development and evaluation; **D** for data collection and model-data integration.*

(Peng, Guan, et al., 2020, Nature Plants)

9

Topics in this talk:

(1) A multiscale crop modeling framework for climate change adaptation assessment

(2) Improving the crop growth representation in earth system model by developing CLM-AgSys

(3) Towards model-data integration: New T-FACE field experiments for model benchmarking

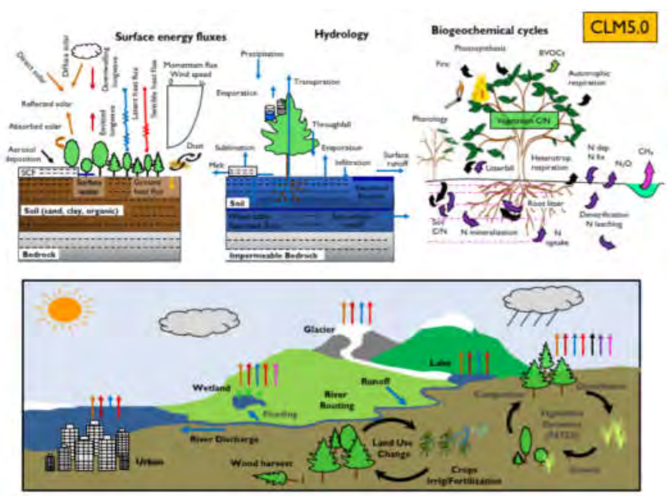
(4) Towards model-data integration: Multi-source remote sensing observations

(5) Modeling sustainability from field to watershed scales in the Midwest agroecosystems

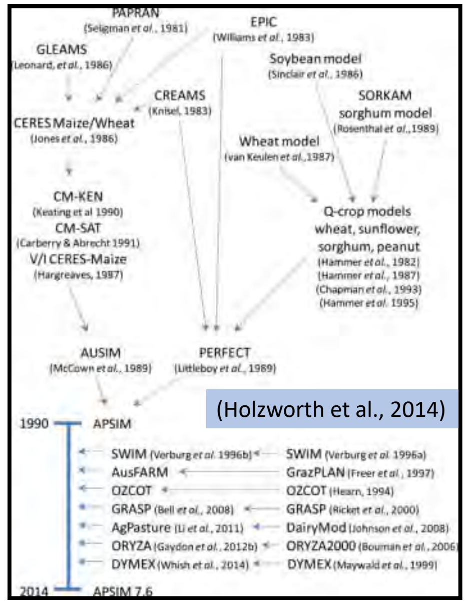
10

10

[CLM]+[APSIM]=[CLM-AgSys]



(Lawrence et al., 2019, JAMES)



(Holzworth et al., 2014)

11

ESM-based versus agronomy-based crop models

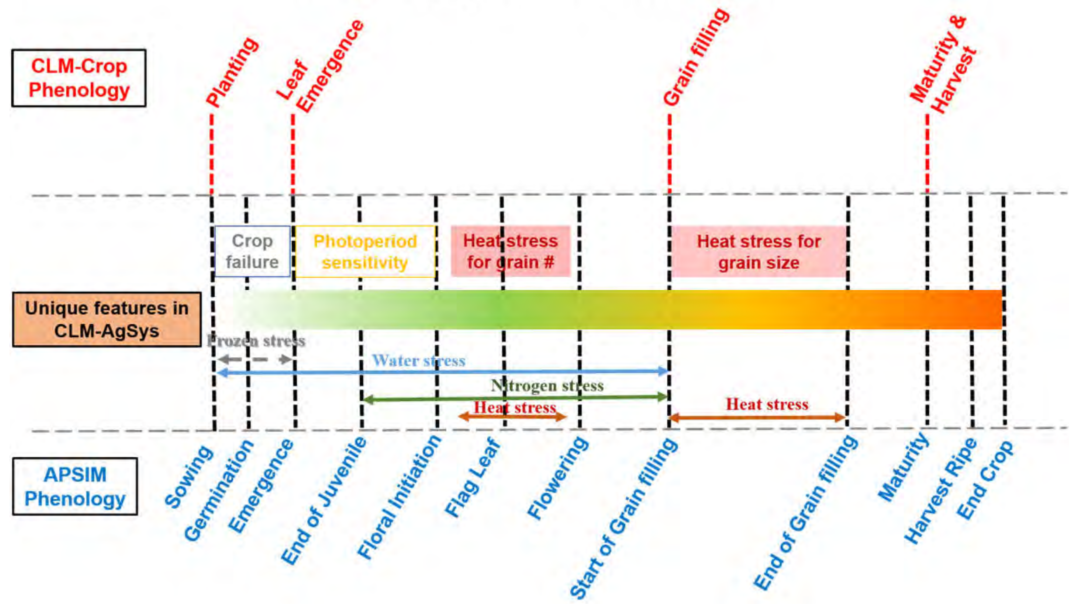
Model	Strength	Weakness
CLM4.5	• Sophisticated soil and canopy hydrology • Two-stream approximation of canopy radiative transfer • Physical-based stomatal conductance, photosynthesis, and respiration • Explicit calculation of canopy temperature • More process-driven CO_2 fertilization effects • Can be 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
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 idea is to combine strengths from two types of models!

(Peng, Guan, et al., 2018, AFM)

12

CLM-AgSys maize model



(Peng, Guan, et al., 2018, AFM)

13

Comparison among CLM-Crop, CLM-AgSys and APSIM model

Processes	CLM-Crop	CLM-AgSys	APSIM
Photosynthesis	• Biochemical model for leaf level psn and two-big-leaf (sunlit/shaded) model for canopy scaling • Medlyn or Ball-Berry stomatal conductance model	• Biochemical model for leaf level psn and two-big-leaf (sunlit/shaded) model for canopy scaling • Medlyn or Ball-Berry stomatal conductance model	• RUE approach for canopy level photosynthesis
Phenology	• 3-phase phenology without stresses • Linear accumulation of GDD	• 11-phase phenology with stresses • piece-wise linear accumulation of TT	• 11-phase phenology with stresses • piece-wise linear accumulation of TT
Allocation	• GDD based approach	• Prescribed stage-allocation relationship for potential allocation and then modified by stress factors and source-sink limitations	• Source-sink approach
Grain number	• NA	• Optimal grain number with heat stress	• Optimal grain number with heat stress
Canopy structure	• Constant SLA for LAI estimation with maximum LAI constraint • Canopy height estimation from LAI • Leaf angle distribution considered	• Stage-dependent SLA • Canopy height from stem biomass • Leaf angle distribution considered	• Dynamic simulate leaf number and area increase • Canopy height from stem biomass
Root structure	• Prescribed root distribution	• Prescribed root distribution	• Dynamic root growth

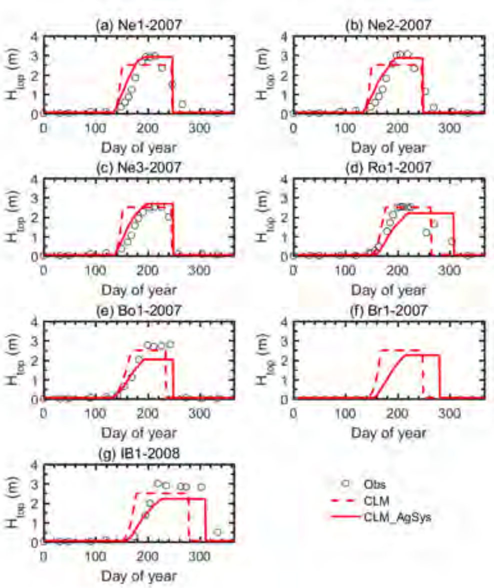
14

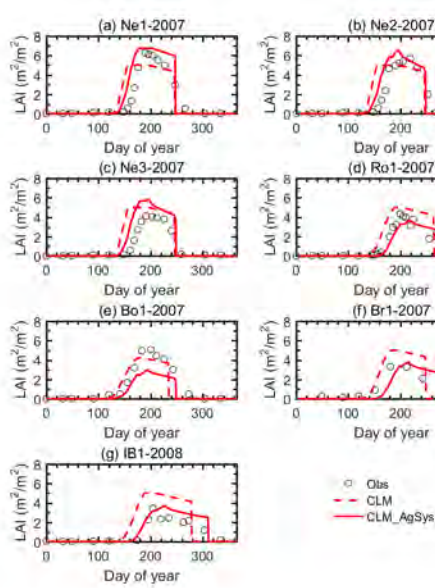
Comparison among CLM-Crop, CLM-AgSys and APSIM model

Processes	CLM-Crop	CLM-AgSys	APSIM
Canopy energy balance	• Explicitly solved for canopy temperature	• Explicitly solved for canopy temperature	• Not solved
Canopy radiative transfer	• Direct and diffusive separation • Two-stream approximation	• Direct and diffusive separation • Two-stream approximation	• Not solved
Soil temperature dynamics	• 25-layer for heat conduction	• 25-layer for heat conduction	• SoilTemp module
Soil water dynamics	• Top 20 layers active for Richards equation	• Top 20 layers active for Richards equation	• Cascading Bucket water balance model • Or Richards equation based SWIM module
Soil biogeochemistry	• Top 20 layers active for soil C, N	• Top 20 layers active soil C, N	• SoilCN, SoilP, SurfaceOM, Soulte
Management	• Fertilizer • irrigation	• Fertilizer • irrigation	• Fertilizer • Irrigation • More management practices

15

Site-level evaluation of CLM-AgSys

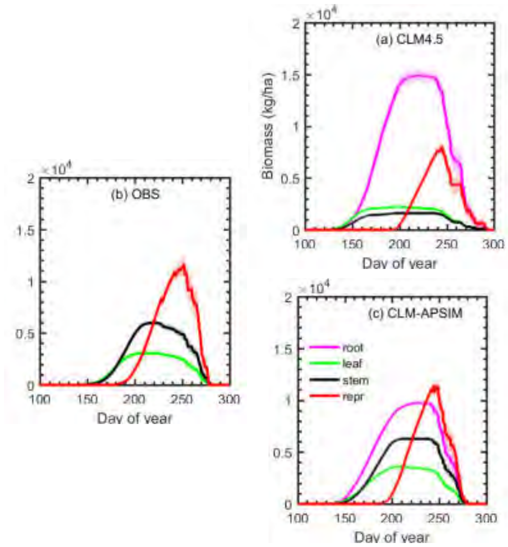


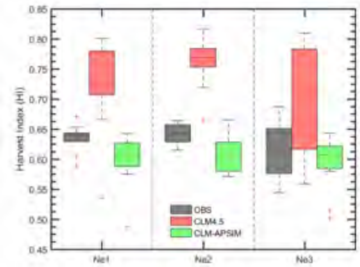


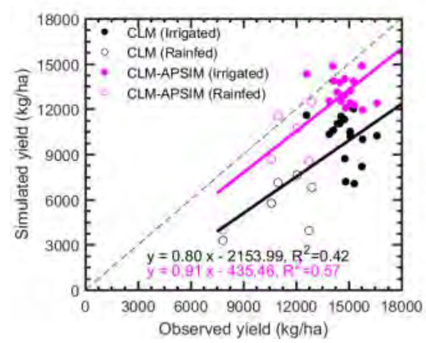
(Peng, Guan, et al., 2018, AFM)

16

Site-level evaluation of CLM-AgSys





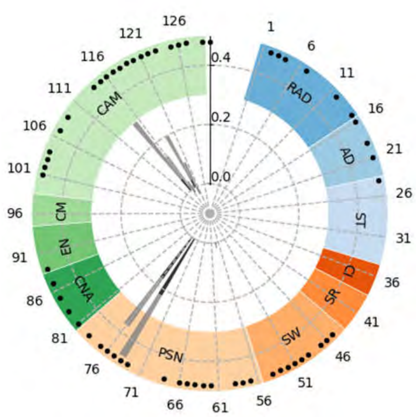


(Peng, Guan, et al., 2018, AFM)

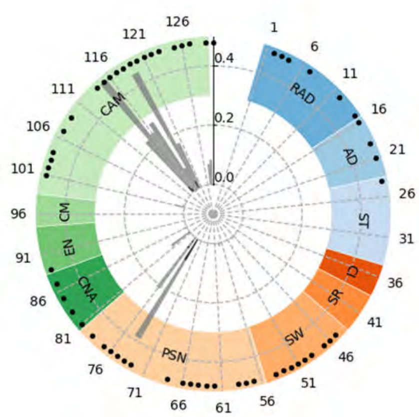
17

Quantitative Parameter Sensitivity Analysis

Gross Primary Productivity

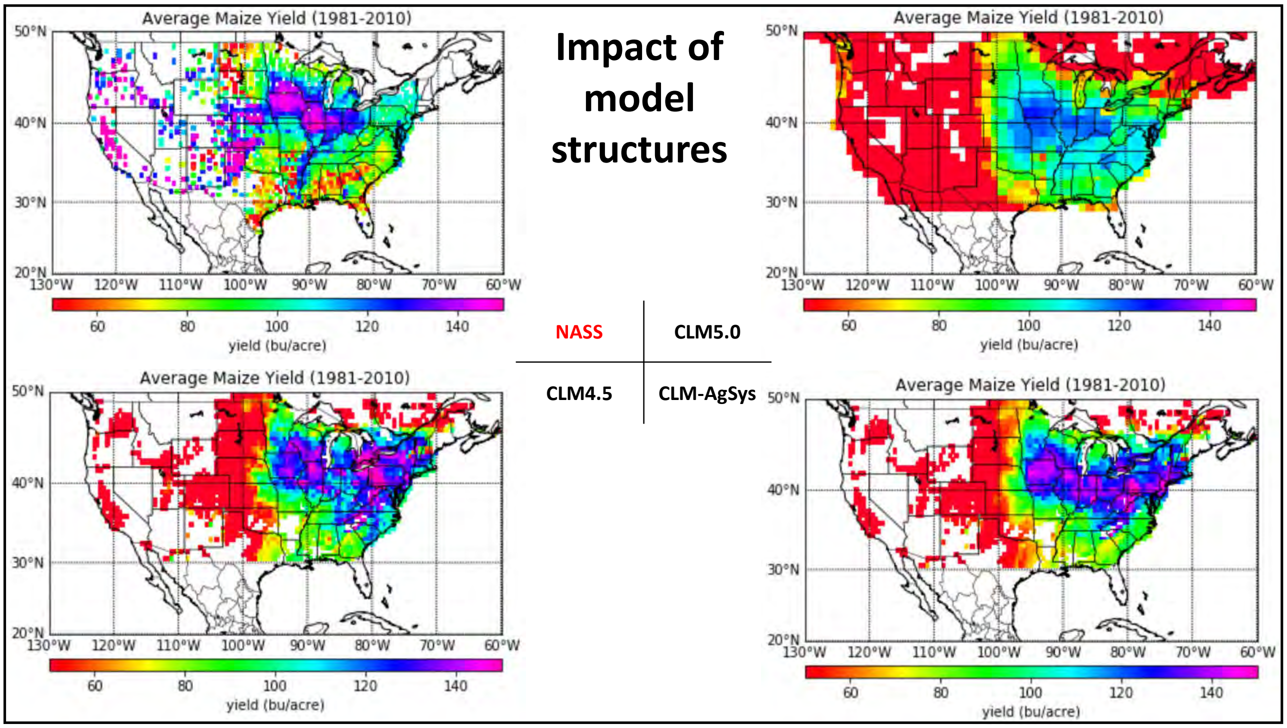


Grain Carbon



(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-AgSys Maize (CAM)

18



19

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

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)

20

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

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)

21

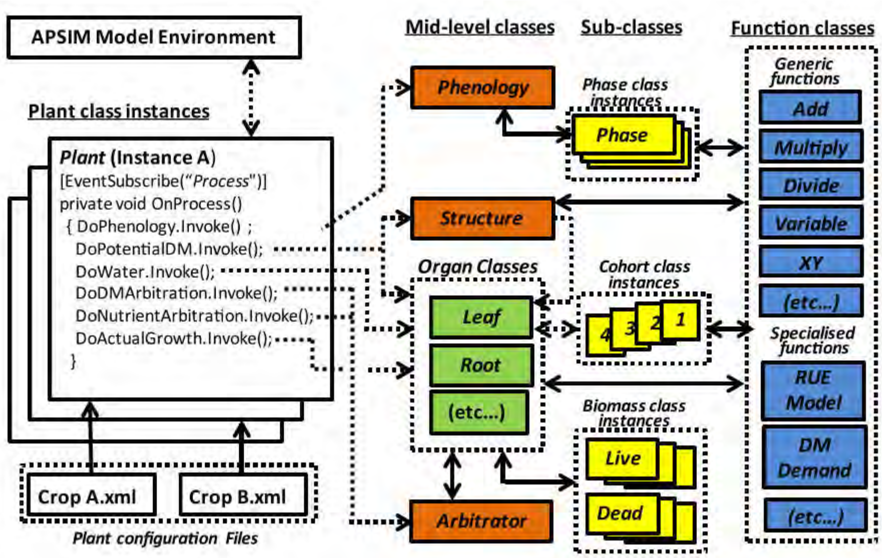
Towards a generic crop template-the APSIM approach

- **Generic legume model** (Robertson and Carberry, 1998; Robertson et al., 2002; Turpin et al., 2003): chickpea, mungbean, peanut, and Lucerne
- **Generic Crop template (GCROP)** (Wang et al., 2002): 26 crop types including cereals, horticultural crops, vines, pastures and weeds
- **Generic Plant template**=GCROP+generic legume model: 30 crop types out of 41 crop types simulated in APSIM
- **Plant Modelling Framework** (Brown et al., 2014): all crops species in APSIMX

These generic templates are also favored by the earth system modeling community

22

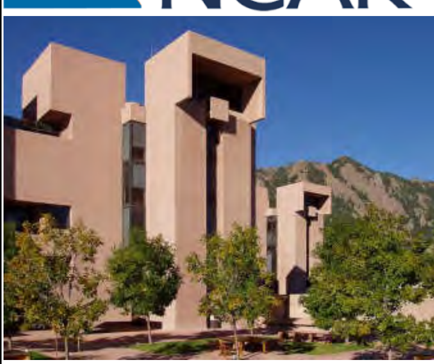
Towards a generic crop template-the APSIM approach

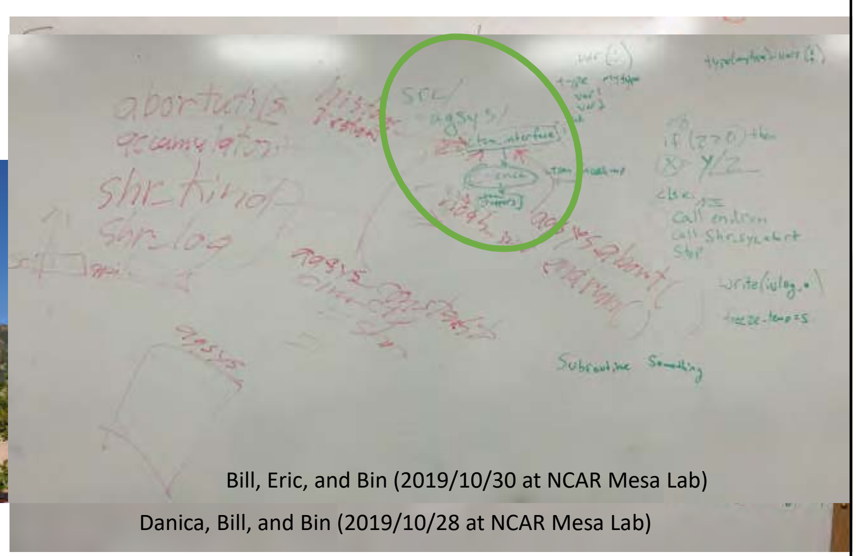


(Brown et al., 2014)

23

We are now working on the next step…





Bill, Eric, and Bin (2019/10/30 at NCAR Mesa Lab)

Danica, Bill, and Bin (2019/10/28 at NCAR Mesa Lab)

24

We are now working on the next step…

```
[pengbin@cheyenne3 ~/ctsm_agsys/src]$ls
agsys          dyn_subgrid          soilbiogeochem
biogeochem     fates                unit_test_shr
biogeophys     init_interp          unit_test_stubs
CMakeLists.txt main                 utils
cpl            README.unit_testing
```

```
.
├── agsys
    ├── CMakeLists.txt
    ├── ctsm_interface
    │   ├── AgSysInterface.F90
    │   ├── AgSysParamReader.F90
    │   ├── AgSysRuntimeConstants.F90
    │   ├── AgSysType.F90
    │   └── README
    ├── ctsm_wrappers
    │   ├── AgSysExcepUtils.F90
    │   ├── AgSysKinds.F90
    │   ├── AgSysPhysicalConsts.F90
    │   └── README
    ├── science
    │   ├── AgSysConstants.F90
    │   ├── AgSysCropTypeGeneric.F90
    │   ├── AgSysCropTypeMaize.F90
    │   ├── AgSysCropTypePhotoSensitive.F90
    │   ├── AgSysCropTypeVernalization.F90
    │   ├── AgSysCropTypeWheat.F90
    │   ├── AgSysEnvironmentalInputs.F90
    │   ├── AgSysPhases.F90
    │   ├── AgSysPhenology.F90
    │   ├── AgSysRoot.F90
    │   ├── AgSysUtils.F90
    │   └── README
    └── test
        ├── AgSys_Enumerations_test
        │   ├── CMakeLists.txt
        │   └── test_enumerations.pf
        ├── CMakeLists.txt
        └── README
```

25

Topics in this talk:

(1) A multiscale crop modeling framework for climate change adaptation assessment

(2) Improving the crop growth representation in earth system model by developing CLM-AgSys

(3) Towards model-data integration: New T-FACE field experiments for model benchmarking

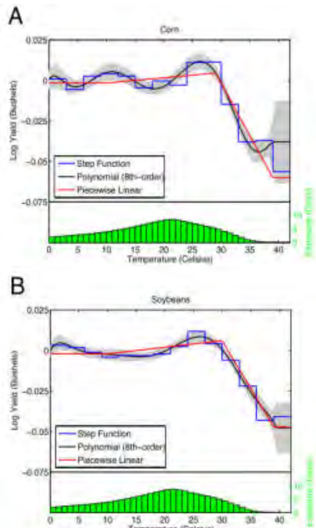
(4) Towards model-data integration: Multi-source remote sensing observations

(5) Modeling sustainability from field to watershed scales in the Midwest agroecosystems

26

26

USDA NIFA funded project: **"Parsing multiple mechanisms of high temperature impacts on soybean yield combining infrared heating experiments and process-based modeling"**
(PI: Kaiyu Guan; Co-PI: Lisa Ainsworth, Carl Bernacchi)



(Schlenker and Roberts, 2009)

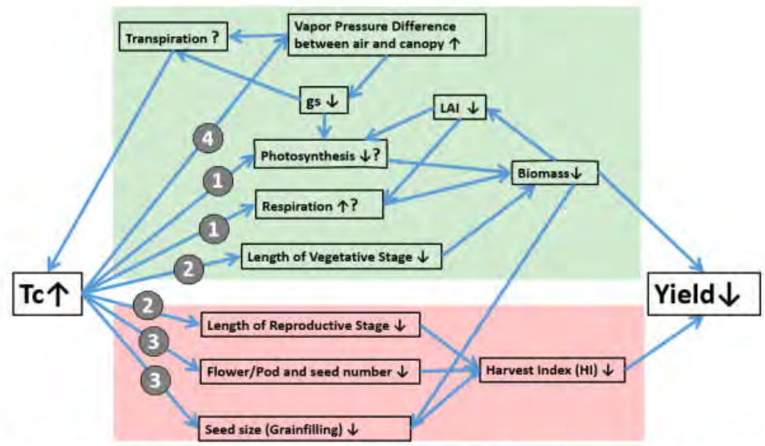
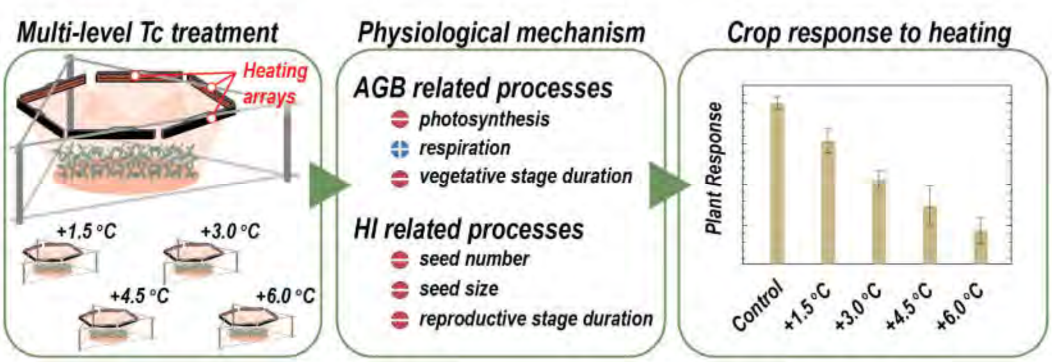


Fig. 3. The conceptual diagram of different processes that are involved in crop responses to higher canopy temperature (Tc), which also contains all the major hypotheses, with "↑" indicating a hypothesized increase, "↓" indicating a hypothesized decrease, and "?" indicating unclear direction of change. The processes in the green box are mostly related to biomass production, while those in the red box are mostly related to the Harvest Index.

27

USDA NIFA funded project: **"Parsing multiple mechanisms of high temperature impacts on soybean yield combining infrared heating experiments and process-based modeling"**
(PI: Kaiyu Guan; Co-PI: Lisa Ainsworth, Carl Bernacchi)



- Heating plots at SoyFACE site, Champaign, Illinois
- Three growing seasons: 2017, 2018, 2019
- Control/ambient + four levels of temperature treatments (+1.5, +3.0, +4.5, +6.0 degree)
- Irrigated to control soil moisture impact
- Leaf gas exchange and biometric measurements (leaf area index, canopy height, phenology stage, node number, pod number, seed number, biomass etc.)

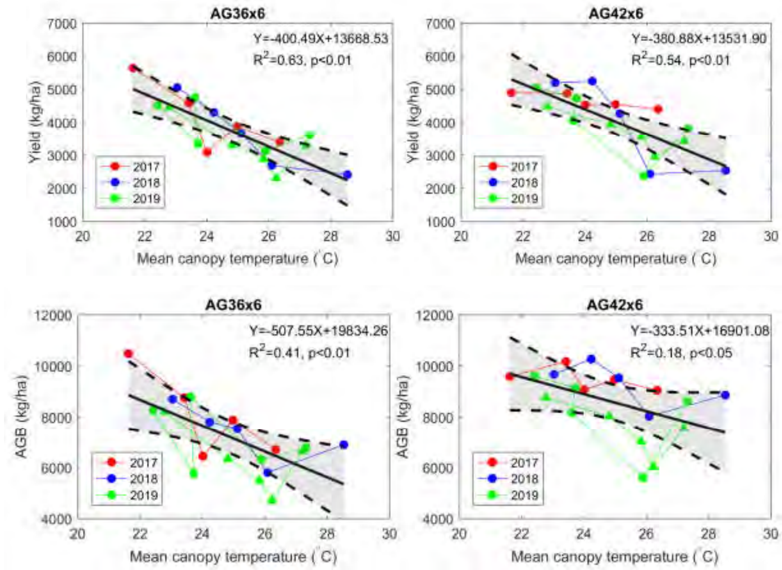
28

USDA NIFA funded project: **"Parsing multiple mechanisms of high temperature impacts on soybean yield combining infrared heating experiments and process-based modeling"**
(PI: Kaiyu Guan; Co-PI: Lisa Ainsworth, Carl Bernacchi)

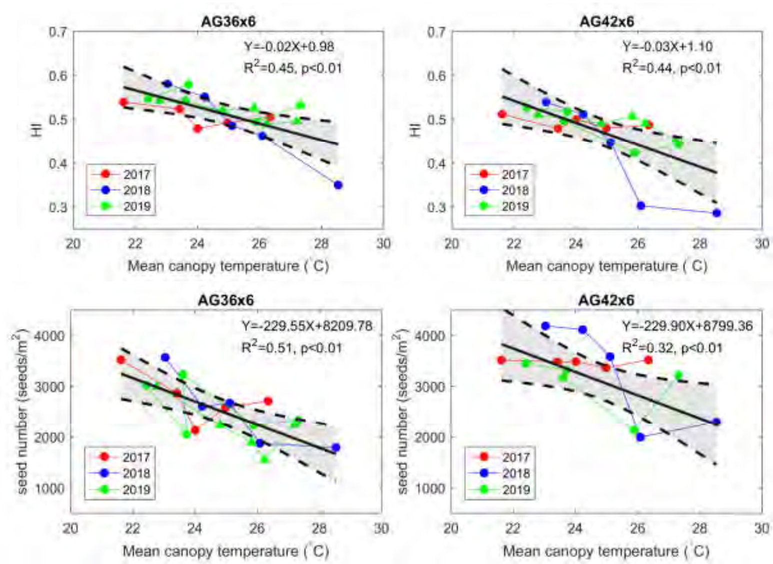
Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
152A	Drummer silty clay loam, 0 to 2 percent slopes	50.3	39.1%
154A	Flanagan silt loam, 0 to 2 percent slopes	73.3	57.0%
171B	Catlin silt loam, 2 to 5 percent slopes	4.0	3.1%
198A	Elburn silt loam, 0 to 2 percent slopes	1.1	0.9%
Totals for Area of Interest		**128.7**	**100.0%**

29

30


AG36x6
Y=-400.49X+13668.53
R^2=0.63, p<0.01
Yield (kg/ha)
2017
2018
2019
Mean canopy temperature (°C)
AG42x6
Y=-380.88X+13531.90
R^2=0.54, p<0.01
Yield (kg/ha)
2017
2018
2019
Mean canopy temperature (°C)
AG36x6
Y=-507.55X+19834.26
R^2=0.41, p<0.01
AGB (kg/ha)
2017
2018
2019
Mean canopy temperature (°C)
AG42x6
Y=-333.51X+16901.08
R^2=0.18, p<0.05
AGB (kg/ha)
2017
2018
2019
Mean canopy temperature (°C)

31


AG36x6
Y=-0.02X+0.98
R^2=0.45, p<0.01
HI
2017
2018
2019
Mean canopy temperature (°C)
AG42x6
Y=-0.03X+1.10
R^2=0.44, p<0.01
HI
2017
2018
2019
Mean canopy temperature (°C)
AG36x6
Y=-229.55X+8209.78
R^2=0.51, p<0.01
seed number (seeds/m^2)
2017
2018
2019
Mean canopy temperature (°C)
AG42x6
Y=-229.90X+8799.36
R^2=0.32, p<0.01
seed number (seeds/m^2)
2017
2018
2019
Mean canopy temperature (°C)

32

Topics in this talk:

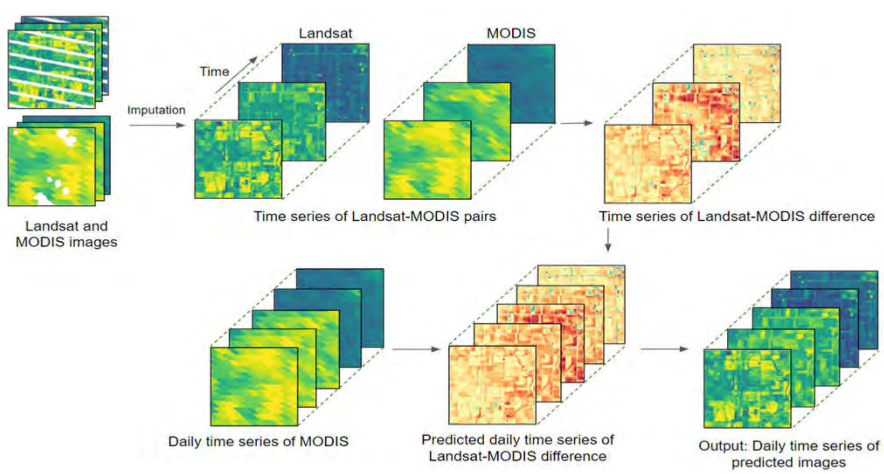
(1) A multiscale crop modeling framework for climate change adaptation assessment
(2) Improving the crop growth representation in earth system model by developing CLM-AgSys
(3) Towards model-data integration: New T-FACE field experiments for model benchmarking
(4) Towards model-data integration: Multi-source remote sensing observations
(5) Modeling sustainability from field to watershed scales in the Midwest agroecosystems

33

33

We have developed scalable fusion algorithm to fuse various public satellite data to generate daily, 10-30 meter, gap-free/cloud-free images from 2000 to present.

Luo, Y., **Guan, K.***, and Peng, J.* (2018) "STAIR: A generic and fully-automated method to fuse multiple sources of optical satellite data to generate a high-resolution, daily and cloud-/gap-free surface reflectance product", ***Remote Sensing of Environment***.



STAIR fusion images
resolution 10-30 m
frequency 1 day
High resolution
High frequency
Cloud-free/Gap-free

34

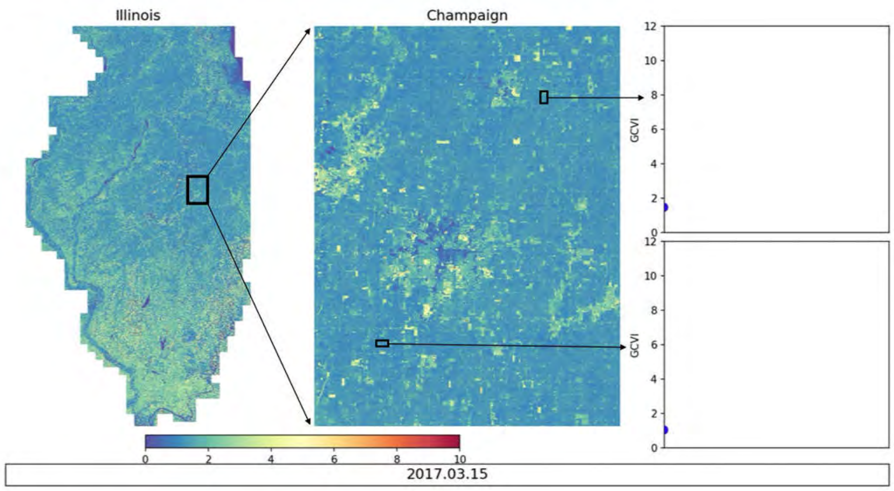
34

ASPIRING UNIVERSE

Cloud-free, field-scale, daily satellite fusion images, from 2000 to present, covering everywhere on the planet

STAIR fusion images
resolution 10-30 m
frequency 1 day

High resolution
High frequency
Cloud-free/Gap-free



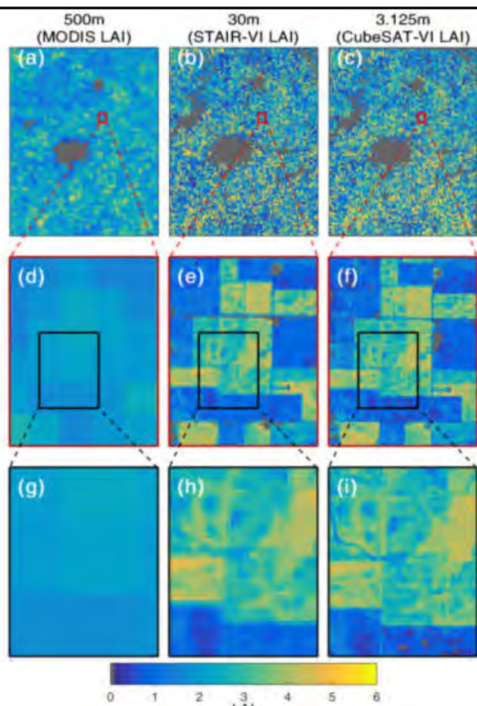
Kaiyu Guan's Group
(kaiyug@Illinois.edu
kaiyuguan@gmail.com)

ILLINOIS

Check the demo video on YouTube: https://youtu.be/IXVEVWlMQg4

35

35



Leaf area index (LAI) estimations at high resolutions

Take home message:

STAIR fusion data provides higher-quality and more consistent performance than Planet Lab's data.

More importantly, STAIR fusion data can go back to 2000 to present, with an unprecedented daily and historical insights covering everywhere in this planet.

36

36

Solar-induced fluorescence (SIF) for Photosynthesis

We have developed the **first long-term agricultural network for Solar-induced fluorescence (SIF) and hyperspectral sensing**. We integrated it with **novel satellite data** and significantly improved monitoring capability of agricultural landscapes' **carbon cycle** for the US Corn Belt.

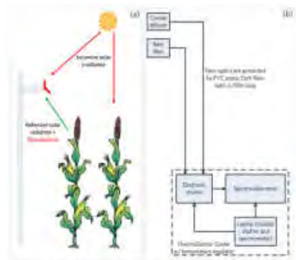
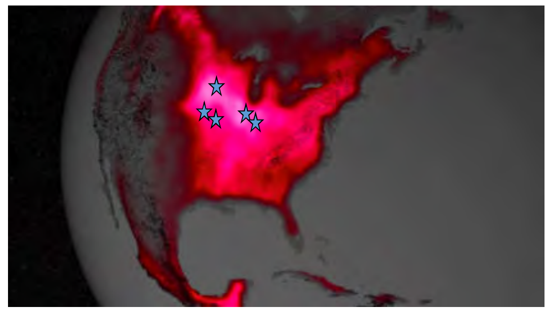


Fig 5. The design of FluoSpec2 designed by Dr. Xi



Sun-induced chlorophyll fluorescence (SIF) as a proxy of photosynthesis.

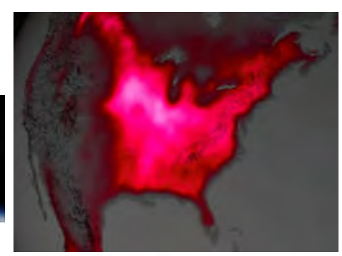
37

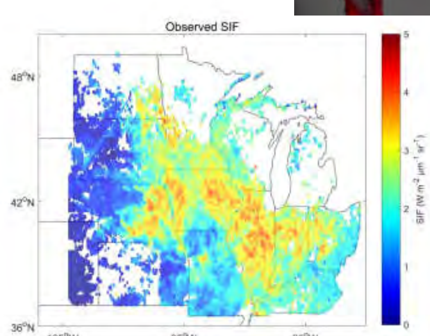
37

Satellite SIF data

- GOSAT (2 degree, monthly)
- GOME-2 (0.5 degree, biweekly)
- SCHYMACHY (1 degree, monthly)
- OCO-2 (~1-2 degree, monthly)

- TROPOMI (5km, daily)

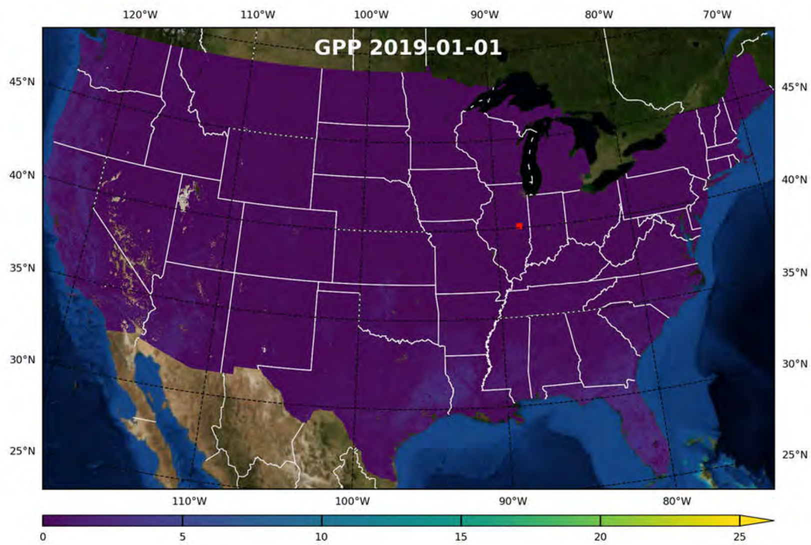




38

38

GPP (Photosynthesis)
10 meter resolution
daily



Wu,G., **Guan,K.***, ***Jiang,C.****, ***Peng, B.***, ***Kimm,H.***, Chen,M., Yang,X., ***Wang,S.***, Suyker.A.E.,Bernacchi,C. and Moore, C.E. (2019) "Radiance-based NIRv as a proxy for GPP of corn and soybean", ***Environmental Research Letters***.

ILLINOIS

Kaiyu Guan's Group
(kaiyug@Illinois.edu
kaiyuguan@gmail.com)

Check the demo video on YouTube: https://youtu.be/daKSh1km7uA

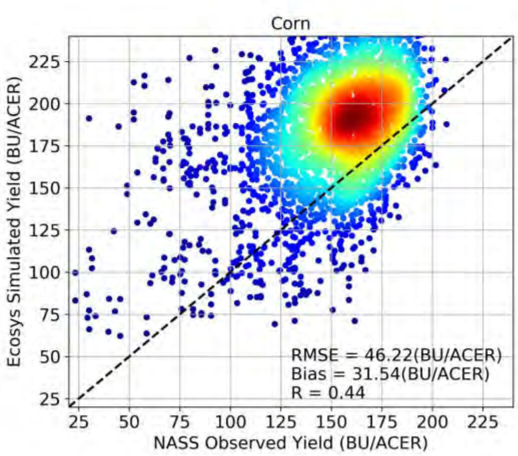
39

Model-data integration: harnessing the power of satellite observations

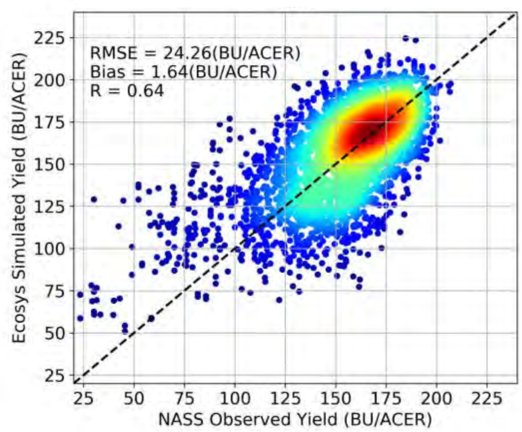
ILLINOIS

Kaiyu Guan's Group
(kaiyug@Illinois.edu
kaiyuguan@gmail.com)

Simulation without any observation constraints

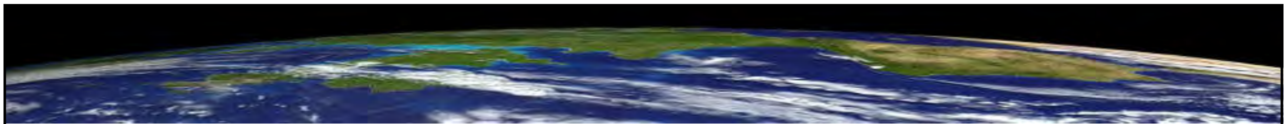


Simulation with constraints from satellite-based photosynthesis (GPP) and LAI



40

40



Prof. Kaiyu Guan (kaiyug@Illinois.edu) & Dr. Bin Peng (binpeng@Illinois.edu)

Nature Resources and Environmental Sciences
National Center for Supercomputing Applications
University of Illinois at Urbana-Champaign
(Website: http://faculty.nres.illinois.edu/~kaiyuguan/)

ILLINOIS

E3SM All-Hands Webinar Apr 28, 2020

41