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

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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)
Environmental Sustainability

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)
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
Agricultural Adaptations to Climate Change

Towards a multiscale crop modeling framework for climate change adaptation assessment

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

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

*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)

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5. Modeling sustainability from field to watershed scales in the Midwest agroecosystems
**ESM-based versus agronomy-based crop models**

<table>
<thead>
<tr>
<th>Model</th>
<th>Strength</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLM4.5</td>
<td>- Sophisticated soil and canopy hydrology</td>
<td>- Missing critical crop phenology stages (e.g., flowering) and reproductive processes (e.g., grain number formation)</td>
</tr>
<tr>
<td></td>
<td>- Two-stream approximation of canopy radiative transfer</td>
<td>- Lack of stage-dependent stress simulation</td>
</tr>
<tr>
<td></td>
<td>- Physical-based stomatal conductance, photosynthesis, and respiration</td>
<td>- Linear accumulation of thermal time</td>
</tr>
<tr>
<td></td>
<td>- Explicit calculation of canopy temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- More process-driven CO₂ fertilization effects</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Can be coupled in climate model (CESM)</td>
<td></td>
</tr>
<tr>
<td>APSIM</td>
<td>- More detailed crop phenology stages</td>
<td>- RUE-based calculation of NPP and no explicit simulation of photosynthesis and respiration</td>
</tr>
<tr>
<td></td>
<td>- Stage-dependent stress simulation</td>
<td>- Lack of resolving energy balance</td>
</tr>
<tr>
<td></td>
<td>- Piece-wise linear response of thermal time</td>
<td>- Simplified soil hydrology</td>
</tr>
<tr>
<td></td>
<td>- More detailed management practices</td>
<td></td>
</tr>
</tbody>
</table>

*Our idea is to combine strengths from two types of models!*

(Peng, Guan, et al., 2018, AFM)
Comparison among CLM-Crop, CLM-AgSys and APSIM model

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

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

### Site-level evaluation of CLM-AgSys

(Peng, Guan, et al., 2018, AFM)
Site-level evaluation of CLM-AgSys

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

Quantitative Parameter Sensitivity Analysis

Gross Primary Productivity

Grain Carbon

17

(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)
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)*
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

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
Towards a generic crop template—the APSIM approach

We are now working on the next step...
We are now working on the next step...

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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.)
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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.


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

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)
GPP (Photosynthesis)
10 meter resolution daily


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

Model-data integration: harnessing the power of satellite observations

Simulation without any observation constraints

Simulation with constraints from satellite-based photosynthesis (GPP) and LAI
Prof. Kaiyu Guan (kaiyug@Illinois.edu) & Dr. Bin Peng (binpeng@Illinois.edu)

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