Improving WRF Through Enhanced Representation of Cropland-Atmosphere Interactions

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Abstract

Agriculture is highly influenced by weather and climate. At the same time, cropland also plays an important role in land-atmosphere interactions and in the modification of local and regional weather and climate. However, croplands are poorly represented in the current version of the coupled Weather Research and Forecasting (WRF)/ Noah-MP land-surface modeling system. To better understanding the role of cropland in the land-atmosphere interactions, a new crop model (Noah-MP-Crop) has been developed and implemented into the land-surface modeling system and the weather forecasting model. Results indicate that by enhancing the representation of crop vegetation index and rooting depth, the land surface model achieves a better performance in simulating surface heat fluxes and soil moisture/soil temperature fields. When this modified version is used in the models, there is marked improvement in the simulation of cropland surface conditions from the perspective of weather forecasting. For the case studied the Noah-MP-Crop model based WRF run resulted in improved dew point temperatures and more intense rainfall and decreased the model bias in simulating rainfall for local convective events. For seasonal predictions, Noah-MP-Crop also can provide an improved regional simulation of crop yield by incorporating more specific information on planting dates, land cover and cultivar information.

Through this project cropland interactions within the Noah-MP model have been successfully incorporated and this has been coupled to WRF suite. The enhanced Noah-MP and WRF have been released and are now available in the community version. These model enhancements show promising results to improve the weather, as well as hydrological simulations, in cropland dominated landscapes. The modeling tool also now provides the opportunity for studying the different crop-atmosphere interaction processes that are often linked with severe weather occurrences.

Synthesis

The outcomes from this project contributed to four manuscripts and one PhD dissertation by Xing Liu. This report is a brief review of this project, for more information, please refer to Xing Liu's manuscripts and dissertation.

The following is also adapted from the Ph.D. dissertation of Xing Liu recently submitted at Purdue University. The doctoral work was a direct result of this DTC project.

The coupled WRF/Noah-MP-Crop model has been released as a public version (WRF v3.9) in April 2017.

Background

The objective of this study is to enhance warm weather forecasts through the incorporation of a dynamic crop-growth model in the WRF/Noah-MP coupled model.

Croplands cover 12.6% of the global land, and 19.5% of the continental United States (e.g. Fig. 1). Via seasonal phenology and transpiration, crops can efficiently transfer moisture from the surface to the atmosphere (Niyogi et al., 2015). Crops have detectable influence on regional distributions of atmospheric water vapor and temperature, and can aid convective trigger via mesoscale boundaries (Raddatz, 1998; Changnon et al. 2003; Levis et al. 2012). Therefore, croplands can strongly influence land-atmosphere coupling, surface exchanges of heat, water vapor, and momentum, which in turn can impact boundary layer growth and mesoscale convergence/convection (McPherson et al., 2004). Significant summer temperature warm biases exist in the current version of WRF coupled to Noah-MP (e.g. Fig. 2).

Despite considerable improvements in Land Surface Models (LSMs), the representation of croplands within numerical weather prediction (NWP) models such as the WRF model has been largely stagnated. Climate models on the other hand, have evolved two-way crop interactions and showed improved performance (Kucharik, 2003; Levis et al., 2012). The challenge with NWP models is that any cropland formulation needs to be relatively simple, computationally efficient, and build on biophysical rather than biogeochemical based input data.

The overarching goal of this project is to couple a crop-atmospheric simulation system (Noah-MP-Crop) to WRF and to evaluate the impact of incorporating dynamic crop models on weather forecasting during the crop-growing season.

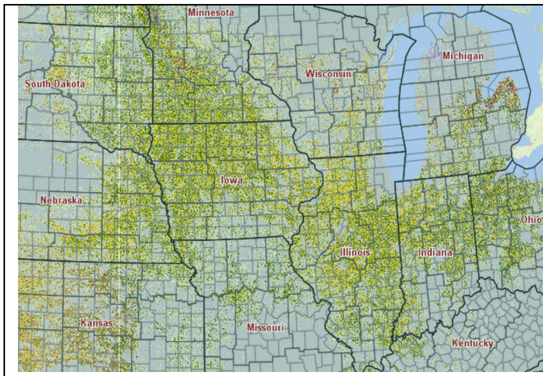

Fig. 1 Extent of soybean (green)/corn (yellow) across Midwest for the 2014 growing season (National Agricultural Statistics Service (NASS) CropScape).

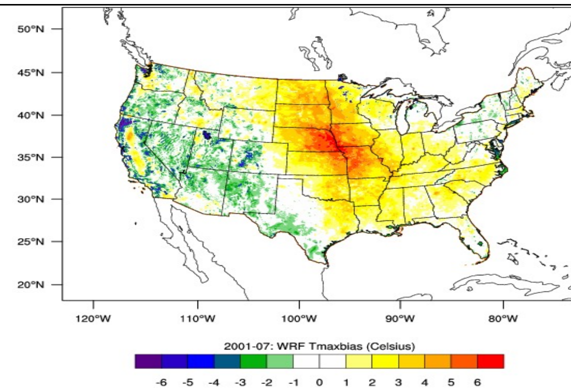

Fig. 2 Monthly averaged WRF/Noah-MP simulated daily maximum temperature bias in July 2001. Note the warm bias over cropland dominated regions.

In pursuing this project, we seek to develop capabilities in WRF and the Noah land model that would ultimately help answer three questions: (i) How do crops influence the simulation of soil moisture/temperature and regional weather?; (ii) How do crops influence the land–atmosphere interactions over the U.S. Corn Belt?; (iii) To what degree can a dynamic crop-growth scheme coupled with WRF improve short-term weather forecasting?

Croplands can impact regional weather and climate by altering the evapotranspiration and surface energy fluxes; weather, in turn impacts crop phenology (leaf area index - LAI, height/roughness). The current version of Noah-MP as used in WRF and in NCEP operational models does not include a dynamic crop-growth scheme and uses only one generic type of crop (as compared to five forest types) in combination with irrigated/unirrigated and shrubland/grassland mosaic. We hypothesize that the lack of feedback and response of croplands is one critical weakness in the WRF model. Moreover, the spatially-varying field management data (e.g., planting, irrigation, harvesting) are also lacking in current NWP-LSMs. Therefore, to enhance the simulations of interactions between the cropland and the atmosphere, there is an urgent need for improving the Noah-MP LSM within WRF. This in turn, has the potential to improve weather forecasts and also reduce the uncertainties in regional hydroclimatic studies/ projections.

This project leverages on our current Noah-MP-Crop model development effort, based on Noah-MP within HRLDAS (High-Resolution Land Data Assimilation System, Chen et al., 2007) and existing crop models [e.g. Decision Support System for Agrotechnology Transfer (DSSAT, Jones et al., 2003), Hybrid-Maize (Yang et al., 2004)]. The HRLDAS includes Noah-MP (Niu et al., 2011), which allows users to combine multiple physics options for better simulations of the land state. Compared to traditional crop models, which normally use multiple empirical factors to calculate the plant response such as transpiration, Noah-MP can provide photosynthetically active radiation (PAR) and transpiration-photosynthesis rates for simulating crop growth in a more dynamical way (Niyogi et al. 2009; Kumar et al. 2011). We have evaluated Noah-MP-Crop using meteorological and biophysical observations from two Ameriflux sites at Bondville, IL and Mead, NE. The Bondville site is a non-irrigated corn/soybean rotation site while the Mead site is an irrigated corn/soybean rotation site. Results from this feasibility study (Liu et al., 2014) indicate that the proposed model enhancement shows promising performance in simulating surface heat fluxes and LAI phenology (Fig. 3). The preliminary study provides confidence to expand the model to regional-scale simulations.

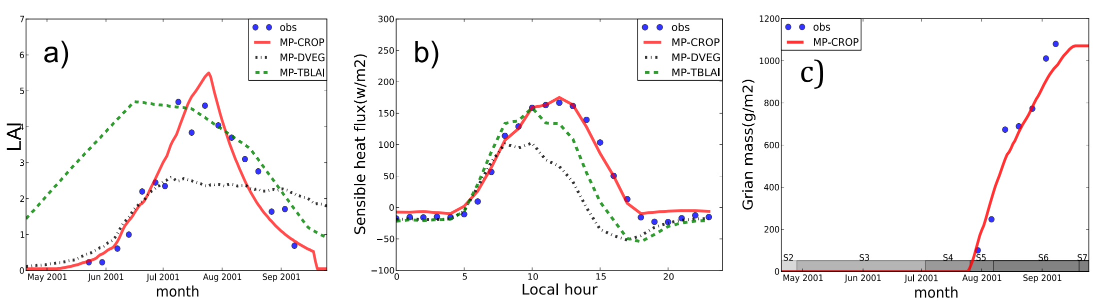

Fig 3. Model validation/comparison at Bondville, IL (2001) for a): LAI; b): average sensible heat flux in May; c) grain mass (yield). MP-CROP: the crop enhanced Noah-MP proposed in this study; MP-DVEG: default Noah-MP; MP-TBLAI: using prescribed LAI in Noah-MP. Corn growth- S2: emergence; S3: initial vegetative; S4: normal vegetative; S5: initial reproductive; S6: normal reproductive to maturity; S7: after maturity (Liu et al., 2014).

Results Summary

Task 1. The development and validation of Noah-MP-Crop

We successfully developed and validated the Noah-MP-Crop model. The crop growth models (corn and soybean) were implemented into Noah-MP along with a customizable look-up table for specific crop biophysical and management parameters. When comparing with observed data from two agricultural flux sites (Bondville, IL and Mead, NE), Noah-MP-Crop shows good performance in capturing seasonal and annual variations in corn and soybean phenology and biomass (Fig. 3). Further more, the improved simulations of Leaf area index (LAI) in Noah-MP-Crop lead to improved surface heat fluxes, especially in the early period of the growing season. These results address the importance of correctly simulating the seasonal evolution of crops and its implications in affecting land-atmospheric interactions through the exchange of heat and water vapor over agricultural regions. For a more detailed description on this task, please refer to Liu et al. (2016; 2017a).

Task 2. Implementing dynamic rooting depth into Noah-MP-Crop

Rooting depth and root distribution for crop lands are poorly represented in current land surface models. The majority of models assume rooting depth as a constant value through the entire growing season. We hypothesized that the lack of diversity and dynamics of rooting depth is one of the important factors that causes inferior performance in simulating soil moisture by land surface models. To test this hypothesis, we implemented a biomass-based dynamic rooting depth option into the Noah-MP-Crop. The new scheme allows roots "to grow" dynamically into different soil layers throughout the growing season. By incorporating dynamic rooting depth, the model shows relatively improved performance in simulating surface fluxes, especially at the peak of growing season. More importantly, the dynamic rooting depth also improves the simulations of soil moisture especially the vertical variability within the soil. By allowing the roots to grow deeper, the soil moisture profile shows a distinct change as compared to the default. Due to the limited observations direct validation was not possible but the results obtained are encouraging and highlight the importance and necessity of incorporating dynamic rooting depth in land surface models.

For a more detailed description on this task, please refer to Liu et al. (2017a, b.)

Task 3. Preliminary tests with coupled crop modeling with Noah-MP-Crop

In this task, we focus on investigating the performance of Noah-MP-Crop in regional mesoscale simulations. We also incorporated the new management maps (e.g. Fig. 4) with the model. The results indicate that Noah-MP-Crop has good performance in simulating yield especially in the Corn Belt. The model is also able capture the severe drought impacts on corn yield in 2012 (e.g. Fig. 5). By adding the management maps, the model bias in simulating yield is significantly decreased. Based on the results, for the future studies on regional modeling, we suggest that it is necessary to consider the impacts from planting dates and cultivar selections. For a more detailed description on this task, please refer to Liu et al. (2017b, c).

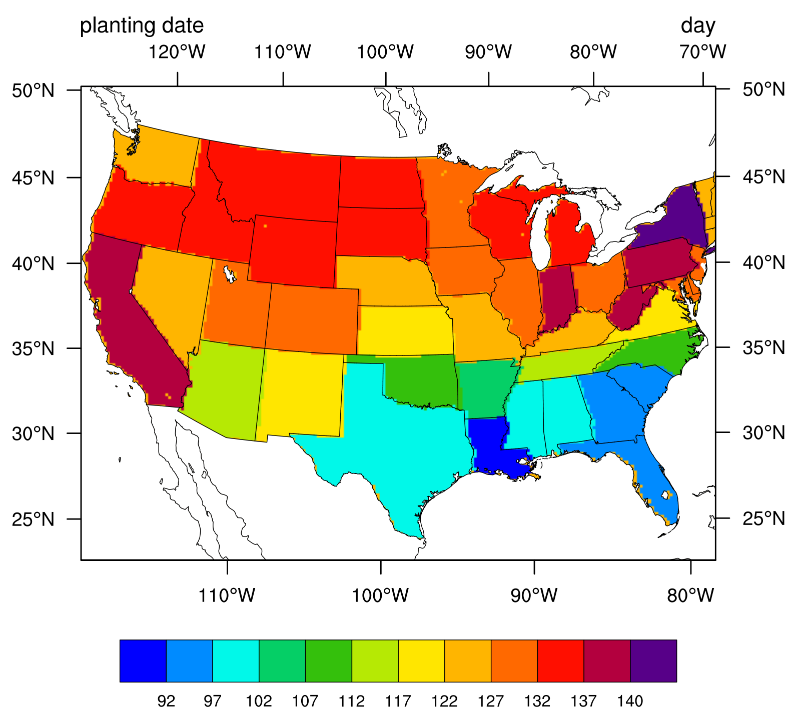

Fig. 4 Map of planting dates by states (Liu at al., 2017a,c)

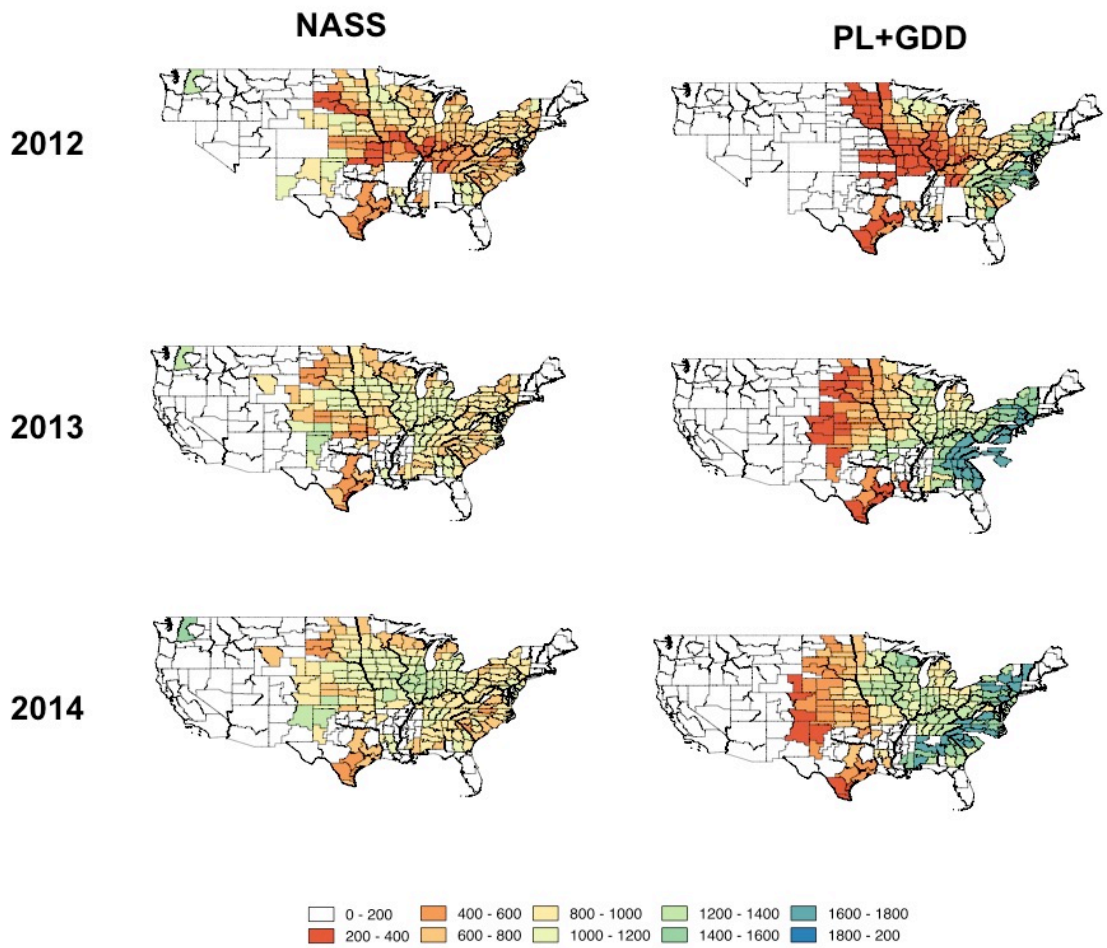

Fig. 5 NASS surveyed yield and simulated yield with PL+GDD (Liu at al., 2017a,c) (unit: g/m2) (PL+GDD means simulations with Planting dates and cultivar selection information)

Task 4. Preliminary results with WRF Through Enhanced Representation of Cropland-Atmosphere Interactions

In this task, we introduced the enhanced crop simulation into the WRF model. Results indicate that Noah-MP-Crop brings a higher level of spatial heterogeneity on crop vegetation and soil moisture profiles (e.g. Fig. 6). With incorporating the new vegetation and soil moisture profiles, WRF model predicts higher mean values of surface fluxes, as well as higher variations. For the specific convective event on 2015-06-24, when compared with DEFAULT simulations, Noah-MP-Crop simulations present improved dew point temperatures, as well as more intense precipitation at the event location (e.g.

Fig. 7). Although models still underestimate the precipitation, Noah-MP-Crop predicts a more intense convective event than the DEFAULT. We can conclude the enhanced crop simulation improves the representation of heterogeneity of cropland in WRF model, and contributes to higher dew point temperatures and intensifies the precipitation. For a more detailed description on this task, please refer to Liu et al. (2017c, d).

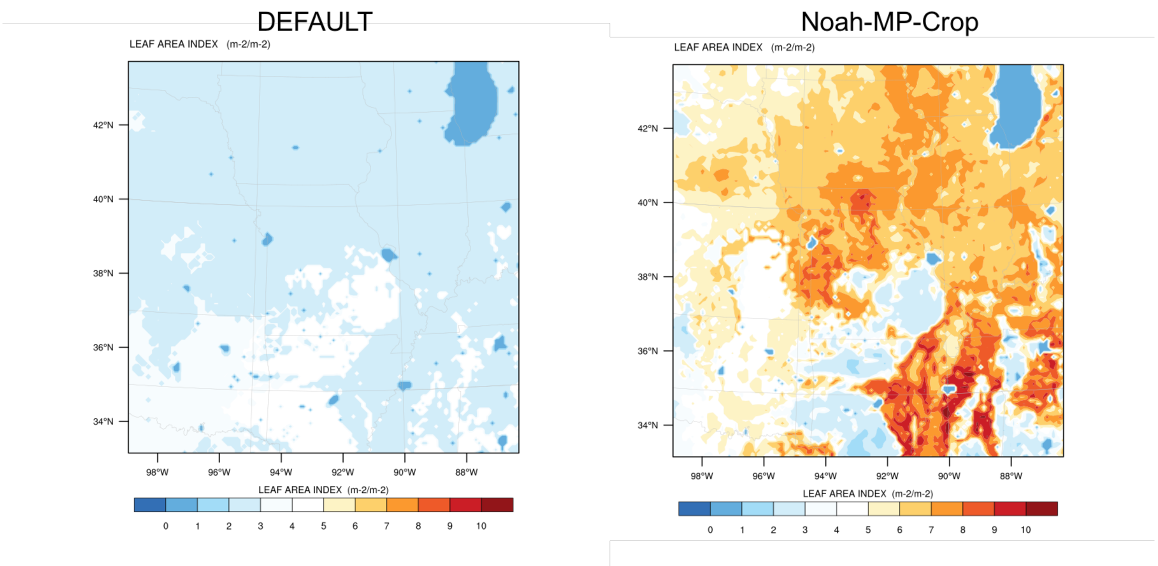

Fig. 6 Simulated LAI with two different model options (Liu at al., 2017a,d).

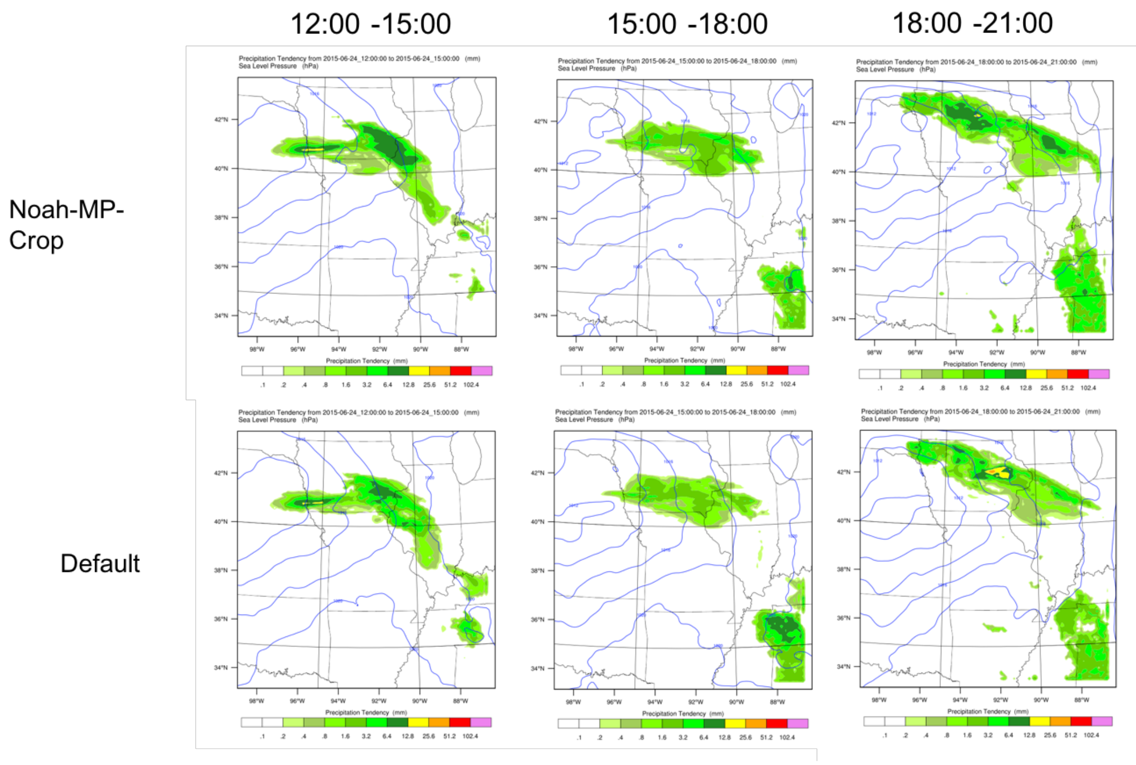

Fig. 7 Simulated rainfall for 2015-06-24 (Liu at al., 2017a,d). (The rainfall data are 3-hour accumulations, unit: mm)

Conclusion:

Through this project, cropland interactions within the Noah-MP model have been successfully incorporated and coupled to the WRF suite. The enhanced Noah-MP and WRF have been released to the community as part of WRF v3.9.

Thes model enhancements show promising results to improve the weather, as well as hydrological simulations, in cropland dominated landscapes. The modeling tool also now provides the opportunity for studying the different crop-atmosphere interaction processes that are often linked with severe weather occurrences.

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References

Changnon, D., Sandstrom, M., Schaffer, C., 2003: Relating changes in agricultural practices to increasing dew points in extreme Chicago heat waves. *Climate Research*, 24, 243-254.

Chen, F., Manning, K. W., LeMone, M. A., Trier, S. B., Alfieri, J. G., Roberts, R., Tewari, M., Niyogi, D., Horst, T. W., Oncley, S. P., Basara, J. B., Blanken, P. D., 2007: Description and evaluation of the characteristics of the NCAR high-resolution land data assimilation system. *Journal of Applied Meteorology and Climatology*, 46, 694-713.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J. and Ritchie, J.T., 2003. The DSSAT cropping system model. *European Journal of Agronomy*, 18(3), pp.235-265.

Kucharik, C.J., 2003. Evaluation of a process-based agro-ecosystem model (Agro-IBIS) across the US Corn Belt: Simulations of the interannual variability in maize yield. Earth Interactions, 7(14), pp. 1-33.

Kumar, A., Chen, F., Niyogi, D., Alfieri, J.G., Ek, M. and Mitchell, K., 2011. Evaluation of a photosynthesis-based canopy resistance formulation in the Noah land-surface model. Boundary-layer meteorology, 138(2), pp. 263-284.

Levis, S., Bonan, G. B., Kluzek, E., Thornton, P. E., Jones, A., Sacks, W. J., Kucharik, C. J., 2012: Interactive crop management in the Community Earth System Model (CESM1): Seasonal influences on land-atmosphere fluxes. *Journal of Climate*, 25, 4839- 4859.

Liu, X., Chen, F., Barlage, M. and Niyogi, D. (2014). Noah-MP-CROP: An integrated atmosphere-crop-soil modeling system for regional agro-climatic assessments. 2014 AGU Fall Meeting, San Francisco, CA.

Liu, X., Chen, F., Barlage, M., Zhou, G. and Niyogi, D., 2016. Noah-- MP-Crop: Introducing Dynamic Crop Growth in the Noah-MP Land Surface Model. Journal of Geophysical Research: Atmospheres.

Liu, X., 2017a, Introducing Agricultural Feedbacks in Noah-MP Land Surface Model for Improved Weather and Regional Crop Yield Simulations (Doctoral dissertation).

Liu, X., Chen, F., Barlage, M. and Niyogi, D., 2017b, Implementing Dynamic Rooting Depth for Improved Simulation of Soil Moisture and Surface Fluxes in Noah-MP-Crop. Journal of Applied Meteorology and Climatology (Under Review).

Liu, X., Chen, F., Barlage, M. and Niyogi, D., 2017c, Regional Crop Modeling with Noah-MP-Crop and Roles of Planting Dates and Cultivar Selections -- Introducing Crop Management Information in Land Models (Manuscript Ready).

Liu, X., Chen, F., Barlage, M. and Niyogi, D., 2017d, Mesoscale Weather forecast skills via improving the simulation of Cropland-Atmospheric Interactions (Manuscript Ready).

McPherson, R.A., Stensrud, D.J. and Crawford, K.C., 2004. The impact of Oklahoma's winter wheat belt on the mesoscale environment. Monthly Weather Review, 132(2), pp. 405-421.

Niu, G.Y., Yang, Z.L., Mitchell, K.E., Chen, F., Ek, M.B., Barlage, M., Kumar, A., Manning, K., Niyogi, D., Rosero, E. and Tewari, M., 2011. The community Noah land surface model with multiparameterization options (Noah- MP): 1. Model description and evaluation with local- scale measurements. Journal of Geophysical Research: Atmospheres, 116(D12).

Niyogi, D., Alapaty, K., Raman, S. and Chen, F., 2009. Development and evaluation of a coupled photosynthesis-based gas exchange evapotranspiration model (GEM) for mesoscale weather forecasting applications. Journal of Applied Meteorology and Climatology, 48(2), pp. 349-368.

Niyogi, D., Liu, X., Andresen, J., Song, Y., Jain, A.K., Kellner, O., Takle, E.S. and Doering, O.C., 2015. Crop models capture the impacts of climate variability on corn yield. Geophysical Research Letters, 42(9), pp. 3356-3363.

Raddatz, R.L., 1998. Anthropogenic vegetation transformation and the potential for deep convection on the Canadian prairies. Canadian journal of soil science, 78(4), pp. 657-666.

Yang, H.S., Dobermann, A., Lindquist, J.L., Walters, D.T., Arkebauer, T.J. and Cassman, K.G., 2004. Hybrid-maize—a maize simulation model that combines two crop modeling approaches. *Field Crops Research*, 87(2), pp.131-154.

Dissertation Abstract from Liu (2017)

"This study is motivated by the needs posed from two perspectives: 1) to study crop yields' response under the changing climate, there is an increasing demand for large-scale, regional crop growth simulations; and, 2) croplands play an important role in the modification of local and regional weather and climate but this aspect has been under studied. The poor representation of cropland in the current weather forecast models such as the community Weather Research and Forecasting (WRF)/ Noah-MP land-surface modeling system is a example of the current state of the cropland - atmosphere feedback studies. The lack of detailed crops in the weather models not only limits the ability to better understand the role of agricultural feedbacks in the regional weather, but also directly and indirectly affects the numerical weather prediction of high impact events especially over crop dominated landscapes.

In response to these needs and with the objectives to improve weather and regional crop yield simulation, a new crop model (Noah-MP-Crop) has been developed and implemented into a regional land-surface modeling system. The model was initially developed for corn and soybean, and evaluated at field scale with observations from two crop sites (Bondville, IL, and Mead, NE Ameriflux sites) over a six years period (2001-2006). Results shows improved in the ability of simulating regional meteorological parameters such as dew points and surface energy fluxes. Results also highlighted the importance of soil moisture processes and the rooting depth for further enhancements in the model. A dynamic rooting depth module was developed and introduced into the model, which further improved the model performance.

The newly developed modeling system was then used for conducting regional-scale crop simulations (20km grid spacing and hourly time step for the entire continental U.S. domain) for the 2012 through 2014 calendar year in an offline land data assimilation system (LDAS) mode. The implementation of the regional model also required the development of additional modules to integrate: (i) USDA planting dates dataset, (ii) heuristic estimation of cultivar information using regionally representative planting as well as harvesting dates and climatological growing degree estimates, and (iii) detailed crop land cover by merging satellite and regional and global model based estimates of crop cover. Crop (corn) yield simulations were compared with surveyed data for different agricultural statistics district (ASD) from National Agricultural Statistic Services. Results indicate that by implementing the planting dates and cultivar selections, the Noah-MP-Crop model is able to provide a more accurate regional yield simulation.

The regional version of the crop model and associated datasets were then used to couple Noah-MP-Crop with the WRF model for investigating the impact of cropland on mesoscale short-term convective weather events. The coupled system was used to simulate and study a thunderstorm event that was observed over eastern Iowa- western Illinois region corresponding to a field experiment (PECAN: Plains Elevated Convection at Night experiment, Intensive Observation Period 15). The results show that the enhanced crop simulation captured the spatiotemporal heterogeneity of crop leaf area index (LAI). This in turn influenced the surface energy fluxes and the dew point temperatures as well as mesoscale boundaries. These interacted to modify the precipitation forecasts. Results show promising improvements in the WRF models ability to simulate the land – atmosphere interactions and mesoscale convection by better representation of croplands.

The uniqueness of this study is that by bridging the traditional crop model community and land surface and weather model community, it provides us a new tool and approach for regional crop modeling. Noah-MP-Crop is an easier, faster and open-sourced approach with the potential for real-time crop modeling at flexible spatial and temporal resolutions. By enhancing the cropland representation in weather model, improvements in the regional hydroclimatology as well as weather simulation are now possible. This research is a result of collaborations with researchers from National Center for Atmospheric Science (NCAR), and National Centers for Environmental Prediction (NCEP) and utilizes multiple publicly available datasets and model frameworks."