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Key Points:
- Rooting depth significantly impacts the soil moisture profile
- Simple dynamic rooting depth formulation was implemented in Noah-MP-Crop to complement the dynamic LAI changes
- The dynamic rooting depth enhanced the model performance, especially for surface energy fluxes calculation under droughts

Supporting Information:
- Supporting Information S1

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Implementing Dynamic Rooting Depth for Improved Simulation of Soil Moisture and Land Surface Feedbacks in Noah-MP-Crop

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Abstract The study postulates that crop rooting depth representation plays a vital role in simulating soil-crop-atmospheric interactions. Rooting depth determines the water access for plants and alters the surface energy participation and soil moisture profile. The aboveground crop growth representation in land surface models continues to evolve and improve, but the root processes are still poorly represented. This limitation likely contributes to the bias in simulating soil-crop-related variables such as soil moisture and associated water and energy exchanges between the surface and the atmosphere. In Noah-MP-Crop, the rooting depth of crops is assumed as 1 m regardless of crop types and the length of growing seasons. In this study, a simple dynamic rooting depth formulation was integrated into Noah-MP-Crop. On comparing with soil moisture observations from the in situ Ameriflux, USDA Soil Climate Analysis Network, and the remote-sensed Soil Moisture Active Passive data set, the results highlight the improved performance of Noah-MP-Crop due to modified rooting depth. The improvements were noted in terms of soil moisture and more prominently in terms of the energy flux simulations at both field scale and regional scale. The enhancements in soil moisture profiles reduce the biases in surface heat flux simulations. The impact of rooting depth representation appears to be particularly significant for improving model performance under drought-like situations. Although it was not possible to validate the simulated rooting depth due to lack of observations, the overall performance of the model helps emphasize the importance of enhancing the representation of crop rooting depth in Noah-MP-Crop.

Plain Language Summary Current land surface models such as Noah-MP-Crop represent rooting depth as a constant (typically around 1 m). The constant rooting depth has been designed in the model framework to retain simplicity and also because there are very few observations to guide more spatiotemporally variable rooting depth information into the model. In this paper, reviewing the model performance, particularly under drought conditions, it was concluded that the roots need to have dynamic growth to simulate realistic evapotranspiration and soil moisture. This study added a simple dynamic rooting depth formulation into the Noah-MP-Crop model. The new formulation could simulate the root growth in response to the aboveground phenology, and the corresponding estimates of soil moisture and energy fluxes were compared with in situ measurements and satellite products. The results show that the formulation improves soil moisture simulations when compared with both field-scale and regional-scale data sets. The enhancements in soil moisture simulation, in turn, improve surface energy simulations. The impact of rooting depth simulation is significant for improving model performance under drought-like situations. The overall performance of the model emphasizes the importance of enhancing the representation of crop rooting depth in land surface models.

1. Introduction

Croplands have a detectable influence on the surface exchanges of heat and water vapor. These surface exchanges, in turn, can impact boundary layer growth and mesoscale convergence/convection (Changnon et al., 2003; Freedman et al., 2001; Levis et al., 2012; McPherson et al., 2004; Raddatz, 1998). To study the impacts of land use/land change on hydroclimatic systems, a better understanding of the interactions between soil-crops-atmosphere is necessary. Recently, the Noah-MP model was enhanced to include crops, and a new version, Noah-MP-Crop (Liu et al., 2016), was introduced to the community. The model development follows a series of recent studies that seek to link crops in weather studies (e.g., Harding et al., 2015; Levis et al., 2012; Liu et al., 2016; Lu et al., 2015; Song et al., 2013).

Rooting depth plays a vital role in soil-crop-atmospheric interactions. Researchers have found that rooting depth has impacts on the atmospheric process and water, carbon, and nutrient cycling (Aanderud & Richards, 2009; Siqueira et al., 2008; Sulis et al., 2019). In this study, we focus on the role of rooting depth in soil moisture simulation and the exchanges of sensible heat and latent heat (evapotranspiration) between land surface and atmosphere.

Rooting depth is an important component in the water uptake process, which determines water and nutrient accessibility for crops (Kleidon & Heimann, 1998a; Yu et al., 2016). The growth of plants directly affects the exchange of heat and water between cropland and atmosphere via changes in albedo and transpiration. Rooting depth also shows impacts in water distribution across the soil layers via hydraulic redistribution (Breazeale & Crider, 1934; Hawkins et al., 2009; Lee et al., 2005). Hydraulic redistribution is a process that moves water from moist soil to dry soil through roots (Neumann & Cardon, 2012). As a result, soil moisture and surface evaporation also changed.

Despite the enhanced simulations of aboveground crop growth, rooting depth is still poorly represented in land surface models (LSMs) and has been implicated in contributing to the bias in simulating soil-crop-related variables such as soil moisture, water, and heat fluxes (Gayler et al., 2013, 2014; Kleidon & Heimann, 1998a, 1998b; Liu et al., 2016). For example, in the Noah LSM family (including Noah-MP and Noah-MP-Crop), the rooting depth for all crop types are set as 1 m regardless of spatial changes, temporal differences, and crop type. This aspect of static representation of rooting depth is not singular to the Noah LSM alone and has also identified as a problem in the Community Land Model (CLM) 3.5 and its performance in simulating soil moisture (Gayler et al., 2013). In CLM 4-Crop as well, the rooting depth was represented as a static equation and is linked to the underestimation of soil moisture during the growing season (Chen et al., 2015).

Canadell et al. (1996) reviewed 290 measurements of maximum rooting depth available in the literature and found the global average to be 2.1 ± 0.2 m for cropland. The reported maximum rooting depth for crops varied from 1.1 (Sorghum) to 3.7 m (Alfalfa), while the maximum rooting depth for corn, wheat, and soybean was 2.4, 3, and 1.8 m, respectively. Therefore, it is unrealistic to assume that (i) all crops have the same rooting depth and (ii) the rooting depth is constant during the entire growing season. Rooting depth is poorly represented in LSMs, mainly due to the lack of rooting depth observational data sets for contemporary large-scale models. There is also a constraint in terms of the different terminology used between root ecologist/agronomist and land surface modelers that becomes an impediment in the model development (Smithwick et al., 2014). Using constant rooting depth is also a result of the simplifications that are necessary for running the land models. However, in this study, it is postulated that this simplified assumption may be at the root of a significant bias that gets introduced in the modeled surface energy balance and soil moisture fields.

Recently, Song et al. (2013) and El Masri et al. (2015) implemented a dynamic rooting depth into a detailed biogeochemical LSM (ISAM) for improving the model performance in cropland and high latitude ecosystems. They found that introducing variable rooting depth could enhance the ability of a model to capture seasonal variability in water and energy fluxes. Gayler et al. (2014) integrated a rooting depth simulation submodule, based on an empirical equation, into Noah-MP and showed notable improvements are possible in the model performance. Fu et al. (2016) incorporated the hydraulic redistribution scheme from Ryel et al. (2002) into CLM 4.5; the results indicate improved performance in simulating energy and water fluxes, especially during the dry season. Recently, Sulis et al. (2019) introduced a macroscopic root water uptake model into CLM 4.0; the simulated results showed good agreement with site-observed transpiration fluxes and soil water content. In this hydraulic redistribution as well as root water uptake model, dynamic rooting depth/root fraction was identified as a crucial component.

Recognizing the improved performance in different contemporary LSMs, in this study, we focus on field crops (e.g., corn and soybean) and implement a simple dynamic rooting depth simulation scheme into the Noah-MP-Crop model. This development is part of a series of studies on coupling Noah-MP-Crop with the High-Resolution Land Data Assimilation System (HRLDAS; Chen et al., 2007) and the Weather Research and Forecasting (WRF) model.

2. Methodology

2.1. Noah-MP-Crop

The Noah-MP-Crop model (Liu et al., 2016) is a LSM based on the Noah-MP model (Niu et al., 2011; Yang et al., 2011) but with explicit crop growth simulation capabilities. The model can simulate the time-varying Leaf Area Index (LAI) and dynamically allocate carbohydrates to different crop components (leaf, stem, grain, and root). Instead of treating crop as a single and uniform plant form, Noah-MP-Crop takes account of crop varieties and field management information (e.g., planting and harvesting). Using these crop-specific schemes, the model improves the simulation of biomass and surface energy fluxes over cropland (Liu et al., 2016). Noah-MP-Crop has been implemented into the current version of the HRLDAS and the Weather Research and Forecasting model (since WRF v3.9) to provide improved representation and simulation of cropland surface conditions. While Noah-MP-Crop can dynamically simulate aboveground growth, the rooting depth in the default version of the model is a constant value (1 m) throughout the growing season.

2.2. Dynamic Rooting Depth Formulation

To assess how the rooting depth dynamics can influence the LSM simulations, a new formulation to calculate the rooting depth was introduced. Since Noah-MP-Crop already can dynamically simulate the root biomass, the new scheme allows an explicit link between the rooting depth and biomass availability. The conceptual framework is similar to how leaf biomass is utilized in altering the LAI in different dynamic LSMs. In this study, an initial review was undertaken of the different approaches available, and the method from Song et al. (2013), which is based on the original study of Arora and Boer (2003), is adopted. The rooting depth, *Droot*, will increase with accumulating root biomass (*Broot*):

$$Droot = (3^*(Broot)^{\alpha})/bb, \tag{2}$$

where α is the root growth direction parameter and *bb* is the variable root distribution parameter. These parameters were set to 0.7 and 0.53, respectively, following Song et al. (2013); the values are calibrated based on the observations in Bondville, IL, and Mead, NE.

The formulation is a simple representation of how crop roots grow, and some factors such as a bedrock layer and water table that can also restrict the growth of roots were ignored. This representation is consistent with the overall philosophy behind the development of Noah-MP-Crop, which is to provide realistic surface energy fluxes from a land model for Numerical Weather Prediction or Land Data Assimilation System (LDAS) studies. Thus, the assumptions and simplifications would likely not be appropriate for agroecological studies but were considered sufficient for the application of interest (i.e., Numerical Weather Prediction and LDAS). Furthermore, since it is difficult to obtain the rooting depth profile for the entire growing season, it was recognized that such data would be limited. Therefore, to maintain simplicity and in line with the study objective to investigate if the implementation of a dynamic rooting depth profile can significantly impact surface fluxes and soil moisture, the model was considered adequate. Due to the limitations of the algorithm, we acknowledge that these assumptions and simplifications may lead to some bias in the simulation.

2.3. Field-Scale Experiments

Data were available from two long-term Ameriflux crop sites (http://ameriflux.ornl.gov/): Bondville, IL (US-Bo1, 40.00°N, 88.29°W, PI: Tilden Meyers, 2016), and Mead, NE (US-Ne3, 41.18°N, 96.44°W, PI: Andy Suyker, 2016). Both sites are rainfed fields with annual rotation between corn and soybean. The dominant soil type at Bo-1 is silt loam and clay loam at Ne-3. In this study, we ran the model for three corn years of Bo-1 (2001, 2003, and 2005) and three soybean years for Ne-3 (2002, 2004, and 2006). The cultivar for corn at Bo-1 is Pioneer 33P67BT (as reported for 2001, not known for 2003 and 2005), and the soybean varieties at Ne-3 are Asgrow 2703 (2002), Pioneer 93B09 (2004), and Pioneer 93M11 (2006). The planting dates for corn in Bo-1 are between 16 and 22 April. Planting dates for soybeans in Ne-3 are from 11 May to 2 June. The planting dates and the model setting were aligned with the actual dates. Half-hourly (US-Bo1) and hourly

Table 1
Selected Agricultural Sites From SCAN for Validating Regional Simulations

Site number	Name	State	Location (lat, long)
2093	Phillipsburg	Kansas (KS)	(39.79°, −99.33°)
2005	Princeton	Kentucky (KY)	(37.1°, −87,83°)
2075	McAllister Farm	Tennessee (TN)	(35.06°, −86.59°)
2111	Johnson Farm	Nebraska (NE)	(40.37°, −101.72°)

(US-Ne3) in situ meteorological forcing data were collected to drive the model in offline mode. For both the study sites, observed hourly sensible heat flux (H), latent heat flux (LE), soil moisture of the top layer (0.1 m, sensor measured at 0.05 m), and the second layer (0.1–0.4 m, sensor measured at 0.3 m) were used to evaluate the model.

The parameterizations of Noah-MP-Crop in this study use the default values from Liu et al. (2016) to allow direct comparison with prior results. Simulations conducted with the control or the constant rooting depth are referred to as *fixed_root*, while those with the new dynamic rooting depth are referred to as *dynamic_root*. Both Bondville and Mead are rainfed corn-soybean rotation sites, so the simulations for corn are conducted at Bondville for 2001, 2003, and 2005, and for soybean are conducted at Mead for 2002, 2004, and 2006. To quantify differences in results from those experiments, the mean absolute error (MAE), root mean square error (RMSE), and *p* values were calculated.

2.4. Regional-Scale Experiments

To evaluate the impacts of *dynamic_root* at the regional scale, we also ran Noah-MP with the HRLDAS for the cropland-dominated U.S. Corn Belt domain with 10 km grid spacing resolution. HRLDAS is an offline driver of the LSMs primarily designed to provide a more accurate initial land condition for WRF model. Considering the vegetation cover and the crop phenology over the study domain, we conducted the model experiments and evaluated the simulated results for June (2015). The meteorological input data were obtained from North American LDAS (NLDAS-2) hourly forcing (https://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php). The model simulates the soil moisture at four layers: 0–0.1, 0.1–0.4, 0.4–1, and 1–2 m. The fixed rooting depth of cropland in the regional-scale experiment was the default value of 1 m. We assumed that the whole cropland area was corn. We evaluated the regional simulation results (top soil layer) with Soil Moisture Active and Passive (SMAP; Entekhabi et al., 2010) Level-4 product (L4-SM), the top layer soil moisture or L4-SM are an interpolated product from SMAP observations. We also extracted soil moisture/soil temperature from the regional simulation and validated with selected agricultural sites (Table 1) from the Soil Climate Analysis Network (SCAN; https://www.wcc.nrcs.usda.gov/scan/) data set.

3. Results and Discussion

3.1. The Simulation of Dynamic Rooting Depth

Figure 1 shows that the *dynamic_root* can simulate the seasonal variation of rooting depth. In contrast with *fixed_root*, which assumes rooting depth as a constant value for the entire year, *dynamic_root* presents the root growth dynamically postplanting. The root grows deeper following the accumulation of root biomass and then starts to decrease when newly added biomass is smaller than the total consumption of respiration, turnover, and death.

During the entire season (from planting to maturity), *dynamic_root* considers the number of soil layers that contain roots, which in the simulation results show a change from the surface layer to all the four layers. There is no observed rooting depth in this experimental site for validating and calibrating the model, but based on the reported rooting depth from other literature (Canadell et al., 1996), the simulated results appear to be within the expected range.

3.2. The Impacts of Dynamic Rooting Depth on Surface Heat Fluxes During the Growing Season

For simulations considering corn at the Bondville site, the monthly diurnal pattern of site-observed sensible heat flux (H) is generally well captured by both *dynamic_root* and *fixed_root* (Figure 2a). *Dynamic_root* shows significant (p value < 0.05) improved performance in simulating H for cropland around August with the planting date around the first week of May (Table 2). In August, which corresponds to the peak in the growing season, the daytime sensible heat flux MAE of *dynamic_root* is 20.9 W/m^2 and is considerably lower than the MAE of *fixed_root*: 52.6 W m^{-2}. For latent heat flux (LE) simulations (Figure 2b), the *dynamic root* also shows significant improvement in August (Table 2). For other months, the differences between *dynamic_root* and *fixed_root* are not statistically significant.

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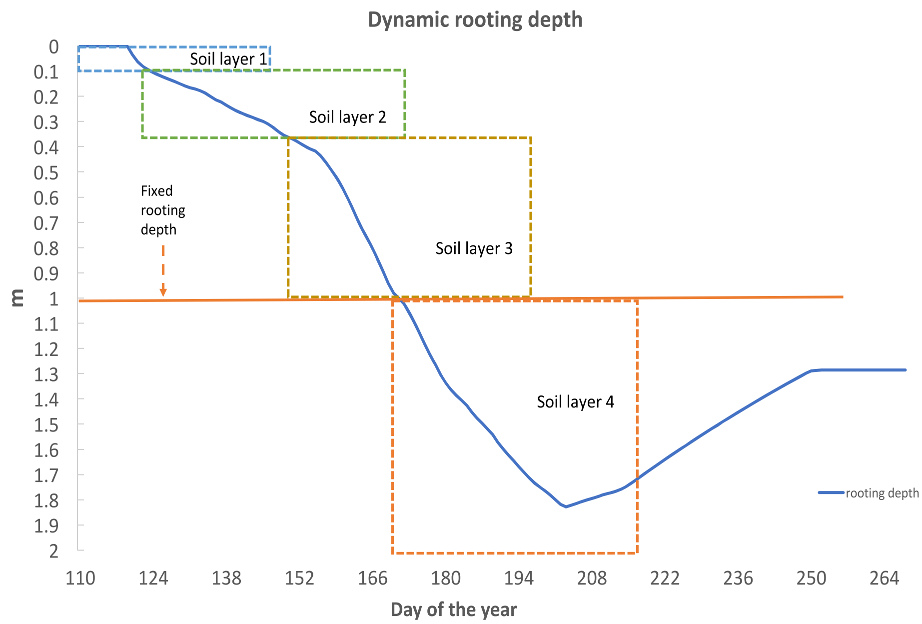

Figure 1. Dynamically simulated rooting depth of corn at the Bondville, IL, site (2001) (fixed rooting depth = 1 m is the default constant rooting depth for cropland in Noah-MP-Crop). Boxes with different colors represent the depth of each soil layer in the model.

For simulations corresponding to soybean at the Mead site, *dynamic_root* shows significantly enhanced performance in sensible heat flux estimates for May and June (Figure 3a and Table 2). For example, in June, the MAE of the dynamic root is 35.1 W/m^2, which is 52% lower than the MAE for fixed root. Similar to the H simulations, in the LE simulations (Figure 3b), *dynamic_root* has better performance than *fixed_root*, especially in May and June. In June, the daytime MAE of the dynamic root is 78.0 W/m^2, which is 41% lower than the fixed root.

In summary, *dynamic_root* significantly improves the simulations in peak growing season (August) at Bondville site and substantially enhances simulations in May and June at Mead site. The difference in the simulation results over Bondville and Mead is likely due to the differences in the soil types, meteorological forcing, and possibly other local (unknown) management practices. The impacts of the root process are the interactive results among soil, crops, and weather. When comparing the performance of the two model schemes for the entire growing season (May to October), the results indicate that *dynamic_root* significantly improves the simulation of surface heat fluxes at the Mead site (supporting information Table S1). (The model minus observations residual plots shown in Figures S1 and S2 further illustrate the model performance). These results highlight the different impacts on heat flux simulations from the two modeling schemes. The results also highlight that the simple approximation used, while functional at average, will likely need more enhancements and corrections in the future.

3.3. The Impacts of Dynamic Rooting Depth on Soil Moisture

Simulating soil moisture is a common challenge in LSMs (Chen et al., 2007; Chen & Mitchell, 1999; Koster & Milly, 1997). In a previous study (Liu et al., 2016), we ran the Noah-MP model with three different vegetation options: MP-LAI (using prescribed monthly LAI), MP-DVEG (generalized dynamic vegetation simulation), and MP-CROP (crop-specific dynamic simulation). The results showed notable improvements in the LAI simulations using the dynamic crop options; however, when the simulated results of soil moisture were compared, there was no significant difference between these three options. We hypothesize that this lack of variability in the three model options is a result of the fixed rooting depth for the entire simulation period. In this study, the simulated soil moisture was reevaluated after incorporating the dynamic rooting depth.

For the Bondville site, the *dynamic_root* shows a significant difference in simulating soil moisture as compared to *fixed_root* run at monthly scale (Figure 4 and Table 3). Taking 2001 as an example, from July to September, the MAE and RMSE of *dynamic_root* simulations for both soil layers are significantly lower

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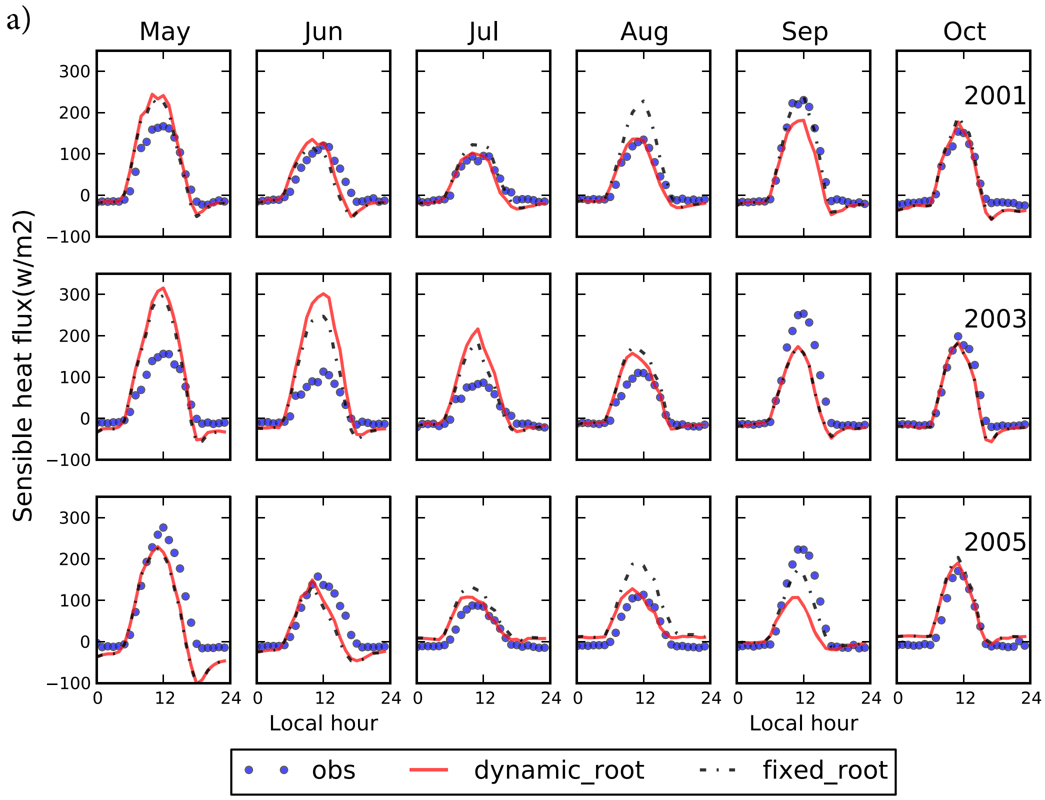

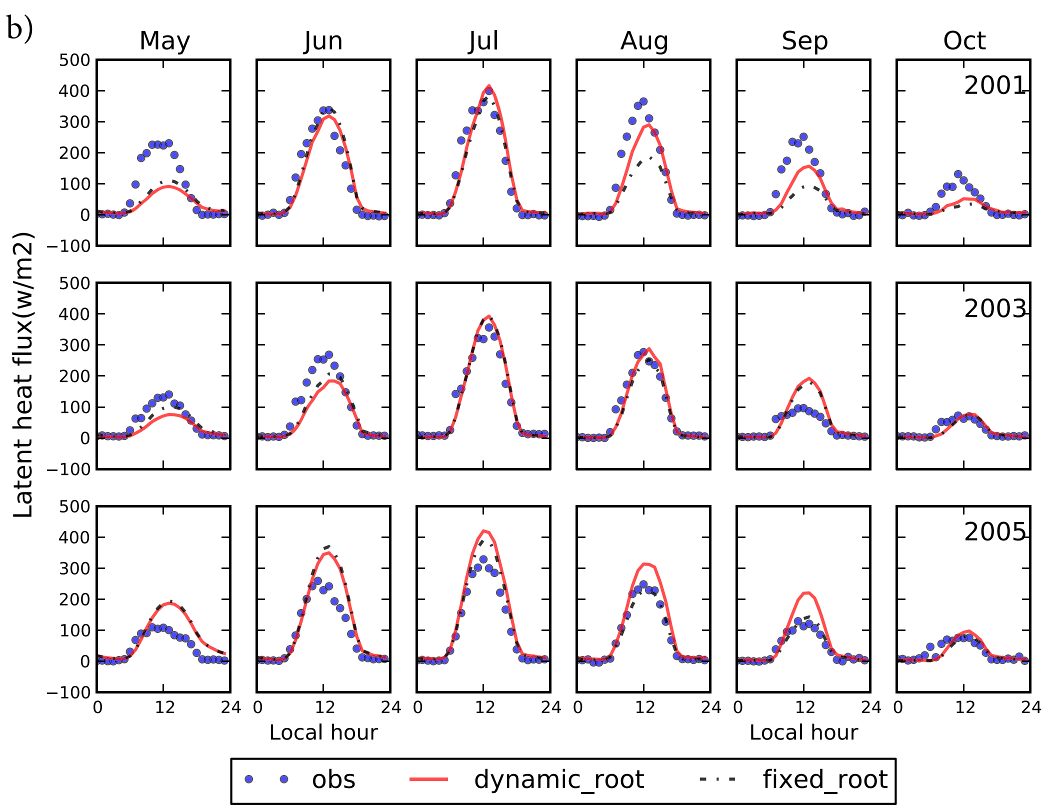

Figure 2. (a) Comparison of simulated sensible heat flux of corn at the Bondville, IL, site (obs: observations, collected from the Ameriflux site), for the dynamic and the fixed rooting depth model runs. (b) Same as Figure 2a but for latent heat flux at the Bondville, IL, corn site.

Table 2
MAE and RMSE of Sensible Heat Flux and Latent Heat Simulations During the Daytime (8 a.m. to 6 p.m., unit: W/m^2) Averaged Over Three Growing Seasons

			Dynamic root		Fixed root		
Sites	Crop	Month	MAE	RMSE	MAE	RMSE	*p* value
Bondville, IL	Corn	May	68.7	81.6	64.9	76.0	0.56
Sensible heat flux		June	67.8	90.0	59.7	73.3	0.34
		July	32.4	47.8	33.4	41.0	0.44
		August	**20.9**	**26.6**	**52.6**	**58.7**	**0.01**
		September	61.4	72.8	38.6	50.2	0.23
		October	21.1	25.8	24.4	28.3	0.70
		Average	*45.4*	*57.4*	*45.6*	*54.6*	
Mead, NE	Soybean	**May**	**54.5**	**63.6**	**85.8**	**91.7**	**0.01**
Sensible heat flux		**June**	**35.1**	**41.1**	**72.3**	**77.7**	**0.00**
		July	**23.2**	**27.3**	**19.2**	**25.3**	**0.01**
		August	31.0	36.1	23.6	27.4	0.42
		September	51.6	60.0	53.8	64.2	0.76
		October	48.7	56.6	53.3	62.7	0.44
		Average	*40.7*	*47.4*	*51.3*	*58.2*	
Bondville, IL	Corn	**May**	**67.4**	**81.4**	**60.7**	**74.5**	**0.10**
Latent heat flux		June	59.6	69.6	58.3	71.2	0.44
		July	50.1	57.9	41.8	48.4	0.56
		August	**42.3**	**53.8**	**46.9**	**73.7**	**0.01**
		September	**56.8**	**68.5**	**53.0**	**72.9**	**0.05**
		October	23.7	31.0	24.8	35.2	0.23
		Average	*50.0*	*60.4*	*47.6*	*62.7*	
Mead, NE	Soybean	**May**	**96.8**	**106.0**	**132.6**	**142.1**	**0.01**
Latent heat flux		**June**	**78.0**	**87.4**	**131.8**	**140.7**	**0.00**
		July	42.0	48.1	65.6	79.0	0.31
		August	24.8	29.4	19.7	24.2	0.73
		September	62.9	74.0	63.4	76.2	0.92
		October	60.4	69.8	62.2	73.7	0.83
		Average	*60.8*	*69.1*	*79.2*	*89.3*	

Note. Bold represents statistically significant at P-value < 0.05, Italic parts indicate average value.

than the MAE and RMSE of *fixed_root* simulations. For 2003, during August and September, *dynamic_root* significantly improved the simulation; however, the results do not show improvement during the early growing season in May and June. Comparing the performance of the two model schemes for the entire growing season, the results (shown in Table S2 and Figures S3 and S4) again highlight the significant improvements from *dynamic_root* in 2001. By design, roots with the *fixed_root* option are static and confined to the first three layers (1 m), while with the dynamic simulation, the roots were considered to have reached down to the fourth layer (~2 m) and utilizing water from the deeper layer. As a result of this rooting depth change and the hydraulic redistribution, in Figure 4, *dynamic_root* simulated soil moisture in the first layer and second layer are higher than *fixed_root* simulations.

Despite the improvements noted above, the simulated results underestimate the soil moisture observations. These underestimations could be a result of uncertainties in the measurements and due to the vertical homogeneity of soil type for all soil layers in the model. For example, the soil texture for Bondville is silty loam, which leads to the maximum soil moisture value as 0.476 m^3/m^3. However, in 2003, some observations of the first layer exceeded this value (of 0.476 m^3/m^3), while for 2005, the observations seem erroneous as in the middle of June, soil moisture values do not respond to precipitation forcing, even for the shallow soil layer. Since there is no published documentation that shows these data are incorrect, they were retained in the plots. However, for 2005, because the standard deviation of the first layer soil moisture in July is almost zero (0.002 m^3/m^3) while we do see the variance in precipitation, we exclude 2005 in the statistical analysis presented in Table 3. There are also differences possibly due to variation in the footprint associated with the measurements and the representation of the soil texture input; errors also creep in due to the model forcing fields. The model simulates the soil moisture as an average value to represent each layer while the sensor has a smaller footprint and represents the soil moisture value in the vicinity at the depth the probe is located. The differences in the sensor versus grid footprint can also cause bias in the comparisons.

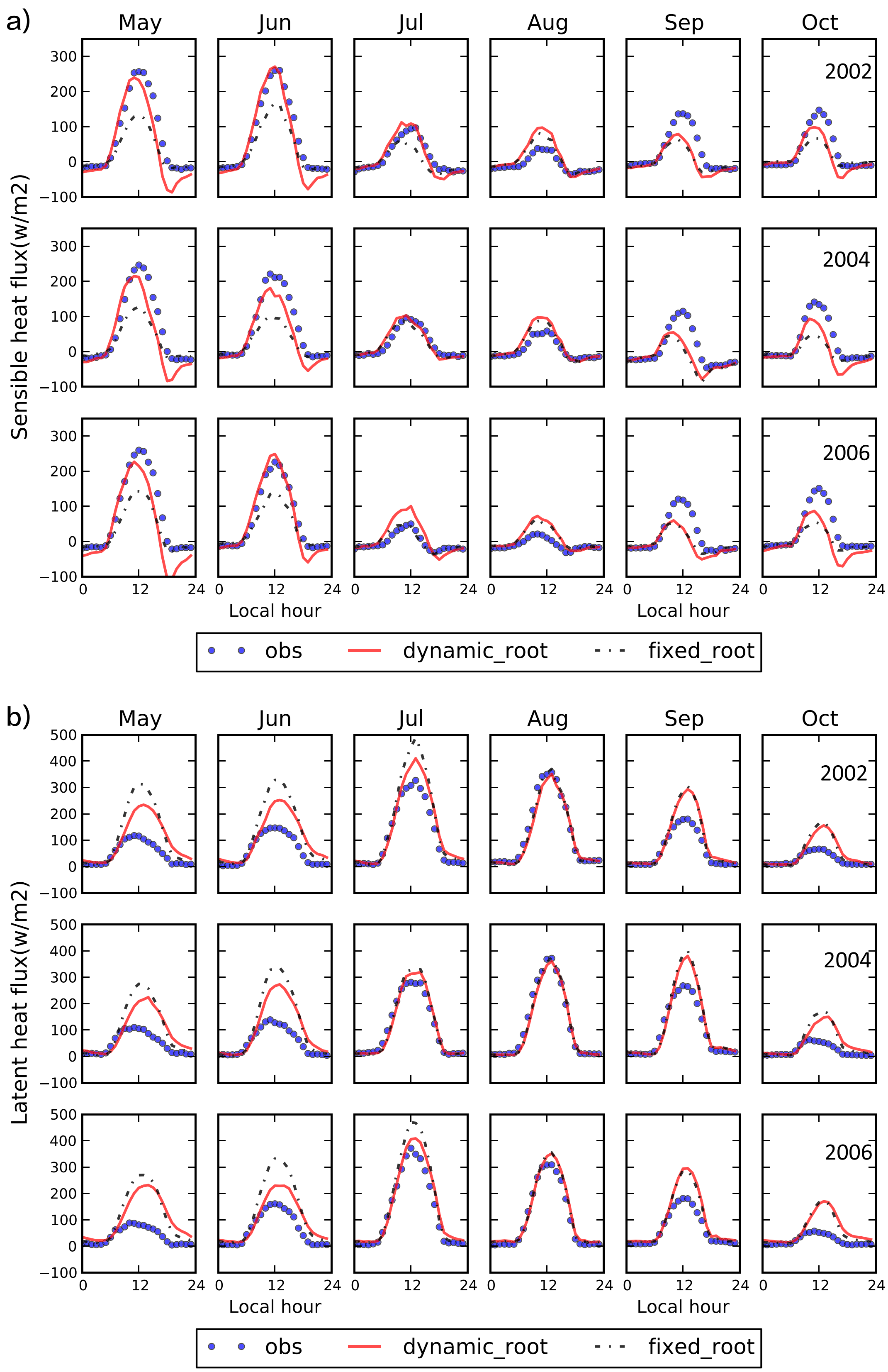

Figure 3. (a) Same as Figure 2a but for soybean at the Mead, NE site. (b) Same as Figure 2b but for latent heat flux for soybean at the Mead, NE site.

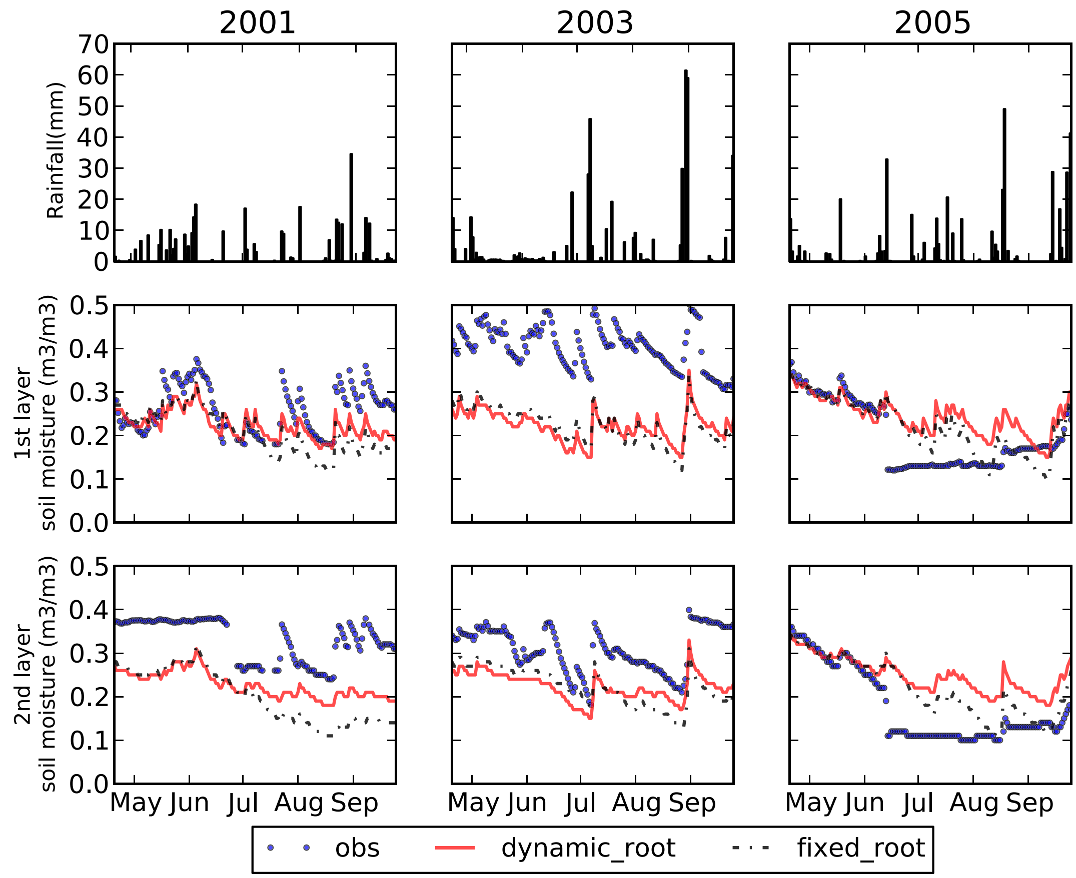

Figure 4. Daily precipitation (mm, upper panel) and comparisons of simulated first soil layer (0.05 m, middle panel) and second soil layer (0.3 m, lower panel) soil moisture for the Bondville site (obs: observations from the Ameriflux site).

Due to the lack of observed soil moisture for soil layers below 0.4 m at the field site, it is not possible to evaluate the soil moisture simulations for all the simulated layers. Figure 5 is representative of the advantage associated with the use of a dynamic rooting depth within the model. Substantial differences are noted in simulated soil moisture values for the two root options, particularly at Layer 4 (1–2 m). The fourth layer soil moisture simulated with *dynamic_root* starts to decrease in July, while with *fixed_root*, they remain unchanged for the entire growing season. For the *fixed_roo*t run, the soil moisture gap between Layers 3 and 4 reaches 0.18 m^3/m^3, which is equal to nearly a third of the maximum soil moisture possible for the soil. The wilting point for silt loam in the model is set to 0.179 m^3/m^3. The *fixed-root* simulated soil moisture for Layers 1–3 crosses the wilting point after Day 193, while the fourth layer has soil moisture levels at 0.28 m^3/m^3. Such a soil setup appears to be unrealistic for the root system not to seek water from the deeper layers, while the shallower layers are approaching a wilting point. The simulations conducted with *dynamic_root* show a different mechanism since roots can reach the deeper layer; the moisture gap between Layers 3 and 4 is smaller than 0.05 m^3/m^3. As a result, the soil moisture in all the soil layers is above the wilting point, which aids crop growth. The results thus indicate the relatively apparent, but a missing feature within the current default version, that simulations of root zone soil moisture and the soil moisture profile depend on how deep the root can grow. More broadly, considering the numerous interactions that exist within the LSM, incorporating dynamic rooting depth could be a practical and straightforward approach to improve the soil moisture simulations—particularly in the deeper layers.

3.4. Regional-Scale Simulation

3.4.1. Evaluations With SMAP Data

The dominant land use corresponding to the regional research domain is primarily cropland (Figure 6). After integrating the dynamic rooting depth into the model and reviewing the results for the growing

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Table 3
MAE and RMSE of Soil Moisture for Bo-1 in 2001 and 2003 Growing Season

		Dynamic root		Fixed root		
Year	Month	MAE	RMSE	MAE	RMSE	*p* value
2001	May	0.032	0.039	0.033	0.038	0.106
First soil layer	June	0.049	0.056	0.041	0.048	0.311
	July	0.038	0.047	0.049	0.065	**0.002**
	August	0.040	0.053	0.085	0.089	**0.000**
	September	0.082	0.083	0.115	0.116	**0.000**
	Average	*0.048*	*0.056*	*0.065*	*0.071*	
2001	May	0.118	0.119	0.109	0.110	**0.012**
Second	June	0.112	0.116	0.103	0.107	0.288
soil layer	July	0.074	0.083	0.110	0.122	**0.000**
	August	0.084	0.091	0.154	0.159	**0.000**
	September	0.130	0.131	0.188	0.189	**0.000**
	Average	*0.104*	*0.108*	*0.133*	*0.138*	
2003	May	0.175	0.176	0.159	0.161	**0.001**
First soil layer	June	0.212	0.214	0.187	0.189	**0.001**
	July	0.206	0.206	0.204	0.205	0.932
	August	0.179	0.180	0.202	0.203	**0.012**
	September	0.134	0.142	0.152	0.159	**0.012**
	Average	*0.181*	*0.184*	*0.181*	*0.183*	
2003	May	0.084	0.086	0.068	0.071	**0.000**
Second	June	0.081	0.087	0.056	0.067	**0.000**
soil layer	July	0.085	0.088	0.082	0.088	0.977
	August	0.053	0.054	0.090	0.090	**0.000**
	September	0.135	0.136	0.156	0.157	**0.001**
	Average	*0.087*	*0.090*	*0.090*	*0.094*	

Note. Bold represents statistically significant at P-value < 0.05, Italic parts indicate average value.

season (June in particular), the median value of first layer (0–0.1 m) soil moisture simulations is 0.26 m^3/m^3, which is lower than the median value of simulation with *fixed_root*: 0.29 m^3/m^3. The median value of *dynamic_root* simulated deeper layer soil moisture is 0.33 m^3/m^3, which for the *fixed_root* simulations is 0.32 m^3/m^3 (Figure 6). This indicates that in June, the roots are located in the shallow layers, and the crops can access water mainly from the shallow layers rather than having to reach the reserves in the deeper soil layers. In the probability distributions plots shown in Figure 7, it is also seen that the *dynamic_root* simulated first layer soil moisture has a more "dry" area (soil moisture below 0.2 m^3/m^3) than the *fixed_root* simulated soil moisture.

We also compared the simulated soil moisture for the top soil layer with the SMAP L4 data product. The SMAP fields have shown to have considerable similarity and ability to reproduce the soil moisture conditions from in situ and NASS soil moisture conditions (Colliander et al., 2017). As a satellite-derived product, the SMAP data set is, however, treated as a reference and not a direct measurement. The results shown in Figure 8 indicate that the model can capture the drought impacts over the Western Corn Belt with the integration of dynamic rooting depth. However, both the *fixed_root* and *dynamic_root* simulations overestimate the top layer soil moisture for the central area of the Corn Belt. There are several possible reasons for this overestimation: the issue of different grid spacing and projection between SMAP and model runs; the hydraulic and other soil properties considered in the reference data sets versus those used in Noah-MP-Crop; and unknown errors in the forcing fields for the model runs that cause uncertainty in the model simulations.

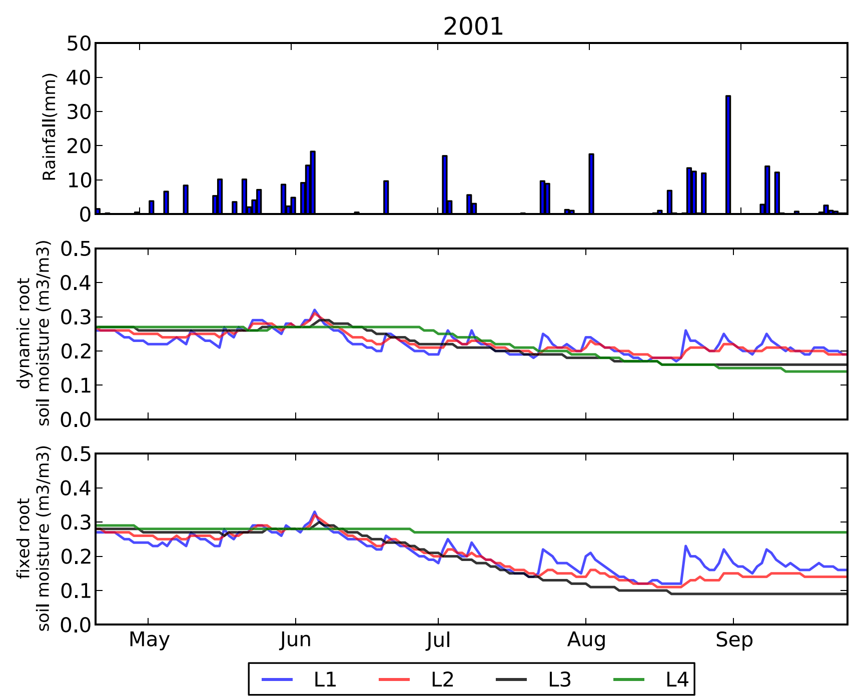

Figure 5. Daily precipitation (mm, upper panel) and comparisons of simulated 4-layer soil moisture for the Bondville site (obs: observations from the Ameriflux site).

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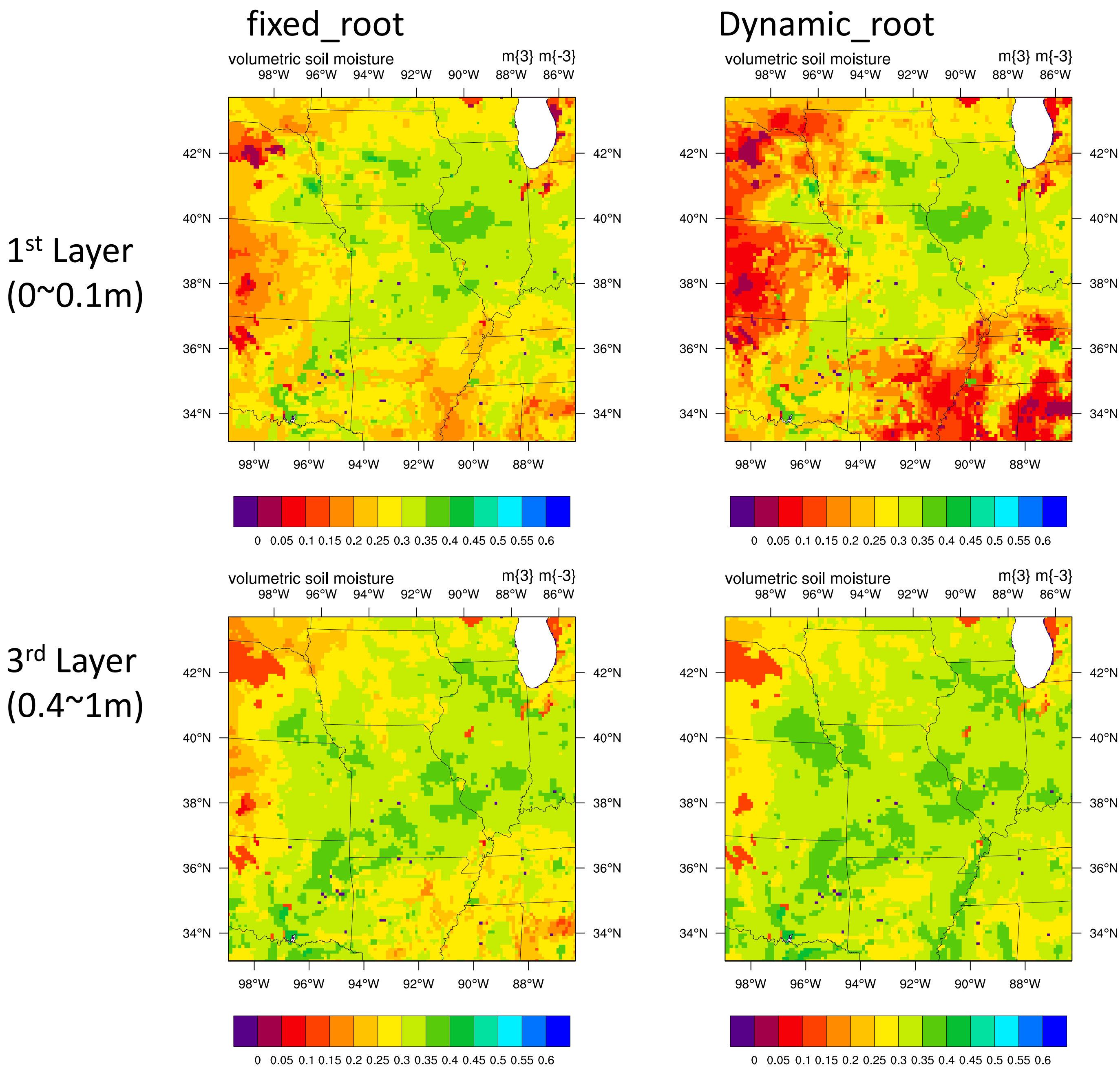

Figure 6. Simulated soil moisture of first soil layer (0~ 0.1 m, upper panel) and third soil layer (0.4–1 m, lower panel) in June 2015.

Similar to the findings from the field-level experiments, the low soil moisture availability limits the soil evaporation, which leads to a lower latent heat flux (LE) to the atmosphere (Figure 9). The probability distribution indicates that, with *dynamic_root*, there is a larger area that has low LE (<200 W/m^2) values. The impacts of rooting depth on LE is found to be substantial in the subregional-scale soil moisture fields. Reviewing the region around Kansas as an example (Figure 9), and the median LE is 249 W/m^2 with *dynamic_root* simulation, which is 34% lower than the *fixed_root* simulation value of 380 W/m^2. The significant difference in the simulated surface fluxes between *fixed-root* and *dynamic-root* are expected to have different impacts on the simulation of atmospheric processes when coupled with WRF (and will be reported in a follow-up study).

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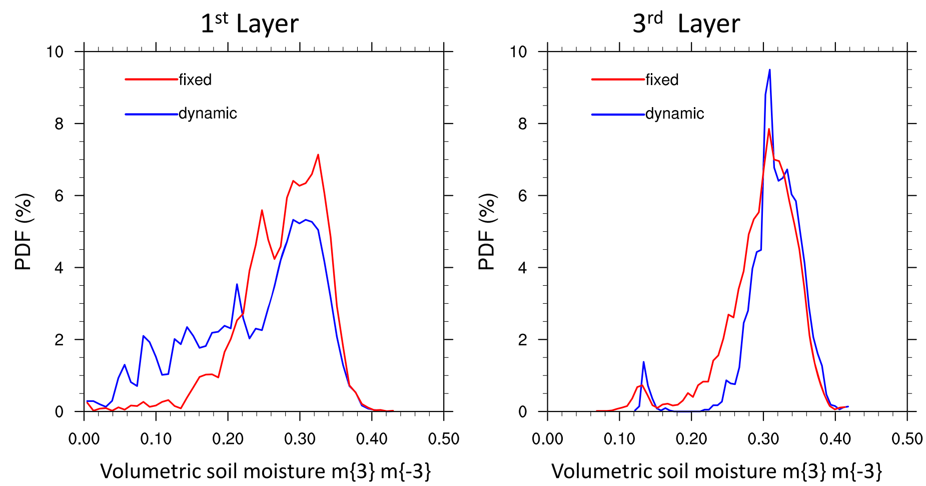

Figure 7. The probability distribution of simulated soil moisture of first soil layer (0– 0.1 m, upper panel) and third soil layer (0.4–1 m, lower panel) for June 2015.

3.4.2. Evaluations With SCAN Data Sites

To further evaluate the regional-scale simulation results, we compared results against in situ data from four agricultural locations from the SCAN network. These sites are distributed across different states and include Phillipsburg, KS; Princeton, KY; McAllister Farm, TN; and Johnson Farm, NE. We extracted the simulated soil moisture fields corresponding to grids overlaying the SCAN sites from the regional-scale simulation and compared the data against the in situ measurements. The SCAN soil moisture is measured at 5 cm using a dielectric constant measuring device (https://www.wcc.nrcs.usda.gov/scan/scan_brochure.pdf). The comparison is for the early stages of the growing season: 1 May to 24 June in 2015. Based on USDA NASS (1997) report, the most active state-level planting dates for the four sites are 25 April (KS), 21 April (KY), 15 April (TN), and 3 May (NE). The results summarized in Figure 10 show that *dynamic_root* has lower RMSE when compared to *fixed_root* for the four sites. At Princeton site, the RMSE of *dynamic_root* is 50% lower than *fixed_root*. Since Princeton site and McAllister Farm have earlier state-level planting dates, the

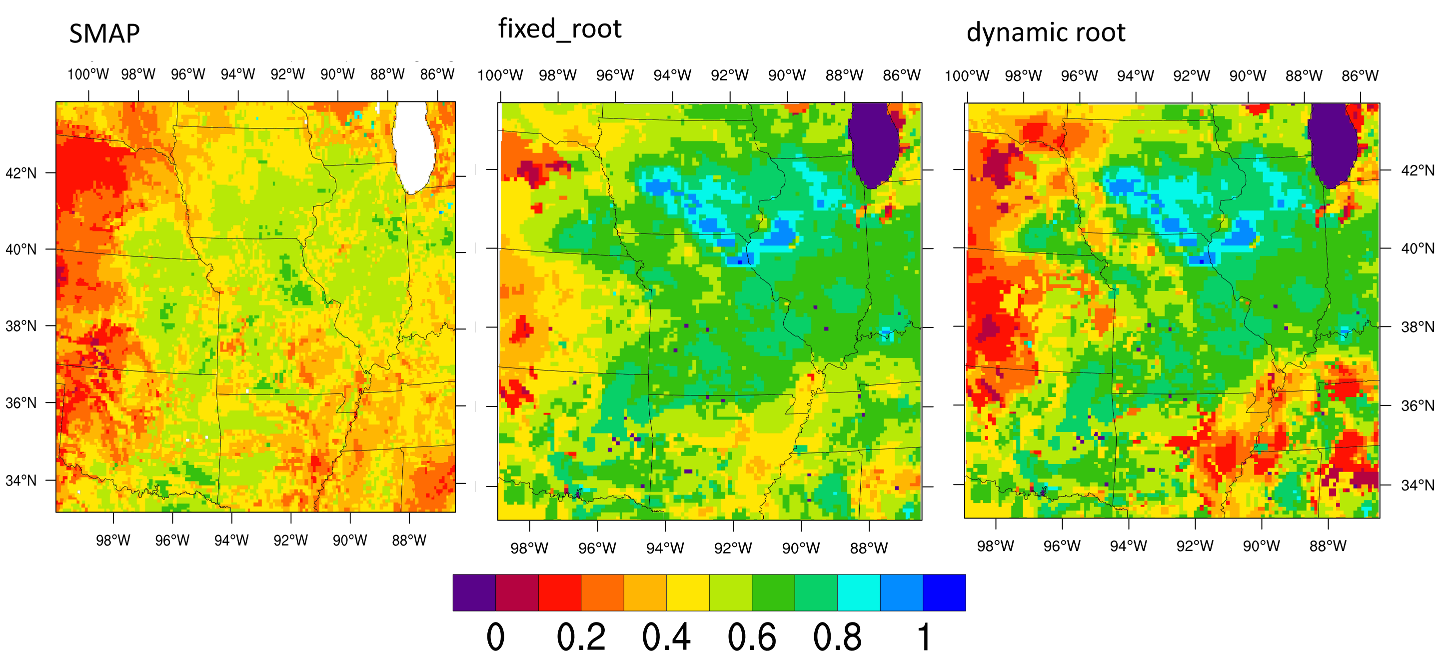

Figure 8. Comparison between model simulations and SMAP L4 imagery data of the first layer soil moisture (normalized).

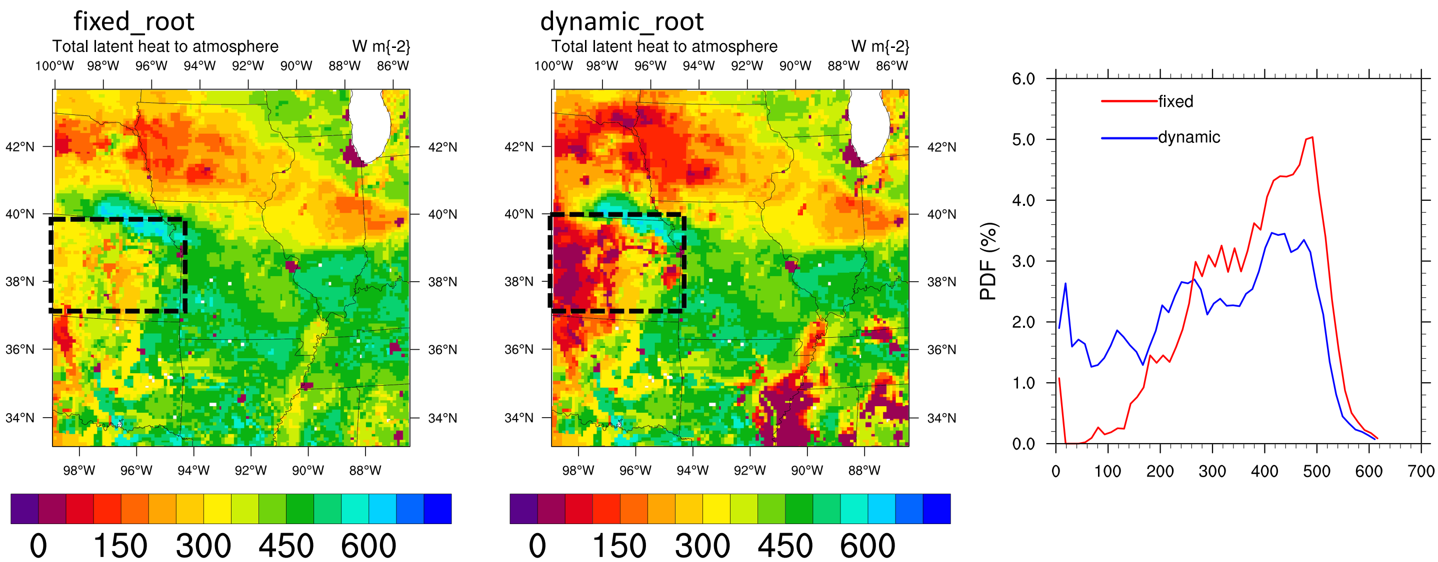

Figure 9. Simulated total latent heat flux and the probability distribution of the same corresponding to 25 June 2016 18:00 UTC. The area within the black dotted box represents part of State of Kansas.

soil moisture observations show a drawdown in June because of the root process, which is captured by *dynamic_root*. However, both the *dynamic_root* and *fixed_root* fail to reproduce the reduction observed in early May at the Princeton site and also overestimated the soil moisture at Johnson Farm. Indeed, a limitation

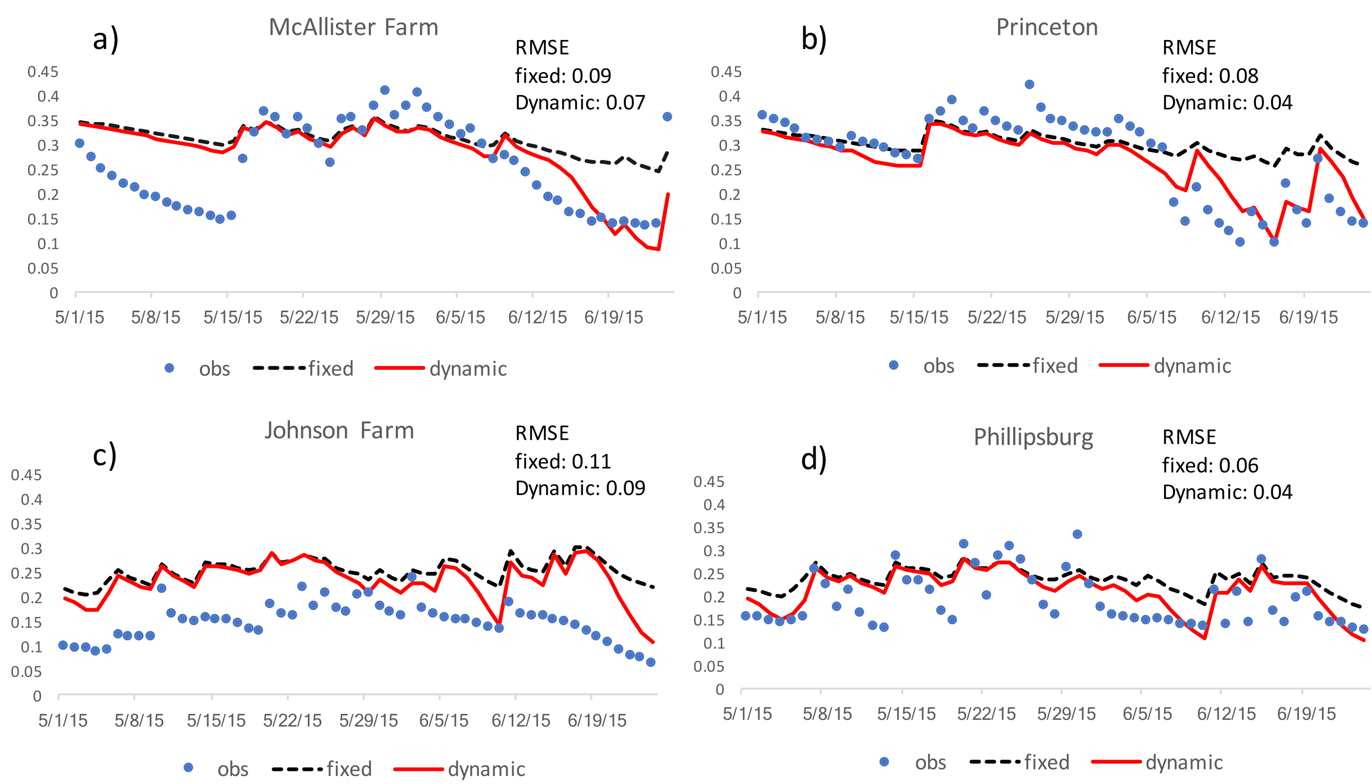

Figure 10. Comparison between simulated (fixed: *fixed_root* simulation; dynamic: *dynamic_root* simulation) soil moisture top layer (0–0.1 m) with observed soil moisture (obs) from SCAN sites at (a) McAllister Farm, TN; (b) Princeton, KT; (c) Johnson Farm, NE; and (d) Phillipsburg, KS. RMSE of each site is also displayed in the figure.

in comparing gridded model results with in situ measurement is that the 10 km grid spacing cannot capture the site-specific observations because of differences expected in the soil type and precipitation amount that can vary significantly within the grid.

4. Conclusions

A biomass-based dynamic rooting depth formulation was successfully implemented into the Noah-MP-Crop. The new scheme allows the root to access moisture dynamically from different soil layers throughout the growing season. By incorporating dynamic rooting depth, the model showed improvement in simulating soil moisture in a field-level experiment (Bo-1, 2001), as well as at four SCAN sites for a regional-scale experiment. The *Dynamic_root* also shows significant improvements in the surface fluxes at field-level experiments (Ne-3). The enhanced performance was particularly notable at the peak of the growing season. By allowing the roots to grow deeper, the soil moisture profile showed a noteworthy change—mainly when there were water limiting conditions during crop development.

Because of the lack of measurements of actual rooting depths and field level and the gap between representativeness of grid-level soil moisture and point-level measurements, it is indeed difficult to fully assess the impact of the implementation of the *Dynamic_root* in the regional LDAS simulations. However, the results provide convincing and consistent overall improvements in the model results regardless of the spatial scales. At the regional level, modifying the rooting depths can cause drastic differences in the simulated soil moisture and latent heat flux values, which can significantly impact the atmospheric feedbacks, and remains to be carefully evaluated using coupled modeling studies. The results highlight the importance of dynamic rooting depth on the simulation of land surface processes.

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