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Impact of cover crop on corn–soybean productivity and soil water dynamics under different seasonal rainfall patterns

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Abstract

The effect of cover crop (CC) on soil water balance and agricultural production is closely related to rainfall amount and distribution in rainfed cropping systems. This study used the root zone water quality model, RZWQM2, calibrated and validated with 4-yr field measurements to predict the effect of planting a winter wheat (*Triticum aestivum* L.) CC in a no-till rainfed corn (*Zea mays* L.)–soybean (*Glycine max* L.) rotation on soil water balance, crop yield, and grain water-use efficiency (WUE) in northeast Mississippi. Seasonal rainfall for 80 consecutive years (1938–2017) was classified as 'wet,' 'normal,' and 'dry' years using frequency analysis, and the data sets matched chronologically to wheat, corn, and soybean growth periods were used as an input parameter in RZWQM2 simulations. During autumn and spring (early October to early April), the CC reduced deep drainage by 69 (11%), 53 (15%), and 51 mm (21%) in wet, normal, and dry years, respectively. Averaged across 40 yr, the CC decreased surface evaporation by 64 (32%) and 38 mm (24%) for corn and soybean growth periods, respectively. Wheat CC also improved soil water storage in early crop growth period during April–June in any of the three rainfall patterns. Regardless of rainfall patterns, the increase in WUE can be attributed to a decrease in evapotranspiration during cash crop period without sacrificing cash crop yield in the CC system. Introducing CC into cropping systems is beneficial to reduce annual deep drainage and evaporation while maintaining higher crop yields under different rainfall patterns.

1 | INTRODUCTION

To meet needs of a growing world population in the face of increasing climate variability, agricultural systems will be required to be more efficient in water use (Dietzel et al., 2016; Jin et al., 2017; Kang et al., 2017). There is a need to promote efficient use of water for ensuring food security in the 21st century under increased climate variability (Araya, Kisekka, Gowda, & Prasad, 2017; Kunkel et al., 2013; Wallace, 2000). The southeastern United States is one of the nation's leading commodity crop planting regions due to its intensive crop production systems (Feng, Ouyang, Adeli, Read, & Jenkins, 2018; Yang et al., 2019a). Corn (*Zea mays* L.)–soybean (*Glycine max* L.) rotation is a common conventional cropping system in Mississippi, where these two crops are often not limited by water resources. Annual rainfall in the region is approximately 1400 mm, with roughly 37% received during summer crop growth period and the remainder occurring

Abbreviations: CC, cover crop; ET, evapotranspiration; NCC, no cover crop; RZWQM2, root zone water quality model; WUE, water-use efficiency.

during autumn and spring (from early Oct. to early Apr.) when much of the land is left unseeded (Feng et al., 2016). However, the changes in dry events during summer growing season in the region are predicted to increase (Feng et al., 2018; Iqbal et al., 2018). In eastern Mississippi, over 90 yr, 61% was moderate dry, 32% was severe drought, and 11% was extreme drought (Vories & Evett, 2014). These predicted rainfall changes may have the potential to affect soil water balance, crop yield, and water-use efficiency (WUE) under corn and soybean cropping systems (Cai, Wiebe, Wang, & Sheldon, 2000; Yang et al., 2019a).

Core ideas

- An 80-yr seasonal soil water balance was simulated with root zone water quality model, RZWQM2.
- Wheat cover crop reduced deep drainage and increased evapotranspiration during autumn and spring.
- Cover crop did not improve cash crops yield in any of the three seasonal rainfall patterns.
- Cash crop grain WUE and soil water storage during summer growing season were improved by cover crop.

Employing cover crop (CC) agronomic practices, as used for improving soil water dynamics (such as improved soil water storage through reducing subsurface drainage), is one approach to potentially mitigate the adverse effects of rainfall variability on crop yield in cropping systems (Camarotto et al., 2018; Gabriel, Muñoz-Carpena, & Quemada, 2012; Martinez-Feria, Dietzel, Liebman, Helmers, & Archontoulis, 2016; Schipanski et al., 2014; Ward, Flower, Cordingley, Weeks, & Micin, 2012). The favorable role of CC in reducing subsurface drainage and in increasing soil water storage has been widely reported (Drury et al., 2014; Hanrahan et al., 2018; Krueger, Ochsner, Porter, & Baker, 2011). However, the recent review by Blanco-Canqui et al. (2015) indicates some uncertainties in the amount of soil water storage in CC-based cropping systems under different rainfall conditions. In central Iowa, with a mean annual rainfall of 950 mm, Basche et al. (2016a) found that consecutive 7-yr use of a cereal rye (*Secale cereale* L.) CC contributed to improved soil moisture while maintaining high corn and soybean yields, and led to increases in field capacity water content of 11–12% and plant available soil water of 21–22%. A meta analysis, based on 93 paired observations, showed that planting cover crop significantly increased water retained at field capacity by 9.3%, and this favorable effect was more obvious in relatively drier climate (Basche & DeLonge, 2017). Qi and Helmers (2010) demonstrated plots planted to rye CC for a 3-yr period had lower soil water storage and subsurface drainage and greater evapotranspiration (ET) than the bare plots. In a dry year of 2012, rye CC did not change or increased soil water storage in the different sites in Iowa and Indiana (Daigh et al., 2014). Some have found that CC residue significantly improved soil water storage under relatively dry summer conditions (Wang et al., 2015; Zhang, Lövdahl, Grip, Jansson, & Tong, 2007).

In general, direct measurement of subsurface drainage, ET, and soil water storage in cropland is difficult and costly (Dietzel et al., 2016b; Qi, Helmers, Malone, & Thorp, 2011). Computer simulation provides a promising approach for quantification of soil hydrological components. The process-based agro-system models, such as the Root Zone Water Quality Model (RZWQM2; Ma et al., 2012), Agricultural Production Systems sIMulator (APSIM; Keating et al., 2003), Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al., 2003), and Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS; Brisson et al., 2003), are widely used to simulate soil water balance and agricultural crop production. Few studies have reported on the role of winter cereal CC in modifying soil water budgets for cropping system productivity with computer simulators under climate variability. In central Iowa, Qi et al. (2011) found long-term (40-yr) planting of cereal rye CC in corn and soybean rotation reduced RZWQM2-simulated annual subsurface drainage by 11% (29 mm) and increased annual ET by 5% (29 mm), as compared to no cover crop. They also found that there was a 20 mm yr^{-1} decrease in actual evaporation simulated in April–June after the rye was terminated compared to no rye CC treatment. Under temperate climate with dry summers, incorporating CC reduced mean annual subsurface drainage by 20 mm yr^{-1} but increased mean annual ET by 20 mm yr^{-1} as simulated by STICS model over 45 yr (Tribouillois, Constantin, & Justes, 2018). Dietzel et al. (2016) used 28-yr historical precipitation data in APSIM-model to simulate the optimum growing season rainfall, runoff, and drainage for maintaining optimum system WUE for corn and soybean in the northwestern United States. While these simulations within a cropping season provide better understanding of the influence of CC on soil water dynamics, the changes in water balance components and agricultural production in the CC-based cropping system are less well-known under different rainfall conditions. In the present study, on the basis of 4-yr field experiment and previously calibrated and validated RZWQM2 model, a long-term simulation study was conducted to determine the effect of winter CC on soil water balance, yield, and WUE in the corn–soybean rotation in northeast Mississippi under three different rainfall patterns, hereafter referred to as dry, normal, and wet years.

The objectives of this study were to: (a) quantify differences in deep drainage and ET with and without wheat (*Triticum aestivum* L.) CC systems under different seasonal rainfall amounts; (b) determine wheat CC effects on soil water storage under seasonal rainfall patterns; (c) identify mechanisms associated with planting a winter CC that lead to enhanced grain WUE of cash crop under different seasonal hydrological years.

2 | MATERIALS AND METHODS

2.1 | Climate, soil, and cropping system

The field site is located at the Mississippi Agricultural and Forestry Experiment Station in Pontotoc County, Upper Coastal Plain Region, Mississippi State (34°7′55″ N, 89°0′ 23″ W, and 150-m elevation). This site has a humid climate with average annual precipitation of 1,375 mm (1938–2017). Approximately 60% of annual precipitation falls between early October and early April. The average annual air temperature is 17°C and the average air temperature between May and September is 26°C. The soil texture in a 30-cm soil profile is silt loam. For the soil depths of 0–30 cm, the pH, total N, and total C averaged 6.0, 0.8 , and 10.3 g kg^{-1}, respectively.

An experiment compared a corn–soybean rotation with (CC) and without (NCC) winter wheat cover crop from October 2013 to October 2017. The experimental design was a complete randomized block design with four replications. The plot dimension was 27 m^2 (9 m by 3 m) with four rows and row spacing of 0.75 m. All crops were grown with continuous no-tillage and without supplemental irrigation. All corn and soybean field operations were performed at the same time and rates except for the cover crop. All experimental plots received NH_4NO_3–N (190 kg N ha^{-1}) surface broadcast by hand to plots after planting of corn in May 2014 and May 2016. Winter wheat CC (cultivar 'Terral 8861') was broadcast at the soil surface at 2.67×10^6 seed ha^{-1} in mid-October each year. Corn (cultivar 'Dekalb 63–84 VT3') was planted at 10.5×10^4 seed ha^{-1} in April in even years. Soybean (cultivar 'Asgrow 4632') was planted at 3.0×10^6 seed ha^{-1} in May in odd years. Agronomic details can be found in Table 1.

2.2 | RZWQM2 model calibration and evaluation

The RZWQM2 was developed by the USDA-Agricultural Research Service (Ahuja, Johnsen, & Rojas, 2000; Ma et al., 2012), and was widely used to simulate soil water balance (Anapalli, Reddy, & Jagadamma, 2018; Li et al., 2008; Qi et al., 2011), carbon and nitrogen (Ma et al., 2007; Malone et al., 2014; Yang, Feng, Tewolde, & Li, 2019b), and crop growth and development (Anapalli et al., 2018; Yang et al., 2019a) in various agricultural soils. The current RZWQM2 (current version 4.00.2017) was calibrated and validated in simulating water budget components in the agricultural production systems at Mississippi State (Anapalli et al., 2016, 2018, 2019; Tang et al., 2017). According to these calibrated procedures, parameters, and modeling performance, the RZWQM2 used in the study has been calibrated and validated with 4-yr comprehensive field measurements in the no-tillage and rainfed corn–soybean rotation with wheat CC and without CC in Pontotoc County, Mississippi (Yang et al., 2019a).

The CC and NCC treatments were used to calibrate and validate the model respectively. A 1.8-m soil profile was divided into seven horizons. Particle size distribution, bulk density, and volumetric water content at 15 and 1/3 bars for each soil layer were measured at the start of the field experiment in October 2013 and were input to the model (Yang et al., 2019a). Measured saturated hydraulic conductivity for each soil layer was estimated based on measured bulk density, particle size distribution, and volumetric water content at 1/3 bar (Ahuja et al., 2000). Initial soil moisture and saturated hydraulic conductivity were calibrated for reasonable hydrological variables. Albedo values for wet and dry soils were .11 and .21 as observed by Post et al. (2000) and used in the RZWQM2. Detailed calibrated processes for soil water balance (Anapalli, Fisher, Reddy, Rajan, & Pinnamaneni, 2019; Feng et al., 2016; Yang et al., 2019a) and soil physical parameters, as required by the model, were adapted from Yang et al. (2019a). Measurements of soil organic C were used to calibrate initial conditions for the three organic matter pools (residue, organic, and microbial) in the nutrient component of model (Anapalli et al., 2018; Feng et al., 2015). Across soil layers, the transfer coefficients for various organic C pools, including slow residue to intermediate organic pool (.3), fast residue to fast organic pool (.7), fast organic pool to intermediate organic pool (.4), and intermediate organic pool to slow organic pool (.7), were adapted from Ma et al. (2007) and used in Anapalli et al. (2016), Feng et al. (2015), and Yang et al. (2019b) at Mississippi. Residue cover factor type (2.5), age of surface residue (60 d), height of standing residue (15 cm), and C/N ratio (30:1) were input to the nutrient module of the model (Feng et al., 2015). The NO_3–N and NH_4–N concentrations from precipitation were predicted to be .7 and .2 mg L^{-1} at Mississippi State (Feng et al., 2015; Qi et al., 2011). Soil NO_3–N and NH_4–N at 1.2-m depth were observed and used in the model run, and assumed to be the same below 1.2 m (Yang et al., 2009a). Plant physiological parameters of corn, soybean, and winter wheat calibrated by Feng et al. (2015), Malone et al. (2014), and Qi et al. (2011) were input to initial the crop growth models. Following these, parameters were recalibrated based on measured phenology, leaf area index, crop yield, and aboveground biomass over the 4-yr experimental period. The final calibrated crop physiological parameters of wheat, corn, and soybean are listed in a table developed by Yang et al. (2019a).

After calibrating the model with "satisfactory" performance, the parameters calibrated above were used to validate the model in terms of phenology, leaf area index, soil

TABLE 1 Field operations for a corn–soybean annual rotation under no-tillage and rainfed conditions in 2013–2017 at Pontotoc, MS

Crop	Sowing date	Cash crop harvest and wheat termination	N amount kg N ha^{-1}	N application date
Wheat	12 Oct. 2013	10 Apr. 2014	–	–
Corn	12 Apr. 2014	5 Sept. 2014	190	7 May 2014
Wheat	20 Oct. 2014	9 Apr. 2015	–	–
Soybean	15 May 2015	15 Oct. 2015	–	–
Wheat	17 Oct. 2015	5 Apr. 2016	–	–
Corn	25 Apr. 2016	12 Sept. 2016	190	6 May 2016
Wheat	16 Oct. 2016	5 Apr. 2017	–	–
Soybean	16 May 2017	18 Oct. 2017	–	–

moisture, ET, crop yield, and aboveground biomass (Yang et al., 2019a). Simulated ET values during corn and soybean growth periods over 4-yr were comparable with the ranges of Anapalli et al. (2018), Anapalli et al. (2019), Feng et al. (2016), and Zhang et al. (2018) in the cropping system at Mississippi State. According to modeling performance of calibration and validation treatments, the RZWQM2 model was considered to be acceptable as "satisfactory" in the corn and soybean system with wheat CC (calibration plots) and without CC (validation plots) under no-tillage and rainfed conditions at the site, in terms of results of statistical criteria (Yang et al., 2019a): percent error <11%, relative root mean square error <23%, coefficient of determination <.88, and Nash–Sutcliffe modeling efficiency < .93.

2.3 | Simulation scenarios setup

We used the calibrated and validated RZWQM2 model to predict the long term effect of wheat CC on soil water balance (deep drainage, runoff, evaporation, and transpiration, and soil water storage) and cash crop productivity in wet, normal, and dry years. Two scenarios were simulated with RZWQM2: (a) corn–soybean rotation with CC; and (b) corn–soybean rotation without cover crop (NCC). Meteorological data from 1938 to 2017 was input to the model. Missing meteorological data including air temperature, relative humidity, and wind speed were supplemented with data from the Tupelo weather station, 35-km north of site (https://www.wunderground.com/history/airport/KTUP).

The simulated planting date of wheat was 10 October every year, while the termination date was set at 9 April in the period 1938–2017. Simulated corn planting date was 15 April and harvest date was 10 September (even years only). Simulated soybean planting date was 15 May and harvest date was 8 October (odd years only). Simulated seeding rates for wheat, corn, and soybean were 2.67×10^6, 10.5×10^4, and 3.0×10^6 seeds ha^{-1}, respectively. Simulated N application rate as NH_4NO_3–N was 190 kg N ha^{-1}, and it was applied as surface broadcast on 10 May in corn (even years only).

2.4 | Classification of wet, normal, and dry years

To compare the differences in soil water balance, yield, and WUE under CC and NCC scenarios, rainfall patterns were classified as 'dry,' 'normal,' and 'wet' years using frequency analysis of 80 consecutive years (1938–2017) for separately growing season rainfall of each crop (wheat, corn, and soybean). The detailed calculation procedures for classifying rainfall patterns in a certain period were demonstrated by Feng et al. (2018) and Tang et al. (2017). First, accumulative rainfall values for each of the simulated crops, wheat, corn, and soybean from planting date to harvesting date, were ranked (n) and labeled from largest to lowest according to rank (m). Here, n = 80, 40, and 40, and m = 80, 40, and 40 for wheat, corn, and soybean, respectively. Second, the rainfall probability (P) for each crop growth period was computed for each ranked year (m) with an equation: $P = m\,(n+1)^{-1}100\%$. Third, each seasonal year for each crop was categorized as 'wet' if $P \leq 25\%$, 'normal' if $25\% < P < 75\%$, and as 'dry' if $P \geq 75\%$. Accordingly, there were 20 wet, 40 normal, and 20 dry years for wheat; 10 wet, 20 normal, and 10 dry years for corn; and 10 wet, 20 normal, and 10 dry years for soybean (Figure 1).

2.5 | Soil water balance and water-use efficiency

For any of the three rainfall patterns, simulated water balance components and change in soil water storage at 1.8-m soil profile during cash crop growth periods in the RZWQM2 model were calculated as (Thorp, Jaynes, & Malone, 2008):

$$\Delta S = P - \mathrm{RO} - E - T - D$$

where ΔS is the change in soil water storage (mm), P is precipitation (mm), RO is runoff (mm), E is evaporation (mm), T is transpiration (mm), and D is deep drainage (mm).

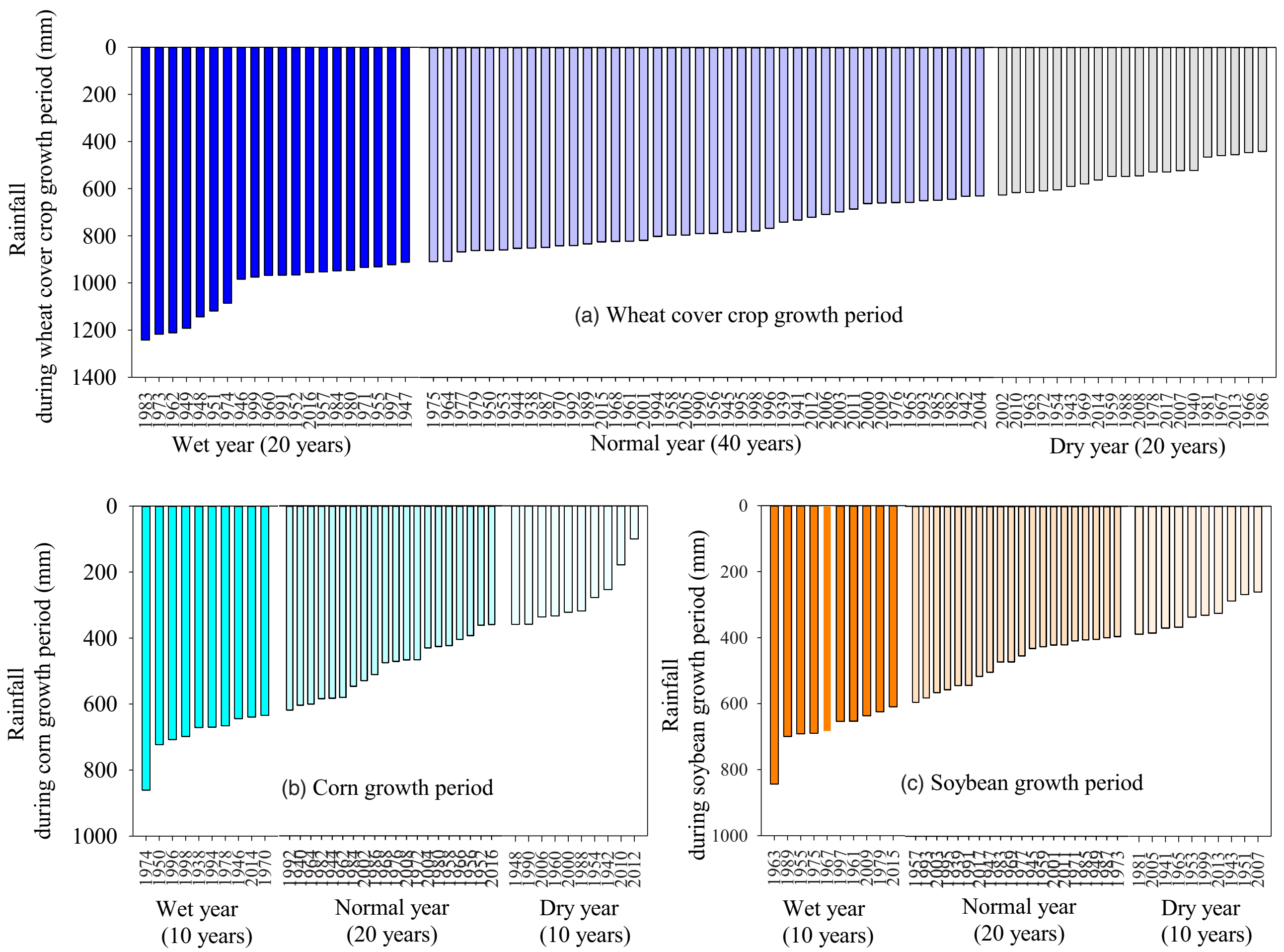

FIGURE 1 Total rainfall during wheat cover crop, equivalent to seasonal-year total (a) during corn (b) and soybean (c) growth periods that had different rainfall patterns, based on rainfall accumulated in the corresponding crop growth periods during 1938–2017

The predicted grain WUE during cash crop growth periods was estimated as:

$$\text{predicted grain WUE} = \frac{\text{predicted grain yield}}{\text{predicted } E + \text{predicted } T}$$

where the units of grain yield and WUE are kg ha^{-1} and kg ha^{-1} mm^{-1}, respectively.

3 | RESULTS

3.1 | Rainfall and frequency

The range of rainfall accumulated in the CC growth periods was 912–1242 mm (mean = 1029 mm) in wet years, 603–908 mm (mean = 771 mm) in normal years, and 441–626 mm (mean = 540 mm) in dry years (Figure 1). The median values of rainfall for CC in wet, normal, and dry years were 967, 790, and 545 mm, respectively. The average rainfall amount in wet years during CC growth period was 1.33-times greater than that in normal years and 1.89-times greater than that in dry years. The range of rainfall accumulated during corn growth period was 634–861 mm (mean = 692 mm) in wet yeas, 360–690 mm (mean = 492 mm) in normal years, and 101–359 mm (mean = 284 mm) in dry years. The maximum rainfall accumulated during corn growth period was 861 mm in 1974, and the minimum was 101 mm in 2012. The median values of rainfall for corn in wet, normal, and dry years were 670, 473, and 320 mm, respectively. The range of rainfall accumulated during soybean growth season was 609–843 mm (mean = 679 mm) in wet years, 395–595 mm (mean = 463 mm) in normal years, and 259–388 mm (mean = 331 mm) in dry years. The median values for soybean in wet, normal, and dry years were 669, 442, and 333 mm, respectively. Among the 40 years of simulated soybean cropping, 12 years (30%) had rainfall below 400 mm, 10 years (25%) had rainfall between 401–500 mm, 8 years (20%) had rainfall between 501–600 mm, and the remaining 8 years had rainfall above 600 mm.

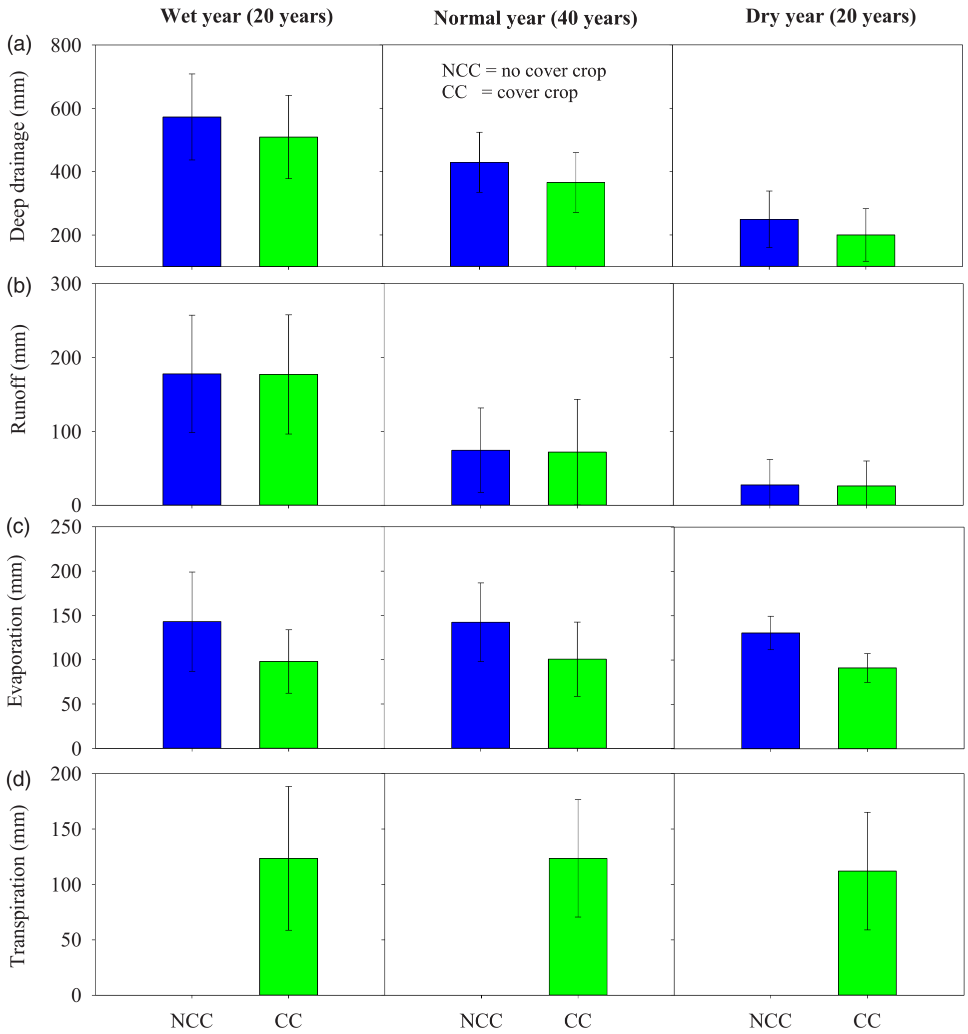

FIGURE 2 Simulated average deep drainage (a), runoff (b), evaporation (c), and transpiration (d) for no wheat cover crop (NCC) and cover crop (CC) scenarios during the cover crop growth period under different rainfall patterns, based on rainfall accumulated in the cover crop growth period. The vertical lines represent the standard deviation of the mean

3.2 | Water balance components

3.2.1 | Winter wheat cover crop growing season

As shown in Figure 2, the range of simulated deep drainage below 1.8-m soil profile in NCC system was 305–859 mm (mean = 589 mm) in wet years, 245–581 mm (mean = 426 mm) in normal years, and 140–379 mm (mean = 239 mm) in dry years. The range of deep drainage under CC was 228–793 mm (mean = 520 mm) in wet years, 135–502 mm (363 mm) in normal years, and 90–351 mm (mean = 188 mm) in dry years. These results suggest that, compared to NCC system, planting CC reduced deep drainage by approximately 69 mm (11%) in wet years, 63 mm (15%) in normal years, and 51 mm (21%) in dry years. The largest difference in deep drainage between CC and NCC systems was 139, 130, and 99 mm for wet, normal, and dry years, respectively. For the CC system, average deep drainage was 157-mm greater in wet years than normal years and 331-mm greater in wet than dry years. In contrast, average deep drainage for NCC system was 162-mm greater in wet years than in normal years, and 349-mm greater in wet than dry years. Simulated surface runoff averaged 178 mm in wet years, 74 mm in normal years, and 27 mm in dry years in NCC system. These simulated runoff values were correspondingly comparable to the simulated runoff values in CC system. Relative to fallow soil, the CC system increased average plant transpiration by 123, 124, and 112 mm in wet, normal, and dry years, respectively; however, it reduced average surface evaporation by 45 (31%), 42 (29%), and 39 mm (30%) in wet, normal, and dry years, respectively. Thus, the CC system increased average ET by 78 (55%), 82 (57%), and 73 (56%) in wet, normal, and dry years, respectively.

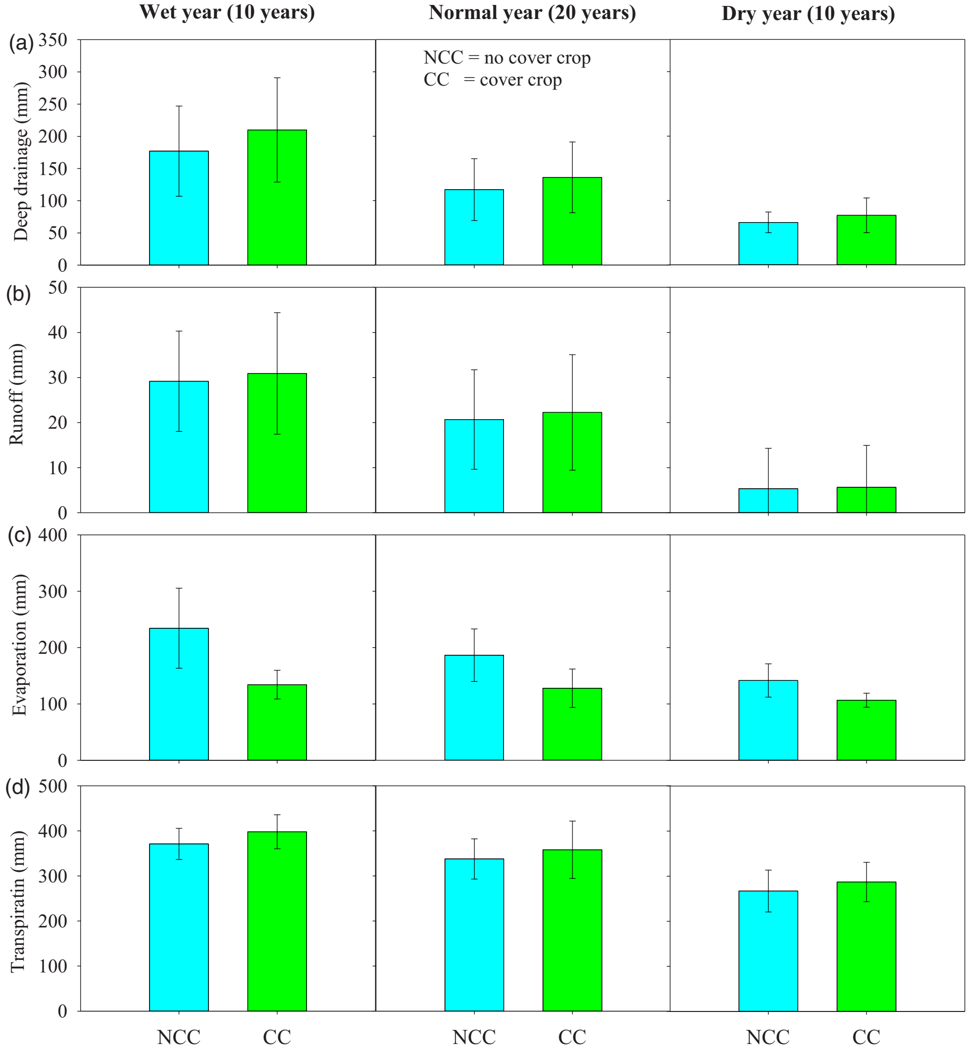

FIGURE 3 Simulated average deep drainage (a), runoff (b), evaporation (c), and transpiration (d) during the corn growth period under the no wheat cover crop (NCC) and cover crop (CC) scenarios and different rainfall patterns, based on rainfall accumulated in the corn growth period. The vertical lines represent the standard deviation of the mean

3.2.2 | Corn growing season

During corn growing seasons, simulated deep drainage averaged 21 mm (17%) lower under NCC system than CC system over 40 historical years (Figure 3). For the scenario with CC, the range in annual deep drainage during corn growth period was 87–338 mm (mean = 209 mm) for wet years, 57–234 mm (mean = 136 mm) for normal years, and 42–116 mm (mean = 77 mm) for dry years. Relative to plots without CC, the CC system increased annual deep drainage by 33 (19%), 19 (16%), and 11 mm (15%) in wet, normal, and dry years, respectively. Without CC residue, the deep drainage during crop growth period was 60 mm greater in wet than normal years, and 111 mm greater in wet than dry years. In contrast, results with CC system indicated a 74-mm (54%) difference in deep drainage between wet and normal years, and 133-mm (172%) difference between wet and dry years. There was basically no difference in simulated runoff for CC and NCC systems in wet (29 vs. 31 mm), normal (20 vs. 21 mm), and dry year (5 vs. 5 mm). Relative to NCC system, the CC system reduced surface evaporation by 100, 59, and 35 mm in wet, normal, and dry years, respectively, giving an average reduction of 64 mm. Compared with NCC system, CC led to annual transpiration increase of 27 (7%), 21 (6%), and 21 mm (8%) in wet, normal, and dry years, respectively, giving an average increase of 23 mm (7%). It was concluded that CC reduced ET by 62 (507 vs. 569 mm), 25 (482 vs. 507 mm), and 12 mm (363 vs. 375 mm) across wet, normal, and dry years, respectively, with a reduction of 33 mm over all 80 simulation years. We further observed that planting winter wheat CC improved soil water storage, especially in early growth period during April–June (Figure 4).

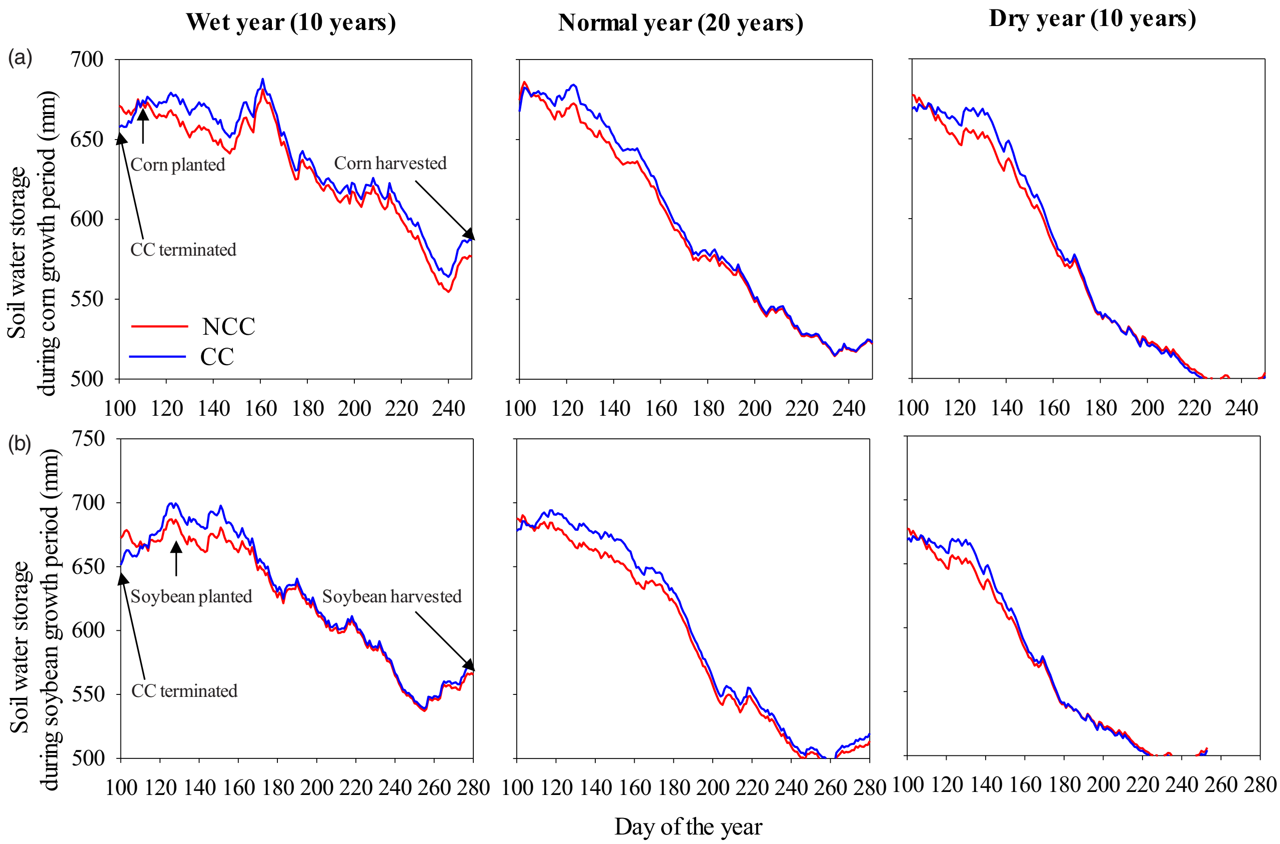

FIGURE 4 Simulated daily average soil water storage in the 1.8-m profile during 40 years of corn (a) and 40 years of soybean (b) growth periods under the no wheat cover crop (NCC) and cover crop (CC) scenarios and different rainfall patterns, based on seasonal rainfall from chemical termination of wheat in spring to grain harvest of summer crop in fall.

3.2.3 | Soybean growing season

Over the 40 years, average simulated deep drainage during soybean growth period ranged from 4.9 to 336 mm (mean = 113 mm) for CC system, and from 9.0 to 281 mm (mean = 92 mm) for NCC system (Figure 5). Compared to NCC system, average deep drainage under the CC system was increased by 41 mm in wet years, 26 mm in normal years, and 7 mm in dry years. Without CC, mean deep drainage values across wet years were 75 mm greater than normal years and 116 mm greater than dry years. For CC system, annual deep drainage averaged 86 mm greater under wet than normal years, and 144 mm greater under wet than dry years. Compared with dry years, the difference in deep drainage during crop growth period between CC and NCC systems was enlarged in normal and wet years. The simulated runoff was basically same under CC and NCC systems in each of three rainfall patterns. On average, relative to plots without CC, wheat CC reduced surface evaporation by 53 mm (29%) in wet years, 40 mm (24%) in normal years, and 22 mm (17%) in dry years, with mean value of 38 mm. Average surface evaporation was decreased by 53, 40, and 22 mm for CC system under wet, normal, and dry years, respectively, giving an average reduction of 38 mm (24%) across years. Compared to NCC system, CC system increased crop transpiration by 24, 19, and 17 mm (mean = 20 mm) in wet, normal, and dry year. Similarly, relative to NCC system, CC system led to ET reductions of approximately 30 mm (537 vs. 567 mm) in wet years, 20 mm (504 vs. 524 mm) in normal years, and 6 mm (449 vs. 455 mm) in dry years. For the CC-based scenario, in the dry years, these differences were 55 and 88 mm less than wet and normal years, respectively. The simulations indicated that planting CC enhanced soil water storage in early crop growth period during April–June in any of the three rainfall patterns (Figure 4).

3.3 | Crop yield and water-use efficiency

For both NCC and CC systems, the largest coefficient of variation for simulated corn grain yield was in dry years, followed by normal years, and the smallest was in wet years. Averaged yearly and compared to plots with NCC, planting CC increased yield by 144 kg ha^{-1} (5,004 vs. 5,148 kg ha^{-1}) in dry years, but did not improve yield in either wet or normal year. In general, average simulated yield did not differ

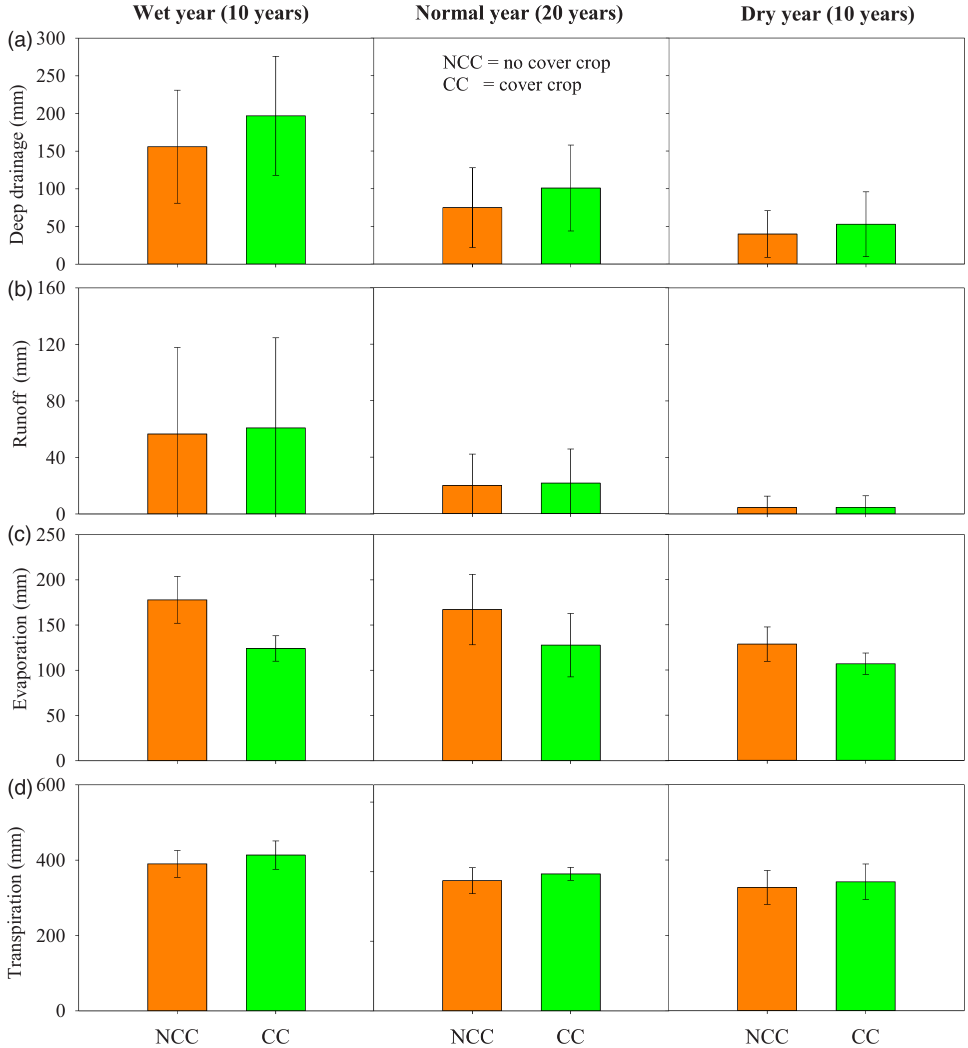

FIGURE 5 Simulated average deep drainage (a), runoff (b), evaporation (c), and transpiration (d) during the soybean growth period under the no wheat cover crop (NCC) and cover crop (CC) scenarios and different rainfall patterns, based on rainfall accumulated in the soybean growth period. The vertical lines represent the standard deviation of the mean

significantly between NCC and CC scenarios in any of the three rainfall patterns (Table 2). For NCC scenario, average yield was 1,866 kg ha^{-1} (27%) greater in wet than normal years, and 3,839 kg ha^{-1} (76%) greater in wet than dry years. Similarly, in the CC system, average yield was 1850 kg ha^{-1} (26%) greater in wet than normal years, and 3,673 kg ha^{-1} (72%) greater in wet than dry years. Simulated values for WUE in corn ranged from 9.5–18.8 kg ha^{-1} mm^{-1} for NCC system and 9.7–22.8 kg ha^{-1} mm^{-1} for CC system. Relative to simulated WUE values in dry years, the mean WUE for NCC scenario was improved by 26% in wet years, and 6% in normal years; whereas, mean WUE for CC scenario was increased by 33% in wet years and 20% in normal years, respectively.

For either NCC or CC scenario, simulated soybean grain yield had the largest coefficient of variation in dry years, followed by normal years and wet years (Table 3). Averaged yearly and relative to NCC scenario, planting CC resulted in slight increase in simulated soybean yield of 16, 52, and 41 kg ha^{-1} in wet, normal, and dry years, respectively. For the NCC-based system and compared with yield values in wet year, mean and maximum yields decreased by approximately 2,113 kg ha^{-1} (52%) and 1,029 kg ha^{-1} (23%) in dry year, and by approximately 919 kg ha^{-1} (23%) and 292 kg ha^{-1} (6%) in normal year. As compared to NCC, use of CC improved WUE on average by 5, 4, and 2% in wet, normal, and dry years, respectively. For CC system and relative to values simulated in dry years, simulated average WUE increased by 79% in wet years and 44% in normal years; however, for the NCC system and as compared to dry years, simulated average WUE increased by 73% in wet years and 40% in normal years.

4 | DISCUSSION

Weather records over the past 80 years for the study site in northeast Mississippi indicate approximately 1,375 mm

TABLE 2 Simulated grain yield and water-use efficiency (WUE) for corn under different rainfall patterns, based on rainfall during the corn growing season

	Rainfall mm	Statistical parameter	Predicted grain yield kg ha^{-1} NCC[a]	CC[b]	Predicted WUE kg ha^{-1} mm^{-1} NCC	CC
Wet years (n = 10)	634–861	Average	8,843	8,821	15.8	17.1
		Maximum	10,389	10,389	18.8	22.8
		Minimum	7,973	7,991	13.0	13.6
		Median	8,516	8,473	14.5	15.6
		Standard deviation	824	826	2.2	3.3
		Coefficient of variation	.093	.093	.217	.193
Normal years (n = 20)	360–618	Average	6,977	6,971	13.5	14.2
		Maximum	9,097	9,120	16.6	17.6
		Minimum	4,446	4,537	8.4	8.8
		Median	6,959	6,973	13.6	14.5
		Standard deviation	1,440	1,445	2.5	2.6
		Coefficient of variation	.206	.207	.185	.183
Dry years (n = 10)	101–355	Average	5,004	5,148	12.1	12.8
		Maximum	7,267	7,530	15.4	17.2
		Minimum	2,290	2,164	9.5	9.7
		Median	5,120	5,291	12.2	12.8
		Standard deviation	1,424	1,505	2.2	2.4
		Coefficient of variation	.285	.292	.181	.187

[a]NCC, no cover crop.
[b]CC, cover crop.

rainfall annually with nearly 60% received from early October to early April, outside the summer growing season for corn and soybean. Reducing rainfall loss as deep drainage from bare soil with winter CCs is promising for better environmental quality and water conservation (Basche et al., 2016a, 2016b; Hanrahan et al., 2018). Deep drainage increased with increasing rainfall amount in the study, and was reduced by CC during CC growth period (Figure 2). Compared with NCC system, during living CC growth period, a long-term simulation found that planting CC reduced deep drainage by 59 mm (21%) on average in corn–soybean rotation system. Over 80-yr of corn–soybean rotations, simulated annual drainage was reduced by 36 mm (6%) when a wheat CC was planted in experimental plots when averaged over three rainfall patterns. The simulation result was within a range of 18–106 mm reported for a rye CC in consecutive 4-yr corn and soybean rotation (Li et al., 2008). The annual drainage reduction simulated in the present study was similar to results of Martinez-Feria et al. (2016), who reported that planting rye CC did not always reduce subsurface drainage (−4±13%) in a 30-yr simulation study. Qi et al. (2011) noted a 29-mm (5%) reduction for annual subsurface drainage in the 40-yr CC system in Iowa. The result was 16 mm higher than the simulation study of Tribouillois et al. (2018) in temperate climate with dry summers in France, as most annual rainfall was in early October through early April. Based on previous long-term simulation studies (30–80 years), the increase of annual ET is responsible for reduction of deep drainage across sites (Qi et al., 2011; Tribouillois et al., 2018; Yang et al., 2019a). However the reduction in drainage with rye CC-cultivated agricultural production was variable, mainly due to difference in CC biomass and rainfall amount between years (Blanco-Canqui et al., 2015; Malone et al., 2014). Martinez-Feria et al. (2016) suggested that annual deep drainage is correlated with annual rainfall amount (r = .98, n = 12) and CC biomass (r = −.75, n = 12) in the rye CC-planted cropping systems. In the current study, therefore, planting CC into corn–soybean rotation is a promising conservation practice for reducing annual deep drainage in upland soils in northeast Mississippi.

Across three types of rainfall pattern, simulated wheat CC shoot biomass averaged 3,865 kg ha^{-1} with 109 mm of plant transpiration (water use) during living CC growth period (Figure 2). Martinez-Feria et al. (2016) demonstrated strong correlation between measured rye CC shoot biomass (y) and its transpiration (x) as estimated by a water balance difference method using experimental data in Central Iowa: y = 47.414x (r = .91, n = 5). The simulated transpiration for wheat CC in the present study was higher than the value reported by Martinez-Feria et al. (2016). The difference in CC transpiration is mainly attributed to higher CC biomass in

TABLE 3 Simulated grain yield and water-use efficiency (WUE) for soybean under different rainfall patterns, based on rainfall during the soybean growth season

	Rainfall		Predicted grain yield		Predicted WUE	
			kg ha^{-1}		kg ha^{-1} mm^{-1}	
	mm	Statistical parameter	NCC[a]	CC[b]	NCC	CC
Wet years (n = 10)	609-843	Average	4,084	4,100	7.3	7.7
		Maximum	4,507	4,549	8.7	9.3
		Minimum	3,529	3,592	5.4	5.9
		Median	4,146	4,136	7.4	7.7
		Standard deviation	273	259	0.9	1.0
		Coefficient of variation	.066	.063	.123	.129
Normal years (n = 20)	395-594	Average	3,165	3,217	5.9	6.2
		Maximum	4,215	4,223	7.9	8.0
		Minimum	2,046	2,106	3.8	3.9
		Median	3,100	3,220	5.9	6.4
		Standard deviation	829	809	1.3	1.3
		Coefficient of variation	.261	.251	.220	.209
Dry years (n = 10)	259-338	Average	1,971	2,012	4.2	4.3
		Maximum	3,478	3,704	6.9	7.3
		Minimum	709	656	1.9	1.7
		Median	2,011	2,073	4.3	4.5
		Standard deviation	911	973	1.7	1.8
		Coefficient of variation	.462	.483	.405	.418

[a]NCC, no cover crop.
[b]CC, cover crop.

the current scenario simulation as compared to other studies (Martinez-Feria et al., 2016; Qi et al., 2011). The CC-induced increase in plant transpiration was closely associated with an increase in CC biomass and a reduction in deep drainage for 45-yr scenario simulations (Tribouillois et al., 2018). There was strong correlation between rye CC transpiration and deep drainage (r = –.94, n = 30) over long-term simulation conducted by Martinez-Feria et al. (2016). Planting wheat CC reduced evaporation by 37 mm during early April to early October when averaged across three rainfall types (Figure 2). These findings are comparable to other studies (Qi & Helmers, 2010; Tribouillois et al., 2018). For each given rainfall patterns, simulated runoff during crop growth period for CC system was comparable to that for NCC system, mainly because the model uses the modified Green-Ampt approach to estimate infiltration rate (Ahuja et al., 2000; Ma et al., 2007; Smith, Qi, Grant, VanderZaag, & Desjardins, 2019). This method does not consider the effects of soil management and crop residue on runoff. Qi et al. (2011) and Gu (2018) reported the same infiltration rate and runoff in the CC- and NCC-based cropping systems. Further simulation studies should therefore include improved runoff simulation based on field measurements. The runoff number curve method developed by USDA-Natural Resources Conservation Services (NRCS) could be incorporated into the RZWQM2 model for improved quantification of surface runoff effects of cover crops, improving the simulation accuracy of runoff in the model (Smith et al., 2019; Yang et al., 2019a).

In any of the three rainfall patterns, wheat CC system slightly increased deep drainage during cash crop growth period (Figure 3). This led to a larger decrease of evaporation in April–June and an increase of plant transpiration during crop growth period while runoff was not changed by CC scenario. Yang et al. (2019a) also found a greater reduction in simulated evaporation than simulated transpiration during corn and soybean growing period in the CC system. Across rainfall classifications, simulated evaporation and transpiration for corn and soybean growth season were similar to results of Anapalli et al. (2016), Feng et al. (2018), and Tang et al. (2017) at Mississippi State. The simulated evaporation for corn and soybean growth seasons was lower with the CC system than the NCC system, and the simulated plant transpiration was higher with the CC system than the NCC system (Figs 3, 5). The decreased evaporation during crop growth period can be attributed to the residue on the soil that remained after the wheat CC was terminated in mid-April (Haghverdi, Yonts, Reichert, & Irmak, 2017; Qi & Helmers, 2010; Qi et al., 2011). These simulations are consistent with Qi et al. (2011), who reported a 21% reduction in evaporation and a 132% increase in transpiration during April–June for 40-yr corn–soybean rotation with rye CC.

Simulated soil water storage at a depth of 1.8 m was increased under the CC scenario in any of the rainfall patterns, especially at early crop growth period (Figure 4). These simulations are consistent with Yang et al. (2019a). Generally, the simulation models with wheat CC terminated chemically in early April each year suggest that wheat CC system enhanced water storage for the following summer crops in normal, wet, and dry years and that water storage for soybean growing season was better in normal year than dry and wet years (Figure 4). Sanders, Andrews, and Hill (2018) found that living CC system may be most favorable for water storage in soils with high water-holding capacity in regions with high precipitation. In a dry year, planting a winter CC increased soil water storage for the cash crops (Dabney, Delgado, & Reeves, 2001; Daigh et al., 2014). Blanco-Canqui et al. (2015) similarly reported a significant increase in soil water storage for the CC-based crop production system during dry or extreme drought years. Planting rye CC was more beneficial for improvement of water storage at a 30-cm soil depth in the wetter year than normal during 7-yr corn and soybean rotation (Basche et al., 2016a). The terminated CC mulch led to water storage increase of approximately 60 mm in the 1.83-m soil profile compared to the NCC system toward the end of the growing season (van Donk et al., 2010). Zhang et al. (2007) found that CC residue mulch increased soil water storage by 5–8%, as compared with the conventional management practice. For CC-induced better soil moisture conditions during cash crop growth period, long-term simulations showed that CC resulted in efficient use of rainfall and improved rainfall conservation in a temperate climate with dry summer.

Over 80 historical years, simulated mean yields for corn and soybean under CC scenario were similar to those predicted under NCC scenario (Tables 2, 3). The chief cause for this was that same N application rate of 190 kg N ha^{-1} was used in corn for these two scenarios. Over the longer-term field experiment in regions with different rainfall patterns, some research found a winter CC of cereal rye did not significantly increase grain yield in rainfed corn and soybean systems in regions with different rainfall patterns (Basche et al., 2016a; Li et al., 2008). Under deficit irrigation conditions, planting CC did not improve dry bean yield significantly (Yonts, Haghverdi, Reichert, & Irmak, 2018). For both CC and NCC scenarios, crop yield across dry years had the largest coefficient of variation, followed by normal years and wet years (Table 3). The rainfall was infrequent in dry summer seasons and rainfall amount did not meet requirements for normal crop growth at critical growth stage, so enlarging the yield difference between the inter-annual yield predictions, especially when drought conditions occurred in August–September in the region (Feng et al., 2018; Li, Li, & Kushnir, 2012; Tang et al., 2017).

For CC system, simulated WUE averaged 6.1 kg ha^{-1} mm^{-1} for soybean and 14.7 kg ha^{-1} mm^{-1} for corn (Tables 2, 3). Simulated values were comparable to the range reported by Dietzel et al. (2016) in regions of western United States. In general, planting wheat CC improved crop WUE for corn and soybean and was associated with the reduction of predicted evaporation and attainment of crop yield similar to NCC treatment (Tables 2, 3). The increase of WUE was largely attributed to a slight reduction of evapotranspiration while maintaining higher yields. The lower evapotranspiration in CC scenario was that the magnitude of decrease in evaporation was more than that of increase in transpiration, when drainage was slightly increased by CC. The long-term simulation study showed that terminated CC residue reduced surface-soil evaporation by 11–13% and increased crop transpiration by a lesser amount of 2–5%, thus enhancing soil water storage and crop WUE under rainfall variations (Zhang et al., 2007). For corn, the WUE was higher in wet than in normal and dry years. Thus, CC did not improve cash crop yield in the corn and soybean rotation, so CC planted in conditions with wetter summer could be favorable for water-saving and favorable agricultural yield. In contrast, rainfall in normal and dry years often did not fully meet crop growth needs; some rainfall was lost either as surface runoff or deep drainage below the root zone, limiting the effectiveness of rainfall and increasing the frequency of periods of water stress. In the southeastern states, the typical ET for corn averaged 569 mm for Mississippi (Feng et al., 2018) and 635 mm for Georgia (Salazar et al., 2012). In contrast, under normal and dry conditions, the rainfall frequently did not fully meet crop growth needs, thus limiting the effectiveness of rainfall and increasing frequency of water stress.

5 | CONCLUSION

Soil water balance and cash crop growth are closely linked to summer rainfall variations, thus we have classified the rainfall patterns with wet, normal, and dry years based on the growing season rainfall of two cash crops under conditions with or without a winter wheat CC. Long-term, 80-year RZWQM2-simulation studies found that introducing winter CC into corn and soybean rotation is a promising management practice to improve rainfall storage in the soil profile and reduce surface evaporation and increase transpiration during cash crop growth season. When averaged across the three types of rainfall patterns and compared to no CC-based corn–soybean cropping system, CC led to deep drainage decrease of 59 mm and ET increase of 78 mm on average during autumn–spring season, from early October to early April. The simulations also showed that planting CC enhanced soil water storage in early cash crop growth period during April–June in any of the three rainfall patterns. Regardless of the simulated rainfall pattern, planting a CC did not substantially improve cash crop grain yield but enhanced crop grain WUE.

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