Conservation tillage increases corn and soybean water productivity across the Ohio River Basin

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Abstract

Optimizing agricultural management practices is imperative for ensuring food security and building climate-resilient agriculture. The past several decades have witnessed the emergence of conservation tillage practices to combat soil erosion and degradation. However, the effects of conservation tillage on crop water productivity (CWP) remain uncertain, especially from a regional-scale perspective. Here, we used an improved process-based agroecosystem model (DLEM-Ag) to quantify the long-term effects of conservation tillage (e.g., no-tillage, NT; reduced tillage, RT) on CWP (defined as the ratio of crop productivity to evapotranspiration) of corn and soybean across the Ohio River Basin during 1979-2018. Our results revealed an average increase of 2.8% and 8.4% in CWP for corn and soybean, respectively, under the NT adoption scenario. Compared to the conventional tillage scenario, NT and RT would enhance CWP, primarily due to reductions in evapotranspiration, particularly evaporation. Further analysis suggested that, although NT and RT may decrease surface runoff, these practices could also increase subsurface drainage and nutrient loss from corn and soybean farmland via leaching. These results indicate that conservation tillage should be complemented with additional water and nutrient management practices to enhance soil water retention and optimize nutrient use in the region's cropland. Our findings also provide unique insights into optimizing management practices for other areas where conservation tillage is widely applied.

Keywords: Conservation tillage, Crop water productivity (CWP), No-tillage, Ohio River Basin (ORB), Process-based agroecosystem model

Abbreviations

CWP	crop water productivity
CT	conventional tillage
ET	evapotranspiration
GPP	gross primary productivity
NT	no-tillage
RT	reduced tillage
ORB	Ohio River Basin

1. Introduction

Water deficits and surpluses represent the greatest challenge facing rain-fed agriculture worldwide (Shekhar and Shapiro, 2019). Increasing drought and extreme rainfall events have already caused significant impacts on water resources and food security globally (Daryanto et al., 2017a; Drum et al., 2017; Li et al., 2019). Adaptation of management practices is critical to improve water resource use efficiency and build climate-resilient agricultural systems (Tian et al., 2018). In that regard, conservation tillage has emerged as a promising option that can help conserve soil moisture and reduce soil erosion, thus alleviating the impact of rainfall deficit on crop yields (Busari et al., 2015; Holland, 2004; Phillips et al., 1980). However, its effects on regional crop water productivity (CWP, defined as the ratio of crop carbon gain to water consumption, Van Halsema and Vincent, 2012) have not yet been fully investigated.

Conservation tillage refers to any tillage system with a seedbed preparation technique in which at least 30% of the soil surface is covered by crop residues (Lal et al., 2017), including no-tillage (NT), reduced tillage (RT), mulch tillage, and ridge tillage. Compared to conventional tillage (CT), conservation tillage decreases soil disturbance and leaves more crop residues on the soil surface. Some studies have reported the positive effects of conservation tillage on CWP across different agroecosystems (Cantero-Martínez et al., 2007; Jabro et al., 2014; Li et al., 2018; Su et al., 2007; Tang et al., 2015). However, other studies have found no effect of conservation tillage on CWP or even lower CWP than CT (Guan et al., 2015; Irmak et al., 2019; Liu et al., 2013). With the recognition that the effects of conservation tillage on CWP involve alteration of soil properties and soil water dynamics in the rhizosphere (O'Brien and Daigh, 2019), these variable results likely reflect not only the direct effect of a tillage practice but also its interactions with climate, soil type, land management history, and cropping systems (Strudley et al., 2008). Failure to account for these differences could lead to uncertainties in regional assessments of the effectiveness of conservation tillage.

Previous studies examining linkages between conservation tillage and CWP have largely in arid/semi-arid regions (Jalal et al., 2014; Yang et al., 2018; Irmak et al., 2019). Less attention has been paid to how conservation tillage affects crop water use in humid areas. These areas face more synergistic effects of water and nutrient supply and are more vulnerable to changes in rainfall (Wuebbles et al., 2017). Although several studies have used remote sensing products (e.g., MODIS GPP and ET) to quantify large-scale variation in CWP (Ai et al., 2020; Lu and Zhuang; 2010), they usually generated results for all croplands but did not provide crop-specific CWP estimates. Moreover, regional and global CWP simulations have generally ignored tillage effects, in part because of the under-representation of tillage processes in global ecosystem models (Tian et al., 2015; Lutz et al., 2019). It is essential to adopt an integrated approach that links process-based agricultural models with ground and satellite observation data to advance predictive understanding of tillage effects on reginal CWP.

Located in the Eastern Corn Belt (Fig. 1), the Ohio River Basin (ORB) is a highly agricultural watershed with almost 98% of its croplands supporting corn and soybean production (according to the 2018 National Cropland Data Layer). The agricultural landscape in the ORB is susceptible to soil erosion due to heavy rains (Drum et al., 2017). Conservation tillage has been promoted as a tool to address soil erosion in this region. Introduced to the ORB region in the 1960s and encouraged by agricultural extension agencies, conservation tillage has steadily grown in adoption during the past several decades (Franklin and Bergtold, 2020). More than 60% of corn and almost 80% of soybean in the ORB are grown under different forms of conservation tillage (CTIC, 2018). The spread of conservation tillage systems in the ORB justifies the need to assess its impact on water use for the dominant crops in the region. Long-term and spatially explicit information on tillage practice effects is urgently needed to address questions of water resource optimization and predicting food production and shortages in the context of climate change. Therefore, the ORB provides an ideal context for a regional examination of these questions using our proposed integrated approach.

Here we used a process-based agroecosystem model (DLEM-Ag) to quantify the magnitude and spatiotemporal patterns of CWP across the ORB corn-soybean cropping system for the period 1979-2018. We noticed that CWP has a long tradition among crop physiologists that continue to call water use efficiency (WUE) (e.g., Bluemling et al., 2007; Perry, 2007). WUE is defined as WUE = [product]/ [water applied/water available], representing an efficiency parameter of water utilization at the farm/plot level, which is scale- and context-dependent (Van Halsema and Vincent, 2012). We defined the CWP as the ratio of GPP and ET to investigate coupled carbon assimilation and water consumption from an ecosystem perspective. Our specific objectives were to 1) investigate the magnitude and long-term trends in CWP for corn and soybean in the ORB, 2) quantify changes in CWP as affected by different tillage practices, and 3) explore relationships between carbon and water fluxes in different tillage systems.

<Insert Figure 1>

2. Materials and Methods

2.1 Description of the Study Area

The ORB covers 421,966 km^2 within 11 states. The Ohio River starts at the Allegheny and the Monongahela's confluence in Pittsburgh, Pennsylvania, and ends in Cairo, Illinois, where it flows into the Mississippi River. The humid continental climate is prevalent in the upper half of the basin, and a humid subtropical climate is dominant in the lower half of the basin. Annual rainfall for different regions within the ORB ranges between 990 mm and 1473 mm. From 1979 to 2018, basin-wide annual rainfall averaged 1175 mm, with a coefficient of variation of 0.12. Nearly half of the land area in the ORB is covered by forests, primarily secondary growth deciduous trees. Cultivated cropland (~ 30%) is dominant in the northern and western sections of the ORB, with corn and soybean being the major crops grown (Santhi et al., 2014).

The northern portion of the ORB is near the glacial margin during the Late Pleistocene. The humid temperate climate and predominance of deciduous forests during the Holocene have led to the formation of Alfisols across most of the basin. In the eastern and southeastern portions of the basin, cropland soils are generally well-drained across various slope conditions (~57% well-drained, Schilling et al., 2015). In contrast, croplands in the northern and northwestern portions of the basin are characterized by poorly drained conditions with slopes often < 5%.

2.2 Model description

2.2.1 The DLEM-Ag

The agricultural module of the Dynamic Land Ecosystem Model (DLEM-Ag) is a highly integrated process-based agroecosystem model. The DLEM-Ag is capable of simulating the daily crop growth and exchanges of trace gases (CO_2, CH_4, and N_2O) between agroecosystems and the atmosphere; and quantifying fluxes and storage of carbon, water, and nitrogen within agroecosystems as affected by multiple factors such as climate, atmospheric CO_2, nitrogen deposition, tropospheric ozone, land use and land cover change, and agriculture management practices (e.g., harvest, rotation, irrigation, and fertilizer use). The model has been extensively used to study crop production, soil organic carbon, and greenhouse gas emissions in agroecosystems at regional and global scales. The detailed structure and processes of the model have been well documented in previous work (e.g., Ren et al., 2011; Ren et al., 2012; Ren et al., 2016; Ren et al., 2020; Tian et al., 2010; Tian et al., 2015; Zhang et al., 2018).

2.2.2 Model representation of tillage effects

We have recently incorporated a tillage sub-module in the DLEM-Ag model (Huang et al., 2020). The implementation of tillage mainly focuses on two processes that are directly affected by tillage: 1) the redistribution of surface residues with tillage practice and subsequent effects on soil water dynamics and water-related processes; 2) the increase in decomposition rates. The tillage effects are implemented in combination with residue management, as these management practices are often interrelated (Strudley et al., 2008). Tillage incorporates surface residues into the soil, altering the coverage of residues on top of the soil. Crop residues left on soil surface intercept rainfall, facilitating water infiltration. Surface residues also serve as a barrier that lowers soil evaporation and reduces water losses to the atmosphere. Therefore, crop residues help maintain or improve soil moisture. Soil moisture affects primary production by regulating the amount of available water for plants, and in turn, plant water uptake also changes soil moisture. The tillage sub-module does not consider the direct effect of tillage on soil thermal properties due to the scarcity of studies on soil thermal properties under different tillage regimes (Blanco-Canqui and Ruis., 2018; O'Brien and Daigh, 2019). However, as soil thermal properties are intimately associated with soil hydraulic properties in the DLEM-Ag, the tillage sub-module indirectly affects soil temperature by changing soil water content.

2.3 Input data

2.3.1 Climate, CO_2, and Nitrogen deposition

The daily climate data used to drive the model were derived from the gridMET dataset at a resolution of 4 km × 4 km covering the United States from 1979-2018 (Abatzoglou, 2013), including maximum, minimum, and average temperature; precipitation; shortwave radiation; wind; and relative humidity. The historical atmospheric CO_2 concentration dataset was obtained from the Earth System Research Laboratory of NOAA (National Oceanic and Atmospheric Administration, https://www.esrl.noaa.gov/gmd/). Gridded nitrogen deposition maps were extracted from the North American Climate Integration and Diagnostics – Nitrogen Deposition Version 1 (NACID-NDEP1) dataset (Hember, 2018).

2.3.2 Crop rotation and crop phenology

The crop rotation maps were generated by using the USDA-NASS Cropland Data Layer (CDL) datasets. Following a similar approach by Panagopoulos et al. (2015) and Srinivasan et al. (2010), we overlaid multi-year CDL information to produce crop rotation maps. This process resulted in dominant corn-soybean or soybean-corn rotations for the cropland portion of the region. The 2018 CDL data showed that approximately 98% of croplands in the ORB were planted with corn and soybean. Based on a three-year rotation pattern in the ORB from 2015 to 2017, we derived eight cropland rotation types involving corn and soybean: 1) corn/soybean, 2) corn/soybean/soybean, 3) corn/corn/soybean, 4) soybean/corn, 5) soybean/corn/corn, 6) soybean/soybean/corn, 7) continuous corn, and 8) continuous soybean. These eight rotation types constitute approximately 90% of all the three-year rotations that involve corn or soybean in the ORB (Table. S1). Therefore, minor rotation types such as corn/soybean/wheat and corn/corn/wheat were not included. We then aggregated the 30-m rotation information to produce fractional rotation types at a spatial resolution of 4-km (Fig. 1).

The planting and harvesting dates for corn and soybean were derived using the 500-m crop phenology dataset from Yang et al. (2020) combined with the CDL datasets. Specifically, we: 1) calculated corn and soybean fractions in each 500-m grid cell; 2) overlaid the center of each 4-km pixel on the 500-m phenology map to assign the index of the 500-m pixel to the nearest 4-km pixel; 3) searched within 10 km around the center on the 4-km map to find the pixels with more than 55% of corn or soybean (assuming that corn or soybean phenology information dominates pixels with more than 55% coverage); 4) assigned the planting/harvesting date of corn and soybean at the nearest pixel to the center of the 4-km pixel. For unassigned pixels, we replaced the value with the most adjacent pixels. Overall, the planting date in the ORB was 97-177 (day of the year) for both corn and soybean. The harvesting dates were 289-330 and 277-290 for corn and soybean, respectively.

2.3.3 Tillage and other agricultural management practices

We obtained county-level ORB tillage information from the National Crop Residue Management Survey (CRM) compiled by the Conservation Technology Information Center (https://www.ctic.org/). The tabular data provides the acreages and percentages of five tillage types adopted in all crops, including corn and soybean. For simplification, we grouped the five major tillage types into three categories, i.e., no-tillage, reduced tillage (including ridge tillage, mulch tillage, and reduced tillage), and conventional tillage. We used county acreages combined with the CDL maps to estimate the spatial distribution of conventional and conservation tillage for corn and soybean, assuming each pixel within a county has the same rates of the tillage-specific area. We reconstructed annual tillage maps from 1979-2018 based on the CRM dataset (1989-2011) and assumed that the tillage maps of other years are similar to the nearest year. Moreover, we also generated three tillage maps with all the corn/soybean under a specific tillage regime such as NT, RT, or CT for sensitivity analysis.

Crop-specific nitrogen fertilizer use data were derived from the USDA Economic Research Service statistics on fertilizer use (https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx), covering 1960-2018. A 4-km irrigation map was reconstructed based on the MODIS irrigated agriculture dataset (2012) for the United States (MIrAD-US, Pervez and Brown, 2010).

2.4 Model evaluation

The DLEM-Ag model has been extensively calibrated and validated against both site-level and regional-scale data (Ren et al., 2011, 2012, 2016, 2020; Tian et al., 2010; Zhang et al., 2018). Because we used driving forces different from previous regional studies and mainly focused on corn and soybean systems, we specifically calibrated and validated the simulated crop GPP and ET against published results from cropland sites in the AmeriFlux Network (https://ameriflux.lbl.gov/) within and close to the ORB region. One site is an agricultural field on a corn-soybean rotation at the Fermi National Accelerator Laboratory-Batavia, Illinois (US-IB1, 41.86° N, 88.22°W). The field has been farmed for more than 100 years, and the corn-soybean rotation with conventional tillage was established in July 2005. Soil texture at this site is silt clay loam in the topsoil and clay from in the subsoil. The other site was established in 1996 at Bondville, Illinois (US-Bo1, 40.01°N, 88.29°W). The field is under continuous no-tillage with alternating years of corn and soybean crops. Both sites have a typical humid continental climate with hot, humid summers and cool to cold winters, and they are representative of the northern central lowland. The model was calibrated using the first two-year data at each location and validated against the available data for the remaining years. Our evaluation results showed a general agreement between the simulated GPP and ET with measurements made at the flux towers (Fig. 2a, b).

To evaluate the model performance at the regional level, we further compared simulated NPP with survey and remote sensing products (Fig. 2c and 2d). The temporal pattern of crop NPP at the basin level was evaluated against the historical crop NPP derived from crop yield records reported by the USDA and derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) NPP product (MOD17A3). Specifically, the USDA crop yield records were converted to NPP following the method from Prince et al. (2001) and Li et al. (2014):

$$NPP = yield \times f_{mass} \times f_{dry} \times f_{carbon} \times (1 + RS)/HI$$

where yield is the crop yield in report unit by USDA inventory (bushel, pound, etc.), $f_{mass}$is a factor to convert the raw yield data into a standard unit of biomass, f_{dry} is a factor to convert the mass to dry biomass, f_{carbon} is a carbon content factor to convert the dry biomass to carbon (we use 450 g C/kg), *HI* is the harvested index, and *RS* is the root/shoot ratio. More details can be found in Li et al. (2014) and Ordóñez et al. (2020).

We overlaid the MODIS NPP maps with the CDL land cover data to extract corn and soybean NPP from 2008 to 2017. The results showed that the simulated NPP was generally within the range of survey-based NPP but relatively higher for corn and lower for soybean than those estimated by MODIS. This discrepancy could be attributed partially to the light use efficiency parameterization in the MODIS algorithm, which uses one light use efficiency value to represent all crops (Turner et al., 2006; Bandaru et al., 2013). Our results are in agreement with previous studies that MODIS NPP products tend to overestimate at low productivity sites and underestimate at high productivity sites (Turner et al., 2005; Turner et al., 2006).

<Insert Figure 2>

2.5 Model experimental design

We designed four simulation scenarios to assess the magnitude and spatiotemporal patterns of corn and soybean CWP (calculated as CWP = GPP/ET) during 1979-2018 and analyzed the difference associated with various tillage systems (Table 1). The model simulation began with an equilibrium run using 30-years (1979-2008) mean climate to develop the simulation boundary, in which the year-to-year variations of carbon, nitrogen, and water pools in each grid were less than 0.1 g C/m^2/yr, 0.1 mm H_2O/yr, and 0.1 g N m^2/yr, respectively. Before the transient run, the model was run for another 100 years for the spin-up to remove system fluctuations caused by the shift from equilibrium to transient state, using climate data randomly selected from 1979-2008. The baseline simulation scenario (S1) was designed to produce CWP close to reality and its changes across the ORB. It was driven by historically varying tillage types and other input variables (e.g., climate, CO_2, nitrogen deposition, fertilizer use, irrigation, and crop rotation). For simulation scenarios S2 - S4, we assumed that a specific tillage practice was applied for all the croplands across the basin over the study period. Comparing the four scenarios provides the potential CWP change of adopting conservation tillage in the corn and soybean systems.

<Insert Table 1>

3. Results

3.1 Historical changes in air temperature and precipitation in the ORB

The ORB has been getting warmer and wetter during 1979-2018, with substantial interannual variabilities in temperature and precipitation. The largest temperature increases occurred in the periphery of the ORB region, including western Kentucky, southern and eastern Indiana, and western Ohio (Fig. 3a). At the basin-level, air temperature has increased at a rate of 0.02 °C/year since 1979 ($R^2 = 0.16$, $p < 0.05$; Fig. 3b). Relatively more precipitation increases occurred in the center of the ORB, along both sides of the middle Ohio River, especially in southeastern Indiana and northern/eastern Kentucky (Fig. 3c). The average precipitation increased at a rate of 3.9 mm/year since 1979 ($R^2 = 0.10$, $p < 0.05$; Fig. 3d). The ORB region is characterized by a wet spring and dry autumn, with increased precipitation intensity and frequency in spring. Two severe droughts (large increase in temperature and decrease in precipitation) occurred in 1987 and 2012. Two abnormally wet periods (large increase in precipitation with small temperature change) were recorded in 1996 and 2018.

<Insert Figure 3>

3.2 Tillage effects on GPP and ET over the ORB region

In the ORB region, the mean annual GPP is 1264 ± 174 g $C/m^2/yr$ and 578 ± 150 g $C/m^2/yr$ for corn and soybean, respectively (Figs. 4a, b). The spatial distribution patterns of GPP for corn and soybean are similar to each other, with higher GPP in the northwest ORB region where agriculture is the dominant land use. Compared to the baseline simulation (S1), tillage scenarios (S2, S3, and S4) showed that the effect of tillage on GPP was negligible for both crops (Figs. 4c-h). Nevertheless, NT and RT tended to have a slightly positive effect on GPP relative to CT.

<Insert Figure 4>

The spatial distribution patterns of annual ET for both crops showed an increasing trend from the northeast toward the southwest region of the ORB (Figs. 5a, b). The average annual ET was 654 ± 43 mm/yr for corn and 454 ± 34 mm/yr for soybean. The sensitivity scenarios showed that CT increased ET by 1.6 ± 0.8% in corn and 10.1 ± 3.3% in soybean (Figs. 5c, d; Table 2), while NT decreased ET by 2.6 ± 1.5% in corn and 7.4 ± 4.0% in soybean (Figs. 5g, h), compared to the baseline scenario (S1). Generally, the ET reduction under NT scenario was more pronounced in the northwest of the ORB, where the annual ET was relatively low. The effect of RT on ET relative to S1 was somewhat neutral (-0.2 ± 0.9% and 1.4 ± 2.9% for corn and soybean, respectively, Figs. 5e, f).

<Insert Figure 5>

<Insert Table 2>

3.3 Tillage effects on CWP over the ORB region

The baseline simulation (S1) showed that the mean annual CWP was 1.93 ± 0.25 kg C/m^3 and 1.28 ± 0.36 kg C/m^3 for corn and soybean, respectively, across the ORB region during 1979 - 2018 (Figs. 6a, b). The spatial patterns for the annual CWP were similar for corn and soybean. Areas with higher CWP occurred in the northwest section of ORB and decreased southeastward. The sensitivity scenarios (S2, S3, and S4) revealed that the tillage-induced CWP change varied among different tillage scenarios. Compared to the baseline scenario (S1), CT decreased the mean annual CWP by 1.7 ± 0.8% for corn and 9.2 ± 2.7% for soybean (Figs. 6c, d; Table. 2), while NT increased CWP by 2.8 ± 1.6% and 8.4 ± 4.6% for corn and soybean, respectively (Figs. 6g, h). The increase in CWP was more pronounced in the northern half of the ORB, where the annual ET was relatively lower. However, the impact of RT on CWP was relatively neutral (0.1 ± 0.9% and -1.1 ± 2.7% for corn and soybean, respectively, Figs. 6e, f).

<Insert Figure 6>

The baseline temporal dynamics of the annual CWP showed a significant increasing trend for soybean (0.006 kg C/m^3/yr, $p < 0.01$, Fig. 7b) and corn (0.004 kg C/m^3/yr, $p < 0.01$, Fig.7a). Generally, throughout the simulation period, the NT scenario resulted in the highest annual CWP for both crops in the ORB region (1.98 ± 0.07 kg C/m^3 and 1.37 ± 0.09 kg C/m^3 for corn and soybean, respectively). In comparison, the CT scenario led to the lowest annual CWP (1.89 ± 0.08 kg C/m^3 and 1.13 ± 0.08 kg C/m^3 for corn and soybean, respectively, Figs. 7a, b), despite the variations in the annual CWP. No significant difference in the annual CWP was observed between the RT and the baseline scenario.

<Insert Figure 7>

4. Discussion

4.1 Impacts of tillage management on crop GPP, ET, and CWP

Our results showed that, on average, across the ORB region, different tillage regimes had indistinguishable effects on GPP for corn or soybean crops (Fig. 4). This is not surprising considering that the ORB is often "water-rich" (Fig. 3d, Adler et al., 2003) with plentiful rainfall as well as numerous major rivers and impoundments. Alterations in soil water dynamics caused by different tillage methods would probably not limit water available for crops in the basin. Soil and water conservation technologies do not necessarily lead to enhanced crop productivity (Hellin and Schrader, 2003). Previous studies have suggested that, in comparison to humid regions, dry areas where crop productivity is often limited by soil moisture could benefit more from NT adoption (Huang et al., 2018; Pittelkow et al., 2015). A site-level study in Eastern and Northern Ohio found, compared to CT, a slightly higher crop yield under conservation tillage at a well-drained site, but no significant difference between tillage at a poorly drained site, despite increased soil water retention under NT and RT (Kumar et al., 2012). Climate and soil may be major factors influencing crop productivity response to tillage (Toliver et al., 2012). In Southern Illinois, Kapusta et al. (1996) also observed no difference in corn yield among CT, NT, and RT on a silt loam soil after 20 years under each tillage treatment. Moreover, similar GPP for wheat between CT and NT systems was recently reported in the inland Pacific Northwest region with a Mediterranean climate (Chi et al., 2016) and in the Southern Great Plains with a humid subtropical climate (Kandel et al., 2020) using the eddy covariance method.

With respect to ET, our results are consistent with the current understanding that conservation tillage decreases ET compared to CT (Fig. 5). NT and RT decreased ET by 2 ~ 4% and 9 ~ 18% relative to CT in corn and soybean systems, respectively. These greater reductions in evaporative water loss under NT would translate into more significant improvements in CWP, the ratio of GPP to ET. The enhancement in CWP found under the NT and RT scenarios (Fig. 6) was mainly due to decreased ET and minor changes in GPP. It should be noted that a noticeable increase in CWP occurred in areas with relatively lower annual ET, and where there was a greater reduction in ET under NT and RT compared to the areas with relatively higher ET (Fig. 5, Table. 2). In addition, our results showed that NT and RT reduced evaporation compared to CT (Fig. S1). They did not alter transpiration (Fig. S2), corresponding to the negligible distinctions in GPP among different tillage scenarios. Surface residues create a physical barrier that reduces evaporation and increases infiltration (Irmak et al., 2019). As a form of conservation tillage, NT resulted in more crop residue coverage on the soil surface than CT and less evaporation. Besides, tillage typically increases surface roughness, reduces albedo (Cierniewski et al., 2015), and increases net absorption of solar radiation by the soil (Schwartz et al., 2010), hence fueling evaporation. However, the effects of different tillage types on surface albedo and evaporation are highly variable, depending on soil color, residues color, and residue incorporation. There is a lack of representation of the direct effects of tillage on soil thermal properties (e.g., albedo) in current modeling studies. Therefore, our results might underestimate or overestimate the decrease in evaporation due to conservation tillage.

Soil water evaporation is generally not favorable for crop productivity, although evaporation does slightly cool the surface microenvironment (Klocke et al., 2009), altering the soil energy balance (O'Brien and Daigh, 2019). Thus, adopting conservation tillage can reduce water loss via evaporation and make the soil more productive by maintaining soil moisture. One concern regarding residue cover in conservation tillage systems is that it tends to retard seed germination in the early spring due to the slow rate of soil warming (Blanco-Canqui and Lal,

2009) and could subsequently lead to reductions in crop productivity. For example, long-term tillage studies in Illinois (Kapusta et al., 1996) and Indiana (Griffith et al., 1988) reported lower corn plant populations under NT and RT systems than CT. However, these studies also suggested that plant population differences among tillage systems did not translate into a yield deduction when nitrogen fertilizer was applied. Our results revealed that GPP was also not affected by the tillage regime at large spatial and temporal scales.

The present study also showed that the difference in CWP between NT and CT scenarios was higher in soybean systems (~ 18%) than in corn systems (~ 5%, Fig. 6). In Minnesota, Tang et al. (2015) observed similar results using eddy covariance measurement and MODIS products. The greater response of soybean CWP could be due to its less water-efficient photosynthesis pathway than corn (C3 vs. C4, Dietzel et al., 2016). It is worth noting that the soybean crop has a much lower amount of residue than corn. Tillage after corn might lead to more residues and exacerbate evaporation more than that after soybean. The increase in CWP in NT/RT soybean was observed in rotations that soybean was sown after both corn and soybean. Considering that most of the rotations were soybean after corn or/and corn after soybean (Table. S1), enhanced soil water content due to NT and RT would increase soybean CWP more than corn CWP.

4.2 Role of tillage management in the carbon and water cycles under climate change

Increasing CWP under climate change will largely rely on management practices to reduce soil water evaporation and shift water use to more transpiration (Hatfield and Dold, 2019). Soil preparation plays a critical role in ensuring crop productivity and CWP in response to climate change. Our results support the theory that conservation tillage can make agroecosystem less susceptible to adverse impacts of climate change by partitioning more water into infiltration to maintain soil moisture, thus potentially reducing crop water stress during drought conditions.

Besides, soils in the ORB are vulnerable to water erosion, particularly during heavy spring rainstorms on croplands under CT systems (Van Pelt et al., 2017). Compared to CT, NT and RT decreased surface runoff but increased subsurface drainage in the study region (Fig. 8). However, the sum of runoff and drainage did not vary among different tillage scenarios. This finding is consistent with Daryanto et al. (2017b). The shift in water fluxes (i.e., ET, runoff, and drainage) among tillage systems further suggested the advantages of NT and RT in enhancing soil water storage. Furthermore, it is generally perceived that NT and RT can reduce soil carbon loss compared to CT, which helps maintain or build up soil carbon storage and improve soil structure in the long run (Blanco-Canqui and Ruis, 2018). However, it should be noted that NT and RT also increase subsurface drainage and potentially lead to more nutrient leaching. Daryanto et al. (2017b) reported a greater loss of nitrate via leaching under NT than under CT despite similar nitrate concentration under both systems. Similar results were also observed for dissolvable phosphorus (Daryanto et al., 2017c). Considering the abundant rainfall amount in the ORB region and the increasing trend in rainfall noted in the last several decades, there is a high probability that nutrient leaching from croplands would be a growing concern in the region. Therefore NT systems should be complemented with other measures to mitigate leaching loss. For example, cover cropping and installation of water harvesting technologies (e.g., drainage ditches with runoff filters, riparian buffers) can help increase available water for crops and lower the risk of nutrient leaching (Daryanto et al., 2018; Liu et al., 2020).

<Insert Figure 8>

In addition, a recent study noted a declining trend in NT adoption across the US (including the ORB) corn and soybean croplands since 2008, but increased adoption of RT (from 2006 to 2016) and CT (from 2007 to 2016) (Yu et al., 2020). These trends can be ascribed to the release (2007 and 2016) of land previously enrolled in the Conservation Reserve Program (USDA, Farm Service Agency 2019). Reports of increased resistance of weeds to herbicides may also play a disincentivizing role in regard to NT adoption (Perry et al., 2016). Moreover, farmers tend to make decisions based on many factors such as crop rotations, policies, and weather conditions. Blanco-Canqui and Wortmann (2020) argued that occasionally tillage of cropland under NT could be a potential solution to inadequate weed control and other risks associated with continuous NT. However, more research is needed to identify options for optimizing the environmental and cost-saving benefits of NT. It is essential to point out that our simulations may represent the "best-case" NT vs "worst-case" CT scenarios, and therefore, the results should be interpreted with caution. There is an urgent need for more spatio-temporally explicit data to document agroecosystem-level water partitioning and further our ability to predict how tillage regimes can help mitigate climate change impacts on crop productivity.

5. Conclusions

Process-based agroecosystem models are powerful tools that quantify large-scale carbon-water interactions and explore associated underlying mechanisms under various tillage management scenarios. This study offers the first attempt to quantify tillage effects on regional-scale CWP for the two most important crops in the ORB. Model simulation results showed that if all the croplands in the ORB region were under NT, the corn and soybean CWP would increase by 1-4% and 4-13%, respectively. In contrast, adoption of CT practice would result in CWP decreases of ~2% and ~9%, respectively. Our results indicate that conservation tillage can be a viable approach to enhance CWP in corn and soybean cropping systems across the ORB. This benefit is mainly due to lower water loss through non-beneficial evaporation under conservation tillage systems. However, additional management practices and strategies are needed to decrease nitrogen loss via leaching from croplands under NT. Future research should investigate the synergic effects of these complementary measures and their potential to optimize the environmental benefits of conservation tillage.

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Table 1. Simulation design in this study.

		Drivers used	
Scenarios	Abbr	Tillage	Others[a]
Historical varying tillage	S1	1979 - 2018	Varying
Conventional tillage	S2	1979[b]	Varying
Reduced tillage	S3	1979[c]	Varying
No-tillage	S4	1979[d]	Varying

Note: [a] Others include climate data (e.g., air temperature, precipitation, and radiation from 1979 to 2018), agricultural nitrogen fertilizer (i.e., nitrogen fertilizer from 1979 to 2018), and atmospheric conditions (i.e., CO_2 and N deposition from 1979 to 2018); [b] Tillage intensity across the ORB for the entire period was consistent as conventional tillage (CT); [c] Tillage intensity across the ORB for the entire period was consistent as reduced tillage (RT); [d] Tillage intensity across the ORB for the entire period was consistent as no-tillage (NT).

Table 2. Regional summary of the percentage change from the simulation scenario S1 (GPP, ET, and CWP) owing to CT, RT, and NT.

	Region	Corn			Soybean		
		CT	RT	NT	CT	RT	NT
ΔGPP	NCL*	-0.04±0.02	0.01±0.02	0.08±0.03	-0.03±1.45	0.06±0.12	0.03±0.18
(%)	SILP	-0.03±0.15	-0.01±0.04	0.02±0.08	0.42±1.08	0.54±1.08	0.62±1.10
	AP	-0.05±0.06	0.01±0.05	0.08 ± 0.08	-0.08±0.48	0.11±0.47	0.23±0.48
	ORB	-0.05±0.09	0.00±0.04	0.06±0.07	0.10±0.72	0.23±0.71	0.27±0.74
ΔET	NCL	1.39±0.50	-0.37±0.5	-2.83±0.70	11.28±2.47	1.27±1.49	-8.13±1.82
(%)	SILP	1.59±0.49	0.39±0.37	-1.38±0.56	9.00±3.33	3.04±2.52	-3.91±2.63
	AP	2.04±1.17	-0.46±1.32	-3.71±1.86	9.67±3.82	-1.12±3.72	-11.44±4.42
	ORB	1.63±0.80	-0.17±0.88	-2.64±1.45	10.15±3.27	1.35±2.89	-7.40±3.98
ΔCWP	NCL	-1.43±0.50	0.37±0.52	3.00±076	-10.29±2.04	-1.26±1.47	8.90±2.08
(%)	SILP	-1.63±0.51	-0.42±0.38	1.43 ± 0.61	-7.96±2.56	-2.43±1.91	4.82±2.35
	AP	-2.08±1.15	0.47±1.38	3.96 ± 2.11	-9.01±3.19	1.30±3.95	13.31±5.83
	ORB	-1.68±0.79	0.14±0.93	2.77±1.62	-9.22±2.71	-1.14±2.72	8.38±4.55

* NCL: Northern Central Lowland; SILP: Southern Interior Low Plateaus; AP: Applachia Plateaus; ORB: whole Ohio River Basin.

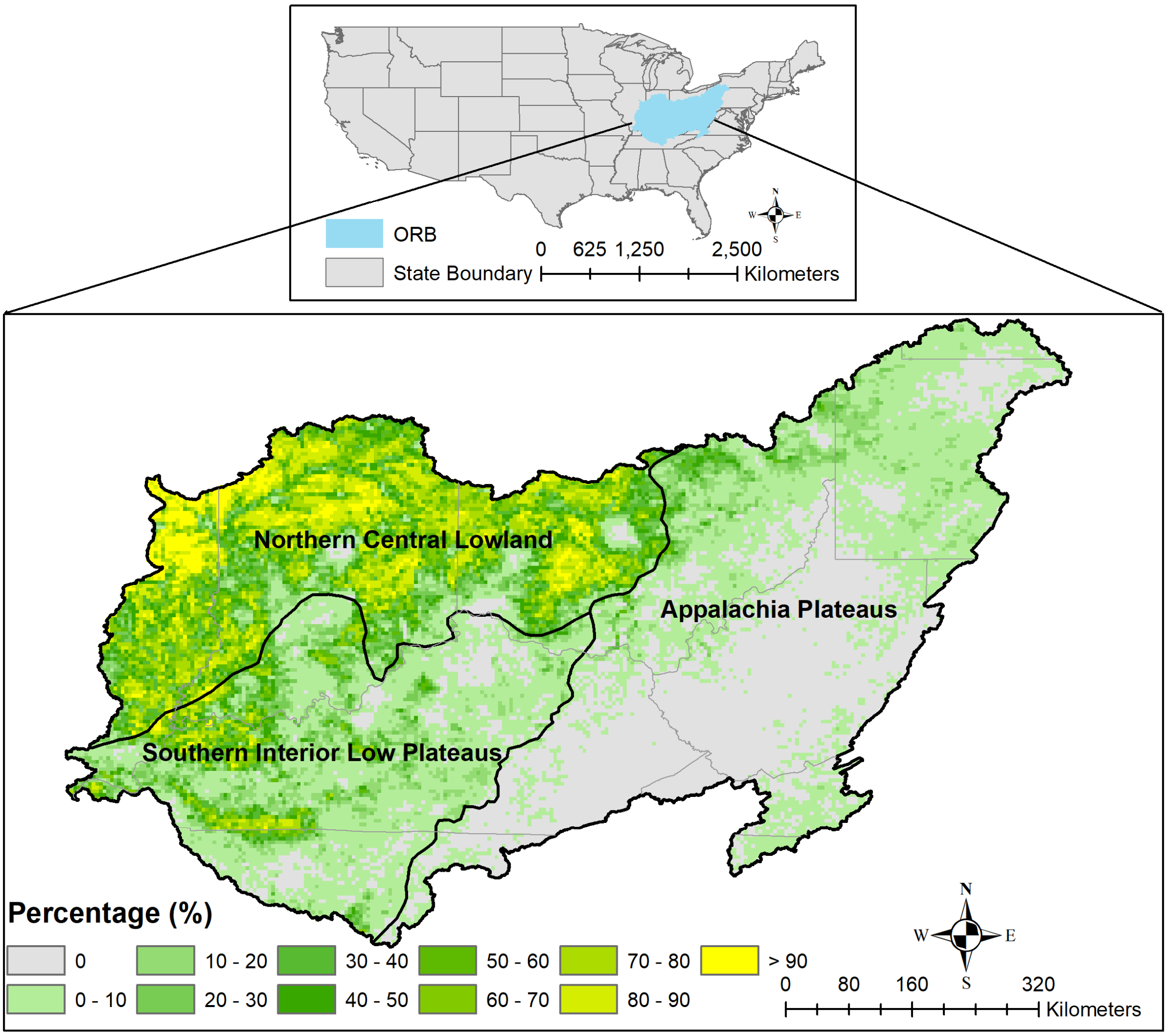
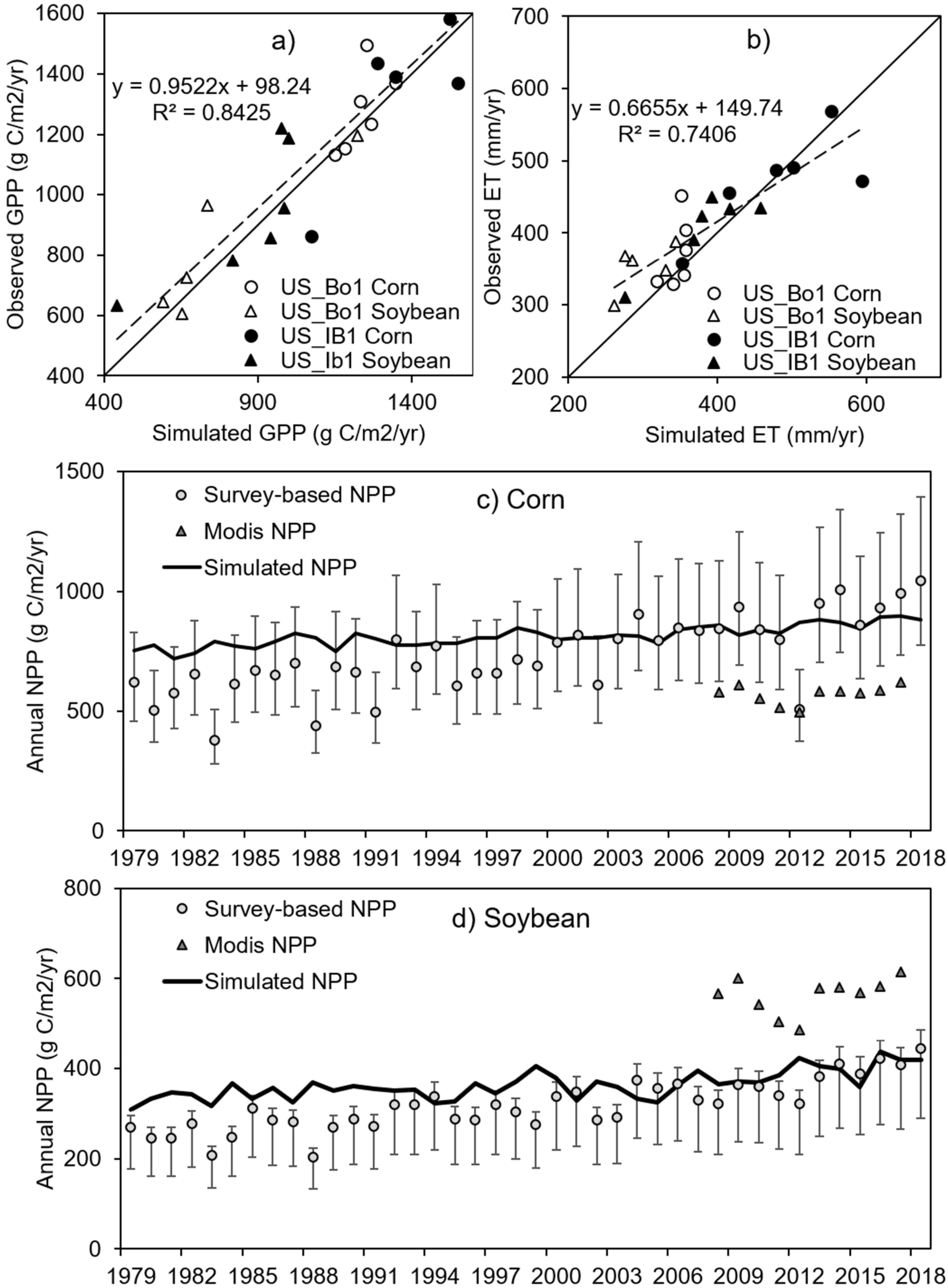


Figure 1. Location of the Ohio River Basin and percentage of cropland are for the eight rotation types at a spatial resolution of 4-km. Subregions are based on the physiographic divisions of the conterminous US.


a)
y = 0.9522x + 98.24
R² = 0.8425
Observed GPP (g C/m2/yr)
Simulated GPP (g C/m2/yr)
US_Bo1 Corn
US_Bo1 Soybean
US_IB1 Corn
US_Ib1 Soybean
b)
y = 0.6655x + 149.74
R² = 0.7406
Observed ET (mm/yr)
Simulated ET (mm/yr)
US_Bo1 Corn
US_Bo1 Soybean
US_IB1 Corn
US_IB1 Soybean
c) Corn
Survey-based NPP
Modis NPP
Simulated NPP
Annual NPP (g C/m2/yr)
d) Soybean
Survey-based NPP
Modis NPP
Simulated NPP
Annual NPP (g C/m2/yr)

691

Figure 2. Comparison of model estimated and observed gross primary productivity (GPP; a) and evapotranspiration (ET; b) for corn and soybean at sites US-BO1 (1997-2006) and US-IB1 (2006-2017) (dashed line is the regression of observed data and modeled results. The solid line is the 1:1 line). Comparisons of basin-level annual NPP derived from USDA survey, MODIS NPP datasets, and model simulations for corn (c) and soybean (d). Error bars represent the upper and lower limits of yield-derived NPP based on the parameter ranges.

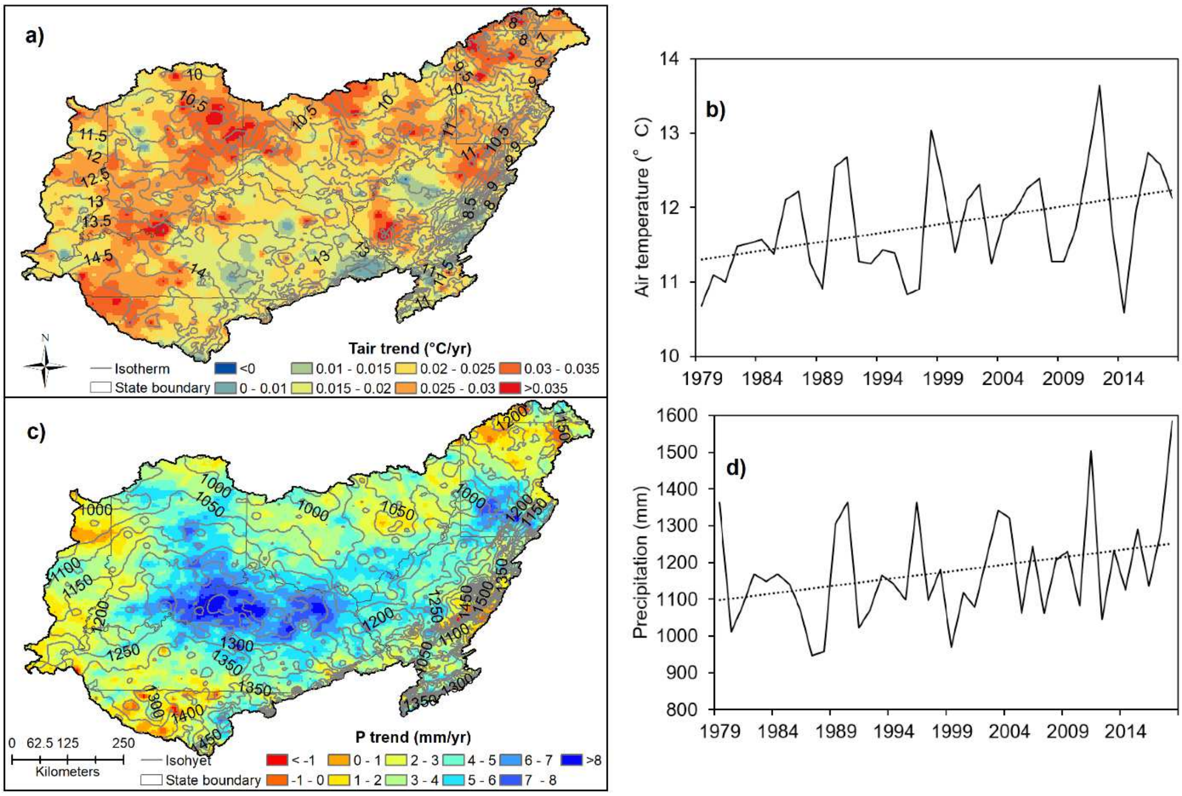
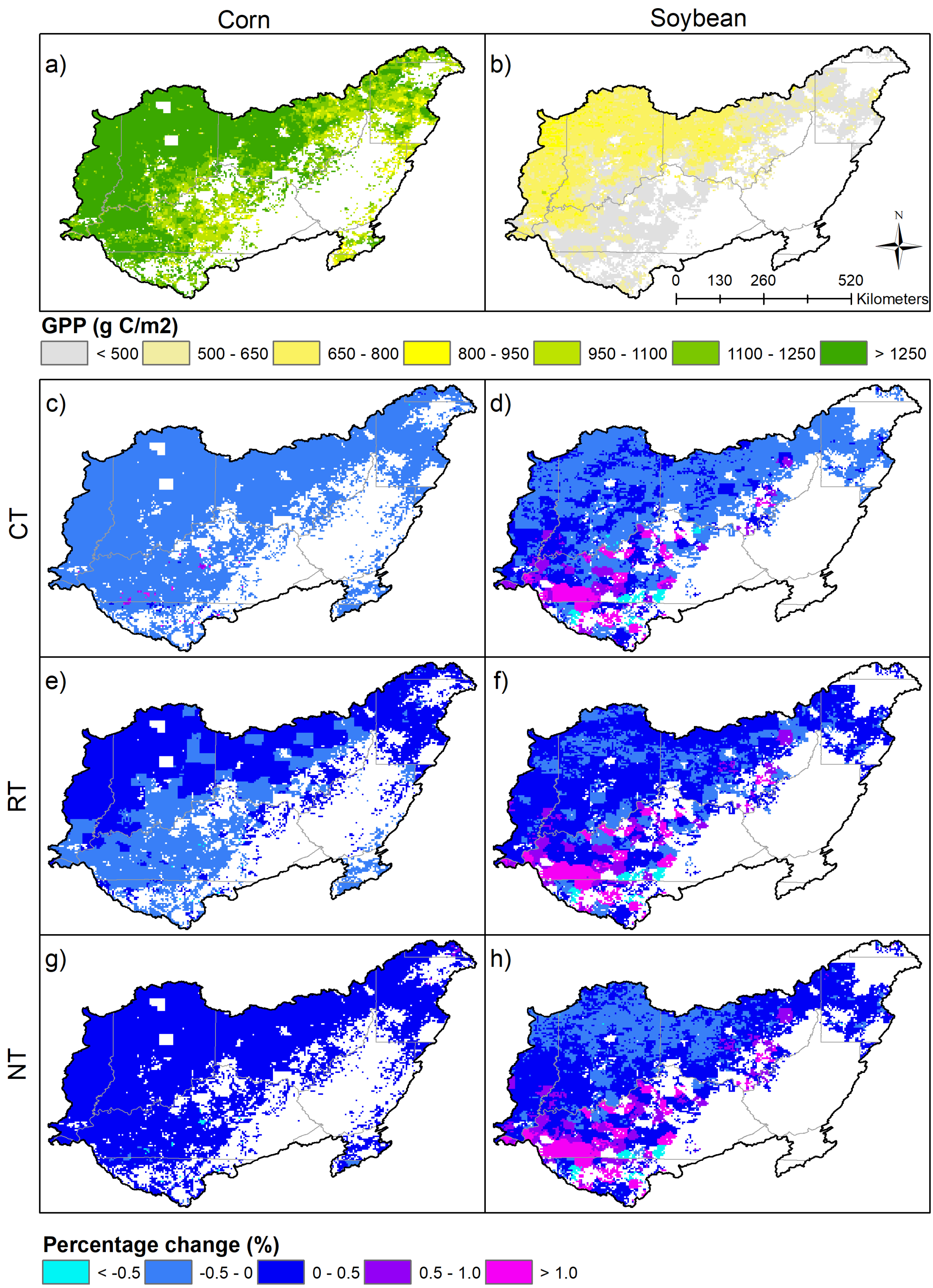
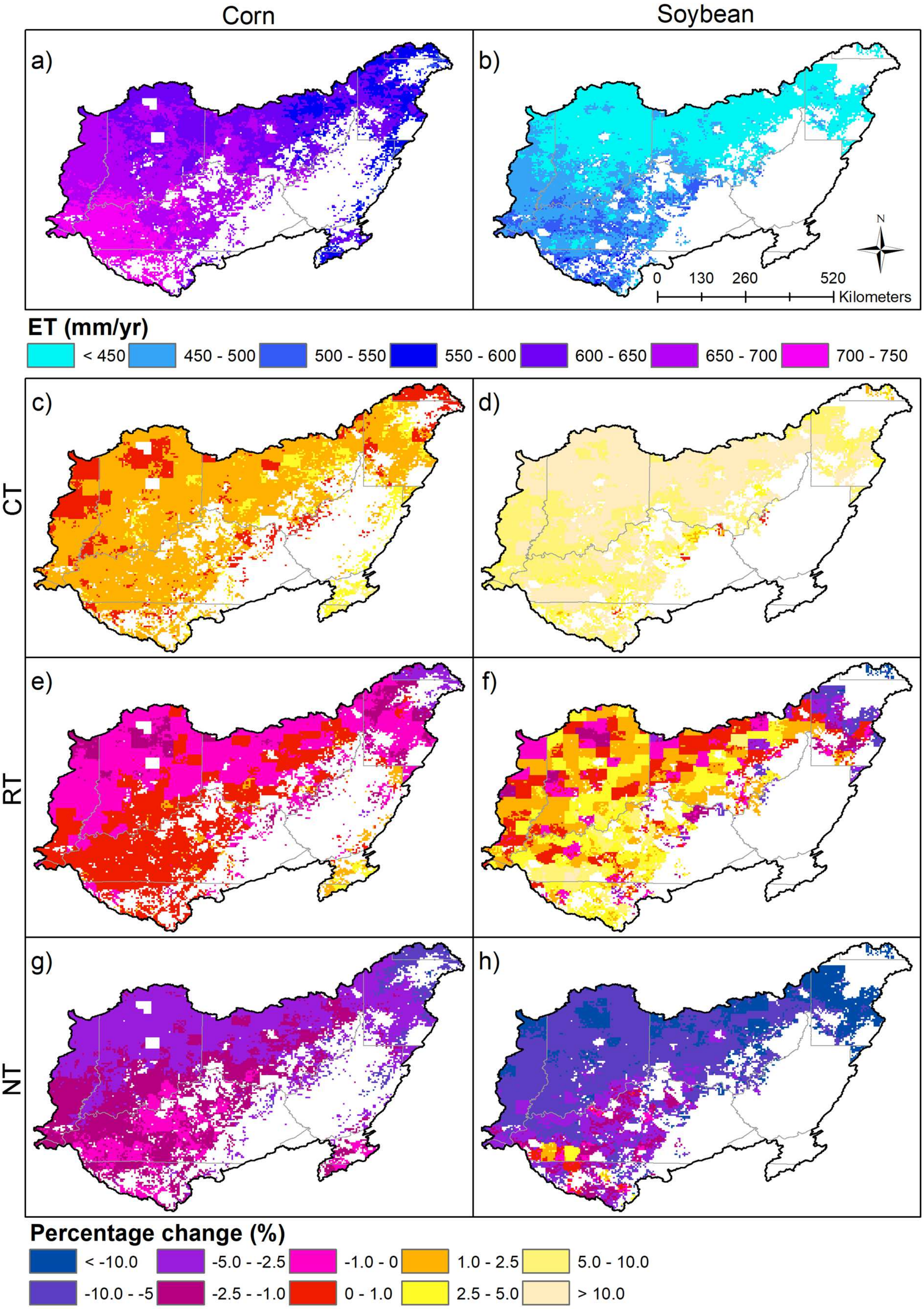


Figure 3. Spatial and temporal change of annual (a, b) air temperature, (c, d) precipitation between 1979 and 2018. Contour lines in a and b represent isotherm and isohyet, respectively.


Corn
Soybean
a)
b)
c)
d)
e)
f)
g)
h)
N
0
130
260
520
Kilometers
GPP (g C/m2)
< 500
500 - 650
650 - 800
800 - 950
950 - 1100
1100 - 1250
> 1250
CT
RT
NT
Percentage change (%)
< -0.5
-0.5 - 0
0 - 0.5
0.5 - 1.0
> 1.0

702

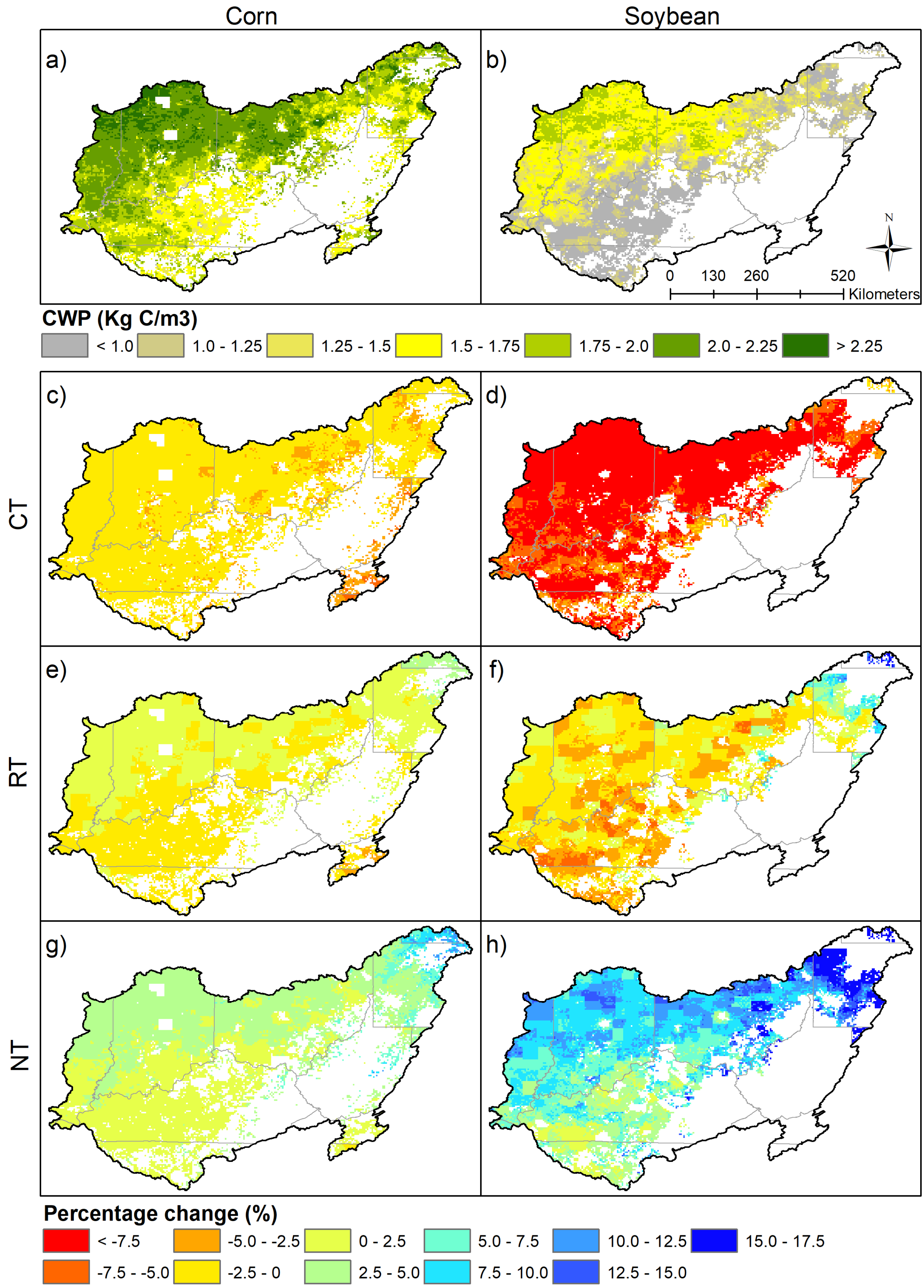
Figure 4. Spatial distribution of the mean annual (1979 - 2018) gross primary productivity (GPP) in the ORB region from simulation scenario S1 (a, b), and the percentage change from the simulation scenario S1 GPP owing to CT (c, d), RT (e, h), and NT (g, h). The left panel is for corn, and the right panel is for soybean.



Corn
Soybean
a)
b)
0
130
260
520
Kilometers
N
ET (mm/yr)
< 450
450 - 500
500 - 550
550 - 600
600 - 650
650 - 700
700 - 750
CT
RT
NT
c)
d)
e)
f)
g)
h)
Percentage change (%)
< -10.0
-10.0 - -5
-5.0 - -2.5
-2.5 - -1.0
-1.0 - 0
0 - 1.0
1.0 - 2.5
2.5 - 5.0
5.0 - 10.0
> 10.0

708

Figure 5. Spatial distribution of the mean annual (1979 - 2018) evapotranspiration (ET) in the ORB region from simulation scenario S1 (a, b), and the percentage change from the simulation scenario S1 ET owing to CT (c, d), RT (e, h), and NT (g, h). The left panel is for corn, and the right panel is for soybean.


Corn
Soybean
a)
b)
c)
d)
e)
f)
g)
h)
CT
RT
NT
N
0
130
260
520
Kilometers
CWP (Kg C/m3)
< 1.0
1.0 - 1.25
1.25 - 1.5
1.5 - 1.75
1.75 - 2.0
2.0 - 2.25
> 2.25
Percentage change (%)
< -7.5
-7.5 - -5.0
-5.0 - -2.5
-2.5 - 0
0 - 2.5
2.5 - 5.0
5.0 - 7.5
7.5 - 10.0
10.0 - 12.5
12.5 - 15.0
15.0 - 17.5

715

Figure 6. Spatial distribution of the mean annual (1979 - 2018) crop water productivity (CWP) in the ORB region from simulation scenario S1 (a, b), and the percentage change from the simulation scenario S1 CWP owing to CT (c, d), RT (e, h), and NT (g, h). The left panel is for corn , and the right panel is for soybean.

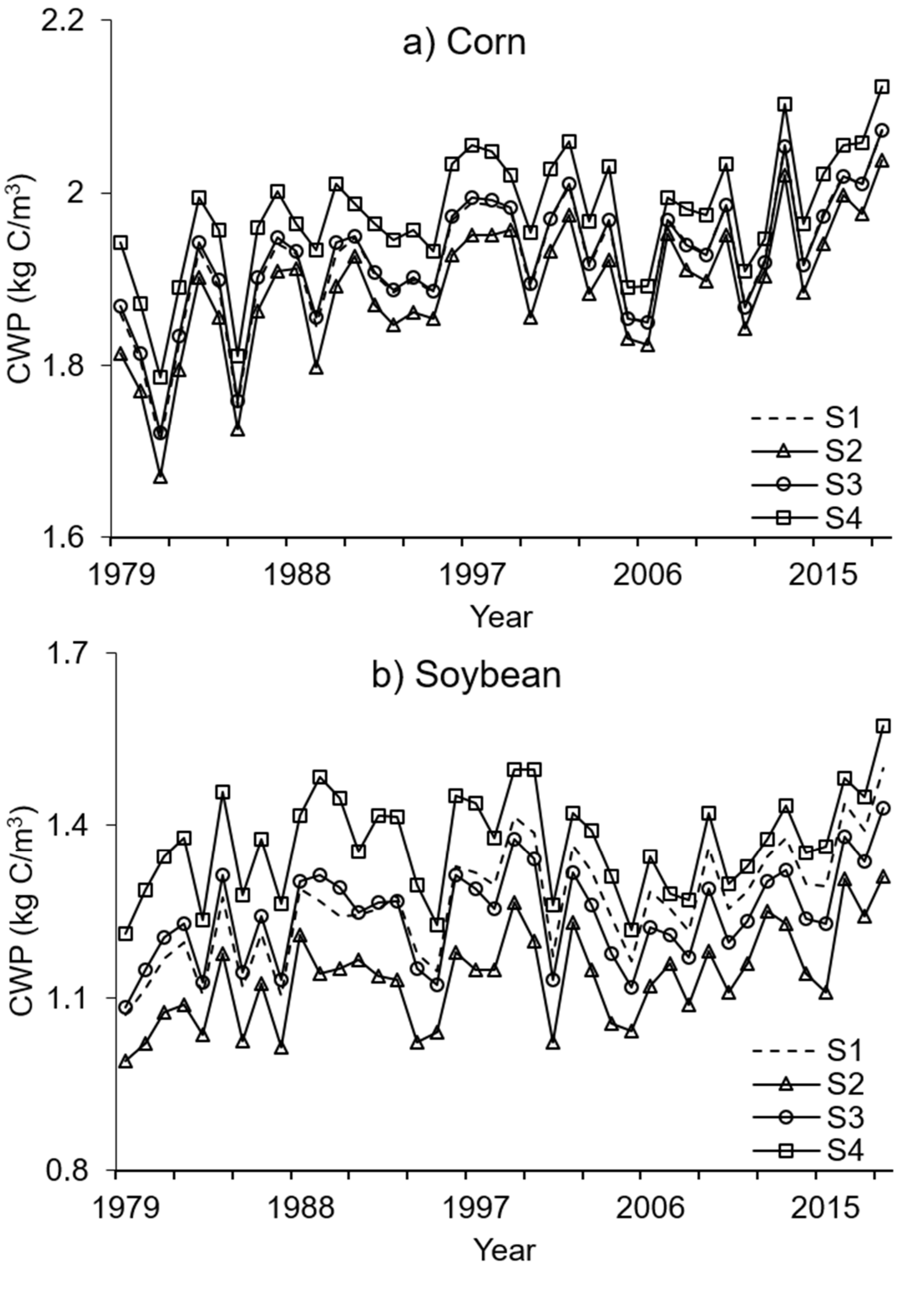


Figure 7. Temporal changes in crop water productivity (CWP) under different simulation scenarios for corn (a) and soybean (b) over the ORB region. S1, S2, S3, and S4 are different simulation scenarios as shown in Table 1.

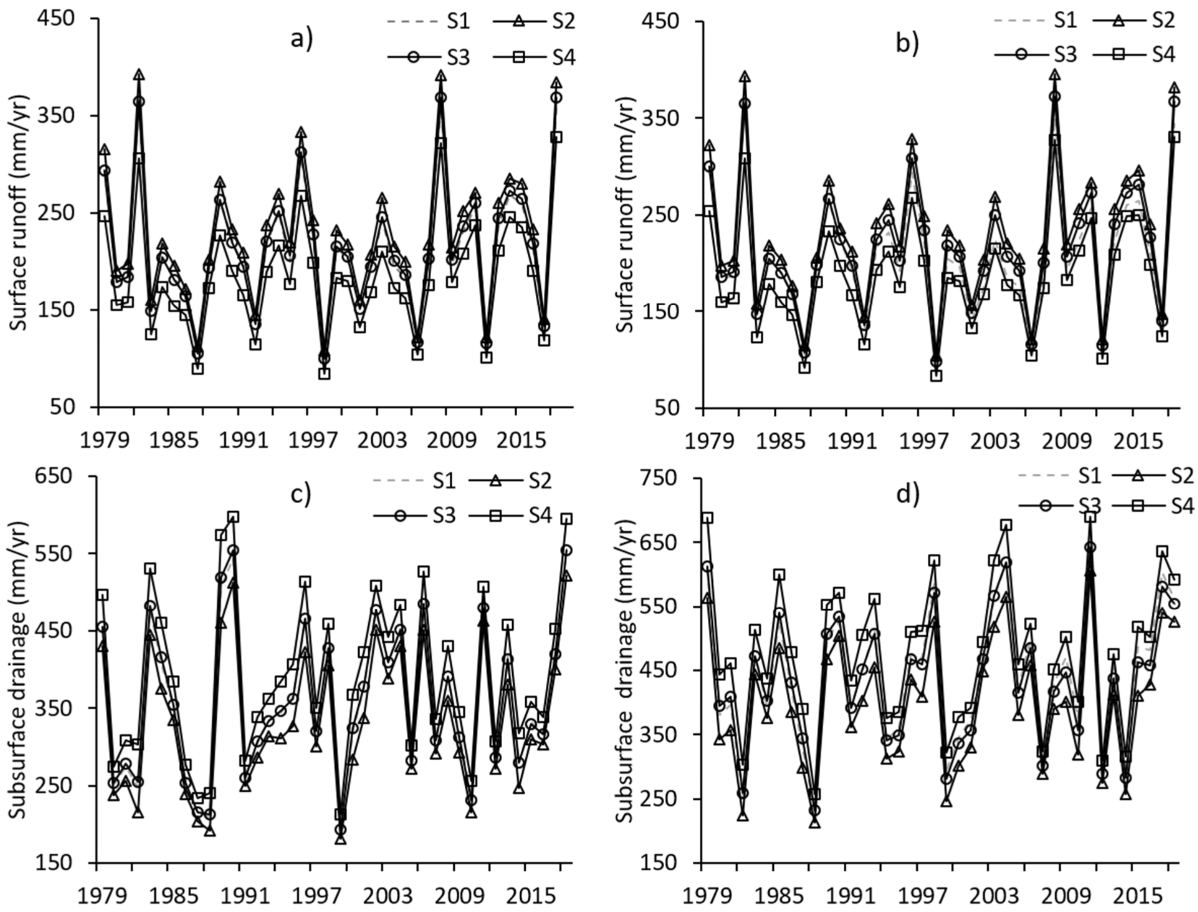


Figure 8. Temporal changes in surface runoff (a, b) and subsurface drainage (c, d) under different simulation scenarios for corn (left panel) and soybean (right panel) over the ORB region. S1, S2, S3, and S4 are different simulation scenarios as shown in Table 1.