Modeled climate change impacts on subirrigated maize relative yield in northwest Ohio

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Abstract

Subirrigation is employed to supply water to crop root zones via subsurface drainage systems, which are typically installed for the purpose of excess soil water removal. Crop yield increases due to subirrigation have been demonstrated in numerous studies, but there is limited information regarding yield under future climate conditions when growing season conditions are expected to be drier in the U.S. Corn Belt. DRAINMOD was calibrated and validated for three locations with different soil series in northwest Ohio and used to investigate maize relative yield differences between subirrigation and free subsurface drainage for historic (1984-2013) and future (2041-2070) climate conditions. For historic conditions, the mean maize relative yield increased by 27% with subirrigation on the Nappanee loam soil, but had minimal effect on the Paulding clay and Hoytville silty clay soils. Maize relative yield under free subsurface drainage is predicted to decrease in the future, causing the relative yield difference between free subsurface drainage and subirrigation practices to nearly double from 9% to 16% between the historic and future periods. Consequently, the subirrigation practice can potentially mitigate adverse future climate change impacts on maize yield in northwest Ohio.

Keywords

Drainage, Maumee, DRAINMOD, Hoytville, Nappanee, Paulding.

1. Introduction

Although the U.S. Corn Belt generally receives sufficient annual precipitation to satisfy the total annual crop evapotranspiration demands, disparities exist between crop water demands and effective water availability during the drier months of the growing season. Irrigation is often used on agricultural lands to supplement precipitation and maintain appropriate soil water during periods of high crop water demands. In the U.S. Corn Belt, supplemental water supply to maize (*Zea mays*) through irrigation may help mitigate the impacts of drought on yield, therefore helping to sustain or increase agricultural productivity (Baker et al., 2012). Irrigation can be implemented using several available methods, including sprinkler, drip and subirrigation. Subirrigation has considerable potential in the U.S. Corn Belt because it relies on subsurface drainage systems to supply water directly to the crop root zone (Brown et al., 1997), therefore minimizing irrigation water losses as well as irrigation system installation and operation costs. The application of water below the ground surface during subirrigation helps raise and maintain the water table at an appropriate depth in the crop root zone (Cooper et al., 1992). The subsurface drainage system serves a dual purpose of a channel network to provide root zone drainage during wet periods or irrigation during periods of drought. More than 30% of agricultural lands in the U.S. Corn Belt have subsurface drainage systems, some of which can be retrofitted for subirrigation (Zucker and Brown, 1998). Drainage system retrofitting usually involves reducing drain spacing by installing new drain lines between old ones, to more effectively distribute water horizontally within the soil profile during subirrigation and to more quickly drain water from the soil in response to large rainfall events.

Subirrigation capable fields are not only operated in subirrigation mode, but also controlled drainage and free subsurface drainage modes as the need arises. In free subsurface drainage systems, the soil profile is allowed to drain freely to the depth of the drains. During controlled drainage, the drainage depth is regulated at a controlled structure, most often installed at the subsurface drainage system outlet, but without the addition of supplemental water. On subirrigation capable fields, water can be supplied continuously to the root zone during the growing season or can be interrupted by short periods of free or controlled subsurface drainage. In this paper, the term “subirrigation” refers to the period during which water is supplied to the crop, whereas “subirrigation practice” refers to the water management practice that includes subirrigation, free and / or controlled subsurface drainage.

Studies of the effectiveness of subirrigation practice on maize yield have generally found that the yield increased significantly and stabilized at a high level under subirrigation practice. Cooper et al. (1999)

found that maize production on Ravenna silt loam and Hoytville silty clay loam soils in Ohio was 2900 kg/ha to 3750 kg/ha higher under subirrigation practice mainly during dry years. In 1998, Drury et al. (2009) found that maize yield was significantly lower under subirrigation practice on Brookston clay loam soil at Woodslee (Ontario), and suggested the large August precipitation as well as the tile spacing and depth as plausible causes for the lower yield. On Omulga silt loam soil in southern Ohio, Fisher et al. (1999) found that maize yield was 19% greater under subirrigation practice than under free subsurface drainage. Maize yield was found to be 64% larger under subirrigation practice in a sandy loam soil in southwestern Ontario (Ng et al., 2002), and 2.8% to 13.8% greater in eastern Ontario (Mejia et al., 2000). Other studies also based on field experiments used wetland-reservoir complexes, where runoff and subsurface drainage water was captured and recycled back into the subsurface drainage system. At Holiday Beach (Ontario), Tan et al. (2007) found that maize yield under subirrigation practice was 91% larger than under free subsurface drainage during dry years, and 7% to 22% larger during wet years. In northwest Ohio, Allred et al. (2014) used a water capture and recycle system designated Wetland Reservoir Subirrigation System (WRSIS) on three different soil types and found that maize yield increased by 19.1% with the implementation of subirrigation practice.

Field measurements need to be extended by modeling studies to predict the impact of subirrigation under future climate conditions. Maize yield performance under subirrigation practice has also been investigated through DRAINMOD simulations. DRAINMOD is a field hydrology water balance computer model that simulates free subsurface drainage, controlled drainage, and subirrigation, either as single water table management practices or in combination with one another (Skaggs et al., 2012). Murugaboopathi et al. (1995) conducted a study based on a 37-year period (1950-1986) simulation with uncalibrated DRAINMOD using the Rains and Portsmouth sandy loam soils found in North Carolina, and found that subirrigation practice had a 21% maize relative yield advantage over free subsurface drainage.

The study in northwest Ohio by Allred et al. (2014) measured crop yield impacts at three sites with different soils for twelve years. Baule et al. (2017) utilized results from Allred et al. and regional climate model output to evaluate the impact of growing season precipitation on yields at the three sites and how yields will respond under projected climate conditions. As the U.S. Corn Belt is expected to experience annual shifts in temperature, solar radiation, and precipitation regimes in the near-term and further into the future toward warmer and wetter conditions (Karl et al., 2009; Pryor et al., 2014), research needs to be conducted to define the benefits of subirrigation practice for maintaining or increasing maize yield under future climate. The goal of this study was to investigate the potential maize relative yield that could be expected in northwest Ohio with subirrigation practice in comparison to free subsurface drainage under historic (1984-2013) and future climate conditions (2041-2070).

2. Material and methods

2.1. Study location

The sites simulated in this study are located in Fulton, Defiance, and Van Wert Counties in northwest Ohio (Figure 1). At each site, similar fields with free subsurface drainage and no irrigation were used as controls. Runoff and subsurface drainage water were collected at each site and routed to a wetland/reservoir complex, and from there used to subirrigate the crops on the subirrigated fields. Because DRAINMOD does not simulate water capture and recycling, the wetland/reservoir was not simulated in this work. The objective of subirrigation was to maintain the water table depth above the drains at 25 cm below ground surface during the growing season (May - September). Therefore, depending on the frequency and the depth of precipitation events, the water table management of the subirrigated fields varied between free subsurface drainage, controlled drainage, and subirrigation. The non-subirrigated fields were under free subsurface drainage year-round. The sites were in operation between 1996 and 2008, during which maize and soybeans were grown in rotation. The system is described more fully in Allred et al. (2014).

2.2. Subirrigation and crop relative yield simulation with DRAINMOD

DRAINMOD simulates subirrigation in shallow soils with impermeable layers. A modification of the water movement rate model developed by Ernst (1974) is implemented to estimate the rate at which water moves into the soil profile from the drains and to determine the depth of the water table at the end of each simulated day (Skaggs, 1981). The user enters the dates at which control weir levels or water table management practice are changed, the new weir depth below ground surface, and the new water table management practice. The control weir is raised above the drain level to create controlled drainage or subirrigation conditions and is lowered to the drain level to create free drainage conditions.

Besides its hydrologic simulation capability, DRAINMOD predicts crop relative yield response to the soil water regime based on a stress day index method (Evans et al., 1991). Therefore, DRAINMOD can be used to quantify the relative yield response of various water management systems and strategies. The relative yield can be defined as the ratio of the yield under a particular set of stress (excess water, drought, planting delay) to the maximum yield potential of a field. DRAINMOD calculates crop relative yield from simulated stresses using the simulated amount and duration of excess water above a defined water table threshold, drought intensity and duration, and extent of the planting delay. During a given simulated year, the overall crop relative yield is estimated using equation (1).

$$YR = YR_w * YR_d * YR_p \qquad (1)$$

Where YR_w is the relative yield with only excess water stress, YR_d is the relative yield with only drought stress, and YR_p is the relative yield that would result from planting delay only. YR_w, YR_d, and YR_p are estimated using linear functions based on the magnitude of wet and drought stresses that occurred during the growing season, and on the planting delay. Singh et al. (2006), Evans et al. (1991), Kanwar et al. (1994), Mukhtar et al. (1990), and Shaw (1978) provided detailed information on the estimation of the crop relative yield and proposed several linear functions to relate wet and drought stresses to relative yield. Previous studies showed that DRAINMOD crop relative yield predictions approached field measurements based estimates depending on the growing season conditions (Ale et al., 2009; Kanwar et al., 1994; Satchithanantham and Ranjan 2015; Wang et al. 2006).

2.3. DRAINMOD setup

A DRAIMOD realization was setup for each location. Inputs of drainage design (according to the conceptual representation shown in Figure 2) and water table management strategy, soil and crop parameters, and weather data are required to simulate a subirrigation system.

2.3.1. Drainage system design

The values of the subsurface drainage system parameters used in this work are presented in Table 1. While the drainage systems on the experimental fields were generally designed based on drainage coefficients of 3.8 to 5.1 cm d^{-1} (Allred et al., 2014), a drainage coefficient of 5.1 cm d^{-1} was simulated at the 3 sites. At Defiance, the soil conductivity greatly decreased at 76 cm below ground surface, so drains were simulated above that depth, while at Fulton and Van Wert 84 cm was used. At each site the drains were either 10 cm diameter corrugated plastic pipes or clay tiles, therefore their effective radius was 0.51 cm, as recommended by Skaggs (1980). Information regarding the subirrigation pump flow rate was not reported, therefore 16 cm d^{-1} representing twice the estimated value of the maximum daily evapotranspiration (ET_p) at the three sites was conservatively selected as the maximum capacity of the subirrigation pump, under the assumption that evapotranspiration needs during drought spells are satisfied exclusively by water supplied via subirrigation.

2.3.2. Soil data

The major soil series found at the Defiance, Fulton, and Van Wert sites are Paulding clay, Nappanee loam, and Hoytville silty clay, respectively (Allred et al., 2014; Soil-Survey-Staff, 2013). These soils are characterized by the presence of a clay subsoil that forms an impeding layer for root growth and water flow. The Paulding clay soil series is a dense glacio-lacustrine deposit mostly located on lake plains, and characterized by a very low permeability, a very poor drainage and frequent ponding, and a significant shrink- swell potential making it prone for large crack development during drying. Located on lake plains as well, the Nappanee loam soil series is also a dense glacio-lacustrine deposit characterized by a flat topography, a somewhat poor drainage, a moderate shrink-swell potential, with a low ponding potential, and a moderately low to high conductivity (Soil-Survey-Staff, 2013). The Hoytville silty clay soil series is also located on lake plains and also characterized by a flat topography. The Hoytville silty clay soil series is a dense glacio-lacustrine deposit as well, and characterized by a low to moderate conductivity, a very poor drainage, and frequent ponding (Soil-Survey-Staff, 2013).

The ponding potential description of the soil series served as base for surface storage parameter values selection (Table 1) based on the recommendations from Skaggs (1980) and Workman and Fausey (1985). Soil texture and hydraulic properties obtained from the SSURGO database of the 3 sites and from previous onsite measurements are reported in Table 2. Besides the hydraulic conductivity of the soil profiles, soil-water characteristics, Green-Ampt infiltration model parameters, the drainage volume–water table depth and the water upflux–water table depth relationships were needed to run DRAINMOD. The soil utility package included in DRAINMOD was used to estimate these hydraulic properties based on pedotransfer function parameters obtained using the pedotransfer estimation software ROSETTA (Schaap et al., 2001). The pedotransfer function parameters were estimated in ROSETTA using the texture and water holding capacity of the soil series.

2.3.3. Crop and trafficability parameter

Relative yield simulation in DRAINMOD requires the soil root zone water content at wilting point, the drought period susceptibility factor, the desired planting date, the growing season length, the limiting water table depth, and the effective root depth vs. days after planting relationship (Skaggs, 1980). Initial values of soil water content at wilting point were selected from the SSURGO database and were calibrated (Table 3). Between 1997 and 2006, the average planting date at the experimental sites was

May 10th, therefore this date was selected as the desired planting date. A growing season length of 136 days was selected as suggested by Barker et al. (2005). Based on the selected planting window and the growing season length, the simulations were conducted over a cropping window extending from April to October.

The effective root depth vs. days after planting relationship is used by DRAINMOD to define the depth at which water is imported to satisfy evapotranspiration (ET_p) needs. The effective rooting depth increases along the growing season, and an effective maximum depth of 45 cm may be reached for maize approximately 80 days after planting (Skaggs, 1980). However, the growth rate and the maximum growth is affected by the presence of physical and chemical barriers as well as water table depth. In this work, maximum effective root depth values greater than 25 cm caused large excess moisture stresses, independently of the simulated soil types, leading to simulated extended planting delays or absence of planting. Therefore, a maximum effective root depth of 25 cm was used for the 3 sites. A fallow period effective root depth of 3 cm and a crop yield limiting water table depth of 30 cm were selected as recommended by Skaggs (1980) for maize.

Field trafficability parameters strongly affect field work, and consequently the planting day. DRAINMOD delays planting until soil moisture satisfies the constraints imposed by the trafficability parameters such as the minimum required air volume to work land, the minimum rain to delay work, and the delay after rain to restart work. The trafficability parameter values used in this study were derived from Nolte et al. (1983). For the minimum soil air volume required to complete field operations, 1.5 cm and 2 cm were used for the planting and the harvest periods, respectively. Planting and harvest operations were delayed for 2 days for daily precipitation amounts larger than 1 cm and 0.5 cm, respectively. Larger daily precipitation amounts above which field operations were delayed were considered based on Nolte et al. (1983) observations and expert recommendations, but resulted in large excess moisture stresses.

2.3.4. Climate data

Two periods were simulated in this work: a historic period from 1984 to 2013 and a future period from 2041 to 2070. For each site, observed daily precipitation and temperature data for 1984 to 2013 were obtained from the Global Historic Climatology Network Daily (Menne et al., 2012). The mean growing season precipitation amounts (May-September) calculated from the observed daily precipitation data were 45 cm for Defiance and Fulton, and 50 cm for Van Wert. DRAINMOD requires hourly precipitation data, which was not available for any of the sites. Hourly precipitation were estimated using the disaggregation utility available in DRAINMOD that evenly distributes the daily rainfall over the user-defined duration (Ale et al., 2009; Singh et al., 2006; Skaggs et al., 2012). It was assumed that daily precipitation events likely occurred between 12:00 pm and 6:00 pm, accordingly the daily precipitation amounts were disaggregated within that time window. Daily ET_p estimates were calculated for each site using the Priestly-Taylor method (Priestley and Taylor, 1972). Daily precipitation and temperature data came from the nearest weather station to each site, while daily solar radiation values used for the ET_p calculation were obtained from the gridded Climatology Resource for Agro-Climatology (White et al., 2011), as no in-situ observations of solar radiation were available.

Projected climate data from the General Circulation Model - Regional Climate Model combinations CRCM_CGCM3, RCM3_GFDL, and MM5I_Hadcm3 forced by the Special Report on Emissions Scenario A2 scenario (IPCC, 2007) were selected to evaluate the impacts of a variety of different projected future climate regimes over northwest Ohio. The climate model-derived projections for daily precipitation, temperature and solar radiation were obtained from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2009) for the historic period 1971-2000 and the future period 2041-2070. The projections were analyzed for biases and corrected using the relative deviations between the observed and the projected data during the historic period. Priestly-Taylor method was used as well to estimate the daily ET_p for the future period.

2.4. Calibration and validation

DRAINMOD was calibrated and validated to simulate the daily water table depths observed at Defiance in 2004 and 2006, respectively, and the annual relative yields calculated from annual yields observed at each site between 1996 and 2008 by Allred et al. (2014). For each site, observation based annual relative yields were calculated as the ratio between the observed annual yields and the largest yield observed during the experimental period at the corresponding site. Refer to supplemental information for full details.

The parameter estimation program (PEST) (Doherty, 2002) was linked to DRAINMOD and used to adjust the pedotransfer function pore tortuosity and connection coefficient, the shape parameter α, and the lateral and overall saturated hydraulic conductivity by soil layer (Table 2). Adjusting these parameters resulted in modifying the relationship between the water table depth and the volume of water drained as well as the upflux, and the Green-Ampt model parameters, for the purpose of improving the fit between observed and modeled daily water table depth. For Fulton and Van Wert, the pedotransfer function parameter values yielded by Rosetta were not modified due to the lack of hydrologic observation data.

Yield prediction parameters (Table 3) were adjusted to replicate the observation based annual relative yields. The coefficients proposed by Kanwar et al. (1994) for wet stress and Shaw (1978) for drought stress were used to initiate the relative yield simulation, and were adjusted within the ranges shown in Table 3 using the linked PEST-DRAINMOD model. An initial value of 1 was selected for drought period susceptibility factor and was also adjusted.

2.5. Long term simulations

Free subsurface drainage and subirrigation practices were simulated for each of the three sites for (1) the period 1984-2013 using observed weather data, and (2) the period 2041-2070 using the three model-based climate projections. For free subsurface drainage, the system was allowed to drain freely year-round. Subirrigation was implemented by setting the drainage control weir at 25 cm below ground surface from June 15th to September 25th and water is added; from September 25th to June 14th, water is allowed to drain freely and subirrigation is not implemented.

The effect of subirrigation practice on the hydrologic regime of the experimental fields under 1984-2013 and 2041-2070 climate conditions was analyzed using t-tests to compare the mean water table depth, drainage, runoff and subirrigation between the two water table management practices at each site. ANOVA test with Tukey procedures were used at 5% significance level to assess the relative yield difference between the historic and the future period, and the impacts of growing season precipitation regime on relative yield.

3. Results and discussion

3.1. Projected climatological changes

The climate projections indicated substantial changes in growing season climate when compared to historical values, particularly in terms of temperature (Table 4). Growing season max, min, and mean temperatures are projected to increase at similar magnitude by the mid-21st century, while precipitation projections are mixed for future growing seasons. The cumulative distribution of the growing season precipitation estimated from the projected data for the future period indicates that the CRCM_cgcm3 growing season precipitation is closely distributed around a mean value, whereas those projected by MM5I_Hadcm3 and RCM3_gfdl are highly variable (Figure 3). MM5I_Hadcm3 had the largest range in growing season precipitation distribution of the three models. As a result of these projected changes in temperature and solar radiation, ET_p is also expected to increase during the growing season.

3.2. DRAINMOD performance assessment

Details of DRAINMOD calibration and validation results with supporting figures are presented in the supplementary material of this paper. Only a brief summary is presented here. The predicted daily water table depth at Defiance generally approached the observations, with mean absolute error of 7.2 cm for calibration and 14 cm for validation. Daily NSE for water table depth at Defiance was 0.35 for calibration and -3.84 for validation. Attempts to further reduce the errors between the observed and the modeled water table depth, especially for 2006 (validation), were unsuccessful and conflicted with observation based annual relative yields. Predicted relative yields generally approached observation based relative yields (Figure 4). The mean absolute errors between simulated and observation based maize relative yield varied between 8% to 11% for subirrigation practice and 10% to 13% for free subsurface drainage.

3.3. Impacts of subirrigation practice on Hydrology

3.3.1. Water table

Subirrigation is expected to raise the water table during the growing season, thereby increasing crop yield. However at Defiance, very low soil lateral hydraulic conductivity limited the effectiveness of subirrigation (Figure 5). In 2004, the water table level at the start of the subirrigation period (shaded) was at the level of the weir, and was able to remain at this height, but in 2005 and 2006, the rise of the water table was slow after the inception of subirrigation, and it took almost the entire subirrigation period for the water table to reach the weir level. As a result, only 36 mm of water could be added to the profile through subirrigation (Table 5) and there was little impact of subirrigation on hydrology or relative crop yield at the Defiance site. At Fulton and Van Wert, faster water table responses to subirrigation were simulated due to the higher soil lateral hydraulic conductivity. The average difference in water table depth between subirrigation practice and free subsurface drainage during the growing season was significant (Table 5) and ranged from 17 cm to 52 cm, indicating that subirrigation effectively raised the water table depth at these two sites.

Hydrology of the subirrigated fields also differed from the free draining fields during the non-growing season when no subirrigation took place, due to the difference in drain spacing. By design, a narrower spacing is used in the subirrigated fields to increase the distribution rate of water within the soil profile during subirrigation events (Allred et al., 2014). As a result, the water table was generally deeper in the subirrigated fields in the non-growing season, with the depth difference between the two practices ranging from 3 cm to 19 cm. The difference at Defiance was the lowest, due to the very slow hydraulic conductivity.

Under future climate conditions, daily water table depths in the subirrigated fields followed the same pattern: shallower during the growing season and deeper during the non-growing season, except at Defiance where the difference was not significant (p-value>0.05, Table 5). In general, the water table depth did not differ significantly between historic and future climate.

3.3.2. Drain flow and runoff

Drain flow was higher in the subirrigated fields during both growing and non-growing seasons (Table 5), due to the narrower drain spacing. Surface runoff was also higher in the subirrigated fields during the growing season, probably due to the higher soil moisture content resulting from the subirrigation, but lower during the non-growing season due to the increased drain flow resulting in lower soil moisture. Ng et al. (2002) also found that the cumulative drain flow from the subirrigated fields was slightly larger than that from free draining fields. Drury et al. (2009) found that runoff was larger under subirrigation, but in contrast to this site, drainage was lower, probably because the drain spacing was the same. ET was higher during the growing season, as expected, since the subirrigation provided more of the crop water needs, and similar in both fields during the non-growing season.

Similar results regarding drainage, runoff, and ET apply to historic as well as future conditions. Hence, although the distribution of seasonal precipitation is expected to change, with the future period expected to frequently receive larger precipitation during the growing season (Figure 3), no significant impacts on mean water table depth, mean drainage, mean runoff, and mean subirrigation patterns are expected.

3.4. Impacts of subirrigation practice on maize relative yield under historic conditions

3.4.1. Annual relative yields

Crop yield response to subirrigation differed among the three sites (Figure 6). At **Defiance**, the low conductivity soils resulted in little response to subirrigation, with relative yield under free drainage and subirrigation almost identical. Allred et al. (2014) observed similar response to subirrigation practice at Defiance (3% relative yield difference). Murugaboopathi et al. (1995) also found that maize subirrigation practice in low conductivity soils tended to result in low relative yields in their North Carolina soils. The greatest impact of subirrigation was found at the **Fulton** site, where the overall relative yield difference for the simulated period was 26.5%. This is very similar to the 27% relative yield difference observed by Allred et al. (2014) at this site for the 1998-2008 period. Subirrigation had less impact at **Van Wert** because relative yields under free subsurface drainage (i.e., without irrigation) were considerably higher than at Fulton. The mean annual relative yields were 80% for subirrigation and 79% for free subsurface drainage, with a non-significant difference of 1% (Figure 6, p-value = 0.6), while the relative yield difference between the two managements reported by Allred et al. (2014) was 7%.

3.4.2. Effects of dry years and wet years

At both **Fulton and Van Wert**, the annual relative yields under the two management practices varied inversely (correlation coefficients -0.63 and -0.55 for Fulton and Van Wert, respectively, Figure 7). This means that wet years, which resulted in higher relative yields in free draining fields, actually lowered the relative yield in the subirrigated fields. This impact was further explored by comparing the relative annual yields based on the growing season precipitation (Figure 7). At **Defiance**, the difference in relative yield between the two practices was not significant in wet or dry years, due to low conductivity soils as discussed previously. At the **Fulton** site, crop yield benefited from subirrigation in both dry and wet years, with the strongest response in dry years as expected. The yield benefits in wet years are likely due to the narrower drain spacing. At **Van Wert** crop yield benefited from subirrigation in dry years but declined in wet years. A supplemental addition of water via subirrigation during periods of frequent rainfall events potentially increases the risks of root zone flooding and crop respiration disruption, which can lead to lower crop yield. In practice, and as always recommended, the farmer would be expected to actively manage subirrigation during the growing season by discontinuing the water supply and lowering the control weir in response to large rainfall events (Allred et al., 2003). Active management of subirrigation systems during the growing season with regard to rainfall events prevents root zone flooding problems, and in fact, leads to modest crop yield increases in subirrigated fields during wet growing seasons (Allred et al., 2014). However, this was not simulated. Results show that implementing subirrigation at Defiance and Van Wert during wet years may not benefit maize, unless an intermittent or active management of the subirrigation system is conducted.

3.5. Implication of climate change on the relative yield differences

The difference between the relative yield simulated for free drainage and subirrigation was affected by changes in climate conditions (Figure 6, Table 6). At Defiance, Fulton and Van Wert, the difference between the mean relative yield under subirrigation practice and that under free subsurface drainage was 2%, 10%, and 8% larger during the future period as compared to the historic period, respectively. The increase in relative yield difference is generally due to the expected drop in relative yield under free subsurface drainage, whereas relative yield under subirrigation practice will remain unchanged. Lower non-irrigated yields in northeast Ohio under future conditions (2041-2060) were also found In a simulation study conducted with DSSAT (Decision Support System for Agro-technology Transfer) by Brumbelow and Georgakakos (2001). Using the EPIC agroecosystem model, Izaurralder et al. (2003) and Brown and Rosenberg (1999) found that maize yield will potentially increase along with atmospheric CO_2 increase in the Corn Belt under future conditions, but assessed that projected water stress and evapotranspiration increase will negatively affect maize yield. Therefore, there is a potential for alleviating the impacts of climate change through the implementation of subirrigation practice that provides enough soil moisture at the appropriate time to compensate for the increased water demands.

By introducing subirrigation in their management, farmers in rainfed areas can lower the threats of occasional droughts and maintain high yields.

4. Limitations

DRAINMOD estimates the relative yield only as a function of the intensity and duration of wet and dry stresses and planting delays predicted for the growing season. Potential stresses such as diseases and nutrient availability are not simulated, while salinity stress (which can be simulated by DRAINMOD) is unlikely in humid Ohio conditions. Therefore, a 100% relative yield indicates the maximum yield that could be obtained during a growing season if there was neither wet nor dry stresses during the growing season, and if planting occurred on time. In reality, other factors may occur during the growing season that affect crop yield. DRAINMOD is being modified to address the potential impacts of other factors on crop yield by incorporation of a crop model (DSSAT) (Negm et al., 2014a, 2014b). A climate factor that was not simulated here but that may strongly affect maize growth and yield is atmospheric concentration of CO_2, which is highly relevant to crop yield under future conditions. Although this study was instrumental at defining the potential implications of climate change on maize relative yield under subirrigation practice in northern Ohio, factors such as adaptive agricultural management response to climate change (planting date shifts, cultivars changes, etc.) were not considered. Further studies that combine the potential impacts of these factors will provide a more complete picture of the climate change impact on maize relative yield under subirrigation practice in northern Ohio.

5. Conclusion

This paper provides the result of a simulation study conducted with DRAINMOD to investigate the effects of subirrigation practice on maize yield under historic (1984-2013) and future (2041-2070) climate conditions. The three sites studied here showed a range of responses to subirrigation, leading to the following conclusions:

- At sites with low soil hydraulic conductivity (Defiance), subirrigation may have little effect. Site selection is critical to identify suitable soils with moderate to high lateral hydraulic conductivities.
- Crop yield response to subirrigation can be as high as 26.5% at sites that respond well to subirrigation such as Fulton. Future benefits are expected to increase. Long-term average benefits of 26.5% under historic precipitation may increase to 36% under future climate conditions. At Fulton, crop yield increased in both dry and wet years, indicating that the soils responded positively to subirrigation and were not unduly harmed by excess water.
- At sites that generally do not require irrigation for high yields (Van Wert), crop yield increased in dry years but decreased in wet years, demonstrating the importance of actively managing the water control structures to limit excess water effects.

Crop yields under free subsurface drainage are expected to decline under future climate conditions, but subirrigation can maintain yields at their historic level. On soils that respond well to subirrigation, the mean relative yield difference between subirrigation and free drainage will potentially nearly double from 15% to 24% between the historic period and the future period.

At the three sites reported here, drain spacing was narrower in the subirrigated fields, resulting in higher drain flow but lower surface runoff during the non-growing season. Larger drain flow can increase the potential for nutrient export. However, capturing and recycling water and nutrients as was done at these sites can be used to curb the negative environmental impacts of narrower drain spacing

Overall, maize relative yield increases can be expected with subirrigation practice on suitable soils. The simulations with future climate projections (2041-2070) indicated that maize relative yield will potentially drop in the future, but subirrigation practice may help alleviate the impacts of climate change by holding relative yields at the level observed during the historic period.

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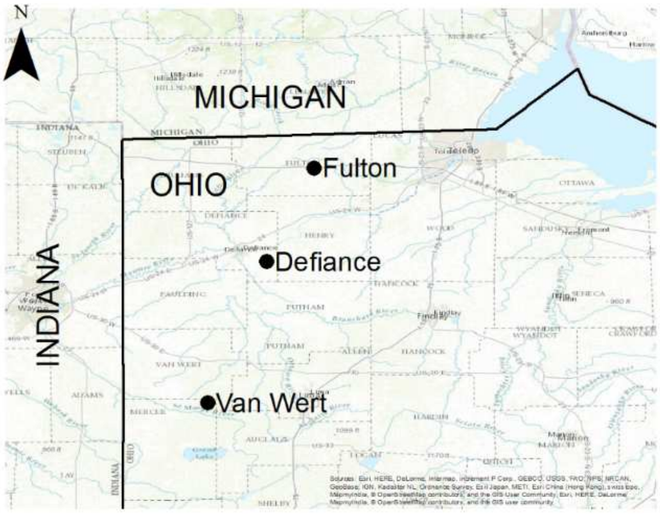

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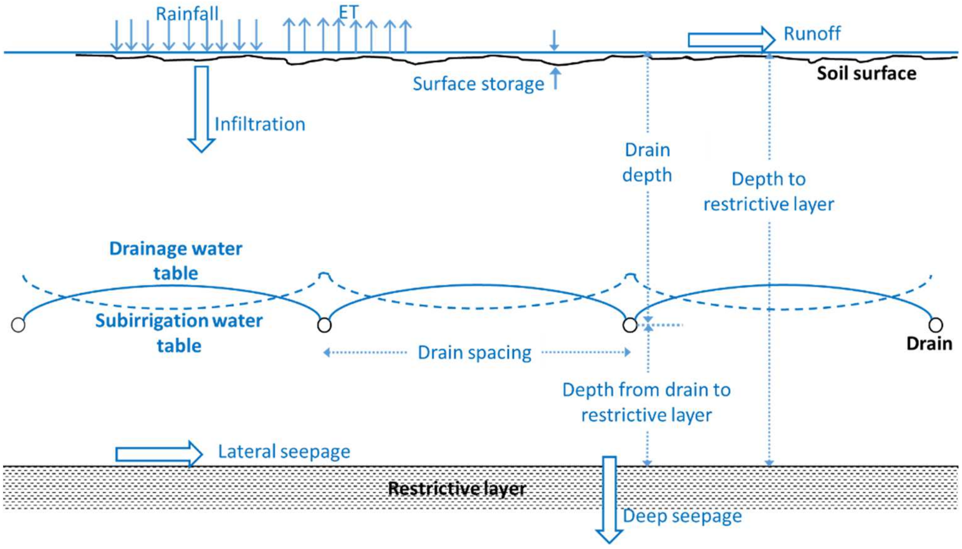
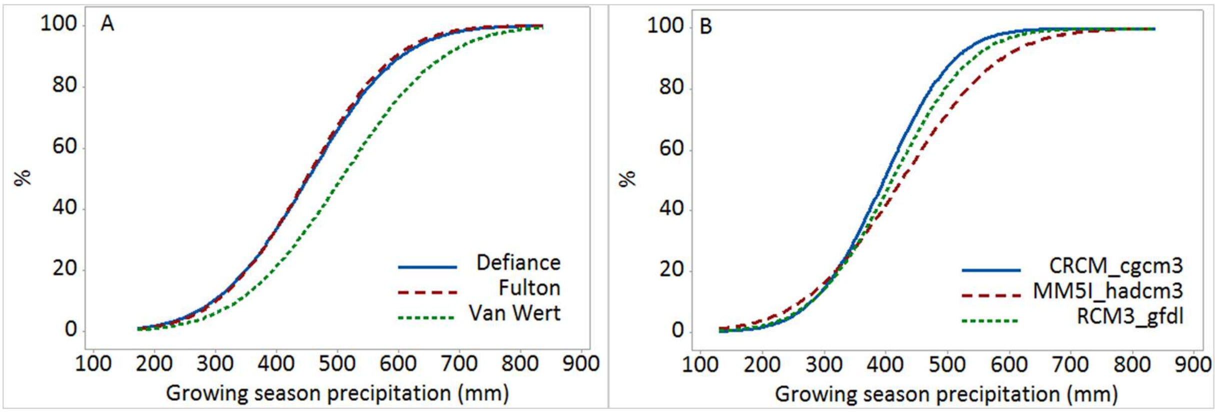
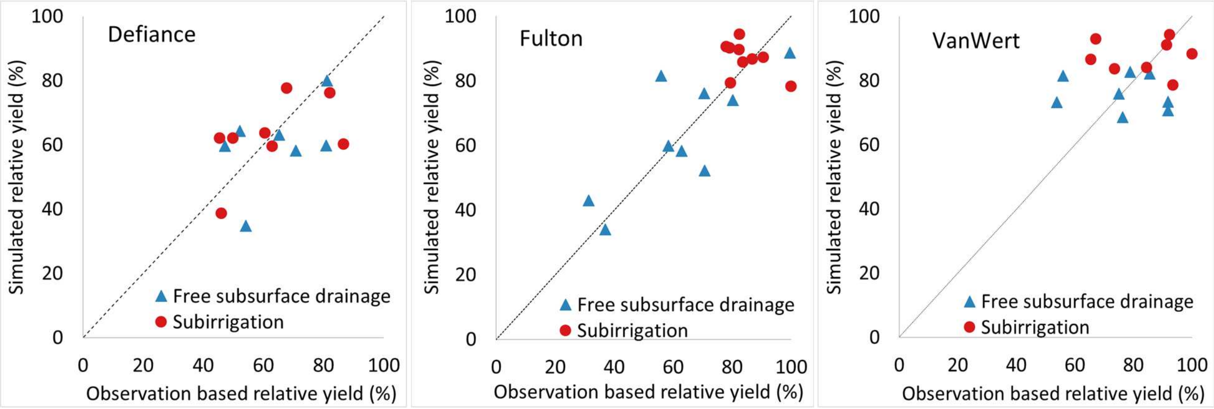
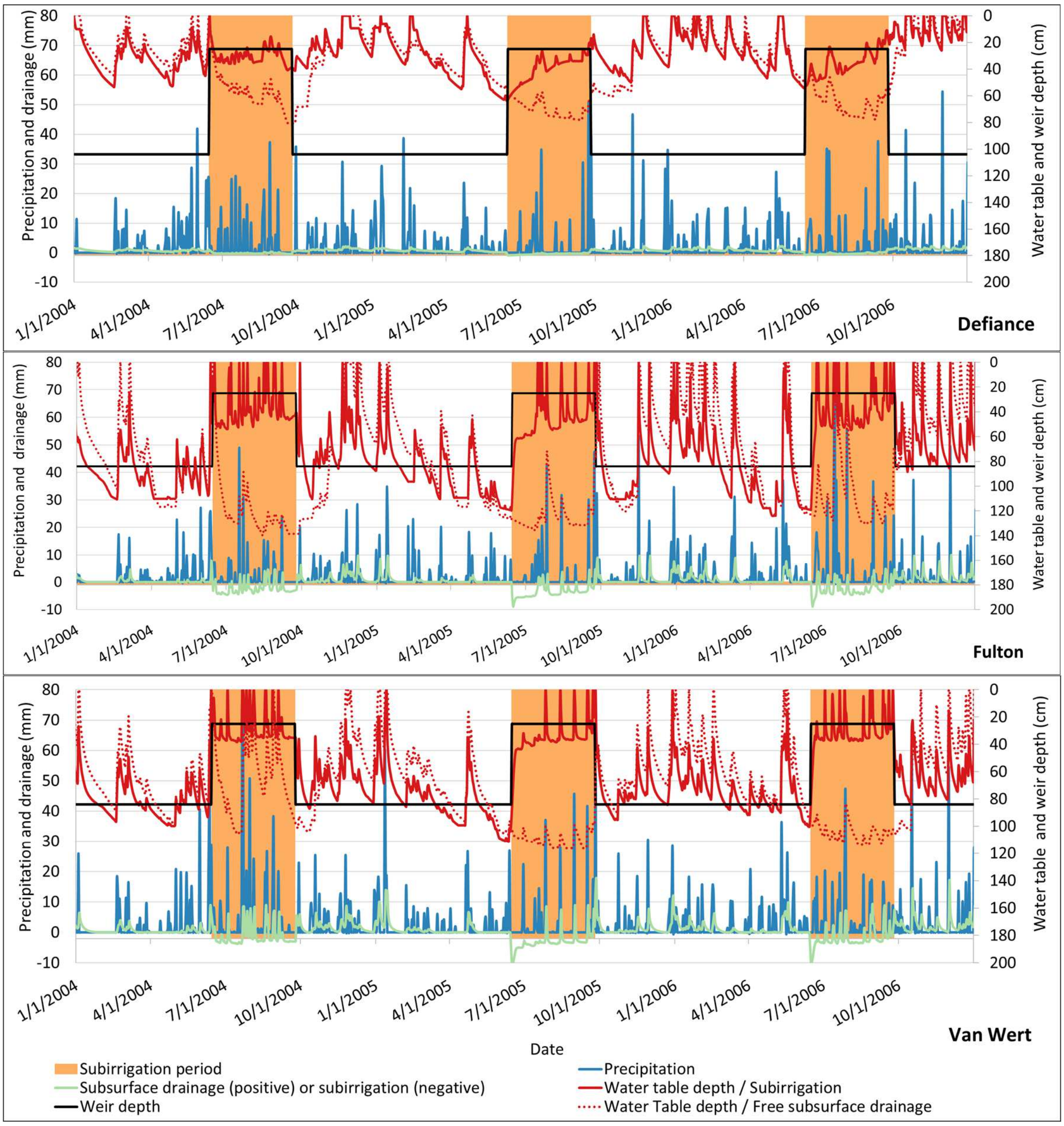
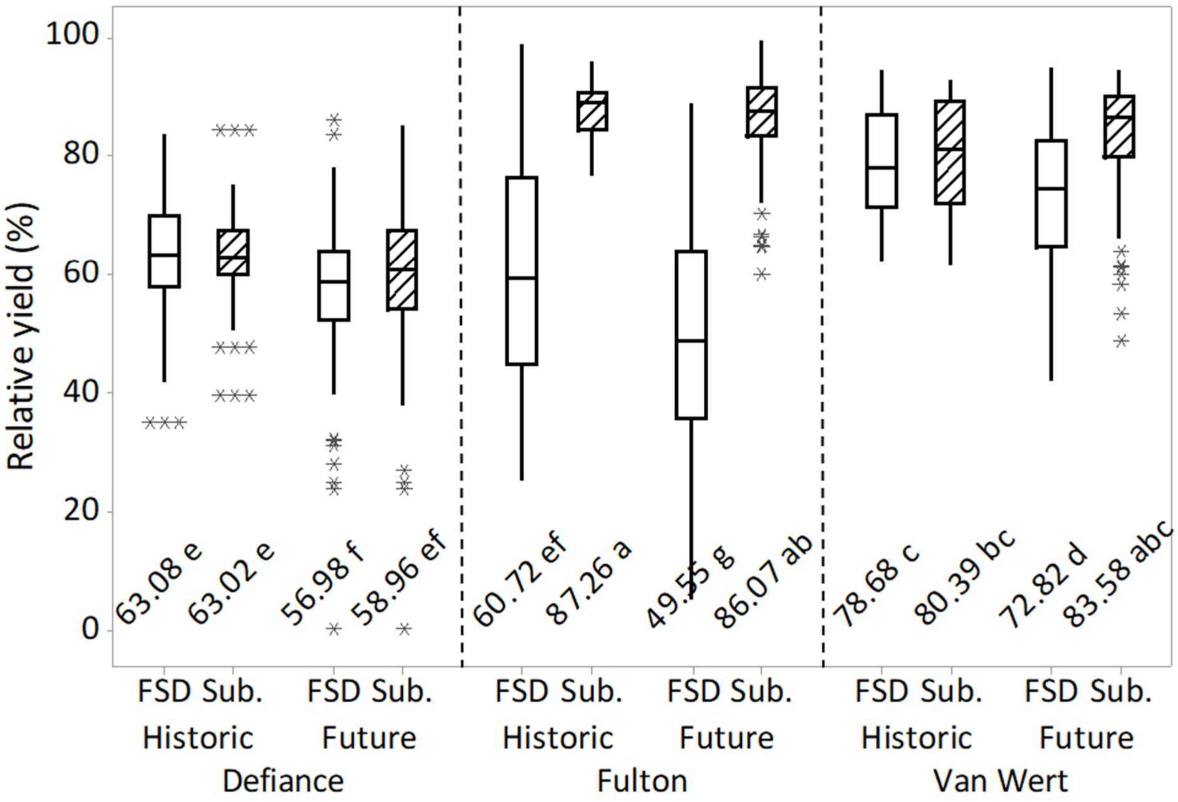

Rainfall
ET
Runoff
Surface storage
Soil surface
Infiltration
Drain depth
Depth to restrictive layer
Drainage water table
Subirrigation water table
Drain spacing
Drain
Depth from drain to restrictive layer
Lateral seepage
Restrictive layer
Deep seepage


A
%
0
20
40
60
80
100
100
200
300
400
500
600
700
800
900
Growing season precipitation (mm)
Defiance
Fulton
Van Wert
B
%
0
20
40
60
80
100
100
200
300
400
500
600
700
800
900
Growing season precipitation (mm)
CRCM_cgcm3
MM5I_hadcm3
RCM3_gfdl


Defiance
Fulton
VanWert
Simulated relative yield (%)
Observation based relative yield (%)
0
20
40
60
80
100
Free subsurface drainage
Subirrigation


Precipitation and drainage (mm)
Water table and weir depth (cm)
80
70
60
50
40
30
20
10
0
-10
0
20
40
60
80
100
120
140
160
180
200
1/1/2004
4/1/2004
7/1/2004
10/1/2004
1/1/2005
4/1/2005
7/1/2005
10/1/2005
1/1/2006
4/1/2006
7/1/2006
10/1/2006
Defiance
Fulton
Van Wert
Date
Subirrigation period
Subsurface drainage (positive) or subirrigation (negative)
Weir depth
Precipitation
Water table depth / Subirrigation
Water Table depth / Free subsurface drainage


Relative yield (%)
100
80
60
40
20
0
63.08 e
63.02 e
56.98 f
58.96 ef
60.72 ef
87.26 a
49.55 g
86.07 ab
78.68 c
80.39 bc
72.82 d
83.58 abc
FSD
Sub.
Historic
FSD
Sub.
Future
Defiance
FSD
Sub.
Historic
FSD
Sub.
Future
Fulton
FSD
Sub.
Historic
FSD
Sub.
Future
Van Wert

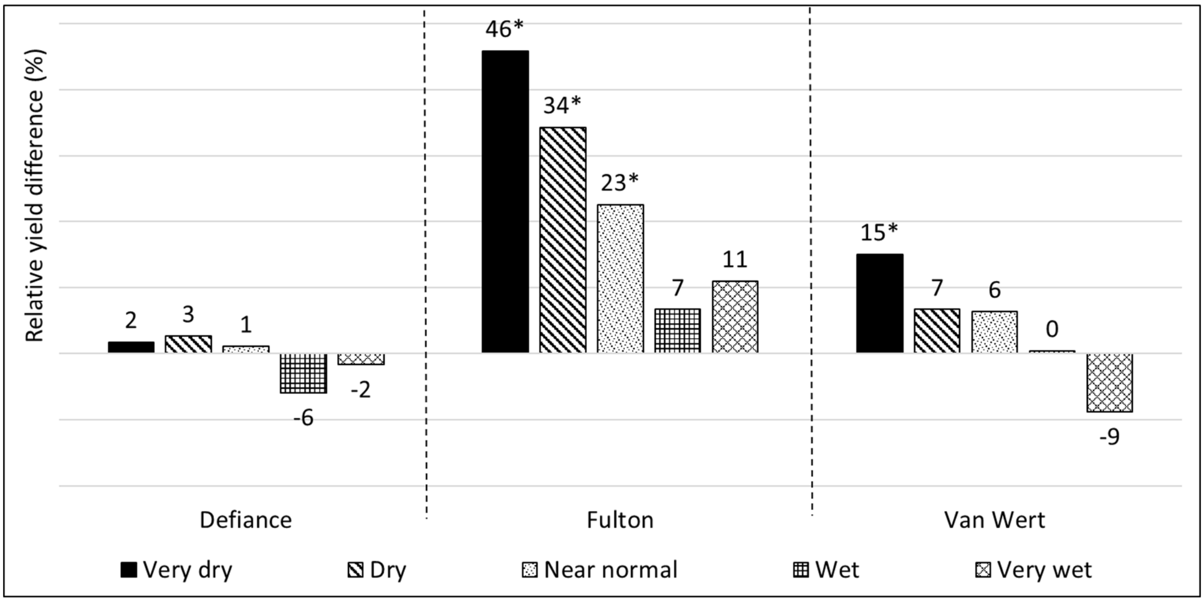

Relative yield difference (%)
2
3
1
-6
-2
46*
34*
23*
7
11
15*
7
6
0
-9
Defiance
Fulton
Van Wert
Very dry
Dry
Near normal
Wet
Very wet

Table 1. Drainage systems design and surface storage.

Parameters	Calibration range	Sites		
		Defiance	Fulton	Van Wert
System design				
Drain depth (cm)[a]		76	84	84
Drain spacing (m)[a]				
Subirrigated field		4.9	4.6	5.3
Free drainage field		6.1	13.7	10.7
Drainage coefficient (cm d^{-1})[a]		5.1	5.1	5.1
Effective radius of drain (cm)[b]		0.51	0.51	0.51
Depth to impermeable layer (cm)[c]		84	122	102
Subirrigation pump capacity (cm d^{-1})		16	16	16
Subirrigation weir depth (cm)[a]		25	25	25
Surface storage [d]				
Maximum surface storage (cm)	0.5 – 1.5	0.74	0.5	1.2
Kirkham’s depth for flow to drains (cm)	0.3 – 1.0	0.5	0.4	0.6

[a] Allred et al. (2014)

[b] Skaggs (1980)

[c] Hothem (1999)

[d] Storage values reported for Defiance are from calibration

Table 2. Soil series texture and hydraulic properties.

Layer top depth cm	Sand [a] %	Silt [a] %	Clay [a] %	Dry bulk density [a] g cm^{-3}	Water content at field capacity [a] cm^3 cm^{-3}	Water content at wilting point [a] cm^3 cm^{-3}	Saturated hydraulic conductivity cm d^{-1}
Paulding (Defiance)							
0	8	31	61	1.49	0.45	0.36	0.60^b – 1.82^b
15	4	29	67	1.61	0.44	0.39	0.60^b – 1.82^b
23	4	27	69	1.61	0.43	0.38	0.60^b – 1.82^b
76	4	26	70	1.67	0.42	0.39	0.02^a – 1.82^b
122	4	27	69	1.74	0.39	0.39	0.02^a – 1.82^b
Nappanee (Fulton)							
0	39	37	24	1.47	0.29	0.15	6 .00^b – 36.00^b
15	18	29	53	1.83	0.34	0.25	6 .00^b – 36.00^b
66	28	29	43	1.98	0.30	0.22	3.60^a – 36.00^b
Hoytville (Van Wert)							
0	16	43	41	1.32	0.35	0.26	18.00^b – 36.00^b
20	15	39	46	1.55	0.33	0.25	18.00^b – 36.00^b
98	18	43	39	1.82	0.34	0.24	18.00^b – 36.00^b
152	22	40	38	2.07	0.27	0.25	3.60^a – 12.24^a

[a] SSURGO database (Soil-Survey-Staff, 2013)

[b] (Hothem, 1999)

Table 3. Crop and trafficability parameters.

Parameters	Calibration range	Sites		
		Defiance	Fulton	Van Wert
Crop				
Limiting water table depth (cm)[a]		30	30	30
Root zone lower limit water content (cm^3 cm^{-3})[b]	0.2 – 0.4	0.30	0.22	0.25
Maximum effective root depth (cm)[b]		25	25	25
Relative yield simulation				
Cropping window[c]		Apr-Oct	Apr-Oct	Apr-Oct
Desired planting date[c]		5/10	5/10	5/10
Growing season length (d)[d]		136	136	136
Yield intercept for crop wet stress (SDI wet)[b]	90 - 110	100	100	95
Slope for yield vs. crop wet stress (SDI wet)[b]	0.3 – 0.8	0.36	0.36	0.36
Drought stress yield intercept[b]	90 – 110	100	100	110
Drought stress yield slope[b]	0.5 – 1.5	1.22	1.22	1.00
Drought period susceptibility factor[b]	0.5 – 1.0	0.6	1.0	0.8
Trafficability[e]				
Minimum required air volume (cm)				
First period		1.5	1.5	1.5
Second period		2	2	2
Minimum rain to delay work (cm)				
First period		1	1	1
Second period		0.5	0.5	0.5
Delay after rain to restart work (d)		2	2	2

[a] (Skaggs, 1980) [b] Calibrated values [c] (Allred et al., 2014)

[d] (Barker et al., 2005) [e] (Nolte et al., 1983)

Table 4. Climatological growing season values (1984-2013) from station observations and relative changes in growing season climate variables between the future period (2041-2070) and the modeled historic period (1971-2000). Positive (negative) values indicate a future increase (decrease) (Data source: Mearns et al., 2009).

Observations (1984-2013)	Maximum Temperature °C	Minimum Temperature °C	Average Temperature °C	Precipitation mm	Solar radiation MJ m^2 d^{-1}	Potential ET[a] mm
Defiance	-	-	20.1	449	19.4	620
Van Wert	-	-	20.4	502	19.4	627
Fulton	-	-	19.6	448	19.4	611
Projected Changes	**Maximum Temperature °C**	**Minimum Temperature °C**	**Average Temperature °C**	**Precipitation mm**	**Solar radiation MJ m^2 d^{-1}**	**Potential ET* mm**
CRCM_cgcm3	3.9	3.3	3.6	-29	0.48	61
RCM3_gfdl	3.3	3.0	3.1	0	0.48	59
MM5I_Hadcm3	2.8	3.0	2.9	37	0.59	59

[a] Potential evapotranspiration

Table 5. Daily water table depth, and annual subsurface drainage, runoff, crop evapotranspiration (ET_c) and subirrigation amount by site, season and management.

Hydrologic variables	Defiance				Fulton				Van Wert			
	GS [a]		NGS [a]		GS		NGS		GS		NGS	
	FSD†	Sub [a]	FSD	Sub	FSD	Sub	FSD	Sub	FSD	Sub	FSD	Sub
Historic period												
Water table (cm)	**54**	37	25*	**28***	**109***	57	61*	**80***	**86**	47	60*	**73***
Drainage (mm)	33	35	131	**181**	16	**75**	101	**177**	56	**135***	210	**266**
Runoff (mm)	111	109	**172**	154	34	**125**	**130**	81	29*	**75**	48	34
ET_c (mm)	338*	345*	151	149	413*	**538**	193	192	450*	**558***	193	194
Subirrigation (mm)	-	36	-	-	-	301*	-	-	-	277	-	-
Future period												
Water table (cm)	**53**	36	25	25	**106**	56	51	**73**	**89**	49	57	**71**
Drainage (mm)	37	**38**	130	**187***	27	**84**	155*	**264***	60	**116**	249*	**310***
Runoff (mm)	102	99	**203**	179	43	**74**	**168**	87*	14	**24**	**56***	39*
ET_c (mm)	316	323	143	141	376	**548***	162	**176**	391	**549**	**160**	177
Subirrigation (mm)	-	36	-	-	-	301	-	-	-	283	-	-

[a] GS: growing season (May-September); NGS: non-growing season (October-April); FSD: Free subsurface drainage; Sub: subirrigation

* Significant difference between historic and future for the corresponding variable within the same column

Bolded numbers show significant difference between FSD and Sub. for the same site, season, and variable

Table 6. Annual mean relative yield by site, period, climate data source, and management.

Time period	Climate data source	Management	Defiance	Fulton	Van Wert
			%		
Historic					
	Observed	FSD[a]	63	61	77
		Sub.[b]	63	87	80
	Sub. - FSD		0	26	3
Future					
	RCM3_gfdl				
		FSD	61	55	77
		Sub.	64	86	84
		Sub. - FSD	3	31	7
	MM5I_Hadcm3				
		FSD	56	50	71
		Sub.	59	87	83
		Sub. - FSD	3	37	12
	CRCM3_cgcm3				
		FSD	55	44	70
		Sub.	55	86	84
		Sub. - FSD	0	42	14
	Mean (Sub. – FSD)[c]		2	36	11
Difference (Future – Historic)[d]			2	10	8

[a] Free subsurface drainage [b] Subirrigation [c] Mean of the 3 circulation models

[d] Difference showing the implication of climate change