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Modeling the impacts of climate change on nitrogen losses and crop yield in a subsurface drained field

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Abstract The effect of climate change on crop production and nitrate-nitrogen (NO_3-N) pollution from subsurface drained fields is of a great concern. Using the calibrated and validated RZWQM2 (coupled with CERES-Maize and CROPGRO in DSSAT), the potential effects of climate change and elevated atmospheric CO_2 concentrations (CO_2) on tile drainage volume, NO_3-N losses, and crop production were assessed integrally for the first time for a corn-soybean rotation cropping system near Gilmore City, Iowa. RZWQM2 simulated results under 20-year observed historical weather data (1990–2009) and ambient CO_2 were compared to those under 20-year projected future meteorological data (2045–2064) and elevated CO_2, with all management practices unchanged. The results showed that, under the future climate, tile drainage, NO_3-N loss and flow-weighted average NO_3-N concentration (FWANC) increased by 4.2 cm year^{-1} (+14.5 %), 11.6 kg N ha^{-1} year^{-1} (+33.7 %) and 2.0 mg L^{-1} (+ 16.4 %), respectively. Yields increased by 875 kg ha^{-1} (+28.0 %) for soybean [*Glycine max* (L.) Merr.] but decreased by 1380 kg ha^{-1} (−14.7 %) for corn (*Zea mays* L.). The yield of the C_3 soybean increased mostly due to CO_2 enrichment but increased temperature had negligible effect. However, the yield of C_4 corn decreased largely because of fewer days to physiological maturity due to increased temperature and limited benefit of elevated CO_2 to corn yield under subhumid climate. Relative humidity, short wave radiation and wind speed had small or negligible impacts on FWANC or grain yields. With the predicted trend, this study suggests that to mitigate NO_3-N pollution from subsurface drained corn-soybean field in Iowa is a more challenging task in the future without changing current management practices. This study also demonstrates the advantage of an agricultural system model in assessing climate change

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impacts on water quality and crop production. Further investigation on management practice adaptation is needed.

List of acronyms

AE	Actual evaporation
AET	Actual evapotranspiration
AT	Actual transpiration
BL	Baseline
BL_M1	Future scenario from CRCM_ccsm
BL_M2	Future scenario from CRCM_cgcm3
BL_M3	Future scenario from HRM3_hadcm3
BL_M4	Future scenario from RCM3_cgcm3
BL_M5	Future scenario from RCM3_gfdl
BL_M6	Future scenario from WRFG_ccsm
CDFs	Cumulative distribution functions
CO_2	Atmospheric carbon dioxide concentration
DSSAT	Decision support system for Agrotechnology transfer
FWANC	Flow-weighted average NO_3-N concentration
GCM-RCM	Coupled General Circulation Model and Regional Climate Model
NARCCAP	North American Regional Climate Change Assessment Program
NO_3-N	Nitrate-nitrogen
PE	Potential evaporation
PET	Potential evapotranspiration
PT	Potential transpiration
RH	Relative humidity
RZWQM2	Root Zone Water Quality Model
WUE	Water use efficiency

1 Introduction

Past and present shifts in Iowa's climate have had and continue to have a significant impact on the state's agricultural, economic and public health sectors. Shifts in precipitation (8 % increase) has occurred from 1873 to 2008 with stronger summer storm systems (changed seasonality) in the last 40 years and a larger precipitation increase in eastern Iowa than in western Iowa, while the current upward trend in temperature is another changing factor influencing agriculture (Takle 2010). Relative humidity, particularly in the summer season, has risen substantially (13 %) over the last 35 years indicated by an increase of 3.5 °C in dew point temperature (Takle 2010). Pryor et al. (2009) reported a declining trend in wind speed in Iowa over the last 30 years. The most possible reason could be increases in land use for urbanization and consequent land encroachments around weather stations. Qian et al. (2007) reported decreasing solar radiation caused by increased cloudiness in the Mississippi River basin between 1948 and 2004. Global CO_2 emissions have increased by 80 % between 1970 and 2004 and are projected to increase to 500 ppm by the 2050s (IPCC 2007).

There is mounting evidence that the current changes in climate will continue and that these changes will affect agricultural systems. One important environmental issue related to agriculture is NO_3 pollution of surface and groundwaters. Nitrogen applied as inorganic fertilizer, manure, or derived from soil organic matter, can be carried off-site through leaching of mainly NO_3-N (vs. NH_4-N, or organic forms of N) in water drained through subsurface tile drainage systems. The leaching of nitrogen from agricultural fields via subsurface drainage is a major factor in nonpoint-source pollution of surface water and the consequences thereof [e.g., the Gulf of Mexico's hypoxic zone (Rabalais et al. 2001)]. Roughly a quarter of Iowa's agricultural land is artificially drained (Baker et al. 2004), and NO_3-N leaching losses from these lands have been found to closely correlate with the volume of subsurface drainage flow (Cambardella et al. 1999). For the 1990s, in Iowa, Singh et al. (2009) showed a strong correlation ($R^2=0.83$) between subsurface drainage and precipitation and suggested that climate change would therefore strongly influence subsurface drainage systems due to its direct impacts on precipitation. The increase in subsurface drainage in response to the increased precipitation has the potential to increase nitrogen leaching from Iowa's subsurface drained landscapes (Singh et al. 2009).

Changes in temperature and precipitation in the future present a challenge to crop production (Hatfield et al. 2011). Tile drainage volume is influenced by evapotranspiration (*ET*). As part of the hydrologic cycle, there are several factors affecting a plant's transpiration rate and therefore *ET*. These include CO_2 (Hatfield et al. 2011), temperature (Allen et al. 2003), relative humidity (Bandyopadhyay et al. 2009) and wind speed (He et al. 2013), amongst others. The level of NO_3 in tile drainage is affected by mineralization-immobilization processes in the soil, which are closely tied to temperature (Melillo et al. 2002) and elevated CO_2 (Reich and Hobbie 2012). For a reference crop of alfalfa (Medicago sativa L.), Kimball (2007) reported ET at Maricopa, AZ increased by 3.4 % $°C^{-1}$ when only the temperature changed. Subsequently, this could lead to increased soil water stress which could, in turn, result in reduced crop growth and yield and associated economic impacts unless the situation was mitigated by other factors such as a corresponding rise in precipitation, an increase in WUE (water use efficiency) related to the effects of elevated CO_2 or the implementation of certain management practices, e.g. greater supplemental irrigation.

Integrated agricultural management practices seek to reduce environmental pollution without diminishing crop production, such as N fertilizer application rate and timing, controlled drainage, tillage, cultivars and planting date. Given the logistical and financial difficulties in incorporating all these various production factors, climates, and their interactions into agricultural field experiments (Ko et al. 2012), agricultural system models serve as essential tools in evaluating the integrated impacts of climate change under given management practices (Ma et al. 2009). While a few studies (Dayyani et al. 2012; Singh et al. 2009) have employed DRAINMOD to investigate climate change impacts on drainage and N loss under agricultural production on subsurface drained lands, an integrated simulation of all three components (drainage, N loss, and crop yield) has never been undertaken. Those studies only looked at the subsurface flow and N loss in isolation but ignored crop interactions under changing temperature, CO_2, and precipitation regimes. Thus, further studies using state-of-the-art agricultural system models are required to investigate the effects of climate change and heightened CO_2 on drainage, N loss and crop yield. Given its capability to accurately predict responses of crops and agroecosystems to changes in climate and especially to elevated CO_2 (Ko et al. 2012), the Root Zone Water Quality Model (RZWQM2; Ahuja et al. 2000; Ma et al. 2005, 2006) should be reliable conducting such research. RZWQM2 is an agricultural system model which considers hydrology, plant nutrition and growth, pesticide transport and transformation and agricultural management practices. RZWQM2 has been shown to be effective in simulating *ET*, tile drainage, nitrogen losses and crop production, as well as the impacts of climate change thereon, at various locations in the United States (Islam et al. 2012; Ko et al. 2012; Ma et al. 1999; Qi et al. 2011a, 2012). Therefore, the objective of this study was to apply RZWQM2, calibrated and validated by Qi et al. (2011b), to assess the impacts of climate change on tile drainage, NO_3-N losses and crop yield in a subsurface-drained field located near Gilmore City, IA.

2 Materials and methods

2.1 Climate scenarios

The future climate data were obtained from The North American Regional Climate Change Assessment Program (NARCCAP), an international program which generates high resolution climate change simulations in order to both investigate uncertainties in regional scale projections of future climate and generate climate change scenarios for use in impacts research. More detail about NARCCAP can be found at its web site (www.narccap.ucar.edu) and in published documents (Mearns et al. 2009, 2012). Regional climate models (RCM) are used to dynamically downscale GCMs (coupled General Circulation Model) results to regional climate for Gilmore City. Site-specific observed historical weather data from 1990 to 2009 was used by RZWQM2 to determine baseline drainage flow, NO_3-N loss, and crop yield. Daily weather data included six parameters: precipitation, maximum and minimum air temperature, solar radiation, wind speed and relative humidity. To obtain potential future daily weather data sets, six coupled General Circulation Model and Regional Climate Model (GCM-RCM) were used to generate six different climatic scenarios. More details about climate data and an overview of RZWQM2 are given in supplemental material.

2.2 RZWQM2 simulations

The RZWQM2 was calibrated and validated using 2005 to 2009 hydrology, crop growth, N-uptake and NO_3-N loss data recorded during a corn-soybean experiment at the Agricultural Drainage Water Quality Research and Demonstration Site (42°45′N, 94°30′W) near Gilmore City, Iowa (Qi et al. 2011b). Input parameters for soil hydraulic properties were determined by site-specific measurements that included soil bulk density, particle size distribution, soil water retention curve and soil hydraulic conductivity (Qi et al. 2011b). Nutrient parameters were mainly adopted from Thorp et al. (2007), and the crop parameters for the crop modules of RZWQM2 (CERES-Maize for corn and CROPGRO for soybean) were calibrated by Qi et al. (2011b). The calibrated model was validated using an extra 16-year (1989–2004) drainage and NO_3-N loss data set from the site (Qi et al. 2012). Based on statistical analyses the model performed “satisfactorily” under these conditions.

The calibrated and validated RZWQM2 was used to simulate water cycle, nitrogen dynamics and crop growth with 20-year observed historical (1990–2009) weather data and 369 ppm CO_2 and then, with 20-year projected future climate scenarios (2045–2064) and 548 ppm CO_2 to study impacts of climate change at this site. Model parameters and management practices were kept unchanged for both historical and future climate scenarios. Planting dates for corn and soybean were set to May 12 and May 20, respectively, which were the averages of planting dates during the 2005–2009 field experiments. Corn and soybean were rotated in alternate years with the corn receiving 140 kg N ha^{-1} as aqueous ammonia 1-day before planting, while soybean received no fertilizer. For each climate scenario, the model was run twice (once with corn in odd years and once with soybean in odd years) ensuring that corn and soybean were grown in every year. For both crops, harvest date was set at the maturity date, and conservation tillage (tandem disk and field cultivator) was applied after harvest. For scenarios under the future 20-year climate (2045–2064), the RZWQM2 was independently executed with each of six sets of projected future weather data (see supplementary material for detailed information). For each climate change projection, the RZWQM2 model was also run with the climate changes applied to only one atmospheric variable (and not the others), in turn, to investigate the effect of the changes in the individual climate variables.

The results in each scenario were expressed as percentage changes with respect to the baseline and as cumulative distribution functions (CDFs) for yields (Islam et al. 2012). The nonparametric Kolmogorov-Smirnov (K-S) test was employed to determine whether the baseline CDF differed significantly from each of the projection's CDFs. Representing the largest absolute deviation of the two empirical distribution functions and therefore the average yield changes compared with the baseline, the D value indicates a significant difference when it exceeds 0.4. The WUE was calculated as the yield per unit of actual evapotranspiration (Islam et al. 2012). Soil derived N is defined as total N uptake minus N fixation and N application rate (Malone and Ma 2009).

3 Results and discussion

A comparison of present day and projected climate data showed that changes in temperature and precipitation were more significant than those of other climate components (Table 1). When averaged over the 6 climate models, mean annual temperature increased by 2.2 °C, to a value + 26.9 % greater than its historical value of 8.1 °C; mean annual precipitation increased from a baseline value of 76.9 to 81.3 cm (4.4 cm, +5.6 %). Absolute/relative (percentage) changes in short wave radiation (0.03 MJ m^{-2} $days^{-1}$/+0.2 %), relative humidity (0.5/−0.6 %) and wind speed (1.7 km $days^{-1}$/−0.6 %) were small to negligible. The magnitude of increase in CO_2 (from 369 to 548 ppm, +48.5 %) was significantly greater than the absolute changes of any climatic parameters.

3.1 Effects of climate change on ET, tile drainage and N loss

3.1.1 Evapotranspiration

Our simulated AET was 44.2 cm for baseline, close to simulated value of 46.8 cm by Thorp et al. (2007) and observed values from water balance method by Hatfield and Prueger (2004). Averaged over all climate scenarios, the increases in *AET* (Actual Evapotranspiration) and *PET*

Table 1 Annual average weather variables for different scenarios

Scenarios	P (cm)	T (°C)	SWR (MJ/m^2/day)	RH (%)	WS (km/day)	CO_2 (ppm)
BL	76.9	8.1	13.1	77.7	320.6	369
BL_M1	80.6	10.2	13.0	79.6	320.8	548
BL_M2	79.3	10.6	13.0	75.6	320.6	548
BL_M3	79.7	10.3	13.3	75.0	320.4	548
BL_M4	79.8	10.4	13.4	76.4	317.6	548
BL_M5	83.7	9.9	13.1	78.2	316.5	548
BL_M6	84.4	10.2	12.8	78.6	317.5	548
AVG	81.3	10.3	13.1	77.2	318.9	548

P Precipitation, *T* Temperature, *SWR* Short Wave Radiation, *RH* Relative Humidity, *WS* Wind Speed, *AVG* averaged over 6 combined future scenarios, *BL* baseline, *BL_M1* future scenario from CRCM_ccsm, *BL_M2* future scenario from CRCM_cgcm3, *BL_M3* future scenario from HRM3_hadcm3, *BL_M4* future scenario from RCM3_cgcm3, *BL_M5* future scenario RCM3_gfdl, *BL_M6* future scenario from WRFG_ccsm

(Potential Evapotranspiration) due to climate change occurring by 2055 (2045–2064) were 0.8 cm (+1.8 %) and 3.3 cm (+5.7 %), respectively (Table 2).

Although the increase of temperature may not occur without an increase in CO_2, we ran the model with a temperature increase only and constant CO_2 in order to separate the impact of temperature and CO_2. Based on the sole increase of temperature, *AET* and *PET* increased from 44.2 to 45.1 (+2.0 %) and from 57.5 to 61.6 cm (+7.1 %), respectively. The 0.6 % reduction in relative humidity resulted in a +3.6 % increase in *AET* and a +4.3 % increase in *PET*. In a prior study, for both C_3 (soybean) and C_4 (corn) plants, stomatal conductance decreased under elevated CO_2, leading to a decline in *ET* and increase in leaf temperature (Bernacchi et al. 2007). Similar results were found in the present study, where elevated CO_2 decreased *AET* and *PET* by −4.5 and −5.9 %, respectively. The effects of elevated CO_2 on potential transpiration were calculated according to the Shuttleworth-Wallace equation. Elevated CO_2 did not have any effect on AE (Actual Evaporation) but decreased AT (Actual Transpiration) by −7.7 % which mainly resulted from a decrease in AET; this was the same as the effect of CO_2 on PET (effects of isolated weather variables can be found in supplementary material).

In general, the increase in ET can be attributed to the effects of temperature and *RH* in increasing ET being outweighed by the effects of elevated CO_2 in decreasing *ET*. The effects of precipitation, short wave radiation and wind speed on *ET* were negligible.

3.1.2 Tile drainage

The baseline mean annual tile drainage volume was 29.0 cm. Across all six future climate scenarios tile drainage increased by 4.2 cm (+14.5 %, Table 2). That precipitation had directly increased tile drainage was shown by the fact that mean tile drainage volume rose from 29.0 to 33.2 cm when the mean yearly precipitation increased from 76.9 to 81.3 cm (+5.7 %). Thus, precipitation alone contributed to +13.7 % increase of drainage flow. The relationship between projected annual mean increase in tile drainage (ΔTD, in cm) and precipitation (ΔP, in cm), shown in the supplementary material, can be expressed as:

$$\Delta TD = 0.888\Delta P + 0.099 \quad R^2 = 0.995 \tag{1}$$

Table 2 Impacts of climate changes on water balance

	AE (cm)	AT (cm)	PE (cm)	PT (cm)	AET (cm)	PET (cm)	Drainage (cm)	$WUE_{soybean}$ (kg m^{-3})	WUE_{corn} (kg m^{-3})
BL	18.3	25.9	29.8	27.7	44.2	57.5	29.0	0.71	2.12
BL_M1	19.1	24.5	32.7	26.2	43.6	58.9	34.0	0.91	1.82
BL_M2	19.9	25.6	35.1	27.3	45.5	62.4	30.8	0.88	1.71
BL_M3	19.9	27.4	35.8	30.2	47.3	66.0	29.0	0.84	1.62
BL_M4	19.5	26.7	34.5	28.5	46.2	63.0	30.4	0.88	1.73
BL_M5	19.4	24.7	32.2	26.3	44.1	58.5	36.2	0.93	1.87
BL_M6	19.8	23.2	31.4	24.4	43.0	55.8	38.7	0.92	1.92
AVG	19.6	25.4	33.6	27.2	45.0	60.8	33.2	0.87	1.83

BL baseline, *AVG* averaged over 6 combined future scenarios, *AE* actual evaporation, *AT* actual transpiration, *PE* potential evaporation, *PT* potential transpiration, *AET* actual evapotranspiration, *PET* potential evapotranspiration, $WUE_{soybean}$ water use efficiency of soybean (kg dry grain per m^3 water), WUE_{corn} water use efficiency of corn (kg dry grain per m^3 water)

An increase in precipitation contributed mainly to drainage rather than ET because the field site is located in a subhumid area where water stress is not a major concern under rainfed agriculture. Under arid or semiarid climate ET might increase due to increase of precipitation.

Factors having an indirect impact on tile drainage were CO_2, relative humidity and temperature, through their influence on *ET*. The rise in CO_2 increased the drainage flow by +7.2 % through its reduction in ET. Relative humidity decreased drainage flow (−5.3 %). Although temperature increased AET by +3.8 %, it had a negligible influence on drainage because it concomitantly decreased corn yield, which resulted in lower water uptake being needed for cell growth. Short wave radiation and wind speed showed negligible impacts on drainage flow (see supplementary material for detailed information).

3.1.3 Nitrogen losses in tile drainage

From the historical 20-year baseline period of 1990–2009 to the future 20-year period of 2045–2064, mean annual NO_3-N loss through tile drainage, averaged across 6 climate scenarios, increased +33.7 % from 34.1 to 45.6 kg N ha^{-1} (Table 3). FWANC increased from 12.2 to 14.2 mg L^{-1} (+16.4 %) when all weather variables were combined (Table 3). The increased N loss in tile drainage can be attributed mostly to greater mean mineralization (10.7 kg N ha^{-1}, Table 3). The impacts of climate change increased denitrification, mineralization and immobilization by +3.3, +9.4 and +5.8 %, respectively. Although N uptake by corn reduced by 12.7 kg N ha^{-1}, soybean uptake (including fixation) increased by 75.5 kg N ha^{-1} every other year (from 291.9 to 367.1 kg N ha^{-1}). Among this increased N uptake by soybean, 62.8 kg N ha^{-1} was a contribution of increased N fixation. In general, when averaged over the 20 years with corn-soybean rotation, the increase in total N uptake in each year was 31.4 kg N ha^{-1}, similar to the increase in N fixation of 31.1 kg N ha^{-1}. This indicates that the increase in N uptake associated with the rise in soybean yield outweighed the decrease in N uptake associated with the decline in corn yield. Therefore, soil derived N showed no difference under climate change because the decrease in soil derived N due to the decrease of corn yield was offset by the increase in soil derived N resulting from the increased soybean yield. Malone and Ma (2009) stated that for the long term N budget to balance:

$$-\left|N_{source}-N_{loss}-N_{crop\uparrow}\right|\leq 1\ \text{kg N ha}^{-1}\text{N} \tag{2}$$

$N_{crop\uparrow}$ represents crop N uptake, i.e. N in grain, stover and roots; N_{loss} reprensents N loss through denitrification, tile drainage and deep seepage; and N_{source} represents the sources of N, including fixation, fertilization application and net mineralization. On this basis, the increase in soil reactive N should account for the increase of N loss.

$$\begin{array}{l} N_{min}+N_{prec}+N_{root}+N_{res}+N_{soil}+N_{immo}+N_{denit}+N_{drain} \\ (+10.7)+(+0.6)+(-3.4)+(+5.9)+(-0.4)+(-0.7)+\ (-0.7)+\ (-11.6)=0.4\leq 1\ \text{kg N ha}^{-1} \end{array} \tag{3}$$

Where, N_{min}, N_{prec}, N_{root}, N_{res}, N_{soil}, N_{immo}, N_{denit} and N_{drain} are N gained by mineralization, gained from precipitation, locked up dead roots, from incorporated residue, derived from soil, lost through immobilization, lost through denitrification and lost in drainage water. Thus Malone and Ma's criterion is met. The N in lateral flow, runoff and deep seepage and volatilization were negligible in the model. Therefore, increased mineralization accounted for most of the increase in N loss in tile drainage. When combined all weather variables, increased temperature accelerated nitrification due to increased growth of autotrophs simultaneously with increased mineralization; increased precipitation promoted the N loss in drainage flow.

Table 3 Impacts of climate changes on N balance

	Deni (kg N ha^{-1})	Mine (kg N ha^{-1})	Immo (kg N ha^{-1})	N loss in drainage (kg N ha^{-1})	N uptake by corn (kg Nha^{-1})	N uptake by soybean (kg Nha^{-1})	N fixation (kg Nha^{-1})	Soil derived N by corn (kg N ha^{-1})	Soil derived N by soybean (kg N ha^{-1})	Soil derived N for corn and soybean (kg N ha^{-1})	FWANC (mg L^{-1})
BL	21.2	113.6	12.0	34.1	199.4	291.9	221.3	59.4	70.5	65.0	12.2
BL_M1	21.6	121.6	12.2	43.3	185.3	362.0	278.4	45.3	83.6	64.4	12.9
BL_M2	21.4	127.3	13.1	46.7	188.9	366.5	280.5	48.9	86.0	67.5	15.5
BL_M3	21.3	127.3	13.0	41.7	191.9	368.9	273.4	51.9	95.5	73.7	14.7
BL_M4	20.3	128.0	13.2	48.4	185.4	375.1	289.3	45.4	85.9	65.6	16.3
BL_M5	22.6	123.0	12.5	44.4	187.6	372.4	292.4	47.6	80.0	63.8	12.4
BL_M6	24.3	118.7	11.9	49.4	181.2	359.7	286.4	41.2	73.3	57.2	13.0
AVG	21.9	124.3	12.7	45.6	186.7	367.4	283.4	46.7	84.0	65.4	14.2

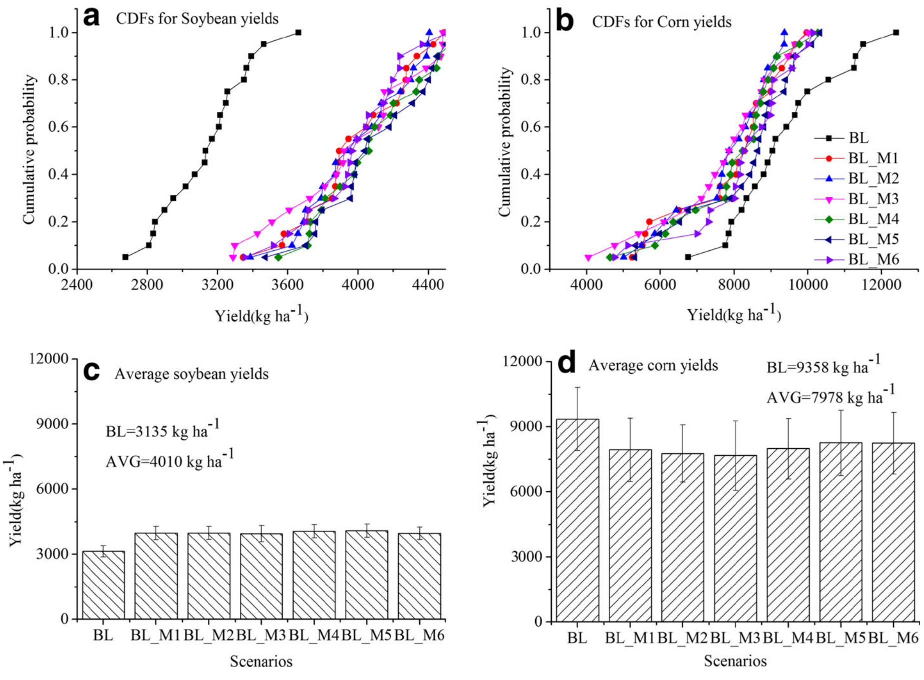
N fertilization of 140 kg N ha^{-1} was applied to corn every other year

AVG averaged over 6 combined future scenarios, *BL* baseline, *BL_M1* future scenario from CRCM_ccsm, *BL_M2* future scenario from CRCM_cgcm3, *BL_M3* future scenario from HRM3_hadcm3, *BL_M4* future scenario from RCM3_cgcm3, *BL_M5* future scenario RCM3_gfdl, *BL_M6* future scenario from WRFG_ccsm, *Deni* denitrification, *Mine* mineralization, *Immo* Immobilization, *FWANC* Flow-Weighted Average NO3-N concentration

The rise in FWANC (+16.4 %) was directly influenced by drainage flow (+14.5 %) and N losses (+33.7 %) in tile drainage. Elevated CO_2, temperature and precipitation played a synergic role in N loss in tile drainage under models with combined weather variables. When considering isolated weather variables, temperature increased FWANC greatly because it led to a strongly decreased corn yield. Reduced relative humidity increased nitrogen loss due to its impact on increasing ET resulted in lower tile drainage volume. Wind speed and short wave radiation had negligible impacts on FWANC.

3.2 Effects of climate change on grain yields and WUE

Mean soybean yield under future climate change scenarios was (4010 kg ha^{-1}, with a range of 3976–4092 kg ha^{-1}) significantly ($D \geq 0.8$, $P \leq 0.05$, see supplementary material for detailed information) higher (+28 %) than that under baseline conditions (3135 kg ha^{-1}, Fig. 1). Conversely, corn yield under future climate change scenarios (7978 kg ha^{-1}, with a range of 7670–8262 kg ha^{-1}) was lower than that under baseline conditions (9358 kg ha^{-1}, Table 2 and Fig. 1), but no significant difference was found except for BL_M2 ($D>0.4$, see supplementary material for detailed information). Cumulative distribution functions of simulated soybean and



Note: BL_M1, future scenario from CRCM_ccsm; BL_M2, future scenario from CRCM_cgcm3; BL_M3, future scenario from HRM3_hadcm3; BL_M4, future scenario from RCM3_cgcm3; BL_M5, future scenario from RCM3_gfdl; BL_M6, future scenario from WRFG_ccsm; BL, baseline; AVG, averaged over six models.

Fig. 1 Cumulative distribution functions (CDFs) of soybean and corn grain yields for the future under different scenarios: **a** CDFs of soybean yields; **b** CDFs of corn yields; **c** soybean yields for different models; **d** corn yields for different models corn yields for the baseline years were compared with the future climate change projections for effects of individual factors as well as their combinations (Fig. 1).

3.2.1 Temperature

Unlike the increase in yield seen under elevated CO_2, the mean temperature increase of 2.2 °C alone led to a decrease in crop yields. Piper et al. (1998) reported that across the United States the most productive soybean production occurred in areas with a mean growing season temperatures of 22 °C. No obvious decline in soybean yield simulated under a rise in temperature could be explained by that the mean temperature from June to September for the baseline and future years were similar to the optimal growing temperature (20.1–22.6 °C). Given that the impacts of temperature on soybean yield were negligible [$-0.36\ \%\ °C^{-1}$, similar to $-1.3\ \%\ °C^{-1}$ reported by Lobell and Field (2007)], while those for corn yield were quite significant [$-9.4\ \%\ °C^{-1}$, similar to $-8.3\ \%\ °C^{-1}$ reported by Lobell and Field (2007)], this section focuses only on the effects of temperature on corn grain production.

Temperature extremes during the reproductive stage of development can result in less carbohydrate assimilation and poor grain growth in the model (Jones et al. 1986; Wilkens and Singh 2001). Stress factor for temperature on carbohydrate accumulation, PRFT in the RZWQM2 model, is computed through a set of equations using the daily maximum and minimum temperature in Jones et al. (1986). For example, when the maximum and minimum temperatures are 35 and 28 °C, respectively, PRFT is computed to be 0.87, which indicates a 13 % reduction of carbohydrate accumulation on that day. The poor grain growth under temperature stress is calculated through reduced grain filling duration (Wilkens and Singh 2001). The cardinal base and optimum temperatures for corn development and reproduction are 8 °C (after emergence) and 34 °C, respectively. Climate scenarios BL_M2 and BL_M3 had their highest number of $T_{max}>$ 34 °C days (12.0 day and 12.4 days per year respectively, compared with 1.7 days for baseline) and lowest number of $T_{min}<8$ °C days (4.6 days and 4.7 days respectively, compared with 11.1 day for baseline, see supplementary materials for details) in years corresponding to the lowest corn yields, indicating that a reduction in corn yield could be attributed largely to the effect of a greater number of days with temperatures exceeding 34 °C.

The simulated results showed that increased temperature led to early maturity for soybean and corn, which potentially reduced crop yield. In general, the days to maturity for soybean were 112.5 and 105.9 days under baseline and future scenarios, respectively; comparatively, the days to maturity for corn were 133.3 and 118.9 days for baseline and future, respectively. Decreases in the length of soybean and corn days to maturity were, respectively, 2.6 and 5.7 days per °C increase of temperature (see supplementary material for detailed information), consistent with the finding of another RZWQM2 simulation which found a 5 days shorter physiological maturity in corn grown in Colorado for every 1.0 °C increase in temperature (Islam et al. 2012). In the present study, a strong linear relationship existed between temperature rise and decrease in days to maturity for soybean ($R^2=0.90$) and corn ($R^2=0.96$; see supplementary material for detailed information).

3.2.2 Elevated CO_2 and other climate variables

The simulated +26.8 % increase in soybean yield and +5.7 % increase in corn yield attributable to the sole increase of CO_2 from 369 to 548 ppm in this study were consistent with other studies involving typical C_3 and C_4 crops, respectively. Hatfield et al. (2011) stated that doubling of CO_2 would result in a roughly 30 % increase in C_3 crop production, compared to a less than 10 % increase for a C_4 crop.

Although the mean annual precipitation increased to 81.3 cm (range: 79.3 to 84.4 cm) compared to the baseline value (76.9 cm), yields were negligibly affected. This concurred with the findings of Ko et al. (2012) who showed that seasonal precipitation alone had a negligible impact on crop yields. Relative humidity, short wave radiation and wind speed had limited to negligible impacts on soybean and corn yields due to their smaller changes (data not shown).

3.2.3 Water use efficiency (WUE)

Between the present and future scenarios, mean WUE increased from 0.71 to 0.87 kg m^{-3} (+ 22.5 %) for soybean and decreased from 2.12 to 1.83 kg m^{-3} for corn (−13.7 %, Table 2), respectively. The significant increase in WUE for soybean (0.23 kg m^{-3}, +24.5 %) under elevated CO_2 was attributable to a decrease in transpiration (−7.7 %) and hence evapotranspiration, coupled with an increase in grain yield (+26.8 %) due to elevated CO_2 decreasing stomatal conductance. Temperature had a significant role in decreasing WUE for corn (−0.47 kg m^{-3}, −22.2 %). The greater impact of temperature on decreasing corn yield was the main reason for its decreasing WUE. Other weather variables (e.g. relative humidity, precipitation, short wave radiation and wind speed) had low to negligible impacts on WUE.

4 Summary and conclusions

Climate change impacts on water balance, NO_3-N loss, and crop production in a subsurface drained corn-soybean rotation field were assessed using RZWQM2 for an experimental site near Gilmore City, Iowa. Simulations for the future were conducted with climate change scenarios generated using six GCM-RCM models for the period of 2045 to 2064, with CO_2 rising from 369 to 548 ppm. Averaged across the scenarios, AET and PET increased from 44.2 to 45.0 cm and from 57.5 to 60.8 cm, respectively; tile drainage increased from 29.0 to 33.2 cm; NO_3-N loss through tile drainage increased from 34.1 to 45.6 kg N ha^{-1}; FWANC increased from 12.2 to 14.2 mg L^{-1}; yields increased from 3135 to 4010 kg ha^{-1} for soybean and decreased from 9358 to 7978 kg ha^{-1} for corn, respectively. WUE increased by +22.5 % for soybean and declined by −13.7 % for corn.

Increased temperature and decreased relative humidity were found to enhance ET, overcoming the decreasing impact on ET of elevated CO_2. The impacts of changes in precipitation, short wave radiation and wind speed on ET were small to negligible. Precipitation showed a strong positive correlation with drainage flow. Higher NO_3-N loss by tile drainage can be primarily contributed by enhanced mineralization coupled with nitrification under warmer temperature. Although tile drainage volume varied amongst the different climate scenarios, FWANC increased dramatically for all cases due to the increase of NO_3-N loss in tile drainage.

Soybean production increased substantially because of elevated CO_2 and its negligible responses to increases in temperature. Soybean WUE increased as a result of increased yield and reduced AET. Corn yield decreased predominantly due to a shortened physiological life brought on by increased temperature. The decrease in corn WUE was mainly attributable to a lower yield. The impacts of relative humidity, precipitation, short wave radiation and wind speed on yield were small or negligible for both soybean and corn.

With the predicted trend, this study suggests that to mitigate NO_3-N pollution from subsurface drained corn-soybean field in Iowa is a more challenging task in the future without changing current management practices. This study also demonstrates the advantage of agricultural system models in assessing climate change impacts on water quality and crop production, because those models include as many as possible subroutines. This study does not account for the mitigation and adaptation to climate change. In further investigations, potential management practices to mitigate nitrogen losses and corn yield reduction will be assessed (e.g. lesser N fertilization, breeding corn cultivars less susceptible to heat stress and more days to maturity, advancing corn planting dates, tillage management and controlled drainage).

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