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Drainage N Loads Under Climate Change with Winter Rye Cover Crop in a Northern Mississippi River Basin Corn-Soybean Rotation

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Abstract: To help reduce future N loads entering the Gulf of Mexico from the Mississippi River 45%, Iowa set the goal of reducing non-point source N loads 41%. Studies show that implementing winter rye cover crops into agricultural systems reduces N loads from subsurface drainage, but its effectiveness in the Mississippi River Basin under expected climate change is uncertain. We used the field-tested Root Zone Water Quality Model (RZWQM) to estimate drainage N loads, crop yield, and rye growth in central Iowa corn-soybean rotations. RZWQM scenarios included baseline (BL) observed weather (1991–2011) and ambient CO_2 with cover crop and no cover crop treatments (BL_CC and BL_NCC). Scenarios also included projected future temperature and precipitation change (2065–2085) from six general circulation models (GCMs) and elevated CO_2 with cover crop and no cover crop treatments (CC and NCC). Average annual drainage N loads under NCC, BL_NCC, CC and BL_CC were 63.6, 47.5, 17.0, and 18.9 kg N ha^{-1}. Winter rye cover crop was more effective at reducing drainage N losses under climate change than under baseline conditions (73 and 60% for future and baseline climate), mostly because the projected temperatures and atmospheric CO_2 resulted in greater rye growth and crop N uptake. Annual CC drainage N loads were reduced compared with BL_NCC more than the targeted 41% for 18 to 20 years of the 21-year simulation, depending on the GCM. Under projected climate change, average annual simulated crop yield differences between scenarios with and without winter rye were approximately 0.1 Mg ha^{-1}. These results suggest that implementing winter rye cover crop in a corn-soybean rotation effectively addresses the goal of drainage N load reduction under climate change in a northern Mississippi River Basin agricultural system without affecting cash crop production.

Keywords: drainage; cover crop; RZWQM; model; climate change; nitrate; hypoxia

1. Introduction

Hypoxic or dead zones in coastal oceans have been expanding since the 1960s and are forecast to increase with climate change if reduction strategies are not implemented [1–3]. In North America, the size of the hypoxic area in the Gulf of Mexico correlates strongly with spring nitrate-N loads from the Mississippi River [4]. To address the growing dead zone in the Gulf of Mexico, the USEPA created the Mississippi River/Gulf of Mexico Nutrient Task Force in 1997 [5]. This Gulf Hypoxia Task Force set a goal to reduce total nitrogen (N) loads from the Mississippi River Basin 45% by 2035, as compared with the baseline loads between 1980 and 1996 [6,7]. To achieve this goal, 12 states with surface water discharging to the Mississippi River were tasked to develop strategies to reduce N loading to the Gulf of Mexico [8].

The state of Iowa's strategy includes the goal of reducing N loads to waterways by 41% from non-point sources such as artificially drained corn and soybean fields [9,10]. Central Iowa is one of the more important areas to reduce N loads to meet Iowa's non-point source goal and to reduce N loading to the Mississippi River, because it has a large fraction of land in artificially drained row crops [11]. Artificial drainage coupled with high row crop production contributes to streams within Iowa being among the greatest sources of N loading to the Mississippi River Basin [12,13]. These conditions of relatively large subsurface drainage N loads from row crop production entering streams makes central Iowa a key region for nitrate reduction efforts.

Drainage water N loads have been projected to increase with future shifts in climate conditions [14–16], which will complicate the goal of future N load reduction compared with baseline loads. Wang et al. [16] concluded that studies are needed to better understand management strategies that reduce future projected N loads.

Cover crops are widely regarded as a practice that reduces N leaching and drainage N loads [17–19]. If managed effectively, winter rye cover crops with corn-soybean rotations is one of the more promising methods to reduce drainage N loads in central Iowa without affecting cash crop yield [20,21]. However, nutrient management strategies must be effective not only under current and past climatic conditions, but also under future climate conditions. With an expected shift to higher temperatures and CO_2 and changing precipitation patterns [22,23], the effectiveness of winter rye cover crops as an N reduction strategy in the future needs to be understood.

Studies have addressed several of the environmental benefits associated with winter cover crops under climate change. Bowles et al. [24] reported that a main principle for reducing N loss in a changing climate is to increase agroecosystem resilience, accomplished partly through winter cover crops. Kaye and Quemada [25] reported ecosystem services that are traditionally expected from cover cropping such as soil carbon sequestration, reduced erosion, and retention of N mineralization can be promoted synergistically with services related to climate change. A critical global review reported cover crops significantly decreased N leaching and increased soil organic carbon sequestration and could mitigate net greenhouse gas balances [26]. Studies using agricultural system models suggest that winter cover crops under projected climate change reduce soil erosion, increase soil carbon, and reduce CO_2 emission from soil [27,28]. Malone et al. [29] reported that the effectiveness of winter rye cover crop to reduce drainage N loads increased with higher spring and fall temperatures, which suggests winter rye cover crop may be more effective under projected climate change than baseline climate. Higher fall, winter, and spring temperatures are associated with higher rye grain yield [30–32]. Furthermore, a two-year Free Air CO_2 Enrichment (FACE) experiment reported that elevated CO_2 (600 v 393 ppm) increased winter wheat grain yield and N uptake up to 12% [33].

Few studies, however, have investigated the impact of projected climate change on cash crop production and N budget components that include subsurface drainage N loads with winter rye cover crop in corn-soybean rotations in the Mississippi River Basin. In fact, Wang et al. [16] reported that an integrated study of drainage N loads under projected climate change that considered both advanced crop yield and drainage estimates had never been conducted. Both accurate crop growth and soil N mineralization estimates are required to investigate drainage N loads under climate change [16]. N uptake by crops is often the largest component of a corn-soybean system's overall N budget [29,34], and climate change is projected to adversely affect future corn production [16,35,36]. Additionally, Wang et al. [16] estimated that, under climate change compared to baseline conditions, drainage N loads increased mostly because of increased N mineralization from soil organic matter.

While few, if any, studies have investigated both corn-soybean production and N loss to subsurface drainage with winter rye cover crops under climate change in the Mississippi River Basin, the SWAT model has been used to investigate the effectiveness of winter rye cover crop in reducing N loads to streams within the Chesapeake Bay Watershed under climate change [37].This study [37] also reported that without winter cover crops, annual nitrate loads increased under climate change compared with baseline climate. However, the study did not report the effect of cover crop on cash crop production under climate change and conditions within the Chesapeake Bay Watershed are considerably different from conditions in the northern Mississippi River Basin [37]. Mehan et al. [38] used the SWAT model to estimate that N loads were reduced under climate change compared to baseline conditions in a predominately subsurface drained agricultural watershed in northeastern Indiana, which contrasted with the results of other studies [16,37]. Missing in the studies of Lee and Mehan [37,38] were the complete N budget including mineralization and uptake by crops under projected climate change.

The Root Zone Water Quality Model (RZWQM) has been used by several studies to investigate the effects of climate change on crop production [39–41]. RZWQM has also been used to investigate both crop production and drainage N loads under climate change [16]. RZWQM may simulate N dynamics more realistically than the SWAT simulations mentioned above [37,38]. Malone et al. [42] reported that RZWQM simulates N dynamics in corn-soybean rotations differently and perhaps more accurately than the SWAT model because of more mechanistic soil N mineralization and microbial immobilization routines. RZWQM has been shown to reasonably predict the effectiveness of winter rye cover crop in reducing N loads from drainage at two different Iowa field sites [29,43,44]. Using data from a central Iowa field site [20,21,45], Gillette et al. [34] were able to improve upon the RZWQM simulations of nitrogen dynamics with cover crops made by Malone et al. [29].

We hypothesize that despite possible increased drainage N loads under climate change, including winter rye cover crop in corn-soybean rotations will reduce N loads in central Iowa below the reduction goal of 41% set to address the hypoxic zone in the Gulf of Mexico without reducing cash crop production, due to anticipated increases in rye uptake of crop available N and water under climate change. Here, we use the calibrated and tested RZWQM [34] to estimate drainage N loads (along with other N budget components) and crop yield and growth in a central Iowa corn-soybean rotation both with and without winter rye cover crop under 1) observed baseline 1991–2011 weather and ambient CO_2 and 2) projected future 2065–2085 temperature and precipitation from six general circulation models (GCMs) and elevated CO_2.

2. Materials and Methods

The study site is situated on the Des Moines Lobe landform region in central Iowa, that previous studies described in detail [21,34,42,45]. This area within the Des Moines Lobe has the principal soil association of Clarion–Nicolette–Webster, which requires artificial drainage for corn production [46]. Described below are baseline and projected climate, model scenarios, model calibration and testing against observed field data, and statistical analysis of model simulations.

2.1. Climate Scenarios

Projected temperature and precipitation for 2065–2085 (centered around 2075) were developed for Ames, Iowa. We used six general circulation models (GCMs): CCSM4, GFDL-CM3, GISS-E2-R, HadGEM2-ES, CSIRO-MK3, and MIROC5.1. The GCM projections used in this study were extracted from the Coupled Modeled Intercomparison Project phase 5 (CMIP5) archive of the World Climate Research Programme for the 1/8th degree grid which encompasses the Ames, Iowa rain gauges [47]. The selected GCMs used in this study and details concerning the associated methods were described by Garbrecht and Zhang [48]. Studies evaluating impacts of climate change on water quality often center around mid-century [16,49], late-century [37], or both these periods [50,51]. Our projection centered around 2075 is a compromise of mid and late century periods.

Future temperature and precipitation were determined under greenhouse gas emissions from Representative Concentration Pathways (RCP) 4.5. RCP4.5 is an intermediate stabilization pathway where radiative forcing is stabilized at approximately 4.5 W m^{-2} after 2100 [52]. RCP4.5 and RCP6.0 are considered likely scenarios while RCP8.5 is an unlikely worst-case scenario [53]. We only include likely projected results using RCP4.5 because preliminary model runs suggested very similar cover crop growth and drainage N losses between RCP4.5 and 6.0, which is reasonable, given their nearly identical projected atmospheric CO_2 concentrations and radiative forcing through about 2060 [52,54]. While many studies considered both RCP4.5 and RCP8.5 when projecting agricultural effects under climate change, others considered either RCP4.5 or RCP8.5 [27,51,55].

The selected GCMs simulate climate change processes with a monthly temporal resolution. For agricultural system models, GCM climate projections must be downscaled to daily to accurately model N loss, crop growth, etc. A synthetic weather generator called SYNTOR was used to downscale the monthly GCM projections to daily precipitation and temperature [56,57]. The resulting weather values have the statistical characteristics of the underlying 1986–2015 baseline data of Ames, Iowa and the monthly temperature and precipitation characteristics of the selected GCMs.

RZWQM baseline simulations for the central Iowa site were run from 1991–2011 (centered around 2001) using observed weather data [34] with an atmospheric CO_2 concentration of 370 ppm. Future climate input for RZWQM was produced by superimposing average monthly differences of temperature (°C) and percent change in precipitation for each GCM downscaled as described above. An atmospheric CO_2 concentration of 529 ppm was used for the future simulations.

The (1) method of superimposing monthly weather differences to produce future climate input for RZWQM and (2) region of the current study are similar to those of Wang et al. [16]. That study used baseline climate from 1990–2009 for Gilmore City, Iowa and climate change simulations for the year 2055. They used baseline and future CO_2 levels of 369 and 548 ppm. Gilmore City is approximately 100 km north and 70 km west of Ames. With the similarities of the two studies, we compare our temperature and precipitation projections to theirs. We do not include future projected changes in relative humidity, short wave radiation, and wind speed, because these were reported to have only small impacts on nitrate concentration in drainage and grain yields [16].

Average monthly temperature and percent precipitation over the six climate models increased 2.9 °C and 110.5% from baseline (100% = baseline). These values are greater than the 2.2 °C and 106.9% reported by Wang et al. [16] (Figure 1b,c). We have larger temperature and precipitation changes, even with less CO_2 change. This is partly because of the lag in CO_2 effect and our projections being 20 years further into the future than Wang et al. [16]. The timing difference between a CO_2 emission and the maximum temperature response can be a decade or longer [58,59]. Additionally, the individual climate model with the largest average temperature change was 3.6 °C from HadGEM-ES2 Figure 1b, which Wang et al. did not include [16]. Their largest annual change was 2.6 °C with CRCM_CCSM. The average annual precipitation amount change was +6.2 cm or 7.5% for our study and +4.4 cm or 5.7% for Wang et al. [16].

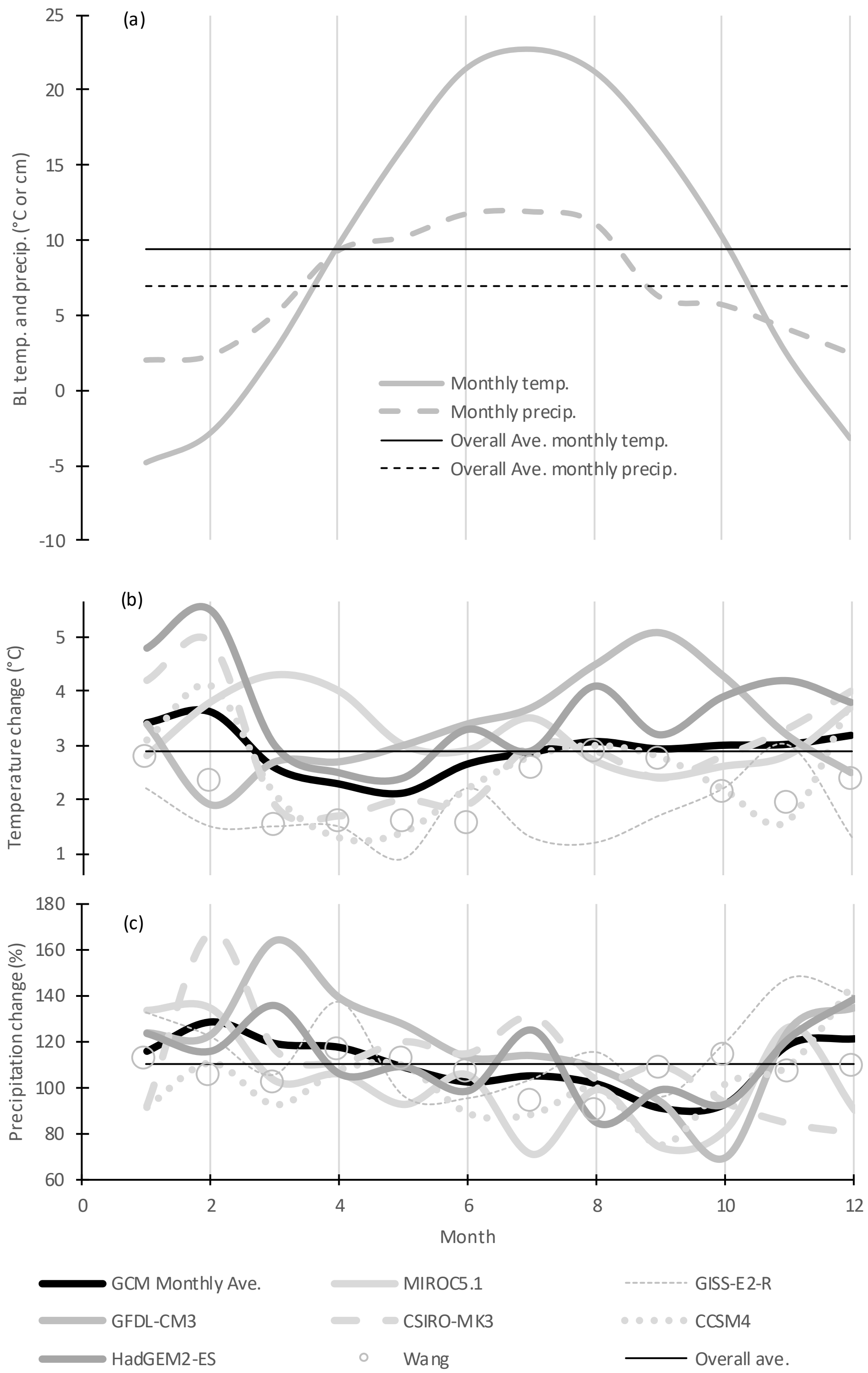

Figure 1. Monthly temperature and precipitation (**a**) under baseline (BL), along with temperature (**b**) and precipitation (**c**) changes under the six different general circulation models (GCMs). Wang et al. [16] average monthly changes are presented (**b**,**c**). Precipitation change is presented on a 100% scale (**c**), so if a GCM had a monthly change of 100% of baseline, it would equal baseline (BL) precipitation for that month. The GCM projections with the greatest average annual temperature change (**b**) are thick, solid, dark grey, and as the temperature changes become smaller, the lines become thinner, broken, and lighter grey. The abbreviations ave., precip., and temp. indicate average, precipitation, and temperature, respectively. Note that the top legend is for baseline conditions (**a**) and the bottom legend is for climate changes (**b**,**c**).

2.2. RZWQM Scenarios

The RZWQM modeling scenarios included corn-soybean rotations with (1) no winter rye cover crop and baseline weather (BL_NCC) or future projected weather from the six GCMs (NCC) and (2) winter rye cover crop with the seven different climate scenarios (BL_CC and CC). The corn and soybean planting dates were 27-April and 13-May. Corn and soybean were harvested within one to three days after simulated crop maturity, following the approach of Wang et al. [16]. The average soybean harvest date was 19-September, and ranged from 10-September to 01-October. The average corn harvest date was 13-September, and ranged from 30-August to 13-October. Winter rye was planted three to six days after simulated maturity of corn and soybean under baseline weather for all scenarios to mimic over-seeding of rye into standing crops [29,60]. All corn, soybean, and rye were planted and harvested or terminated on the same date for all scenarios: baseline climate, projected climate change, and with and without winter rye. For example, corn reached maturity earlier under the future climate scenarios, but the harvest date remained the same as the scenarios with baseline weather. The winter rye was terminated 10 days before corn planting and 3 days before soybean planting [29].

For each climate scenario and treatment, the model was run twice: (1) with corn in odd years and (2) with soybean in odd years. For the N and water budget calculations, we averaged the two scenarios (corn or soybean in odd years) to represent a field in both corn and soybean production for a given year [61]. A total of 28 scenarios were produced and executed to account for the six climate projections and baseline climate, winter rye and no rye treatments, and corn and soybean planted in both odd and even years.

A few additional scenarios were produced and executed. These also included corn and soybean in both odd and even years. First, scenarios were produced with the average future changes of Wang et al. [16]: monthly temperature (Figure 1b), precipitation (Figure 1c), and CO_2. We used these scenarios to compare RZWQM simulated crop yield to a similar Iowa study. For example, RZWQM input included average February temperature and precipitation changes determined by Wang et al. [16] of 2.4 °C and 105% (Figure 1b,c). Second, scenarios were produced with average monthly temperature and/or precipitation changes from the six GCMs (Figure 1b,c) and/or CO_2 changes. We used these scenarios to investigate the impacts of individual climate variables on annual rye growth and the associated N budgets (temperature-only, CO_2-only, precipitation-only, all-). For example, RZWQM input included scenarios with February temperature and precipitation changes of 3.6 °C and 129% (Figure 1b,c). The all-scenario had all three climate-related variables adjusted (CO_2, temperature, and precipitation). Third, several scenarios were produced with the three climate-related variables varied between baseline (BL_CC) values and the "all-scenario" values to investigate effects of likely intermediate climate between the years 2001 and 2075. Temperature and atmospheric CO_2 are projected to continuously increase between the years 2000 and 2100 for RCP4.5 [52].

We simulated a fertilizer application of 200 kg N ha^{-1}, based on the 202 kg N ha^{-1} average applied to corn in these field studies from 2002 to 2010 [34]. Malone et al. [42] discussed that this N rate could be considered high for central Iowa but that lower N rates resulted in N stress and unacceptably reduced RZWQM estimated corn yields. An N rate of 20 kg ha^{-1} was applied in the fall after soybean harvest, associated with P and K application [34]

2.3. RZWQM Calibration and Testing

Gillette et al. [34] used RZWQM to simulate winter rye growth, N uptake by crops, corn and soybean yield, drainage N loads, and N_2O emissions reasonably well compared with 9 years (2002–2010) of observed data near Ames, Iowa. Therefore, we modeled the no cover crop and winter rye cover crop scenarios using nearly the same RZWQM calibration.

A few changes were needed to the RZWQM calibration of Gillette et al., partly because they used the RZWQM default atmospheric CO_2 of 330 ppm [34]. As discussed in Appendix A and shown in Table A1, the model changes resulted in nearly identical model performance to Gillette et al. [34].

2.4. Statistical Analysis

For each GCM, 21 years of annual drainage N load values (kg N ha^{-1}) were produced for scenarios with winter rye cover crop (2065–2085). The 41% target reduction in drainage N load consist of the 21 annual baseline values (1991–2011) for scenarios without cover crops multiplied by 0.59 (BL_NCC*0.59). Statistical analysis of these values was carried out using the JMP software (Pro 14, SAS Institute, Cary, NC, USA).

The drainage N load for each GCM are correlated with the target values, with the correlation coefficients between 0.75 and 0.82 for the six GCMs. The Shapiro-Wilk test [62] showed strong evidence that the N load for five of the six GCMs are non-normally distributed (with p-values all less than 0.024 except for GISS-E2-R). Therefore, the Wilcoxon signed-rank test [63] was used to compare the drainage N load for each GCM with the target drainage N load reduction. This test is non-parametric and used to compare two related samples, which fits well here: the N load for each GCM and the target N load values are correlated (related and matched year by year, 1991 to 2065, 1992 to 2066, etc.), and the test requires no normality assumption for the values [63].

3. Results and Discussion

3.1. Corn and Soybean Yield, Rye Cover Crop Growth, and Evapotranspiration

The analysis begins with crop production because of its role in accurate simulation of drainage N loads. For example, N uptake by crops was the largest component of the N budget in our case. Our results are compared with Wang et al. [16], because they reported that the RZWQM simulated corn and soybean yields without winter rye in the rotation seemed reasonable for projected future climate in Iowa. For brevity and because RZWQM simulated main crop yield patterns followed Wang et al. [16], main crop yield is briefly discussed but not shown. Winter rye growth and the associated uptake of water and N resulted in reduced drainage N loads because of less crop available N and water in soil. Therefore, the effects of winter rye growth on main crop yield and annual evapotranspiration are discussed along with a brief discussion of winter rye growth and N uptake under climate change.

Using the same crop cultivars as under baseline climate conditions, average annual soybean yield under projected climate change was 3.8 Mg ha^{-1} for NCC. The average annual soybean yield range for the six models was from 3.7 to 4.0 Mg ha^{-1}, all of which were higher than the 3.2 Mg ha^{-1} baseline soybean yield (BL_NCC). Average annual corn yield for NCC under projected climate change was 8.0 Mg ha^{-1}. The average annual corn yield ranged from 7.5 to 9.0 Mg ha^{-1} for the six models, all of which were lower than the average baseline (BL_NCC) corn yield of 9.7 Mg ha^{-1}.

The higher soybean and lower corn yields under climate change agree with Wang et al. [16]. For example, both studies show increased soybean yield and decreased corn yield under climate change, compared with baseline (NCC v BL_NCC). Wang et al. [16] showed more soybean yield increase (0.9 Mg ha^{-1}) and less corn yield decrease (1.4 Mg ha^{-1}) under climate change than our simulations, mostly because their climate projections resulted from RZWQM inputs with greater atmospheric CO_2 (548 v 529 ppm) and less temperature increase during the growing season (e.g., average June-August temperature increase of 2.4 v. 2.9 °C, Figure 1b). Using the same average monthly temperature changes and CO_2 level as Wang et al. [16], our average annual soybean and corn yield under climate change for NCC were 4.0 and 8.3 Mg ha^{-1}, resulting in climate change differences with baseline of +0.8 and −1.4 Mg ha^{-1}. Wang et al. [16] more thoroughly discusses RZWQM simulated soybean and corn yield changes under projected climate change in Iowa.

On average, annual crop yields under future climate with winter rye cover crop (CC) were within 0.1 Mg ha^{-1} of NCC (8.1 Mg ha^{-1} for CC corn and 3.9 Mg ha^{-1} for CC soybean). This suggests winter rye did not reduce corn or soybean yield on average because of water or N stress, despite greater rye growth under climate change (Table 1). Gillette et al. [34] also reported that average annual corn and soybean yields from 2002–2010 with winter rye were within 0.1 Mg ha^{-1} of RZWQM simulations without winter rye for the central Iowa field site.

Table 1. Impact of individual climate variables on average annual rye growth and selected components of the associated N budgets. Monthly temperature and precipitation changes were the average of the six GCMs (Figure 1b,c). The all-scenario had all three climate-related variables adjusted (CO_2, precip., temp.). Note that a smaller value for N stress indicates more N stress. Maximum and minimum RZWQM simulated N stress are 0 and 1.

Scenario	Spring Above Ground Rye Biomass (Mg ha^{-1})	Spring Above Ground Rye N (kg N ha^{-1})	Ave. Daily Rye N Stress in April and May	Total Crop N Uptake (kg N ha^{-1})	Net Mineral. (kg N ha^{-1})	Fixation (kg N ha^{-1})	Drain. N (kg N ha^{-1})
Baseline	2.6	53.8	0.79	337.4	157.0	115.3	18.9
CO_2	2.9	54.5	0.75	374.0	164.7	147.5	19.2
Precip	2.6	52.5	0.79	332.5	154.2	116.5	22.3
Temp	4.7	89.2	0.70	397.0	238.0	94.9	14.1
All	4.7	80.3	0.64	429.0	234.8	131.8	16.4

The largest reductions in main crop yield from winter rye (CC) compared with NCC were for year 2071, where corn yield was reduced between 0.4 and 1.3 Mg ha^{-1} for three of the GCMs (HadGEM2-ES, MIROC5.1, and CCSM4). The reduced corn yield was because of simulated water stress during grain filling. On average, June-August future precipitation was reduced to 92% of baseline for two of the GCMs (MIROC and CCSM4; Figure 1c). The largest corn yield reduction resulted from only 3.4 cm of rainfall during August 2071 with the GCM that reduced August rainfall most substantially (85% of baseline; HadGEM2-ES; Figure 1c). August of 2071 was when most RZWQM simulated grain filling occurred.

With the corn yield reduction from water stress induced by rye growth and transpiration in 2071, simulated actual evapotranspiration (ET) is briefly discussed. Average annual actual ET for the six climate scenarios were 58.9 and 49.9 cm for CC and NCC and 55.2 and 48.7 cm for BL_CC and BL_NCC (Figure 2). The ET differences without winter rye for BL_NCC and NCC are comparable to Wang et al. [16], where ET was 44.2 cm for baseline and increased 0.8 cm for future climate. Our ET value for baseline climate without winter rye (BL_NCC) is greater than Wang et al. [16], but less than the average annual central Iowa ET of about 50–60 cm between 1971 and 2000 reported by Sanford and Selnick [64]. Our baseline ET is also similar to other studies that reported < 50 cm average annual RZWQM simulated ET from 2002 to 2009 for corn-soybean sites in central Iowa [44,65].

The winter rye treatment did not reduce crop yield most years. Although ET increased with winter rye treatments for both baseline and future climate (6.5 and 8.9 cm), both observed and RZWQM simulated soil water content in the spring before main crop planting were greater for winter rye treatments [34]. Additionally, the higher average annual ET with winter rye for both baseline and future climate was offset by less drainage (−6.8 and −9.3 cm; Figure 2), illustrating that on average the site had excess rather than deficit soil water for crop production.

Rye biomass and N uptake increased with climate change mostly due to increased temperature rather than increased atmospheric CO_2 or precipitation. This was determined by changing each climate-related variable individually from baseline values (Table 1). Although the above ground rye biomass increased with the CO_2-only scenario (from 2.6 to 2.9 Mg ha^{-1}), the temperature-only scenario had greater average annual spring rye biomass at termination (4.7 Mg ha^{-1}). Additional rye growth with the CO_2-only scenario was somewhat limited, because of slightly more spring nitrogen stress than the baseline scenario with ambient CO_2 (Table 1). The all-scenario (CO_2, temperature, and precipitation adjusted) had 8.9 kg N ha^{-1} less average annual above ground rye N content than the temperature-only scenario, mostly because of greater average annual N uptake by corn and soybean and more N stress for rye (Table 1). The precipitation-only scenario had little influence on N uptake or biomass of rye but did result in increased average annual drainage N, from 18.9 for baseline to 22.3 kg N ha^{-1} (Table 1).

The increase in winter rye cover crop biomass with future climate change seems to be consistent with another Iowa study. While considering only temperature effects in central Iowa, Basche et al. [66] used the APSIM model to show that average annual winter rye cover crop biomass nearly doubled from 2015 temperatures to 2060 temperatures.

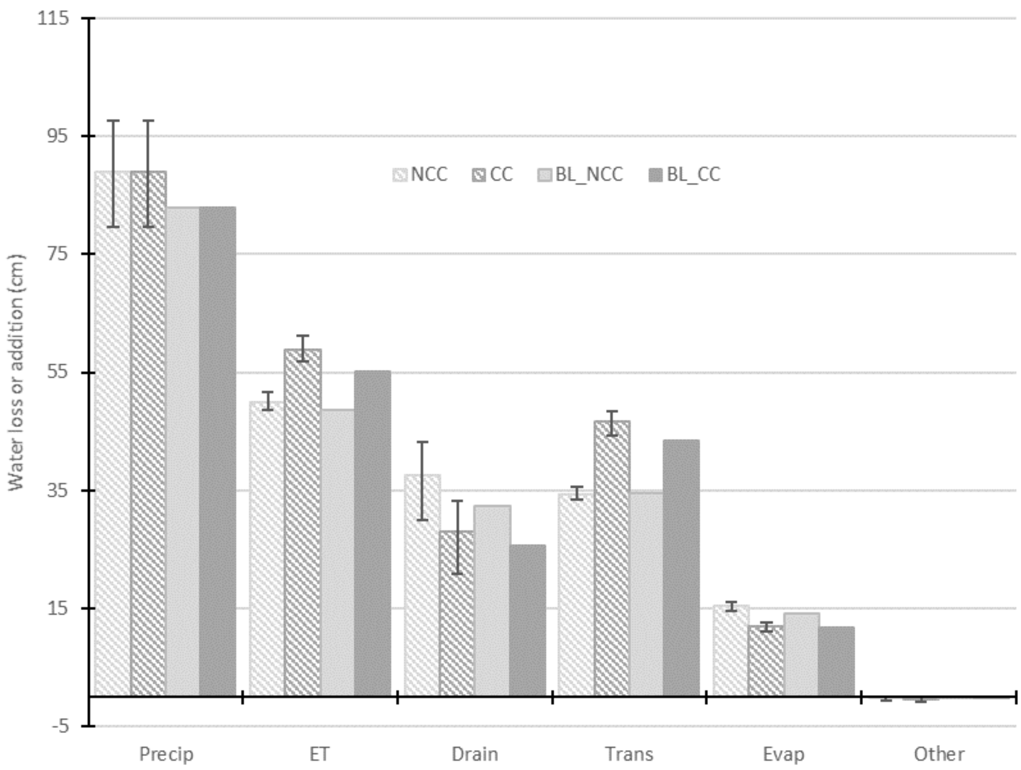

Figure 2. Average annual water budget (cm). BL indicates baseline conditions without projected climate change; NCC indicates no winter rye cover crop; CC indicates winter rye cover crop planted after corn and soybean harvest; ET indicates evapotranspiration; "trans" indicates transpiration; "evap" indicates evaporation; "precip" indicates precipitation; "drain" indicates artificial subsurface "tile" drainage; "other" indicates surface runoff and deep seepage. Values are the average of the two rotations (corn in odd or even years). The error bars for climate change scenarios are the overall range of the six climate models used.

3.2. Drainage N and Other N Budget Components

The average annual drainage N loads under projected climate change with the no cover crop (NCC) and baseline climate with no cover crop (BL_NCC) were 63.6 and 47.5 kg N ha^{-1}, or a 34% increase in N loads with climate change (Figure 3). These results are consistent with the increase of 34% reported and discussed by Wang et al. [16].

As reported by Wang et al. [16], the increase in drainage N loads under climate change was mostly because of greater net N mineralization. Net mineralization for NCC averaged 140.6 kg N ha^{-1} year^{-1}, and ranged from 129.7 to 149.0 kg N ha^{-1} year^{-1} for the six models, while BL_NCC averaged 113.8 kg N ha^{-1} year^{-1} (Figure 3).

Other than net mineralization, the largest components of the simulated N budget were crop N uptake, N fixation, and fertilizer addition and atmospheric deposition (Figure 3). RZWQM simulated N uptake derived from soil organic matter was similar between baseline and projected climate change scenarios (average of 33 v 32 kg N ha^{-1} year^{-1}; Figure 3), which was also reported and discussed by Wang et al. [16]. Average annual soil derived N uptake is defined as N uptake by corn and soybean from organic N mineralization (total crop N uptake-fixation-fertilizer-deposition; see [16]).

Unlike Wang et al. [16], our average annual denitrification for NCC increased 41% under climate change: 21.5 for BL_NCC to 30.0 kg N ha^{-1} year^{-1} for NCC with a range of 27.1 to 31.8 kg N ha^{-1} year^{-1} (Figure 3). This denitrification increase was because of the warmer and slightly wetter spring and early summer future climate (Figure 1b,c). These denitrification projections are consistent with Abdalla et al. [67] that concluded "denitrification is very sensitive to increasing temperature and that future global warming could lead to increased soil denitrification." Butterbach-Bahl and Dannenmann [68] also reported that denitrification in agricultural systems generally responds positively to changes in temperature.

Average annual drainage N loads decreased when including winter rye cover crop in the rotation, from 47.5 to 18.9 kg N ha^{-1} year^{-1} for baseline (60% decrease; 1991–2011), and from 63.6 to 17.0 kg N ha^{-1} year^{-1} for future climate projections (73% decrease; Figure 3). Winter rye cover crop reduces drainage N loads more substantially under projected climate change compared with baseline because of higher projected temperature (Figure 1) and CO_2 resulting in greater simulated winter rye growth and N uptake (Figure 3; Table 1). These results are consistent with a prior study [29], which discussed that winter rye cover crops were more effective at reducing drainage N loss with higher spring and fall temperatures (Figure 1) and increased cover crop growth (Table 1) and N uptake (Figure 3).

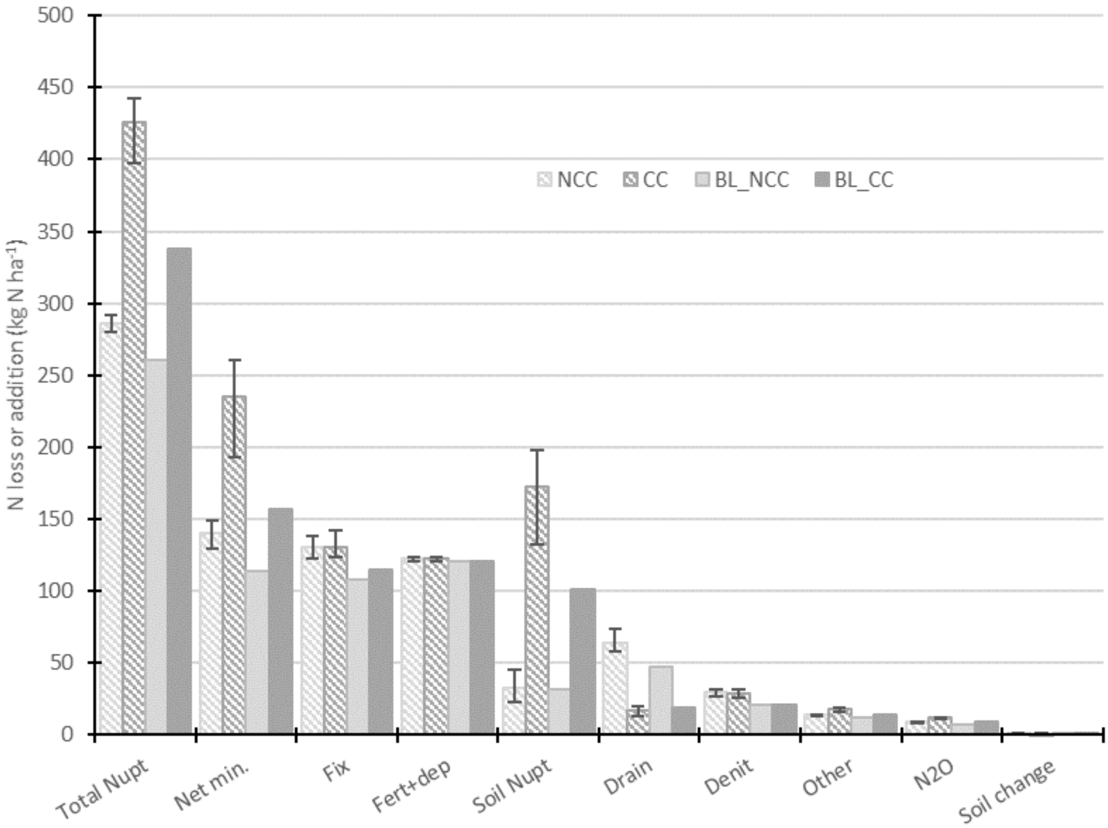

Figure 3. Average annual mineral-N budget (kg N ha^{-1}). BL indicates baseline conditions without projected climate change; NCC indicates no winter rye cover crop; CC indicates winter rye cover crop planted after corn and soybean harvest; "Total Nupt" is N uptake by corn, soybean, and winter rye; "Net min." is net N mineralization; "Fix" is N fixation; "fert + dep" are sum of fertilizer and deposition from rainfall; "Soil Nupt" indicates soil derived N uptake (total crop N uptake-fertilizer added -N fixation-atmospheric deposition); "Drain" is subsurface drainage; "Denit" is denitrification; "Other" N losses include sum of runoff, deep seepage, miscellaneous N emissions other than N_2O and adsorption into organic matter; "Soil change" is annual soil mineral N change. Note that the mineral-N budget balances for all treatments. For BL_NCC, as an example, 113.8 (net mineralization, or mineralization − immobilization) + 121.0 (fertilizer + deposition) + 108.0 (fixation) − 21.5 (denitrification) − 47.5 (tile drainage) − 260.6 (N uptake by crops) − 12.1 (other N losses) = 1.1 (soil change). Values are the average of the two rotations (corn in odd or even years). The error bars for climate change scenarios are the overall range of the six climate models used.

These percent drainage N load reductions with and without winter rye (60% and 73% for baseline and future climate, respectively) are similar to the results of Lee et al. [37], where winter rye cover crops was reported to reduce nitrate yield from cropland in Chesapeake Bay watersheds by 60% under baseline climate and between 67 and 69% under climate change using the SWAT model.

In comparison with the results of Lee et al. [37], our central Iowa site is projected to have colder average annual temperatures than the Chesapeake Bay watersheds under climate change (16.0 v 12.2 °C; Figure 1a,b), and have considerably greater average annual N loads to streams without cover crops (<15 kg N ha^{-1} v. 64 kg N ha^{-1}; Figure 3). Further, Lee et al. provided little information concerning cash crop production under climate change and did not report subsurface drainage area [37]. However, our results using a different model and different conditions (e.g., region, climate, N losses, soils) confirm that study's conclusion that "winter cover crops were effective in mitigating nitrate loads accelerated by future climate conditions, suggesting the role of winter cover crops in mitigating nitrate loads will likely be even more important under future climate conditions" [37]. RZWQM simulates N dynamics differently and perhaps more realistically than SWAT because of more mechanistic N mineralization and microbial immobilization routines [42]. Compared with baseline climate without winter rye (BL_NCC), increased simulation of net N mineralization was the main reason for increased RZWQM simulated drainage N loads for NCC as discussed above.

Drainage N losses for the climate change scenarios with winter rye cover crop (CC) were compared with 59% of N loss under baseline climate with no cover crop (BL_NCC*0.59). This comparison helps assess winter rye cover crop as a practice to address Iowa's goal of 41% reduction in future drainage N loads compared to baseline conditions [9,10]. Average annual N loss for the CC scenarios across the six GCMs were lower than BL_NCC*0.59 for 20 years of the 21-year simulation (Figure 4). Disaggregating to each individual GCM showed more than 41% reduction in N loss for between 18 and 20 years. For example, GFDL-CM3 had the largest average annual drainage N losses for CC of the six GCMs and three years were higher than BL_NCC*0.59 (Figure 4).

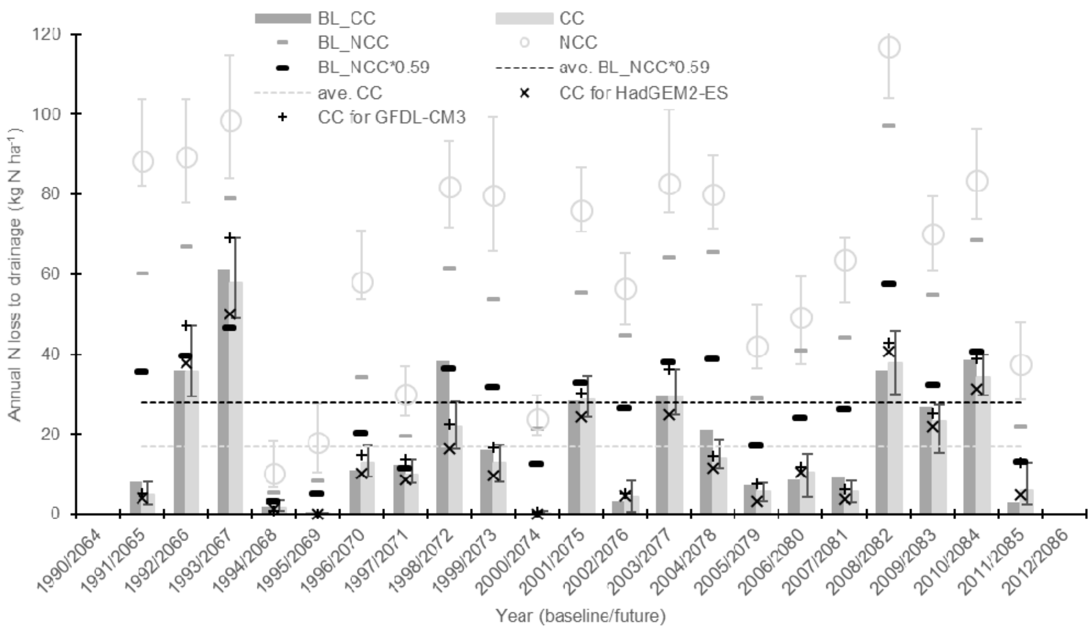

Figure 4. Average annual N loss to drainage. BL indicates baseline climate from 1991–2011; CC indicates cover crop scenarios; NCC indicates no cover crop scenarios. Values are averages of the two rotations (corn in odd or even years). The error bars are the range of the six GCMs. The GCMs with the lowest and highest N loss with CC are shown as × and + (HadGEM2-ES and GFDL-CM3). Baseline with no cover crop (BL_NCC) was multiplied by 0.59, to compare CC with the goal of reducing non-point source N loads to Iowa's waterways 41% [9,10].

With winter rye cover crop (CC), the average annual drainage N loads under the six GCMs were 13.5, 15.2, 15.9, 18.5, 19.0, and 20.1 kg N ha^{-1} for MIROC5.1, HadGEM2-ES, CCSM4, CSIRO-MK3, GISS-E2-R, and GFDL-CM3. These are all well below the target of 28.0 kg N ha^{-1} (a 41% reduction from the BL_NCC average annual N loss of 47.5 kg N ha^{-1}; Figure 4). These average N loads are significantly lower than the target for all six GCMs (p-values < 0.001). Averaged over the six GCMs, the average annual drainage N loads with cover crop was 17.0 kg N ha^{-1}. This, again, is significantly lower than the target of 28.0 kg N ha^{-1} (p-value < 0.001). The average N load of BL_CC was slightly higher than CC (18.9 kg N ha^{-1}; Table 1), but still significantly lower than the target (p-value < 0.001).

Considering the average of the six GCMs, the least effective annual N loss reduction with winter cover crop (CC) compared with BL_NCC was 27% for 2067 compared to 1993 (Figure 4). The year 2067 coincided with the future simulation period's lowest March average maximum air temperature of 4.5 °C, and lowest late April rye biomass of 1.9 Mg ha^{-1}. Malone et al. [29] reported that maximum spring temperature was the most sensitive investigated variable associated with RZWQM-simulated effectiveness of winter rye cover crop in reducing drainage N loads.

The target N reduction final goal is for the year 2035 [8] and our simulations with the GCM climate projections centered around 2075, so we ran several scenarios with monthly temperature, precipitation, and CO_2 levels between the baseline climate (BL_CC) and the "all-scenario" (Table 1). The average annual drainage N loss for these runs were higher than the "all-scenario" and lower than BL_CC losses of 16.4 and 18.9 kg N ha^{-1} (Table 1). This suggests that winter rye cover crop under the simulated conditions will significantly reduce drainage N loads below the target for the current climate and likely projected climate through 2075.

If fertilizer N rates are reduced in the future, then the future drainage N loads should be less than shown in Figure 4 for NCC and CC. Thus, with reduced fertilizer rates the future N loads with winter rye cover crop under projected climate change (CC) should be reduced more substantially compared to the target (BL_NCC*0.59) than currently shown in Figure 4. Note that the fertilizer rates would not change for BL_NCC because these are past baseline scenarios. Reasons for reduced N rates in the future could be because of higher soil N mineralization with projected climate change, as reported above and by Wang et al. [16], or because of more efficient systems (e.g., higher or static corn yield with reduced fertilizer rates and static soil N mineralization).

4. Conclusions

The U.S. National Academy of Engineering listed "Manage the Nitrogen Cycle" as one of 14 grand challenges for the 21st century stating: "controlling the impact of agriculture on the global cycle of nitrogen is a growing challenge for sustainable development" [69]. Sustainable intensification of agriculture (i.e., meeting the future food needs of a growing and increasingly affluent human population, while minimizing environmental impacts that include coastal hypoxic zones) is a major challenge of our time [70,71]. To meet these challenges, we must improve our understanding of the dynamics of nitrogen fate and crop production in corn-soybean rotations in the northern Mississippi River Basin under climate change, which include cover crops and subsurface tile drainage. This is especially true given that N loading from subsurface drainage in this region is one of the main contributors to hypoxia or the dead zone in the U.S. Gulf of Mexico [4,12,13], and this dead zone will likely increase in the future without strategies to reduce N loading to the Mississippi River and Gulf of Mexico [1–3]. To help address these challenges the state of Iowa set the goal of reducing non-point source N loads 41% [9,10].

This study is the first we are aware of that suggests that implementing winter rye cover crop in a northern Mississippi River Basin corn-soybean rotation would achieve the current goal of future drainage N load reduction under climate change without affecting cash crop production. This study also confirms the conclusions of Lee et al. [37] concerning the effectiveness of winter cover crops to mitigate N loads under projected climate change, which is one of the few published studies to include this focus. A more thorough understanding of the effectiveness of conservation practices under future climate change is essential to N reduction efforts in the Mississippi River Basin and elsewhere. Future modeling efforts should address other aspects of climate change and drainage N loads with winter cover crops, such as additional simulation time periods; RCPs; management (e.g., reduced fertilizer rates and earlier cash and cover crop harvest, termination, and planting); cash crop cultivars; types of cover crops; and soils/locations.

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Appendix A

The RZWQM default atmospheric CO_2 concentration of 330 ppm used by Gillette et al. (2018) was changed to 370 ppm for the current baseline climate simulations and model testing. The higher CO_2 concentration input for the current model runs resulted in higher simulated soybean yield compared with field observations and Gillette et al. [34]. Therefore, simulated soybean growth was adjusted downward by reducing the soybean growth parameter LFMAX to 0.6.

With the many model runs required for the current research and model convergence issues and slow processing speed associated with the SHAW energy budget model used by Gillette et al. [34], we used the default energy budget model with RZWQM. This change resulted in less RZWQM simulated net mineralization of N. So, for accurate simulation of N dynamics, the coefficient regulating the soil organic matter rate of decay was increased to 13.5×10^{-10} from the value of 9.5×10^{-10} that was used by Gillette et al. [34]. This revised value is less than the calibrated values reported in [29] and [65] of 22×10^{-10} and 24×10^{-10}.

With these model input changes, average simulated corn and soybean yield were 10.9 and 2.8 Mg ha^{-1} for no winter rye cover crop (NWCC) using the management, conditions, and RZWQM input described by Gillette et al. [34]. These crop yield simulations are similar to the simulated values of 10.8 and 2.9 Mg ha^{-1}, and measured average annual observed yields of 10.7 and 2.6 Mg ha^{-1} for corn and soybean, respectively, reported in [34]. Note that for clarity, the abbreviations for the RZWQM testing scenarios (NWCC and WCC) are different from the baseline and climate change scenarios (BL_NCC, BL_CC, NCC, and CC). Additionally note that field data, management, and RZWQM input and testing details are presented in [34].

The model performance indicators for both winter rye cover crop (WCC) and NWCC suggest these simulations were similar to Gillette et al. [34] for targets such as drain flow volume, drainage N loads, and winter rye biomass and shoot N (Table A1). Perhaps the most notable increase in model performance was for WCC drainage N loads, where relative root mean square error (RRMSE) decreased slightly from 41% to 38%.

Although not shown in Table A1, the N_2O simulations were similar to Gillette et al. [34]. The overall corn and soybean average annual April–October N_2O cumulative emissions for observed NWCC, simulated NWCC, observed WCC, and simulated WCC were 6.7, 6.2, 6.2, and 7.8 kg N ha^{-1}. Gillette et al. [34] reported 6.0 and 7.2 kg N ha^{-1} were simulated for NWCC and WCC for these same years and fields. As discussed in that paper, some of the difference between observed and simulated N_2O emissions was because peak daily emissions in corn years were simulated between field measurement dates.

Other unmeasured components of the simulated N budget appear reasonable. For example, the 2002 to 2009 average annual net N mineralization and denitrification were slightly higher for the current NWCC simulations compared with Gillette et al. [34] (124.0 and 18.3 kg N ha^{-1} compared with

116.7 and 17.3 kg N ha^{-1}). However, these are comparable to HERMES model simulations for the same field site (132.0 and 17.7 kg N ha^{-1}), which were discussed as reasonable for the conditions [72]. The year 2010 was not used for mineralization and denitrification values to maintain equal years for corn and soybean and to conform Gillette et al. [34].

Table A1. Model performance indicators and average annual observed (Obs) and RZWQM (RZ) simulated results for the central Iowa field experiment with winter rye cover crop (WCC) and no winter cover crop (NWCC) for 2002–2010. A summary of the Gillette et al. [34] results are also presented. Note that Gillette et al. [34] reported selected model performance statistics concerning rye biomass and shoot N while discussing results but did not include values in table. Model performance statistics were defined by Gillette et al. and Malone et al. [29,34]: the coefficient of determination (r^2), the Nash-Sutcliffe model efficiency (NSE), and relative root mean square error (RRMSE, %).

Statistic	**Drain Flow Volume (cm)**				**Nitrate Loss to Drain Flow (kg N ha^{-1})**				**Cover Crop Biomass (Mg ha^{-1})**		**Cover Crop Shoot N (kg N ha^{-1})**	
	NWCC		WCC		NWCC		WCC		WCC		WCC	
	Obs	RZ	Obs	RZ	Obs	RZ	Obs	RZ	Obs	RZ	Obs	RZ
Ave	36.7	37.9	35.9	34.4	49.3	49.4	20.8	20	1.6	2.2	48.3	53.8
NSE	0.90		0.89		0.60		0.35		0.21		0.73	
r^2	0.90		0.89		0.61		0.38		0.67		0.79	
RRMSE	14.3		14.7		24.9		37.6		42.3		24.3	
Summary of Gillette et al. (2018)												
Ave	36.7	36.2	35.9	34.2	49.3	48.5	20.8	22.4	1.6	2.1	48.3	52.9
NSE	0.89		0.89		0.61		0.22		0.30		0.76	
r^2	0.90		0.90		0.63		0.43		0.67		0.81	
RRMSE	14.4		14.3		24.7		41.2		40.1		22.7	

Although N mineralization and denitrification were not measured at the field site, Ma et al. (2012) recommended RZWQM calibration and testing should include the complete N budget. Including "soft data" such as unmeasured mineralization in water quality model evaluation has been recommended [73–75]. Soft data are defined as information on individual processes within a nutrient budget that are not directly measured but can be estimated through the literature or expert knowledge.

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