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Corn stover harvest N and energy budgets in central Iowa

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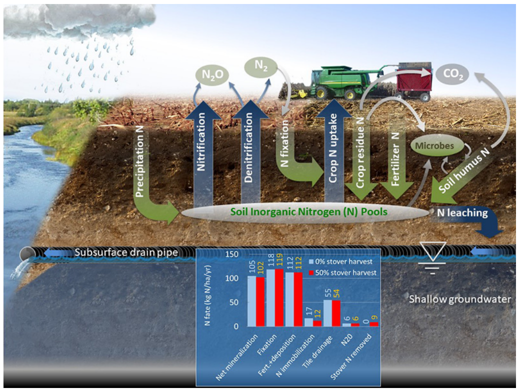
HIGHLIGHTS

- Few field studies have quantified N loss to drainage under corn stover harvest.
- Harvesting 50% of corn stover removed approximately 20 kg N ha^{-1} yr^{-1}.
- N loss to drainage was nearly the same with or without corn stover harvest.
- Simulated microbial immobilization of N was greater without corn stover harvest.
- Previous simulation studies report less drainage N loss with corn stover harvest.

GRAPHICAL ABSTRACT



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ABSTRACT

Harvesting corn stover removes N from the fields, but its effect on subsurface drainage and other N losses is uncertain. We used the Root Zone Water Quality Model (RZWQM) to examine N losses with 0 (NRR) or 50% (RR) corn residue removal within a corn and soybean rotation over a 10-yr period. In general, all simulations used the same pre-plant or post-emergence N fertilizer rate (200 kg ha^{-1} yr^{-1}). Simulated annual corn yields averaged 10.7 Mg ha^{-1} for the post emergence applications (NRRpost and RRpost), and 9.5 and 9.4 Mg ha^{-1} yr^{-1} for NRRpre and RRpre. Average total N input during corn years was 19.3 kg N ha^{-1} greater for NRRpre compared to RRpre due to additional N in surface residues, but drainage N loss was only 1.1 kg N ha^{-1} yr^{-1} greater for NRRpre. Post-emergence N application with no residue removal (NRRpost) reduced average drainage N loss by 16.5 kg ha^{-1} yr^{-1} compared to pre-plant N fertilization (NRRpre). The farm-gate net energy ratio was greatest for RRpost and lowest for NRRpre (14.1 and 10.4 MJ output per MJ input) while greenhouse gas intensity was lowest for RRpost and highest for NRRpre (11.7 and 17.3 g CO_2-eq. MJ^{-1} output). Similar to published studies, the simulations showed little difference in N_2O emissions between scenarios, decreased microbial immobilization for RR compared to NRR, and small soil carbon changes over the 10-yr simulation. In contrast to several previous modeling studies, the crop yield and N lost to drain flow were nearly the same between NRR and RR

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without supplemental N applied to replace N removed with corn stover. These results are important to optimizing the energy and nitrogen budgets associated with corn stover harvest and for developing a sustainable bioenergy industry.

1. Introduction

Corn (*Zea mays* L.) stover was projected to provide between 65 and 140 million tons of feedstock for bioenergy production by 2030 (USDOE, 2011). Harvesting stover for any use has multiple effects including increased N removal (Blanco-Canqui and Lal, 2009; Karlen et al., 2014; Karlen et al., 2011). Stover harvest has been reported to reduce N loss to drainage water and require additional fertilizer N to sustain acceptable corn grain yields (Gassman et al., 2017). Global interest and research in nitrate leaching have continued to increase over time (Padilla et al., 2018). With projections of increasing fertilizer N use and associated N leaching and hypoxia in aquatic ecosystems, the U.S. National Academy of Engineering has listed “Manage the Nitrogen Cycle” as one of 14 grand challenges for the 21st century (NAE, 2018). David et al. (2010) reported that the combination of fertilized corn and tile-drained agriculture is the dominant source of riverine nitrate N in the upper Mississippi River Basin (MRB) and contributes to hypoxia in the Gulf of Mexico. This all suggests the importance of investigating N removed from fields with stover harvest and the effects on N loss to drainage in the upper MRB. Daigh et al. (2015), however, reported that few studies have investigated this topic. Daigh et al. (2015) concluded “bioenergy-based prairies with or without N fertilization and continuous corn with stover removal and a cover crop have the potential to supply bioenergy feedstocks while minimizing NO_3–N losses to drainage waters”, but their study did not compare corn-soybean [*Glycine* max (L.) Merr.] rotations with and without corn stover harvest.

Field studies designed to quantify interactions associated with stover harvest and projected effects on the agricultural system including plant, drainage, and atmospheric losses of N are extremely costly and may require several years to achieve equilibrium. One strategy for addressing complex agricultural problems such as these is to use simulation models to define research priorities and improve our understanding of the soil-plant-atmosphere interactions (Dourado-Neto et al., 1998). Models can be used as tools to evaluate bioenergy production (Bonner et al., 2014), options and solutions for food security (Holzworth et al., 2014), and alternative management practices (Hochman et al., 2009). Simulation models have also been widely used in agricultural sciences to assess scenarios and support decision-making (Delmotte et al., 2017).

A few modeling studies have reported less N loss to water sources with corn stover harvest in corn-soybean rotations (e.g., Gassman et al., 2017; Cibin et al., 2016; Demisse et al., 2012; Meki et al., 2011, 2013). Conversely, Powers et al. (2011) reported slightly increased N loss to subsurface drainage with corn stover harvest using the Agricultural Policy Environmental eXtender model (APEX) for corn-soybean rotations in eastern Iowa, but did not provide a detailed discussion of the subject. Similarly, an Iowa field study with continuous corn and fall manure-N applications (Pederson et al., 2016) reported slightly greater N concentrations in subsurface drainage with than without corn stover removal.

Many bioenergy modeling studies have assumed additional N fertilizer will be needed to replace the amount removed through stover harvest (Gassman et al., 2017; Demissie et al., 2012 and 2017; Cibin et al., 2012, 2016, 2017; Song et al., 2017). Cibin et al. (2012, 2016, 2017) simulated replacement N fertilizer rates for stover harvest based on the assumptions reported by Brechbill and Tyner (2008) for central and/or northeast Indiana corn-soybean rotations using the Soil and Water Assessment Tool (SWAT) ecohydrological model (Arnold et al., 1998, 2012; Gassman et al., 2007). Gassman et al. (2017) simulated replacement N fertilizer rates for central Iowa corn-soybean rotations using SWAT, following the assumptions reported in the Cibin et al. (2012, 2016) studies. Furthermore, Meki et al. (2011) stated “stover removal–induced depletion of nutrient pools implies that increased fertilization rates will be required to sustain productivity”. Thompson and Tyner (2014) reported that nutrient replacement (including N and P) was a more costly component of corn stover harvest than equipment, fuel, labor and “wrap” (used to bind stover bales).

Gramig et al. (2013) investigated environmental and economic trade-offs when using corn stover for bioenergy with the SWAT model and concluded “information is needed about the level of nutrient replacement required to maintain grain yields”. In contrast to these modeling studies that assumed more fertilizer N with corn stover harvest, field studies suggest N removed can be negligible compared to spatial variability of soil N (Karlen et al., 2015). Sindelar et al. (2013) concluded from field experiments that “stover removal can improve short-term agronomic productivity of moderate- to high-yielding continuous corn on productive soils in the Upper Midwest”. They reported that one of the mechanisms involved with greater corn yield with no stover on the soil surface may have been decreased N immobilization. Pederson et al. (2016) reported slightly greater corn yields with corn stover removal compared to no stover removal. Archer et al. (2014) also concluded that with good soil and crop management, stover harvest can be sustainable in Iowa. Therefore, there seems to be uncertainty concerning the level of supplemental N to replace N removed with corn stover, or whether or not supplemental N is required.

The Root Zone Water Quality Model (RZWQM, Ma et al., 2000) has been thoroughly tested and compared to field data from numerous Iowa corn and soybean rotation studies with controlled and uncontrolled subsurface tile drainage (Fang et al., 2012), different fertilizer application rates and times of application (Bakhsh et al., 2001; Thorp et al., 2007; Malone et al., 2010), and winter rye cover crops (Li et al., 2008; Qi et al., 2011; Malone et al., 2014). These RZWQM applications all reported acceptable simulations compared to field observations of subsurface drainage N loss. Several additional studies have also reported acceptable or promising RZWQM simulations of N loss to drainage or leaching in corn-soybean rotations (Jeong and Bhattarai, 2018; Nolan et al., 2010; Ma et al., 2007; Malone et al., 2007; Bakhsh et al., 2004; Bakhsh et al., 1999; Jaynes and Miller, 1999).

RZWQM was recently used to investigate N loss to subsurface drainage with winter rye cover crop harvested as potential animal feed or bioenergy feedstock (Malone et al., 2018) where rigorous RZWQM validation and comparison with field data were previously described by Gillette et al. (2018). RZWQM has also been used to investigate crop yield and nitrate leaching in China (Sun et al., 2018), where the model testing and validation was described by Sun et al. (2016). Also because of a lack of field data, RZWQM was successfully used to investigate pesticide transport to subsurface drains in northeastern Iowa under corn stover harvest (Shipitalo et al., 2016) and used to investigate pesticide transport through surface soil under different rainfall intensity patterns (Malone et al., 2004).

Gramig et al. (2013) stated “no single model is capable of simulating the water quality and soil greenhouse gas emissions that result from agricultural production at the watershed scale”. The SWAT model has been used in a number of studies to simulate drainage N losses (Moriasi et al., 2013; Cibin et al., 2012, 2017; Gassman et al., 2017). Several studies have also recently modified the SWAT model to estimate nitrous oxide (N_2O) emissions (Wagena et al., 2017; Yang et al., 2017; Fu et al., 2018; Shrestha and Wang, 2018). Shrestha and Wang (2018) further simulated stover harvest and concluded that the results suggested stover harvest reduced emissions, but that literature was mixed indicating more research was needed. For example, Baker et al. (2014) reported no significant differences in cumulative N_2O emission as a function of corn stover removal. Drainage N losses were not the focus of these studies that used the SWAT model to simulate N_2O emissions. RZWQM was also modified to simulate greenhouse gas (GHG) emissions (Fang et al., 2015) and then used by Gillette et al. (2018) to investigate drainage N loss and N_2O emissions. That was one of the few studies focused on both pathways of N loss within corn and soybean systems. A possible strength of RZWQM compared to SWAT for simulating N dynamics of agricultural systems is the explicit representation of microbial growth and activity (Wagena et al., 2017).

Camargo et al. (2013) stated “it is increasingly common for GHG analyses to be linked with energy analyses”. Similarly, analyses of bioenergy systems increasingly include energy, GHG, and other environmental variables. For example, peer reviewed scientific articles that include “bioenergy and energy and environment and GHG” increased from 12 articles in 2007 to 115 in 2017 according to the Web of Science. Morales et al. (2015) reviewed life cycle assessment (LCA) of lignocellulosic bioethanol and concluded that studies showed a clear reduction in GHG emissions and ozone layer depletion compared with fossil fuels, while results in other environmental impact categories such as acidification and eutrophication were negatively affected. Although Morales et al. (2015) reported that most bioethanol studies conclude that the net energy ratio (energy output per input) was higher than 1, in some cases this value was <1. Part of the reason bioethanol production can result in higher potential for eutrophication and low energy ratios compared to fossil fuel production is use of fertilizers. The highly cited Life Cycle Assessment (LCA) study by Cherubini and Ulgiati (2010) reported that corn stover as a bioenergy feedstock had a strongly positive net energy ratio of about 5, but had higher potential for eutrophication than fossil fuel systems mostly because of more N leaching with additional fertilizer application to replace the N removed with stover. Cherubini and Ulgiati (2010), however, did not use a mechanistic model such as SWAT or RZWQM to simulate soil N dynamics (leaching, net mineralization, and crop N uptake). If additional N fertilizer is not needed to replace N removed with corn stover harvest used in biofuel production eutrophication potential, GHG emissions, and net energy ratios would be improved.

The Farm Energy Analysis Tool (FEAT) is one of the few methods to estimate energy use and GHG emissions of individual crops and cropping systems (Camargo et al., 2013; Ramcharan and Richard, 2017). Taking into account all the input and output flows occurring along the production chain, life-cycle net energy ratios for fossil-derived fuels have been reported to be between 5 and 20 (Brown and Brown, 2014), while for lignocellulosic bioenergy ranges may be from 1 to 7 (Liu et al., 2017). Within the farm-gate system boundaries, net energy ratios for common U.S. food and biomass crops were estimated to range from 4 to 35 MJ output per MJ input using FEAT (Camargo et al., 2013).

Beyond N leaching and GHG emissions from farm fields, increased fertilizer requirements to replace N removed with stover harvest contributes to GHG emissions when considering the production and transportation of fertilizer inputs. Similarly, increased fuel to harvest stover in a separate pass following corn harvest contributes to emissions. Energy inputs and GHG emissions associated with crop production include fuel for machinery operations and production and transportation of inputs. FEAT accounts for these inputs for estimates of GHG emissions and energy use.

In summary, corn stover as a bioenergy feedstock has generally been reported to have positive net energy potential but the results have been mixed for studies that have investigated either drainage N loss or N_2O emissions under stover harvest. Also, studies often assumed more nitrogen fertilizer was required with corn stover removal but replacement levels are currently uncertain. Models are important tools to investigate complex agricultural systems. The model RZWQM has been thoroughly tested for N loss to drainage in corn-soybean systems and a previously validated version of RZWQM has been used several times to investigate systems that lacked field data. Few studies, if any, have investigated N loss to drain flow and N_2O emissions under corn-soybean rotations with corn stover harvest. We hypothesize that using RZWQM to simulate the same N fertilizer rate for treatments with and without corn stover harvest that: 1) simulated N loss differences between treatments will be less compared to most previous simulation studies that did not explicitly model microbial growth and immobilization and 2) harvesting corn stover will improve the farm-gate net energy ratio compared to no corn stover harvest and corn stover harvest with additional N fertilizer to replace N removed without increasing N loss to the environment as reported by previous LCA studies that assumed more N fertilizer with corn stover harvest and used simplistic N leaching estimates.

For this study, we used the previously field tested and calibrated RZWQM (Gillette et al., 2018) and FEAT (Camargo et al., 2013) to investigate the effects of corn stover harvest on crop yields, N and energy budgets, and greenhouse gas emissions within a central Iowa corn-soybean rotation. We also modified a subset of the original SWAT model runs reported by Cibin et al. (2016) to reflect 50% corn stover harvest from tile drained fields within the St Joseph River Watershed which is located mostly in the northeastern section of Indiana as a comparison to the current RZWQM stover removal simulations. The original study by Cibin et al. (2016) was based on 70% corn stover removal and the detailed SWAT simulated N budgets were not presented that included net N mineralization and immobilization. Our analysis was limited to corn-soybean rotations partly because Gramig et al. (2013) reported that, compared to continuous corn, stover collection from a corn-soybean rotation always maximized stover yield and minimized the costs of the system for those individual years when stover was harvested.

2. Material and methods

2.1. Study site

The study site is situated on the Des Moines Lobe landform region in central Iowa (Fig. 1). Central Iowa is one of the more important regions to investigate N loss under corn stover harvest because: 1) it is among the highest corn yielding and producing regions in Iowa (Malone et al., 2009); 2) Iowa is generally the leading corn yielding and producing state in the U.S.; 3) the U.S. produces approximately 40% of the world's corn; and 4) Iowa is among the greatest sources of nitrogen loading to the Mississippi River Basin (Goolsby et al., 2001). Also, central Iowa is within the area of the U.S. that has the largest quantities of crop residues available for bioenergy feedstock (USDOE, 2018; Milbrandt, 2005).

Predominant soils are poorly drained Canisteo (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and Nicollet (fine-loamy, mixed, superactive, mesic Aquic hapludolls). In the central Iowa segment of the Des Moines Lobe, between 38 and 57% of land was estimated to be in drained row crop agriculture in 2008–2009 (Kladivko et al., 2014). During the study period (2000–2010), annual non-frozen precipitation and RZWQM simulated snowmelt averaged 86 cm and ranged from 56 cm in 2000 to 116 cm in 2010. The long-term average annual precipitation for the site from 1951 to 2010 was 86 cm (Kaspar et al., 2012).

The field study this current research is based on was described by Gillette et al. (2018). Briefly, corn was grown in even years and soybean in odd years (2001–2010). Fertilizer N was applied to corn in split applications with most of the fertilizer applied as a sidedress between 21-May and 19-June (average of 07-June) and smaller amounts of N applied at planting or a few days later. Total annual N fertilizer applied to corn varied between 237 and 174 kg N ha^{-1} and averaged 202 kg N ha^{-1}. Corn planting was between 25-April and 14-May, with an average corn planting of 02-May.

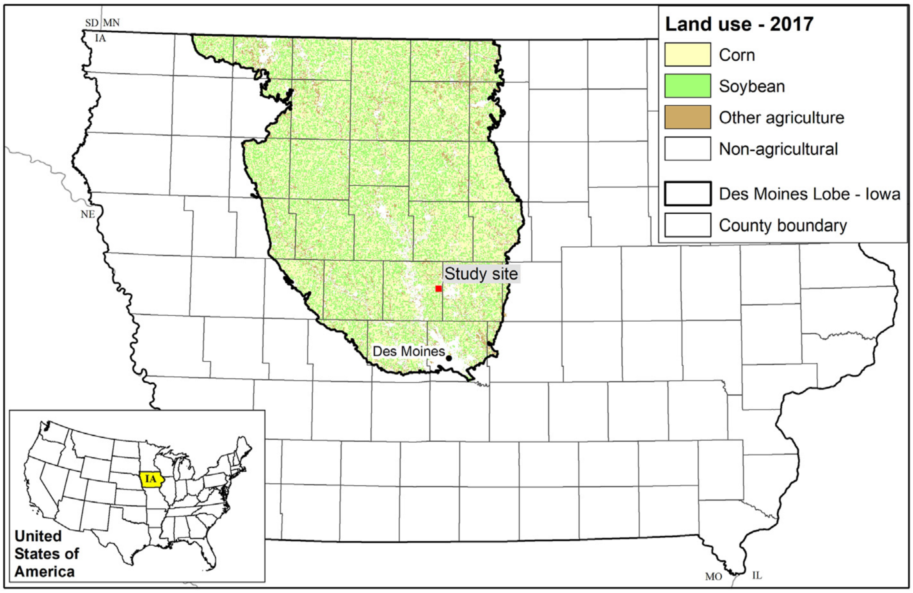

Fig. 1. Study area situated on the Des Moines Lobe landform region in central Iowa (IA) approximately 50 km north of the city of Des Moines. Also presented is the land use in the Des Moines Lobe region in 2017, which was predominantly corn and soybean agriculture. The surrounding states are Minnesota (MN), South Dakota (SD), Nebraska (NE), Missouri (MO), Illinois (IL), and Wisconsin (WI).

2.2. RZWQM scenarios

Table 1 summarizes the modeling scenarios, which included: 1) 0 and 50% corn stover harvest with 200 kg N ha^{-1} applied five days prior to planting corn (NRRpre and RRpre); and 2) 0 and 50% corn stover harvest with 200 kg N ha^{-1} applied 30-d post-emergence (NRRpost and RRpost). Additional scenarios included higher fertilizer N rates to compensate for estimated stover N removal (RRpre + N and RRpost + N). We simulate 50% corn stover harvest because this is within the range that can be sustainably harvested (Scarlat et al., 2010; Khanna and Paulson, 2016; Salinas-Garcia et al., 2001; Lichter et al., 2008), and 50% corn stover harvest was conducted with a large multi-location and multi-year study that include central Iowa data (Karlen et al., 2014).

Most N fertilizer for corn in Iowa is applied pre-emergence. For example, about 44% of N was applied in the fall before corn planting in 2010 in U.S. Corn Belt states (Ribaudo et al., 2012). Post-emergence scenarios N applications were investigated because Jaynes (2015) reported higher corn yields in central Iowa from this treatment compared to pre-emergence N applications. Phosphorus and potassium fertilizers were applied at rates of 6.72 kg P_2O_5 Mg^{-1} and 4.62 kg K_2O Mg^{-1} for corn and 13.79 kg P_2O_5 Mg^{-1} and 22.99 kg K_2O Mg^{-1} for soybean based on dry matter grain nutrient removal as recommended by the Iowa State University Extension and Outreach General Guide for Crop Nutrient and Limestone Recommendations (Mallarino et al., 2013).

Some corn stover removal studies have indicated additional fertilizer is needed to maintain yields (Brechbill and Tyner, 2008), but other studies suggest corn yield may be similar or slightly increased with corn stover harvest compared to without stover harvest (Karlen et al., 2014). None the less, an additional 2.95 kg of P_2O_5 and 15.00 kg of K_2O per Mg of dry matter corn stover removed were applied to all RR scenarios and an additional 7.95 kg N per Mg corn stover removed were applied to the "+N" scenarios, as recommended by Brechbill and Tyner (2008) and utilized by Cibin et al. (2012).

Table 1
RZWQM and FEAT scenarios for 2000–2010.[a]

Treatments	Corn planting years (even or odd)	Corn stover harvest amounts	N fertilizer dates[a]	Average annual fertilizer rates (kg ha^{-1} yr^{-1})					Average annual on-farm fuel use (L ha^{-1} yr^{-1})	
				N	P_2O_5		K_2O			
					Corn	Soy	Corn	Soy	Corn	Soy
NRRpre[b]	Even	0%	26-Apr	200	63	46	43	77	63	54
RRpre	Even	50%	26-Apr	200	75	47	108	79	80	54
NRRpost	Even	0%	07-Jun to 16-Jun	200	70	46	48	77	63	54
RRpost	Even	50%	07-Jun to 16-Jun	200	84	47	122	78	82	54
NRRpre_odd	Odd	0%	26-Apr	200	62	48	43	80	–	–
RRpre_odd	Odd	50%	26-Apr	200	78	49	112	81	–	–
NRRpost_odd	Odd	0%	08-Jun to 13-Jun	200	64	48	44	80	–	–
RRpost_odd	Odd	50%	08-Jun to 13-Jun	200	78	49	114	81	–	–
RRpre + N	Even	50%	26-Apr	234	77	47	111	79	82	54
RRpost + N	Even	50%	07-Jun to 16-Jun	240	84	47	123	79	81	54

[a] Corn was planted on 1-May while soybean was planted on 15-May. Both corn and soybean were harvested on 2-Oct. For the "post" treatments corn emerged each year on different dates depending on weather, which resulted in N fertilizer applied to corn each year on different dates. For scenarios with corn planted in even years the results presented are from 2001 to 2010. For scenarios with corn planted in odd years the results presented are from 2000 to 2009.

[b] Treatment abbreviations: "NRR" and "RR" indicate "No Residue Removal" and 50% "Residue Removal" after grain harvest; "pre" and "post" indicate fertilizer was applied to corn 5-d "pre-plant" or 30-d "post-emergence"; "odd" indicates corn planted in odd years and soybean planted in even years; "+N" indicates 7.95 kg more N fertilizer added per Mg of dry matter corn stover removed.

We simulated a fertilizer application of 200 kg N ha^{-1} which is slightly less than the 202 kg N ha^{-1} average applied to corn in these field studies from 2002 to 2010 (Gillette et al., 2018). This N rate was 33% greater than the long-term late spring soil nitrate test (LSNT) RZWQM-predicted rate of 150 kg N ha^{-1} for studies in nearby corn fields (Malone et al., 2010). Although the 150 kg N ha^{-1} rate may be predicted as being more profitable using a corn/N-fertilizer price ratio of 0.1 (CNRC, 2018), preliminary RZWQM simulations for the current site suggested that N rates below 200 kg N ha^{-1} would result in N stress and reduced corn yields. For example, using a 150 kg N ha^{-1} pre-plant rate to corn resulted in average annual RZWQM simulated corn yield reductions of 0.9 and 0.8 Mg ha^{-1} for NRRpre and RRpre (results not shown). Because nearby soil testing and calculations using the CNRC (2018) suggest lower N rates, 200 kg N ha^{-1} could be considered high. But lower N rates to this site resulted in unacceptably high RZWQM simulated corn yield reductions for both NRRpre and RRpre.

We modeled no corn stover harvest (NRR) and 50% corn stover removal (RR) scenarios using the same input parameters and weather data as Gillette et al. (2018). That study confirmed good agreement between simulated and observed results for crop N uptake, corn and soybean yields, drainage N loss, and N_2O emissions for a nine-year period (2002–2010) in central Iowa, USA. We use the No Cover Crop (NCC) scenarios from Gillette et al. (2018) rather than the Cover Crop (CC) scenarios; the two scenarios (NCC and CC) had slightly different soil parameters.

Soil related input parameters such as soil hydraulic conductivity and macroporosity were kept constant between treatments and expected changes in these variables were not considered in this analysis. This was partly because Shipitalo et al. (2016) reported that RZWQM-simulated drainage and runoff volumes were nearly identical for 0 and 50% corn stover harvest when adjusting macroporosity and soil hydraulic conductivity. RZWQM does not simulate surface water ponding due to roughness and depressional storage, therefore, ponding was not considered in this analysis. Corn stover removal at rates of 50% can reduce infiltration and increase runoff depending on site characteristics (Kenney et al., 2015). For no-till plots in central Iowa, Shipitalo et al. (2014) reported slightly higher runoff for 50% compared to 0% corn stover harvest that was statistically non-significant.

Field studies provided the foundation for this simulation study where a no-till, corn-soybean rotation was planted between May 1 and 15 (2001–2010) and harvested on October 2nd, with corn in even years as the main scenarios. The harvest date was early for central Iowa, but crop maturity was prior to October 2 and simulations showed essentially no differences when compared with later harvest dates (Malone et al., 2018). Post-emergence N fertilizer applications were simulated between June 7 and 16. To determine if key aspects of the simulated results could be repeated for a different set of years, simulations were also conducted for corn grown in odd years. Most of the modeling results and discussion, however, focus on corn planted in even years.

As described below, an energy balance and estimates of greenhouse gas emissions associated with corn stover harvest were also calculated for this study. For those calculations, scenarios were included where N application rates were increased (RRpre + N and RRpost + N). The results suggest that net energy and greenhouse gas emissions were optimized without increasing N application above 200 kg ha^{-1}. Therefore, the effects of increased N applications to the baseline scenarios on N dynamics and crop yield are not discussed because the results suggest additional N was not required. Also, the results suggest that the corn yields were essentially the same between RR and NRR.

2.3. RZWQM soil organic matter (OM) dynamics, nitrogen mineralization and immobilization, and evapotranspiration as influenced by corn stover harvest

Detailed discussions of RZWQM soil organic matter dynamics including surface residue, incorporated residue, and N mineralization/immobilization have been previously described (Ma et al., 2001, 1999, 1998; Shaffer et al., 2000) but are summarized in Fig. 2. Briefly, RZWQM simulates mineralization and immobilization through OM decay and microbe growth. Organic matter decay from each pool is simulated by a first order equation modified for several soil conditions (temperature, oxygen, hydrogen, population of aerobic heterotropic microbes, aerobic condition, and ionic strength). The aerobic heterotrophs grow by decay of the OM pools. A fraction of decayed organic C assimilates into microbial biomass (MB) that is not transferred into other OM pools based on an efficiency factor (E) input of 0.5 (RZWQM default), while the remaining decayed C is released as CO_2 gas. Net assimilation of decayed organic matter N into microbial pools is calculated from the C:N ratio of the respective OM pool and the microbial biomass (MB) C:N ratio of 8:1. Some decay/growth pathways are mineralizing decayed organic matter N (1/CN_OM > E/CN_MB) while others are immobilizing NO_3 and NH_4 in the soil (1/CN_OM < E/CN_MB). Carbon use efficiency (E) as related to microbial growth has been defined as the fraction of C uptake allocated to microbial growth (Li et al., 2014). If net immobilization is occurring, sufficient NH_4 and NO_3 must be present otherwise microbial growth and OM decay processes stop.

In RZWQM, crop residue above the soil surface may be incorporated by either tillage or decomposition (biological and abiotic processes). With tillage, crop residue is incorporated to a user defined depth based on an intensity factor that is related to the fraction of surface residue incorporated during each tillage event. Decomposition of surface residue occurs regardless of tillage based on the Douglas and Rickman (1992) equation which was evaluated as implemented in RZWQM by Ma et al. (1999). The model uses a degree-day concept and adjusts the decomposition rate as a function of air temperature, soil moisture, and N content of surface residue that include crop and manure residue. Douglas and Rickman (1992) assumed a first-order decay with respect to degree-day, such that $M_t = M_{t-1}\ (1\text{-}K_d\text{DGD}_t)$, where M_t and M_{t-1} are surface residue mass at current and previous day (kg ha^{-1}); DGD_t is the degree-day for the current day, which is taken as the average temperature above 0 °C of that day; K_d is a first-order decomposition variable (1/DGD) equal to kf_Nf_w; f_N and f_w are factors accounting for initial crop residue N and soil moisture; and k is a rate coefficient (1/DGD). The decomposed surface residue is uniformly distributed within the first 4 cm of soil as soil incorporated residue (Fig. 2).

The decomposed surface residue is incorporated into the surface soil as fast and slow residue and partitioned based on the three C/N ratios (fast, slow, and surface; Ma et al., 1998). The three soil humus pools have default C/N ratios of 8 (fast pool), 10 (intermediate pool), and 12 (slow pool) and are dynamically connected as shown in Fig. 2. Incorporated residue and humus pools are subject to a first order decay with respect to their C concentration:

$$r_i = k_i\, C_i$$

where r_i is the decay rate of the i^{th} pool (mg C kg^{-1} d^{-1}) ($i = 1$ for slow residue pool, $i = 2$ for fast residue pool, $i = 3$ for fast humus pool, $i = 4$ for intermediate humus pool, and $i = 5$ for slow humus pool); C_i is the C concentration (mg C kg^{-1} soil), and k_i is a first order rate coefficient (d^{-1}) and is affected by soil water O_2 concentration, soil pH, ion strength, heterotrophic microbial population, soil temperature, and degree of soil water saturation (Ma et al., 2000, 2001). A fraction of the decayed OM from each pool is transferred into another pool as a function of the OM interpool transfer coefficients: R_{14}, R_{23}, R_{34}, and R_{45} (Fig. 2). The remaining soil organic matter is assimilated into microbial biomass (immobilization) or released as inorganic carbon (e.g., CO_2) and mineralized nitrogen (e.g., NH_4).

RZWQM simulates three living microorganism pools: aerobic heterotrophs, autotrophs, and facultative heterotrophs. The aerobic heterotrophs grow during the decay processes of each OM pool. Autotrophs are responsible for the nitrification processes, and their growth rate is proportional to nitrification rate (Ma et al., 1998, 2000). During growth, microbes assimilate either NH_4 or NO_3 depending on their availability.

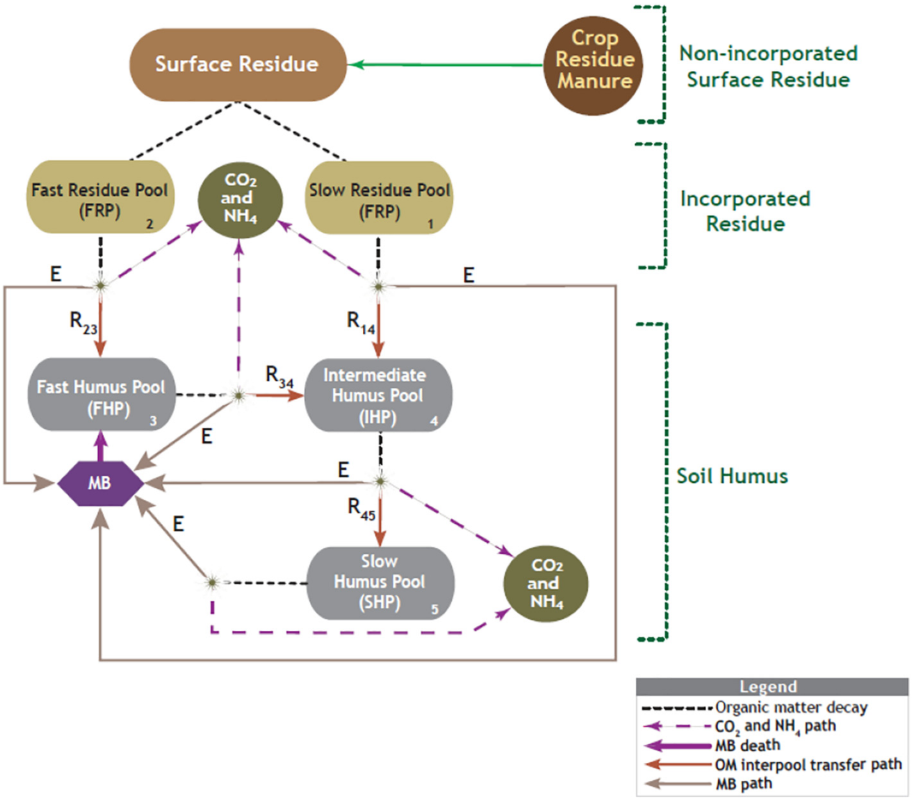

Fig. 2. Soil organic matter (OM) pools and decay pathways. E is an efficiency factor for conversion of carbon available from OM decay to microbial biomass (MB) carbon. Carbon available for assimilation into MB is decayed carbon that is not transferred to another OM pool. The four Rxx are OM interpool mass transfer coefficients: R14, R23, R34, R45.

Microbial death assimilates C and N into the fast humus pool and death is calculated as a first order equation adjusted for soil environmental variables: temperature, water content, pH, oxygen level, and nutrient concentration (Shaffer et al., 2000; Ma et al., 2001).

The Shuttleworth-Wallace equations are used to calculate potential evapotranspiration (Farahani and Ahuja, 1996; Anapalli et al., 2016). As shown in Eq. (7) in Farahani and Ahuja (1996), residue removal decreases residue resistance (r_s^r) and consequently increases potential evaporation from the soil surface. The latter decreases the vapor pressure deficit (VPD_o) according to Eq. (8) in Farahani and Ahuja (1996). Finally, potential transpiration decreases with decrease in VPD_o based on Eq. (5) in Farahani and Ahuja (1996). Therefore, based on the Shuttleworth-Wallace equations, removing residue will slightly increase potential evaporation and decrease potential transpiration.

2.4. SWAT soil organic matter (OM) dynamics and nitrogen mineralization and immobilization

A comprehensive RZWQM and SWAT model comparison using the same field site was beyond the scope of this study. We do, however, compare the simulated N budget including net mineralization, immobilization, and drainage N loss of the current study to the SWAT simulations of Cibin et al. (2016). Cibin et al. (2016) and most related modeling studies focusing on N loss to drainage that include corn stover harvest did not present a detailed N budget. Also, previous related studies such as Cibin et al. (2016) and Gassman et al. (2017) present N loss at the outlets of large watersheds that included drained and non-drained fields along with fields not in corn-soybean production.

In Section 3.2 below, we present the average annual nitrogen budget for eight years (2002–2009) of SWAT model simulations of the St Joseph River Watershed (Cibin et al., 2016) for low sloping tile drained fields in corn-soybean production with 0% and 50% corn stover harvest. Cibin et al. (2016) used the SWAT model to quantify the impacts of biofuel scenarios on hydrology and water quality for the St. Joseph River watershed (drainage area of 2809 km^2) located in Indiana, Ohio and Michigan. The St. Joseph River watershed is characterized by flat to hilly terrain (40% area >2% slope) and mixed land use with 37% corn/soybean rotation and the rest in mostly pasture and forest. Further details such as site description, model testing, validation, and parameterization was presented by Cibin et al. (2016).

SWAT is a process-based, distributed-parameter watershed scale simulation model capable of representing various crops, crop management practices, nutrient uptake, nutrient balance, and nutrient losses from various landscapes at multiple spatial and temporal scales (Arnold et al., 1998; Gassman et al., 2007). SWAT is capable of physically representing major components of nitrogen cycle at landscape scale. The model distributes nitrogen (N) into five pools in the soil column, two inorganic and three organic pools. The three organic pools are fresh plant residue, active organic N and stable organic N. The N from crop residue such as corn stover is accounted in the fresh organic pool after grain harvest and crop kill. The fresh organic N is slowly distributed to active organic pool as residue decay and to the mineral nitrate pool as residue mineralization. The highly mobile nitrogen is transported from soil through denitrification, volatilization, surface runoff, leaching, and plant uptake. The model updates interactions between N cycle components in soil, plants, and water at a daily time scale and nutrient budgets can be synthesized at various spatial and temporal scales.

SWAT uses an adapted version of the PAPRAN mineralization model (Seligman and Van Keulen, 1981) to simulate net N mineralization and accounts for immobilization but does not explicitly simulate microbial pools (Neitsch et al., 2011). Mineralization in each soil layer is a function of the nitrogen available in the organic pools, a decay rate constant which is a function of C/N ratio, soil temperature, and soil moisture. More detailed discussion on residue decomposition and mineralization representation in SWAT is presented by Neitsch et al. (2011).

2.5. FEAT description

FEAT was used to compute energy budgets and estimate greenhouse gas emissions for the simulated scenarios. FEAT is an open-source, evolving database model (Camargo et al., 2013). FEAT scenarios are summarized in Table 1.

Energy inputs included on-farm fuel use for planting, crop management and harvest, as well as the embedded energy in inputs such as fertilizers. Energy output was defined as the higher heating value of harvested corn, soybean, and stover biomass. We did not consider any downstream logistics or energy inputs and processing beyond the farm gate. Energy efficiency was calculated as the net energy ratio, defined as useful energy output divided by fossil energy input required to produce the crop.

The FEAT database (Camargo et al., 2013) provided most of the energy and greenhouse gas related data such as herbicide and insecticide applications, tillage, seeding rates, and fuel consumption. Ramcharan and Richard (2017) used the same database to simulate a corn plus winter rye double crop with different cellulosic biomass harvest scenarios and reported farm level greenhouse gas emission intensities ranging from −1 to 18 g CO_2eq. MJ^{-1}. For many crops including corn and soybean the largest contributor to the farm-gate greenhouse gas footprint is N_2O (Camargo et al., 2013). For this study we used soil, climate, and cropping system specific N_2O emissions simulated by RZWQM as input to FEAT. This approach had performed better for a corn-soybean-rye system in Iowa (Gillette et al., 2018) than the more generic IPCC Tier 1 N_2O emission rates used as default by FEAT. The RZWQM N_2O emissions were, however, higher than IPCC values (Gillette et al., 2018).

Farm operation fuel rates were also taken from the FEAT database, except 1.81 L Mg^{-1} dry matter harvested was used for the two-pass grain and stover harvest (RR scenarios) as reported by Shinners et al. (2012) and 13.45 L ha^{-1} was used for the corn grain only harvest (NRR scenarios; computed from Helsel and Oguntunde, 1981, Ayres, 2000, Downs, 2007, and West and Marland, 2002). Total fuel requirements for an entire crop year (i.e., planting, fertilizing, harvesting grain and stover, and all other operations) averaged 81 L ha^{-1}. This was similar to the value (84 L ha^{-1}) reported by Sokhansanj et al. (2010). The percent increase in fuel use with stover harvest, compared to grain only harvest, ranged from 20 to 33% using the FEAT scenarios presented. This range was similar to the 23% increase in fuel consumption reported by Webster (2011) for stover harvest, but higher than the 11% reported by Keene et al. (2013).

3. Results and discussion

3.1. Crop production, N uptake, N fixation, and water budgets

Simulated N uptake by crops and crop yields must be reasonable to ensure accurate accounting of N loss to subsurface drainage with corn stover harvest and the other scenarios. Seemingly small errors in estimating uptake and yield can lead to larger errors in estimating N loss to drainage. For example in a corn-soybean rotation, Malone and Ma (2009) reported a 4% increase in crop N uptake resulted in 30% less N loss to subsurface drainage. Considering that the average annual N uptake and N fixation of the current simulations were more than twice drainage N (approximately 250 and 120 compared to 50 kg N ha^{-1} yr^{-1}), the analysis begins with corn and soybean yield and N fixation. In general, as discussed below, the simulated corn grain and stover yields and soybean yields and fixation were reasonable when compared to Story County Iowa USDA-NASS records, on-site field observations, and published sources. Discussion is provided for instances where the simulated crop production and the associated evapotranspiration and fixation differences between scenarios were largest.

3.1.1. Corn grain and stover

The simulated corn yields were considered reasonable because: 1) except for 2002, the annual simulated corn yields for NRRpre were within 1.0 Mg ha^{-1} of the Story County averages from USDA NASS (USDA, 2018; Fig. 3); 2) simulated corn yields for the post emergence N application scenarios (NRRpost and RRpost) were within 0.5 Mg ha^{-1} of the observed yields except for 2002 and 2006 (Fig. 3), and were closer to the observed site specific field values than NRRpre and RRpre (Fig. 3); and 3) the simulated corn yields for these plots between 2001 and 2010 using site specific field management were within 0.5 Mg ha^{-1} of the observed yields each year for the plots with no cover crop (Gillette et al., 2018). The observed corn yields were greater than the NASS yields each year partly because most of the N was applied to the corn post-emergence as part of the overall site specific field management (Gillette et al., 2018). As described below, the late April N fertilizer application for the pre-plant scenarios (NRRpre and RRpre) resulted in simulated N loss and N stress during corn growth.

The simulated corn grain yields with post emergence N applications and corn stover harvest averaged 1.4 Mg ha^{-1} more than the simulated corn yield with pre-plant N applications because of less N stress (RRpost v. RRpre). Yield differences between the RRpre and RRpost treatments were greatest in 2008, when NASS and simulated RRpre corn yields were lowest for the nine year period 2002–2010 (Fig. 3). The 20 cm of rainfall during May 2008 (Fig. 4a.) was nearly double the long term average (Kaspar et al., 2012) and presumably resulted in denitrification and leaching of N fertilizer applied pre-plant. This is supported by the 2008 RRpost simulations that showed 30% less N stress during grain fill, 4 Mg ha^{-1} greater grain yield, and 1.4 Mg ha^{-1} more harvested corn stover. Furthermore, compared to the RRpre simulations the RRpost scenario had 11 kg N ha^{-1} less simulated denitrification, 110 kg N ha^{-1} more total N uptake (Fig. 4b), and 60 kg N ha^{-1} less N loss to drainage (Fig. 4a) for the period May through September of 2008. The 2004 simulated corn yield difference between RRpre and RRpost was also relatively large and received nearly 25 cm of rainfall in May (Figs. 3 and 4a).

In contrast to the low 2008 NASS and RRpre corn yields, the observed field-site corn yields and RZWQM simulations with site specific field operations show that greater average corn yield occurred in 2008 (Gillette et al., 2018; Kaspar et al., 2012; Fig. 3). This was most likely because of N being applied post emergence on June 19 in 2008 (Kaspar et al., 2012). Consistent with these results, Jaynes (2015) reported higher corn yields for post emergence N application in a central Iowa corn-soybean rotation.

The predicted average annual corn yields were the same for NRRpost and RRpost at 10.7 Mg ha^{-1}. The predicted average annual corn yields were also essentially the same for NRRpre and RRpre, with NRRpre yield 0.1 Mg ha^{-1} more than the RRpre yield. The simulated yield for RRpre was less because of slightly more nitrogen stress during grain filling. For example, in 2008 when the yield and N uptake differences were greatest between RRpre and NRRpre (Figs. 3 and 4c), NRRpre had 4% less simulated N stress during grain filling and 4% more simulated grain yield. Furthermore, compared to the RRpre yield, the NRRpre had 6 kg N ha^{-1} more total N uptake and 7 kg N ha^{-1} more net mineralization for the period May to September of 2008 (Fig. 4c).

The average annual corn yields with corn planted in odd years were also the same for both NRRpost_odd and RRpost_odd at 9.5 Mg ha^{-1} (results not shown). Similar to our results, Pederson et al. (2016) reported no significant difference in corn yields with stover harvest versus no stover harvest. In contrast, Gassman et al. (2017) applied supplemental N fertilizer to central Iowa corn-soybean rotations with 50% corn stover harvest, based on assumptions reported by Cibin et al. (2012), which resulted in simulated corn yields that were 0.2 Mg ha^{-1} lower than the baseline corn yields (Gassman, P.W. Personal communication. Iowa State University, Ames, Iowa).

Although the predicted corn yields were essentially the same for NRRpre and RRpre, at least 3 kg N ha^{-1} more N uptake was simulated

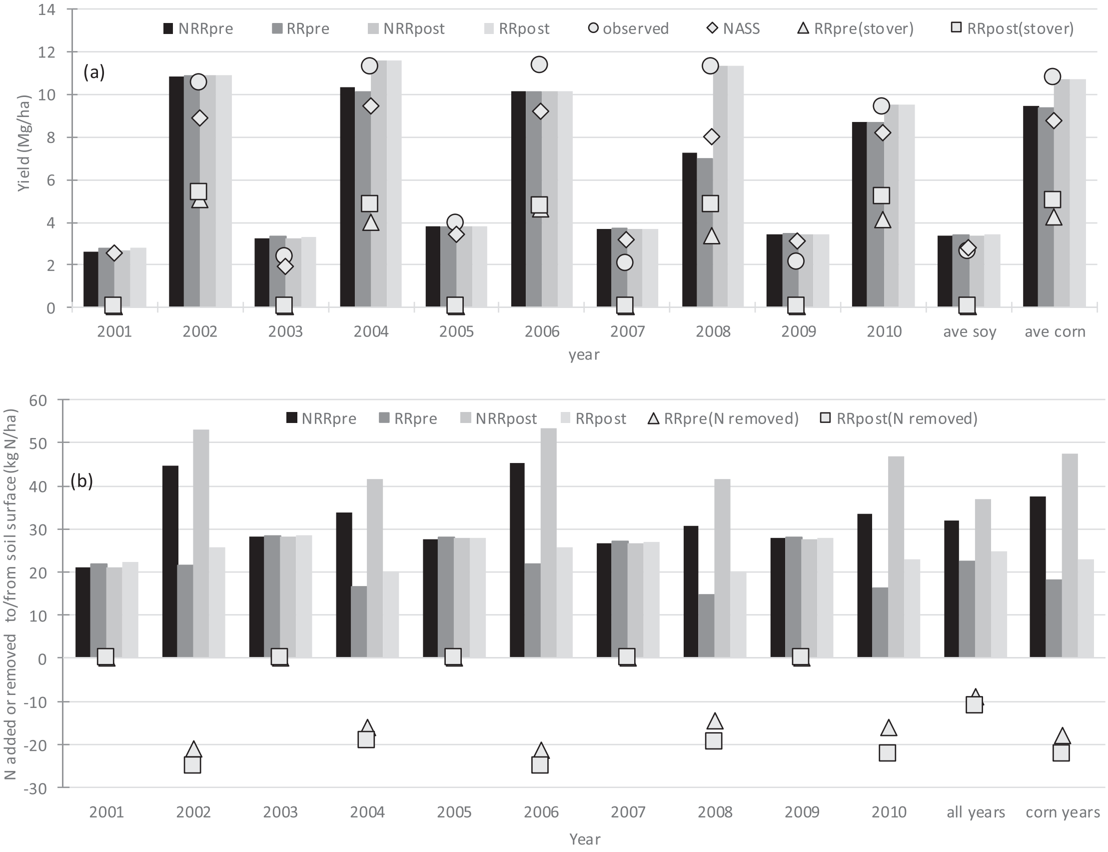

Fig. 3. Annual dry matter crop yield (a), dry matter corn stover harvest (a), and N added or removed to/from system from above ground non-grain crop biomass after harvest (b) from 2001 to 2010. Overall average annual values are also presented. Corn was in even years and soybean was in odd years. The symbols are: NRRpre is no residue removal with pre-emergence fertilizer application, RRpre is 50% corn stover residue removal with pre-emergence fertilizer application, NRRpost is no residue removal with post-emergence N fertilizer application, RRpost is 50% corn residue removal with post-emergence N fertilizer application. NASS are Story County Iowa average corn and soybean yields from the National Agricultural Statistics Service (USDA, 2018). For each corn year, the majority of fertilizer applied within Story County would be pre-emergence and most fertilizer applied for the observed corn yield was post-emergence (Gillette et al., 2018).

each corn year for NRRpre compared to RRpre (Fig. 4c). This was mostly due to the additional N mineralization that occurred with NRRpre during the corn years (Fig. 4c). The additional N uptake and N mineralization with NRRpre resulted in the overall annual cumulative “N to soil” differences between NRRpre and RRpre at corn harvest to be small (Fig. 4c). The small additional “N to soil” with NRRpre was partly compensated most years following corn by less cumulative annual N fixation during the soybean years for NRRpre (Fig. 4c), as described in Section 3.1.2.

With 50% stover harvest, average annual corn stover yields were 4.2 and 5.0 Mg ha^{-1} for RRpre and RRpost (Fig. 3). These yields were similar to the 50% harvest collected in a nearby central Iowa field for 2008–2012 (3.6–4.7 Mg ha^{-1}; Karlen et al., 2014). The simulated corn stover yield was 0.8 Mg ha^{-1} higher for RRpost than RRpre (about 20% greater), which coincided with 15% higher grain yield (Fig. 3).

Average annual N removed with corn stover harvest from RRpre was 17.8 kg ha^{-1}. This resulted in an average of 19.3 kg ha^{-1} more N added to the soil surface with NRRpre compared to RRpre in corn years (Fig. 3). Our simulated N removed for RRpre was low compared to Karlen et al. (2014). Karlen et al. (2014) reported about 23 kg N ha^{-1} removed with 50% corn stover harvest and 4.0 Mg ha^{-1} corn biomass harvested in a different central Iowa field. Our current corn stover harvest simulations result in 50% removal of the total above ground N (excluding grain N), and this stover N then mixes with the surface residue. Our harvested N in corn stover may be low partly because Cantrell et al. (2014) reported less N (g N kg^{-1} dry matter, DM) with the bottom stalk portion compared to the whole stover plant (excluding grain). In contrast, our simulations reflect removal of 50% of the bottom stalk portion along with removal of only 50% of corn leaves. Simulated average annual N removed with stover for RRpost (22.1 kg N ha^{-1}, Fig. 3) was closer to values reported by Karlen et al. (2014).

Another potential reason for low N in corn stover is that current corn hybrids have lower grain N concentration than older hybrids (Fang et al., 2017). Fang et al. (2017) reported that RZWQM over predicted N in corn grain but not corn stover (total above ground N in corn biomass minus corn grain N). Thorp et al. (2007) also reported that RZWQM over predicted N in corn grain compared to central Iowa field values. This suggests we under predict N in corn stover given that Gillette et al. (2018) calibrated the model with N in drainage and corn yield. In fact, unreported results from Gillette et al. (2018) suggest that RZWQM under predicted total above ground N during corn years and over predicted corn grain N compared to field results. Fang et al. (2017) modified RZWQM for reduced grain N concentrations in current compared to older corn hybrids, but this modified version was not used by Gillette et al. (2018).

3.1.2. Soybean

Except for 2003, annual soybean yields were simulated reasonably well with simulations within 0.5 Mg ha^{-1} of Story County NASS yield records, and both NASS and simulated yields were highest for 2005 and lowest for 2001 (Fig. 3). Using site specific field operations, simulated soybean yields compared to field data was also least accurate for 2003 (Gillette et al., 2018), which was consistent with previous HERMES and RZWQM model applications for this site (Malone et al., 2017, 2014; Li et al., 2008). The low observed and NASS soybean yields in 2003 may be because only 2.5 cm of precipitation was recorded in

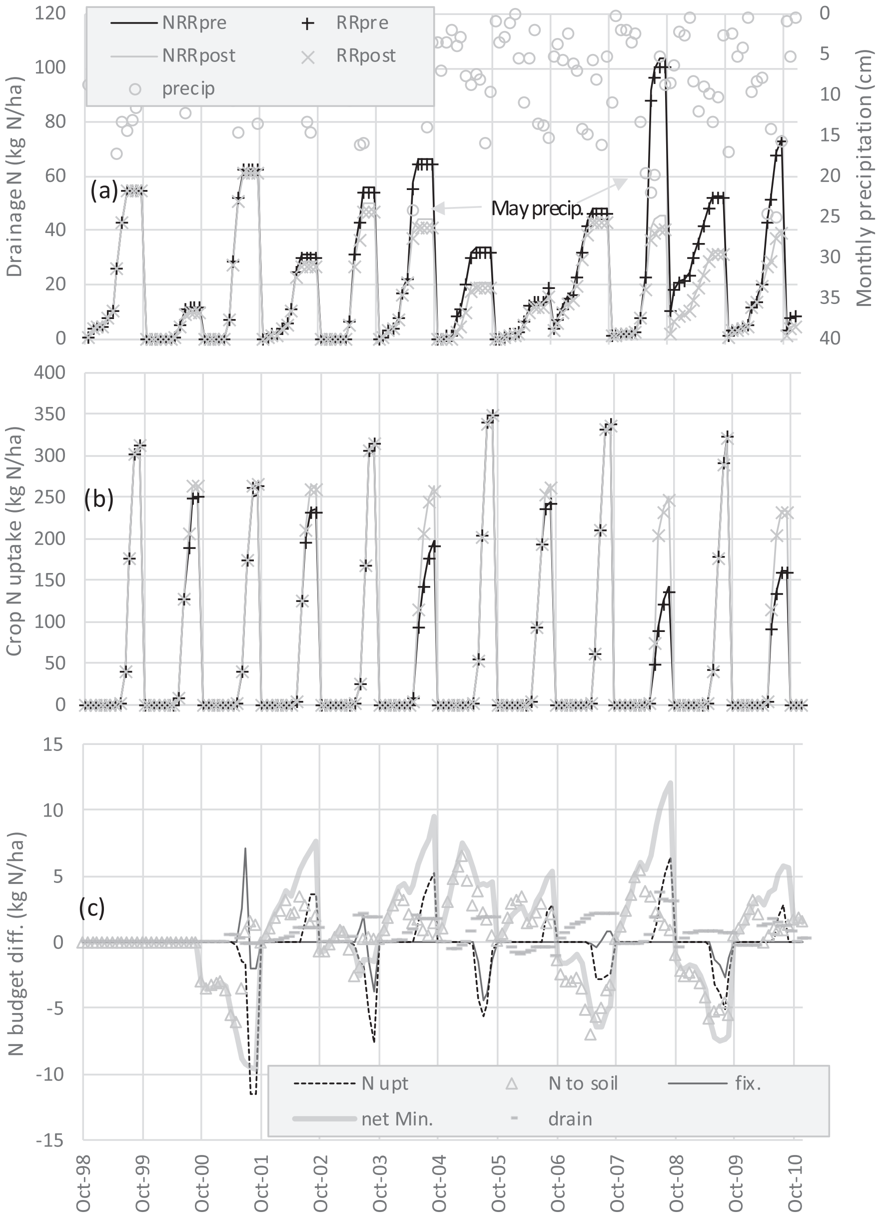

Fig. 4. Cumulative monthly N budget. Also presented are the cumulative monthly differences between NRRpre-RRpre. Cumulative monthly N budgets and differences were restarted each October after crop harvest. (a) The cumulative monthly drain flow N for each treatment and the monthly precipitation. (b) The cumulative monthly crop N uptake for each treatment. (c) The cumulative monthly differences between NRRpre-RRpre for N to drain flow, N fixation, N uptake, net N mineralization, and "net N to soil". Net N to soil = net mineralization + fertilizer + deposition + fixation − denitrification − drain flow − N uptake by crops − "other N losses". "Other losses" were defined in Fig. 5. The "pre" represents pre-plant N fertilizer and "post" represents post-emergence N fertilizer and "NRR" and "RR" indicate "No Residue Removal" and 50% "Residue Removal" after grain harvest.

August (Kaspar et al., 2007), suggesting RZWQM did not accurately simulate soybean water stress for 2003. The site specific observed soybean yields were lower than NASS and RZWQM simulations for 2007 and 2009 because different cultivars were planted (Gillette et al., 2018; Kaspar et al., 2012). The current simulations used the same cultivars for all years.

The average annual simulated soybean yields were about 2% more with corn stover harvest (RRpre and RRpost) than NRRpre and NRRpost (Fig. 3), which was small but important because it contributes to slightly more fixation especially for RRpost compared to NRRpost (Fig. 5). The average annual simulated soybean yield difference between RRpost and NRRpost was mostly due to a 6% yield difference in 2001 (Fig. 3) that was driven by a small simulated water stress difference in August (Fig. 6). Other than 2001, soybean yield differences between RRpost and NRRpost ranged from 0 to 3% (Fig. 3).

In 2001 the cumulative actual ET (AET) gradually increased in the RRpost scenario compared to NRRpost until around day 160 (Fig. 6), because of the 50% corn stover harvest and less corn stover cover on the soil surface (Fig. 3). The soil water storage was also nearly the same between the two treatments between days 100 and 170 because cumulative tile drainage for NRRpost was increasing compared to RRpost while cumulative AET was increasing for RRpost. Around day 160 the plant transpiration becomes greater in NRRpost resulting in less plant available soil water. Then around day 220 the NRRpost scenario simulated more water stress than RRpost resulting in slightly lower LAI and lower soybean yield. In 2001, soybean extracted more water from the NRRpost and NRRpre treatments because of higher potential transpiration as discussed in Section 2.3, which was enough to cause water stress in a few more days than the corn stover harvest treatments in late August and early September (Fig. 6). Very little precipitation occurred in July and August of 2001 (Fig. 6).

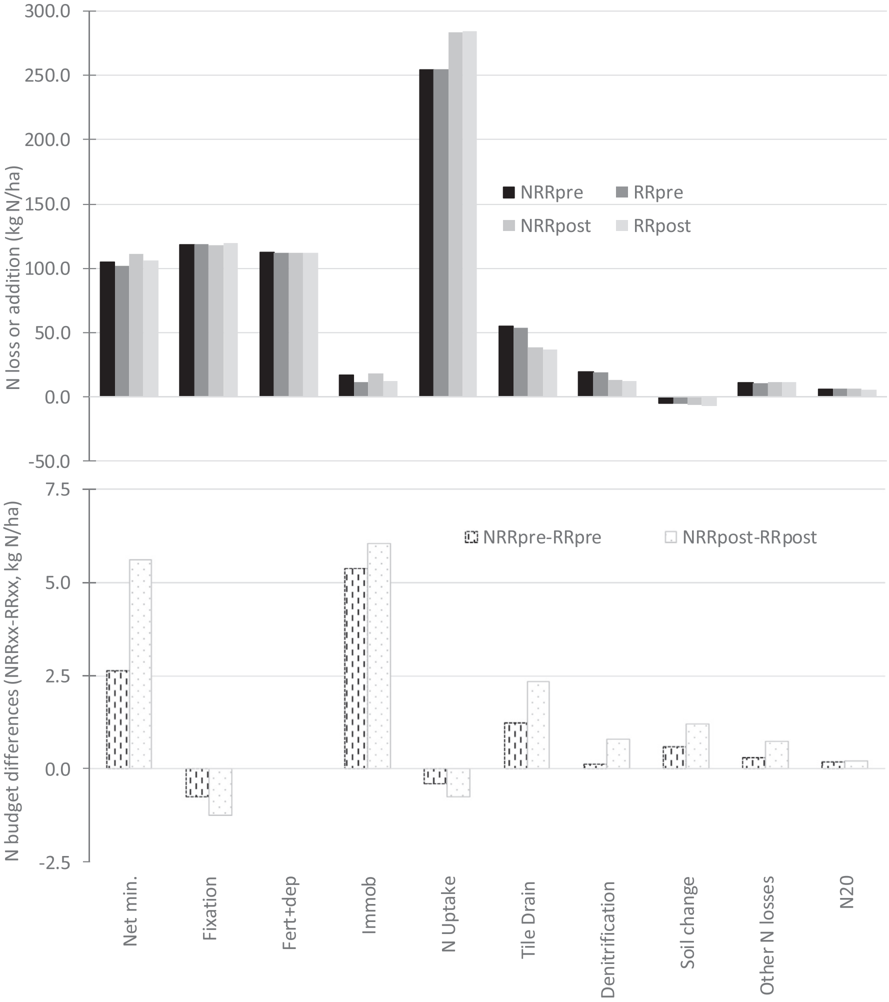

Fig. 5. Average annual mineral-N budget. "Other N losses" include runoff, deep seepage, NxO emissions from nitrification, volatilization, and adsorption into organic matter. "fert + dep" are fertilizer and deposition from rainfall. The "pre" represents pre-plant N fertilizer and "post" represents post-emergence N fertilizer and "NRR" and "RR" indicate "No Residue Removal" and 50% "Residue Removal" after grain harvest. NRRxx-RRxx indicates NRRpost-RRpost and NRRpre-RRpre. Note that the nitrate-N budget balances for all treatments. For NRRpre as an example, 122.0–17.2 (net mineralization, or mineralization − immobilization) + 100 (fertilizer) + 12.3 (deposition) + 118.4 (fixation) − 19.3 (denitrification) − 55.4 (tile drainage) − 254.6 (N uptake by crops) − 11.4 (other N losses) = −5.1 (soil change).

With the slightly higher average annual soybean yields (Fig. 3) and lower average annual net mineralization for RRpre and RRpost compared to NRRpre and NRRpost (Fig. 5), residue removal (RR) had slightly more average annual simulated biological N fixation (BNF, Figs. 5 and 4c). Although the BNF difference between treatments was small, it is important because it partly explains why N loss to drain flow differences with and without corn stover harvest were not greater. For simulation of soybean, we used the CROPGRO model implemented within RZWQM (Ma et al., 2005). The CROPGRO model allocates photosynthate to fixation of atmospheric N (to nodule capacity) if available soil N and remobilization of N from older tissue is lacking based on simulated demand (Sexton et al., 1998).

The greater simulated fixation with less soil N available to soybean with corn stover harvest appears consistent with existing literature. Gelfand and Robertson (2015) reported the percent biological N fixation (BNF) in soybean grain decreased linearly with increasing fertilization, which they also reported held true for above ground biomass and roots. In a review article (Salvagiotti et al., 2008), soybeans showed a negative exponential relationship between N fertilizer rates and BNF. The greater simulated fixation with greater soybean yield in response to our corn stover harvest simulations also reflects literature findings. Meki et al. (2013) reported that the APEX model simulates more soybean N fixation with greater soybean yield, which was supported by research reviewed by Salvagiotti et al. (2008).

Meki et al. (2013) stated "we are not aware of any published data on the impact of corn residue removals on soybean N fixation". In contrast to our simulated soybean yields where the soybean yield was slightly higher with corn stover harvest (Fig. 3), Meki et al. (2013) reported lower APEX simulated soybean yield and lower N fixation with corn stover harvest. They implied this reduction was due to reduced soil water storage and increased soil temperature. Conversely, the soil water content was greater in our RRpost scenario compared to the NRRpost simulation during July and August in 2001. This was due to soybean transpiration as discussed above (Fig. 6), and the trend of slightly greater July and August soil water storage occurred during all simulated soybean growing years.

3.1.3. Water budget

Although this current research did not compare the simulated evapotranspiration (ET) under corn stover harvest to field data, Anapalli et al. (2016) reported RZWQM simulations of ET to be "reasonably close to measured data" in the Texas High Plains. Furthermore, Farahani and Bausch (1995) reported that the Shuttleworth and Wallace ET model used by RZWQM performed satisfactorily for the entire range of canopy cover unlike the Penman-Monteith ET model. Improving on the original RZWQM, Ma et al. (2012) reported that simulated soil temperature and moisture in Iowa were improved using the Simultaneous Heat and Water (SHAW) energy balance routine implemented

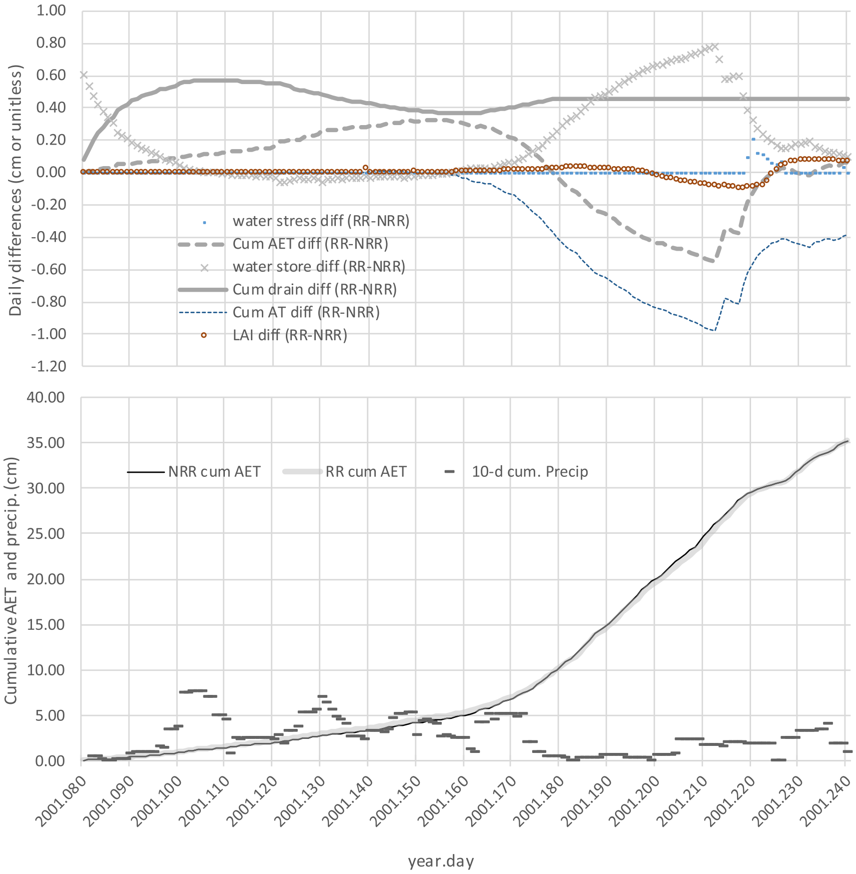

Fig. 6. Water dynamics and plant stress for 2001 beginning on March 21 or day of year 80 (NRRpost and RRpost). Day of year 240 was August 28. Definition of abbreviations and acronyms are: NRR = 0% corn stover harvest; RR = 50% corn stover harvest; post = post emergence N fertilizer applied to corn; cum = cumulative; AET = actual evapotranspiration; diff = difference; AT = actual transpiration; LAI = leaf area index; precip = precipitation. Note that water stress indices of 1 and 0 for the two treatments indicates no stress and maximum stress, thus a positive difference between RR-NRR (e.g., +0.25) indicates more water stress for NRR.

in RZWQM, and the SHAW routine implemented in RZWQM was used for this current study (Gillette et al., 2018). The SHAW model was shown to reasonably simulate the effect of crop residue type and architecture in Iowa (Flerchinger et al., 2003). Other RZWQM assessments have reported acceptable predictions of ET compared to field measurements (e.g., Cameira et al., 2014; Ma et al., 2003; Zhang et al., 2018), but Yu et al. (2006) reported ET simulations of daily values deviated from field-measured data even though the seasonal and inter-annual trends matched field data very well.

The corn stover harvest had little impact on the simulated water budget with average annual drainage for NRRpre and RRpre of 36.3 cm and cumulative ET differing <1%. This is not surprising given that corn residue was harvested only every two years, an average of 4 Mg ha^{-1} of corn residue was added to surface residue for RRpre after corn harvest, crop transpiration was much higher than soil evaporation, and the amount of surface residue was nearly the same between NRRpre and RRpre prior to each corn harvest because of two years of surface corn residue decomposition. Corn stover harvest (RRpre) did result in increased soil evaporation during the simulated soybean years (after corn harvest) from 10.2 to 11.0 cm or about 9%, which is consistent with the lower residue cover (Flerchinger et al., 2003). Flerchinger et al. (2003) reported approximately 30% less SHAW simulated average evaporation in Iowa over 30 years between the extremes of constant 10 Mg ha^{-1} corn stover and bare soil with no plant transpiration. However, evapotranspiration in the current study was dominated by transpiration with slightly more average annual transpiration with NRRpre (38.7 v 37.5 cm). Thus, the reduced evaporation from soil under the NRRpre contributed to slightly more water available for plant transpiration.

3.2. N loss

The predicted average annual N loss to drain flow for RRpre was only 1.1 kg N ha^{-1} less than the NRRpre scenario or about 2%, mostly because of less net mineralization for RRpre (Fig. 5). Similar to our results, Pederson et al. (2016) reported no significant differences in drainage N concentrations with and without corn stover removal.

Other research using model simulations have reported more substantial reduced nitrate losses with corn stover removal because of reduced net mineralization. For example, modifying the SWAT model runs of Cibin et al. (2016) with 50% corn stover harvest on low slope and tile drained land in the St Joseph River Watershed resulted in 20% less N loss to drain flow compared to no stover harvest using the same N rate for both treatments, which was mostly due to 20% less mineralization for 50% stover harvest (Table 2). Gassman et al. (2017) used the SWAT model to estimate potential impacts of bioenergy for the Boone River watershed in north central Iowa and reported simulated nitrate load reductions at the outlet of >6% with 50% stover removal on tile drained land and additional fertilizer N applied to replace N removed with stover.

Meki et al. (2011, 2013) also reported that removal of corn residue reduced the soil N pool resulting in decreased N losses. In contrast to our results, Meki et al. (2013) reported reduced N fixation with corn stover removal. Without the small increase in soybean N fixation discussed

Table 2
Average annual nitrogen budget (kg N ha^{-1}) for SWAT model simulations of the St Joseph River Watershed based on Cibin et al. (2016) (2002–2009).

N component	Baseline with 0% stover harvest	50% stover harvest
Net mineralization	109.3	87.5
N fixation	61.3	70.7
N fertilizer + deposition	96.8	96.9
Immobilization (active to stable)	−22.8	−23.8
N uptake	210.3	209.1
Tile drainage	29.1	23.2
Denitrification	5.7	4.8
Other N loss (surface runoff, lateral, leach, groundwater)	1.5	1.2

above for RR compared to NRR, the small N loss to drain flow difference would be surprising given that 19.3 kg N ha^{-1} more N was added to surface residue with NRRpre in corn years (Fig. 3). Larger contributing factors influencing RZWQM simulated N loss to drain flow include the smaller than expected reduced average annual net mineralization (Fig. 5) and less N uptake each corn year for RRpre compared to NRRpre (Fig. 4c). More net mineralization with NRRpre compared to RRpre was not simulated because of about 5 kg N ha^{-1} yr^{-1} greater average annual microbial immobilization with NRRpre (Fig. 5). "Immobilization of applied N is expected to be less with residue harvest due to reduced microbial activity for digestion of high C/N ratio organic material" (Wortmann et al., 2016). If less fertilizer N is required than currently expected for nutrient replacement under corn stover harvest, farmer profit would increase. For a corn-soybean rotation, Thompson and Tyner (2014) reported that nutrient replacement was the largest component of corn stover harvest cost compared to equipment, fuel, labor and "wrap".

The St. Joseph River Watershed SWAT model results reported in Table 2 show that 50% corn stover harvest resulted in greater net mineralization reduction compared to 0% removal relative to the RZWQM results (Fig. 5), in part because SWAT simulated nearly the same N immobilization for both treatments. Also, compared to RZWQM the SWAT simulations resulted in about twice the N removed with stover harvest (approximately 40 v 20 kg N ha^{-1}, results not shown for SWAT). In contrast to the SWAT simulations (Table 2), RZWQM simulated 5 kg N ha^{-1} less N immobilization with corn stover harvest (RRpre) compared with NRRpre (Fig. 5). The simulated immobilization differences between SWAT and RZWQM could be because SWAT does not explicitly simulate microbial pools (Neitsch et al., 2011), and contains one plant residue and two soil humus pools. Incorporated into RZWQM are microbial pools, two plant residue pools, and three soil humus pools (see Section 2).

These simulated differences between RZWQM and SWAT suggest a thorough model comparison is needed against a high quality, comprehensive field data set that includes: N loss to drainage, 0 and 50% corn stover harvest, grain and stover yield and N content, and surface soil nitrate content. Our results and the lack of published field studies reporting N loss to drainage under corn stover harvest in corn-soybean rotations suggest more research is needed in these areas (relevant field studies and associated model comparisons). Oreskes et al. (1994) argued that one of the primary values of earth science models are to illuminate which aspects of a system are in need of further study and where more empirical data are needed.

The post emergence N application without corn stover harvest (NRRpost) resulted in 16.5 less kg ha^{-1} average annual N loss to drain flow as compared to the NRRpre scenario (30%), mostly because of 29.2 kg N ha^{-1} more uptake by crops (Fig. 5). Among the largest differences in annual N loss to drain flow between NRRpre and NRRpost were 2008 and 2004 (58 and 22 kg N ha^{-1}, Fig. 4a). As discussed above, the heavy May rainfall largely contributed to leaching loss and N stress for NRRpre when fertilizer was applied in April. Higher annual N uptake by NRRpost compared to NRRpre generally resulted in less N loss to drain flow for NRRpost for the same year, and this trend was observed when corn was planted in both odd and even years (Fig. 7). In contrast, Jaynes (2015) did not report N loss differences for pre plant v post emergence N, possibly because the May precipitation during corn years for that study (2010 and 2012) was lower than normal. The May 2010 precipitation for the current study was 8 cm.

The NRRpost simulation resulted in 2.3 kg N ha^{-1} more lost to drain flow on average compared to the RRpost scenario, mostly because of more net mineralization (Fig. 5). But the standard deviation of the annual N loss to drain flow between replicates for these plots was >10 kg N ha^{-1} (Malone et al., 2017), suggesting that the simulated NRRpost-RRpost N loss to drain flow difference would be difficult to detect with field plots.

The average annual RZWQM simulated N_2O emissions ranged between 6.0 and 6.5 kg N ha^{-1} for the treatments with corn in even years (Fig. 5). The average annual N_2O emission for RRpre was only 0.2 kg N ha^{-1} less than NRRpre, or about 3%. Baker et al. (2014) reported no significant differences in cumulative N_2O emission as a function of corn stover removal, with mean yearly cumulative emissions of 1.25 kg N ha^{-1} for 100% removal and 1.19 kg N ha^{-1} for no removal. Similar to our results, field measured and DAYCENT model simulated annual N_2O emissions differences between corn stover removal and no removal were very small (Campbell et al., 2014).

Overall, the RZWQM simulated mineral-N budget differences between NRRpre and RRpre were small for tile drainage, denitrification, soil change, and N_2O emissions while the net mineralization and microbial immobilization were greater for NRRpre (Fig. 5). Supporting the N budget pattern for this site and these years, the pattern of average annual N fate differences between NRRpre and RRpre for corn planted in odd years follows the pattern of corn planted in even years (results not shown). For example the NRRpre_odd minus RRpre_odd differences for net mineralization, immobilization, and drain flow N losses were 2.3, 6.2, and 1.1 kg N ha^{-1}, respectively.

3.3. Soil organic carbon and organic nitrogen

For all treatments the total soil humus decreased <0.4% over the time period 2001–2010, or from 377.2 to 376.1 Mg C ha^{-1} for RRpre (Fig. 8). Both treatments with no corn stover harvested (NRRpre and NRRpost) had slightly lower soil humus loss, or <0.4 Mg C ha^{-1} versus >1.1 Mg C ha^{-1} for the treatments with corn stover harvest. Extending

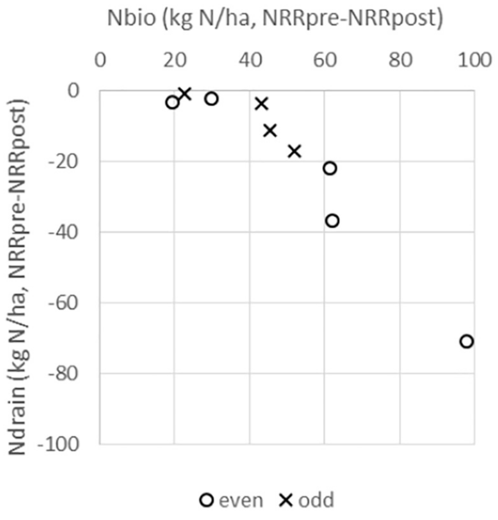

Fig. 7. Calendar year annual drain flow N differences between NRRpost and NRRpre (Ndrain) as a function of N in above ground corn biomass (Nbio) differences at harvest. The symbols "even" and "odd" represent corn in even or odd years. The "pre" represents pre-plant N fertilizer and "post" represents post-emergence N fertilizer and "NRR" and "RR" indicate "No Residue Removal" and 50% "Residue Removal" after grain harvest.

the simulations for NRRpre and RRpre through 2030 under the same weather and management repeated every 10 years still resulted in less than a 0.9% decrease in soil humus, or <4.0 Mg C ha^{-1} (results not shown). For sites with >10 years of data and fields with no-till corn under both corn stover removal and no removal, Campbell et al. (2014) reported that both DAYCENT simulated and field measured 0–20 cm soil changed <5 Mg C ha^{-1}.

The percentage of soil organic nitrogen losses over the 2001–2010 simulation period were similar to the soil humus losses, or from 35,235 to 35,103 kg N ha^{-1} for RRpre (0.4%, Fig. 8). The NRRpre scenario lost an average of 7.2 kg ha^{-1} less organic N each year than RRpre (i.e., more N assimilated into soil organic matter for NRRpre). This helps explain why the average annual nitrate N budgets were more similar than expected for NRRpre and RRpre. For example, a 1.1 kg N ha^{-1} drainage difference and 2.5 kg N ha^{-1} net mineralization difference (Fig. 5), despite nearly 20 kg N ha^{-1} more N added to surface residue in corn years for NRRpre compared to RRpre (Fig. 3).

The predicted values for total soil C and N were not compared to site specific field values by Gillette et al. (2018). However, these simulated values for total C and N were considered reasonable based on overall accurate simulations of several components of the N budget compared to nine years of field data such as: N uptake by winter rye cover crop, N loss to drainage, N_2O emissions, and corn and soybean yield as surrogates for main crop N uptake and fixation. In addition to the soil carbon changes over time appearing consistent with literature (Campbell et al., 2014) as mentioned above, the RZWQM simulated denitrification and net mineralization reported in the Gillette et al. (2018) study were discussed as consistent with literature sources or “soft data”. Recent research recommends accounting for soft data in water quality model evaluation and use (Moriasi et al., 2015; Arnold et al., 2015; Malone et al., 2015). Soft data are defined as information on individual processes within a carbon and nutrient budget such as soil carbon, N mineralization and denitrification that are not directly measured within the study area but can be estimated through the literature or expert knowledge.

3.4. Energy and greenhouse gas emissions using FEAT

The average annual energy output for the combined yield of corn and stover ranged from a low of 81.5 GJ ha^{-1} yr^{-1} (NRRpre, no stover harvest) to 136.9 GJ ha^{-1} yr^{-1} for the RRpost + N scenario (Fig. 9a), or cumulative energy output during the five corn years ranged from 815 to 1369 GJ ha^{-1} for corn years. These results follow the ranking of the corn yield values, as the conversion from dry biomass (Mg) to energy units (GJ) was nearly identical for corn grain and stover. Cumulative energy output during the five soybean years ranged from 399 to 407 GJ ha^{-1}.

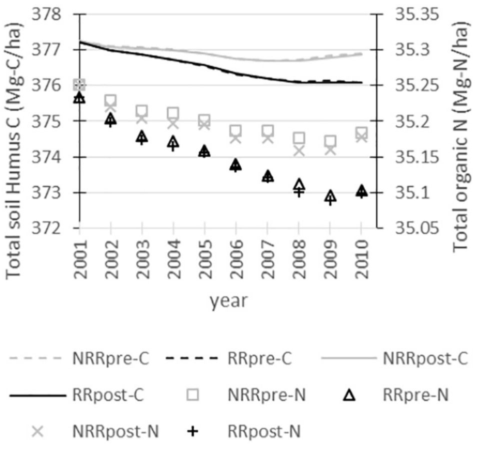

Fig. 8. Average annual total soil humus C and organic N. Organic N includes microbial, crop residue incorporated into soil, and humus pools, but not crop residue on soil surface. The “pre” represents pre-plant N fertilizer and “post” represents post-emergence N fertilizer and “NRR” and “RR” indicate “No Residue Removal” and 50% “Residue Removal” after grain harvest.

Net energy ratios including soybean years ranged from 10.4 (NRRpre) to 14.1 (RRpost), and increased from NRRpre to RRpre to RRpost. This is largely due to the energy output, which is based on yields and is the numerator of the ratio. However, within the RR scenarios the net energy ratio was higher for the 200 kg N ha^{-1} treatment versus the “+N” treatments, as the embedded energy in the fertilizer production (in the denominator of the ratio) was larger in the “+N” scenarios. This suggests that slightly lower yields without additional fertilizer use in this system are beneficial from an energy efficiency as well as a water quality perspective. The average annual N loss to drainage in RRpost + N was 7.9 kg ha^{-1} more than RRpost or +21% (results not shown). The RRpost scenario had the highest net energy ratio indicating that harvesting corn stover increased energy efficiency to the farm gate, and that applying fertilizer application post-emergence compared to pre-plant was better for both energy efficiency and crop production.

The greenhouse gas impacts follow a similar pattern. Fig. 9a reports the greenhouse gas intensity for the treatments, which is on a CO_2 equivalent basis and normalized to energy output (g CO_2-eq. MJ^{-1}). Greenhouse gas intensity was lower for the RR scenarios compared to the NRR scenarios, and lowest for RRpost, ranging from 11.7 g CO_2-eq. MJ^{-1} (RRpost) to 17.3 g CO_2-eq. MJ^{-1} (NRRpre) for the simulation period. Greenhouse gas intensity for RRpre and RRpost were both 23% lower than NRRpre and NRRpost. Although the RRpre + N and RRpost + N scenarios had higher greenhouse gas intensities than RRpre and RRpost with 200 kg ha^{-1} N, intensities were still lower than NRRpre and NRRpost scenarios by 20% and 17% respectively. This indicates a potential benefit of harvesting corn stover even under the assumption of higher fertilizer application rates.

The major components of the greenhouse gas emissions are illustrated in Fig. 9b. On a CO_2 equivalent (CO_2-eq) basis, emissions were dominated by soil nitrous oxide emissions and the embedded emissions in nitrogen fertilizer production, followed by on-farm fuel use, and phosphorus and potassium fertilizers. Emissions including herbicides, insecticides, seeding, and liming were negligible in comparison and nearly the same among scenarios, and therefore were grouped into an ‘other’ category in this analysis. Nitrous oxide emissions were on average >3 times higher than the embedded emissions associated with industrial production of nitrogen fertilizer. Together, the global warming potential associated with N, including both the nitrous oxide emission from soil and from the embedded CO_2eq emissions associated with the production of nitrogen fertilizer, accounted for about 80% of the total emissions. As nitrogen fertilizer rates increased beyond 200 kg N ha^{-1}, the risk of losing nitrogen as N_2O increased, and the consequence of this appears to outweigh the small yield benefit with respect to both greenhouse gas intensity and energy efficiency.

Cherubini and Ulgiati (2010) performed a Life-Cycle Assessment (LCA) for corn stover as a bioenergy feedstock and reported it had a net energy ratio of approximately 5 and reduced GHG emissions compared to fossil fuel energy systems, but that eutrophication potential increased with corn stover systems because of more N fertilizer required to maintain corn yield. In contrast, our results suggest additional N fertilizer with corn stover harvest was not required and the N loss to leaching was slightly reduced while the farm-gate net energy ratio was strongly positive.

4. Summary and conclusions

Corn stover harvest and N fertilizer use are projected to increase over the next few decades. It is vital to improve insights of this likely trend, especially considering that understanding and managing the nitrogen cycle is one of the most critical environmental challenges of the 21st century. While it is known that corn stover harvest removes nutrients such as nitrogen from fields, the effects on N loss to subsurface drain flow and the atmosphere are uncertain. Most published modeling

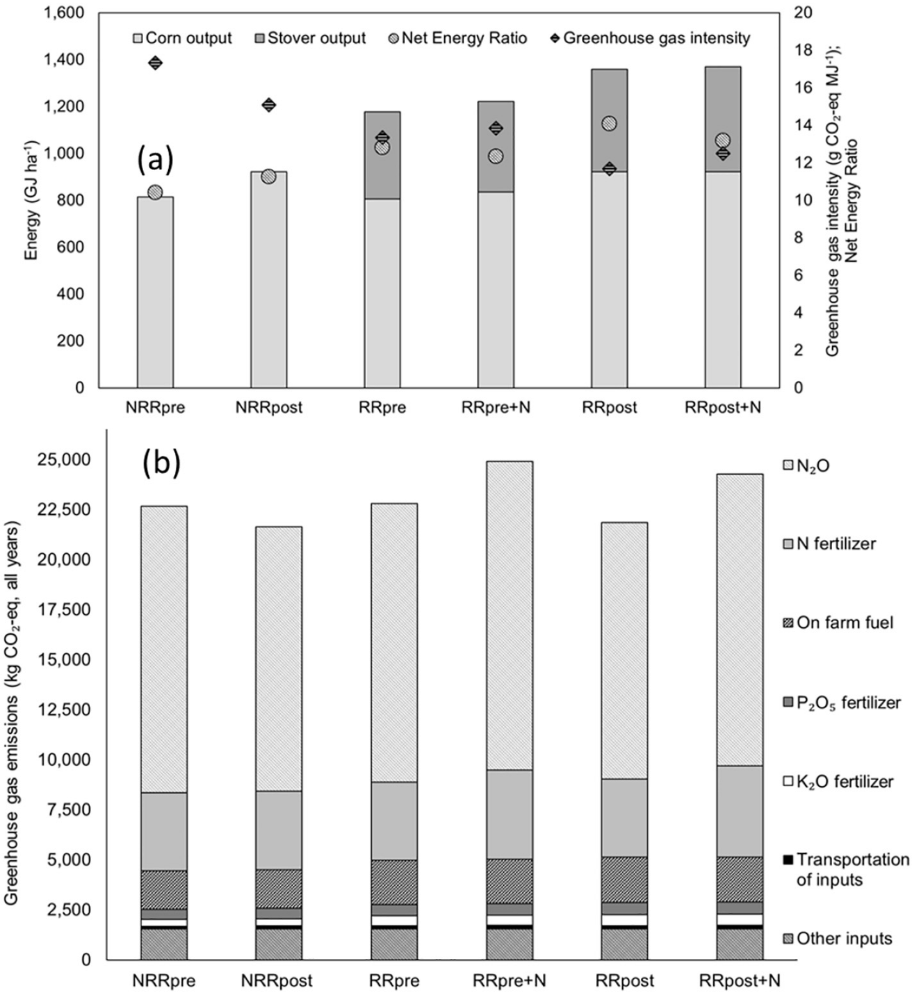

Fig. 9. Total energy and greenhouse gas emission over the ten year study estimated using the FEAT model. a) Output energy for corn and stover, net energy ratio (output/input), and greenhouse gas intensity (GHG emissions divided by energy output, see Camargo et al., 2013). b) Cumulative greenhouse gas emissions from fuel and soil N2O as well as the embedded emissions associated with purchased inputs through the ten year study. The "pre" represents pre-plant N fertilizer, "post" represents post-emergence N fertilizer, "NRR" and "RR" indicate "No Residue Removal" and 50% "Residue Removal" after grain harvest, and "+N" indicates additional N fertilizer added to supplement N removed with harvested corn stover.

studies have assumed supplemental N is required to replace the N removed and simulated N loss to leaching and drain flow has generally been reduced under corn stover harvest. Field results, however, suggest corn yields can increase with corn stover harvest partly because of less microbial immobilization of N. If supplemental N is not required for systems that include corn stover harvest, producer profit, N loss to drainage, energy efficiency and greenhouse gas output may be improved compared to current expectations. In contrast to most previous modeling studies, our results suggest simulated corn yield and N loss to drain flow were nearly the same for NRR and RR under an N rate of 200 kg ha^{-1} for a corn-soybean rotation in central Iowa over a 10 year period. Our results also suggest that applying N fertilizer 30 days post corn emergence compared to pre-emergence N application reduced N loss to drainage much more substantially than harvesting 50% of corn stover.

Future research should consider 1) conducting field studies to investigate N loss to subsurface drainage with and without corn stover harvest; 2) using high quality field data to test RZWQM and other relevant agricultural system models for N loss to subsurface drainage with and without stover harvest; 3) comparing the SWAT and RZWQM models using the same field site and measurement data that includes corn stover harvest and N loss to subsurface drainage.; 4) modifying the SWAT nutrient cycling algorithms to improve the immobilization and other processes relevant to representing systems that include corn stover removal; 5) modifying the corn stover harvest routine in RZWQM to remove greater portions of the upper stalk rather than equal portions of above ground biomass; and 6) using the modified version of RZWQM from Fang et al. (2017) that may more accurately simulate N in corn grain and stover.

Some notable specific results that support these conclusions: 1) the simulated corn yield and stover harvest appear consistent with Story County Iowa USDA-NASS records, on-site field observations, and related published studies; 2) simulated corn yield was greater when N fertilizer was applied 30 days post corn emergence compared to pre-plant N application, which seemed to follow on-site observations with post emergence N application compared to Story County Iowa NASS records and related published studies; 3) the simulated corn yields were nearly the same for NRR and RR for the same N rate and timing of N fertilizer application, which seems to follow related field studies but is in contrast to some previous related modeling studies; 4) simulated N removed in stover for RRpre appeared low compared to related central Iowa field data; 5) the simulated soybean yields were slightly greater for corn stover harvest (RR), which contributed to slightly more N fixation compared to NRR and thus contributed to a small amount of additional nitrate N to soil for RR; 6) despite 19.3 kg ha^{-1} less N added to surface residue after corn harvest for RRpre only 1.1 kg ha^{-1} less N per year was lost to drain flow for RRpre compared to NRRpre, which is in contrast to related SWAT model studies where the N loss to drain flow was reported to be reduced more substantially for RR; 7) greater N loss to drain flow was not simulated for NRR compared to RR by

RZWQM mostly because of more simulated microbial immobilization of N and more assimilation of N into soil organic matter for NRR, which was supported by published field studies; 8) compared to NRRpre, adding fertilizer 30 days after corn emergence (NRRpost) reduced average annual drain flow N loss more substantially than corn stover harvest (38.9 v 55.4 kg N ha^{-1}), mostly because of increased N uptake; 9) the pattern of N fate differences between NRRpre and RRpre for corn planted in odd years followed the pattern of corn in even years; 10) for all treatments the soil humus carbon decreased <0.4% over the time period 2001–2010 and extending the simulations through 2030 under the same weather and management repeated every 10 years resulted in less than a 0.9% decrease in soil humus, which was comparable to previous studies; 11) The percentage of soil organic nitrogen losses over the 2001–2010 simulation period were similar to the soil organic C losses and more N assimilated into soil organic matter for NRRpre, which helps explain why the average annual nitrate N budgets were more similar than expected for NRRpre and RRpre; 12) the net energy ratio and greenhouse gas intensity were optimized with RRpost, without additional supplemental N to replace N removed with corn stover harvest, as the small corn yield benefit with additional N fertilizer did not compensate for increased energy inputs and greenhouse gas emissions.

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