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No-tillage farming enhances widespread nitrate leaching in the US Midwest

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Abstract

Conservation tillage has been promoted as an effective practice to preserve soil health and enhance agroecosystem services. Changes in tillage intensity have a profound impact on soil nitrogen cycling, yet their influence on nitrate losses at large spatiotemporal scales remains uncertain. This study examined the effects of tillage intensity on soil nitrate losses in the US Midwest from 1979–2018 using field data synthesis and process-based agroecosystem modeling approaches. Our results revealed that no-tillage (NT) or reduced tillage intensity (RTI) decreased nitrate runoff but increased nitrate leaching compared to conventional tillage. These trade-offs were largely caused by altered water fluxes, which elevated total nitrate losses. The structural equation model suggested that precipitation had more pronounced effects on nitrate leaching and runoff than soil properties (i.e. texture, pH, and bulk density). Reduction in nitrate runoff under NT or RTI was negatively correlated with precipitation, and the increased nitrate leaching was positively associated with soil bulk density. We further explored the combined effects of NT or RTI and winter cover crops and found that incorporating winter cover crops into NT systems effectively reduced nitrate runoff but did not significantly affect nitrate leaching. Our findings underscore the precautions of implementing NT or RTI to promote sustainable agriculture under changing climate conditions. This study provides valuable insights into the complex relationship between tillage intensity and nitrate loss pathways, contributing to informed decision-making in climate-smart agriculture.

1. Introduction

Reducing nitrogen (N) losses from agricultural systems to the surrounding environment is a longstanding challenge for sustainable agriculture (Robertson and Vitousek 2009, Houlton *et al* 2019). This is especially true in intensive agriculture regions, such as the US Midwest, where N fertilizer application is crucial for optimizing cereal crop yields. Farmers use a variety of strategies to improve N use efficiency, including a maximum return to N approach to identify the most profitable N rate (Sawyer *et al* 2006). Although these strategies are useful, N fertilizer losses still occur, including nitrate leaching into groundwater bodies and emissions of nitrous oxide into the atmosphere (Tian *et al* 2020, Yao *et al* 2020). As the predominant field crop, corn (*Zea mays*, L.) receives a substantial amount of N fertilizer (100–200 kg N ha^{-1} yr^{-1}) in the US Midwest, and even under optimal application rates, a considerable percentage (15%–65%) of the applied N is leached (Hussain *et al* 2019). Nitrate leaching through subsurface flow is one of the major N loss pathways that can reach 44% of total N losses from the US Midwest cropland (USDA 2017). Although some loss of N is inevitable in agricultural settings (Cameron *et al* 2013), excessive nitrate leaching can lead to groundwater contamination, aquatic eutrophication, and indirect nitrous oxide emissions, posting significant threads to the environments, human health, and climate stabilization (Galloway *et al* 2008).

Generally, nitrate leaching from agricultural soils is determined by the nitrate concentration in soil solution and the drainage volume through the soil over a given period (Cameron *et al* 2013). However, it is a complex process that involves many factors, including N fertilization management, cropping systems, tillage, soil, and climate conditions (Dinnes *et al* 2002, Cameron *et al* 2013). In recent decades, various nitrate abatement strategies have been implemented to combat excessive nitrate leaching, such as buffers (Dinnes *et al* 2002), cover crops (Nouri *et al* 2022), optimized fertilizer application (Eagle *et al* 2017), crop residue management (Mouratiadou *et al* 2020), and conservation tillage (Hess *et al* 2020). However, despite a well-recognized positive relationship between N fertilizer input and nitrate leaching loss (Wang *et al* 2019), management-related patterns are still inconsistent in the literature due to the complex interactions of biotic and abiotic factors determining nitrate leaching (Dinnes *et al* 2002, Galloway *et al* 2008, Cameron *et al* 2013).

No-tillage (NT) or reduced tillage intensity (RTI), which involves less soil disturbance compared to conventional tillage (CT), is expected to retard soil N mineralization and reduce the potential of nitrate leaching (Galloway *et al* 2008). While some studies have reported a reduction of nitrate leaching under NT/RTI (Randall and Iragavarapu 1995, Spiess *et al* 2020), other studies have documented no effect (Al-Kaisi and Licht 2004, Trolove *et al* 2019), or even an increase in nitrate leaching (Meisinger *et al* 2015, Hess *et al* 2020). This ambiguity might be related to soil hydrological properties affected by different tillage operations. NT/RTI often leads to better water infiltration and soil water content and, therefore, higher seepage volumes (Randall and Iragavarapu 1995, Li *et al* 2019). The reduced drainage nitrate concentration benefits can be offset by greater volumetric water flow (Christianson and Harmel 2015). Some studies suggested greater nitrate leaching losses under NT, largely caused by changes in water fluxes (Daryanto *et al* 2017, Li *et al* 2023). Additionally, site-specific factors, including management (e.g. crop type, tillage duration) and environmental (e.g. precipitation, soil texture) factors, have substantial impacts on the responses of nitrate leaching to tillage practices (Young *et al* 2021). Considering the continuous improvement of SOM accrual under NT/RTI and resulting changes in soil structural quality and stability, along with variations in annual rainfall, it is challenging to determine a consistently changing trend of nitrate leaching when comparing various tillage practices (Syswerda *et al* 2012, Nouri *et al* 2020).

In the US Midwest, reducing tillage intensity has been widely promoted and implemented in recent decades (Claassen *et al* 2018). Changes in tillage regimes across the Midwest can profoundly affect nitrate loss pathways. However, the corresponding changes in nitrate loss pathways have not been well addressed, especially at the regional scale. Due to the complexity of soil-water-plant interactions, the direct up-scaling of field results can be misleading. Moreover, it is challenging to quantify and link the reduction in nitrate leaching losses with specific practices at a regional scale with confounding soil and climate conditions. In this context, agroecosystem modeling provides a cost-effective and reliable approach to explore 'if-then' scenarios for designing and assessing sustainable management practices.

Here, we applied a process-based agroecosystem model (DLEM-Ag) to assess the effects of various tillage intensities on nitrate losses via surface runoff and subsurface leaching in the US Midwest. Three levels of tillage intensity were considered in this study, i.e. NT, RTI, and CT with a mixing efficiency of 0.1, 0.5, and 1, respectively. It should be noted that RTI includes a broad range of mixing efficiencies. The reduced tillage intensity level selected here represents a medium-level tillage disturbance on average. We hypothesized that (1) NT and RTI would decrease surface runoff nitrate loss but increase subsurface nitrate leaching, (2) NT and RTI could either increase or decrease the total nitrate losses depending on changes in surface runoff nitrate loss and subsurface nitrate leaching, and (3) incorporating other conservation practices, e.g. cover crop, into the management portfolio is essential to alleviate nitrate losses. This study offers a broad-scale understanding of soil nitrate leaching and runoff losses under various tillage intensities, providing science-based insights essential for developing sustainable agriculture in the US.

2. Methods

2.1. Modeling approach

We adopted a process-based agroecosystem model, the agricultural module of the Dynamic Land Ecosystem Model (DLEM-Ag) (Ren *et al* 2012, Huang *et al* 2021), to assess the effects of tillage on nitrate leaching and runoff losses from the US Midwest corn-soybean croplands (see supplementary, sections 1.1 and 1.2, for more details). The DLEM-Ag can simulate the daily crop growth and exchanges of trace gases (CO_2, CH_4, and N_2O) between agroecosystems and the atmosphere and quantify fluxes and storage of carbon, water, and nitrogen as affected by multiple factors such as climate, atmospheric CO_2, N deposition, tropospheric ozone, land use and land cover change, and agriculture management practices (e.g. fertilizer use, harvest, irrigation, and tillage) (Tian *et al* 2010, Ren *et al* 2011, 2012, 2016). This model has been extensively used to study crop production, SOC, N dynamics, and exchanges of trace gases between the agroecosystems and the atmosphere (Tian *et al* 2010, Ren *et al* 2011, 2012, 2016). We have validated the DLEM-Ag's performance in simulating crop yield, gross and net primary productivity, evapotranspiration, SOC content, CO_2 fluxes and tillage impacts on them in the US Midwest in our previous works (Huang *et al* 2020, 2021, 2022). This study implemented additional model validation by comparing model estimates with measured nitrate leaching and subsurface drainage volume at three sites, under continuous corn and corn-soybean rotations, in the US Midwest region (see supplementary, section 1.3, for more details. Table S1 and figures S1 and S2).

We set up a series of simulation experiments by implementing different scenarios of tillage practices across the study region during 1979–2018 to evaluate the impacts of tillage practices on nitrate leaching and runoff losses (see supplementary, section 1.5, for more details). The baseline scenario was driven by historical tillage information and other input data across the US Midwest. Three alternative tillage scenario simulations were designed assuming a specific tillage practice (i.e. CT, NT, and RTI) was applied to croplands across the basin over the study period. The model input data includes daily climate conditions (maximum, minimum, and mean air temperature, precipitation, shortwave solar radiation, and relative humidity), annual atmospheric CO_2 concentration and N deposition, cropland distribution, and major agricultural management practices (such as crop-specific N fertilizer use, irrigation, and tillage practices) at a resolution of 4 × 4 km. More details regarding input data can be found in supplementary information, section 1.4.

We designed site-level simulation experiments to test the combined effects of a winter cover crop (i.e. cereal rye) and tillage applications on nitrate leaching and runoff losses, including three tillage scenarios with and without a cover crop. Relevant results are present in figures 4, S7 and S8.

2.2. Statistical analysis

We used a piecewise structural equation model (SEM) to infer the relative importance of precipitation and soil properties (i.e. bulk density, pH, and texture) on nitrate leaching and runoff. Compared with the traditional variance covariance-based SEM, the piecewise SEM could (1) piece multiple separate linear models together to a single causal network, (2) use Shipley's test of directed separation to test whether any paths are missing from the model and (3) use Fisher's C as the goodness-of-fit statistic. Analogous to traditional SEM, a nonsignificant P value ($P > 0.05$) indicates a well-fit model. We selected five models for the piecewise SEM, with each model representing different tillage scenarios (i.e. CT, RTI, and NT) and the differences between NT and CT, and between RTI and CT. We fitted the component models of the piecewise SEM as linear models. Considering that precipitation and soil pH are highly correlated, and there is also a high correlation among each soil text content (figure S5), we selected precipitation, soil clay content, and bulk density as model predictors using Shipley's test of directed separation. We reported the standardized coefficient for each path from each component model. The overall fit of the piecewise SEM was evaluated using Fisher's C statistic and the χ^2 value. Piecewise SEMs were conducted using the piecewise SEM package (version 2.3.0) (Lefcheck and Freckleton 2016) in R.

3. Results

3.1. Average nitrate leaching and runoff across the US Midwest

Simulated baseline nitrate losses through surface runoff and subsurface leaching during 1979–2018 using the DLEM-Ag are illustrated in figure 1. Tillage management across the Midwest in the baseline simulation was configured as the proportion of three tillage types (i.e. CT, NT and RTI) at the grid level over the study period (see supplementary, section 1.4, for more details). The spatial patterns of surface and subsurface water flow corresponded well to the spatial precipitation pattern—greater surface and subsurface flow occurred in higher precipitation regions (figure S3). In the US Midwest region, the subsurface and surface flow prevailed in the east and west of the 750 mm isopleth line, respectively. The estimated regional average flow of surface and subsurface was 126 mm and 169 mm, respectively, in line with the estimates of 110–151 mm for runoff and 98–297 mm for baseflow as reported from surveys and model predictions for the region (Srinivasan *et al* 2010, Panagopoulos *et al* 2015, USDA Natural Resources Conservation Service (NRCS) 2017). The estimated regional average nitrate losses through leaching and runoff were 1.93 g N m^{-2} and 1.45 g N m^{-2}, respectively, which falls in the range of 0.58–5.84 g N m^{-2} for leaching losses (Kim *et al* 2021) and 0.87–2.27 g N m^{-2} for runoff losses reported by previous studies (Panagopoulos *et al* 2015, USDA 2017).

3.2. Impacts of tillage on water and nitrate fluxes

Three alternative tillage scenarios were compared with the baseline simulation to quantify the changes in water and nitrate fluxes. In the CT and RTI scenarios, the regional-averaged annual subsurface drainage was lower (with a median rate of −26 mm yr^{-1} and −2 mm yr^{-1}, respectively), and the regional-averaged annual surface runoff was higher (with a median rate of 6 mm yr^{-1} and 2 mm yr^{-1}, respectively) compared to the baseline. However, for the NT scenario, more regional-averaged annual subsurface drainage (25 mm yr^{-1}) and less regional-averaged annual surface runoff (−13 mm yr^{-1}) occurred

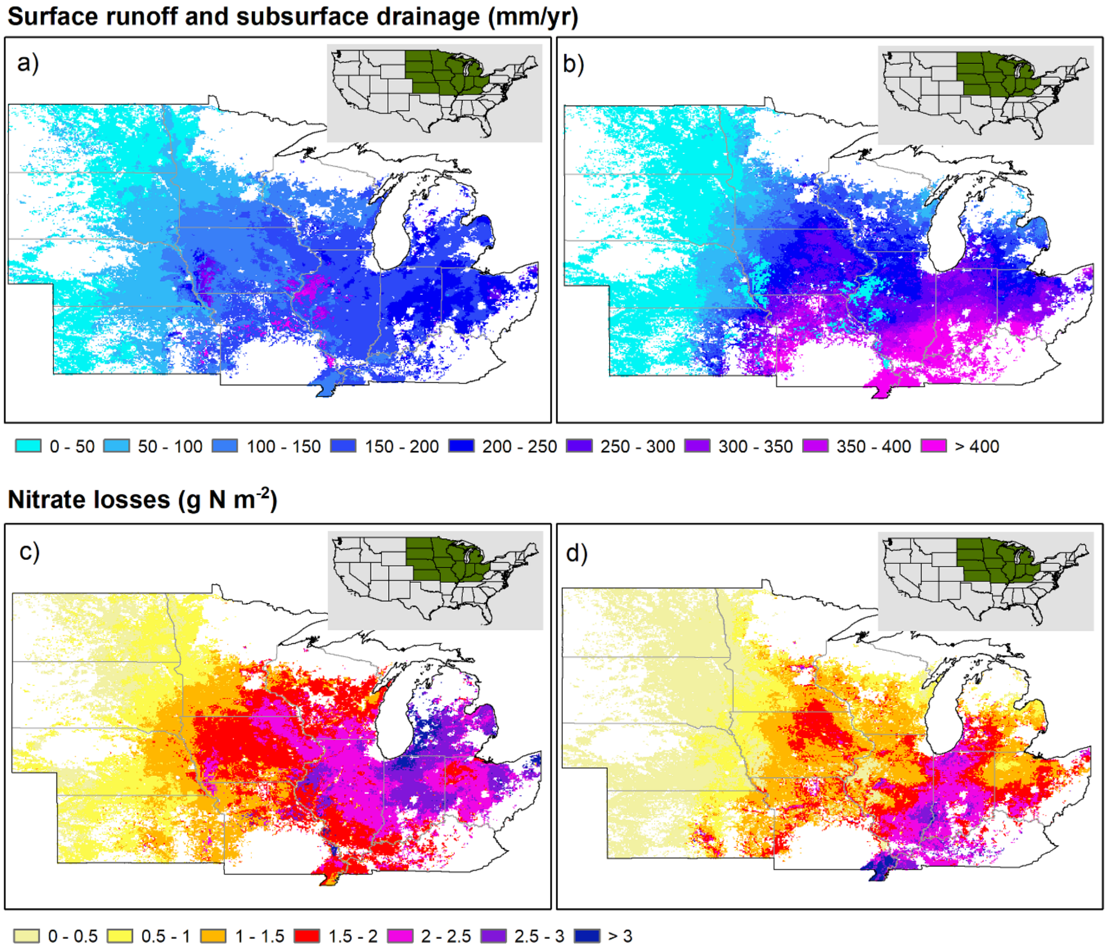

Figure 1. Baseline estimation of surface runoff (a), subsurface drainage (b), and nitrate losses through surface runoff (c) and subsurface drainage (d) in the US Midwest during 1979–2018.

compared to the baseline (figure 2(a)). The corresponding changes in nitrate losses through runoff and drainage showed a similar pattern to the changes in water fluxes under each alternative tillage scenario (figure 2(b)). The change in regional-averaged annual nitrate leaching was -0.21 g N m^{-2}, 0.08 g N m^{-2}, 0.43 g N m^{-2} under the CT, RTI, and NT scenarios, respectively. The change in regional-averaged annual nitrate runoff loss was 0.05 g N m^{-2}, -0.01 g N m^{-2}, -0.16 g N m^{-2}, respectively. We found the NT scenario led to the largest increase in the total nitrate losses, primarily due to the exacerbation of nitrate leaching loss. Compared to the CT scenario, the NT scenario increased subsurface drainage and nitrate leaching by 36.5% and 32.9%, respectively, and decreased surface runoff and nitrate runoff loss by 14.7% and 15.1%, respectively, on average in the Midwest.

3.3. Major effects of precipitation on nitrate losses

Annual precipitation was highly correlated with annual nitrate leaching under all three tillage scenarios in major cropland areas of the Midwest (figure S4). Precipitation also showed strong positive correlations with nitrate leaching and runoff at the regional scale (figure S5). The SEM demonstrated that precipitation was the most significant factor influencing nitrate leaching ($\beta = 0.81 \sim 0.88$, standardized coefficient) and runoff ($\beta = 0.73 \sim 0.92$, figures 3(a)–(c)) regardless of tillage scenarios. Precipitation also negatively impacted NT- and RTI-induced changes in nitrate runoff, with the β values of -0.62 and -0.48, respectively (figures 3(d) and (e)). There was a weaker relationship between precipitation and NT- and RTI-induced changes in nitrate leaching. In contrast, soil clay content negatively correlated with nitrate losses in all three tillage scenarios, with a stronger effect on nitrate runoff ($\beta = -0.37 \sim -0.33$) than that on nitrate leaching ($\beta = -0.23 \sim -0.19$). As for the differences between NT/RTI and CT, clay content showed positive and negative effects on nitrate runoff ($\beta = 0.34 \sim 0.36$) and nitrate leaching ($\beta = -0.31 \sim -0.18$), respectively (figures 3(d) and (e)). Soil bulk density presented a weaker positive correlation with nitrate leaching and runoff; however, bulk density positively affected the differences in nitrate leaching between NT/RTI and CT ($\beta = 0.48 \sim 0.49$) and negatively affected the differences in nitrate runoff between NT/RTI and CT ($\beta = -0.28 \sim -0.21$).

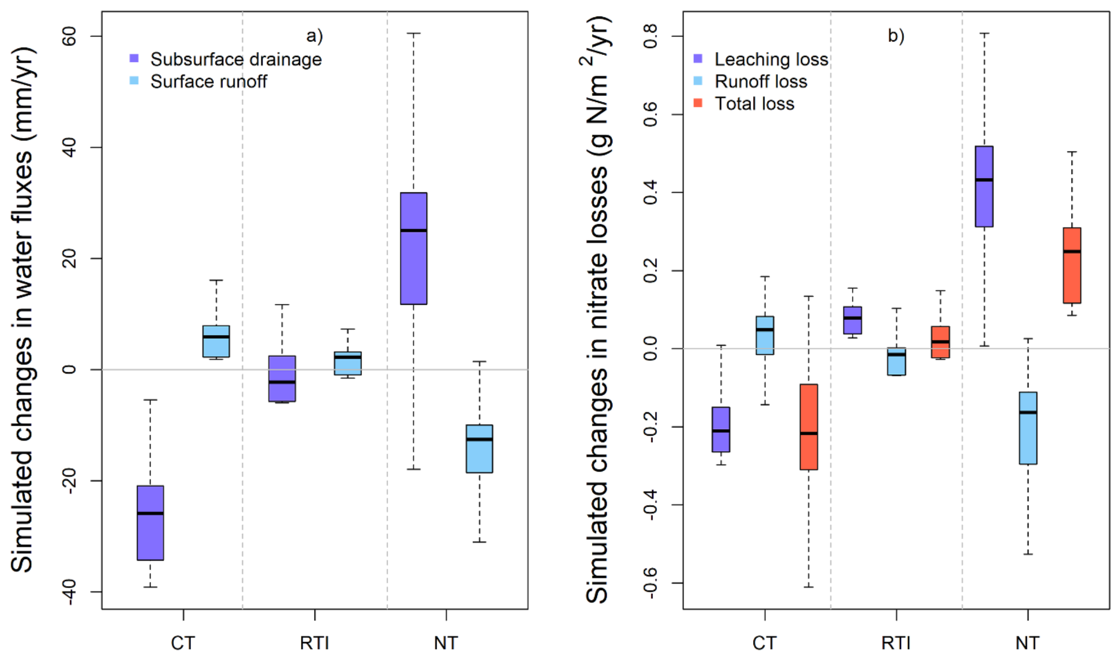

Figure 2. Regional average changes in annual water fluxes (a) and nitrate loss (b) between each tillage scenario (CT, RTI, and NT) and the baseline during the study period. The black mid-lines of boxes represent the median responses during the period, the hinges of boxes indicate the first and third quartiles, and the whiskers extend both to the minimum and maximum values within 1.5 times the interquartile range of the distribution.

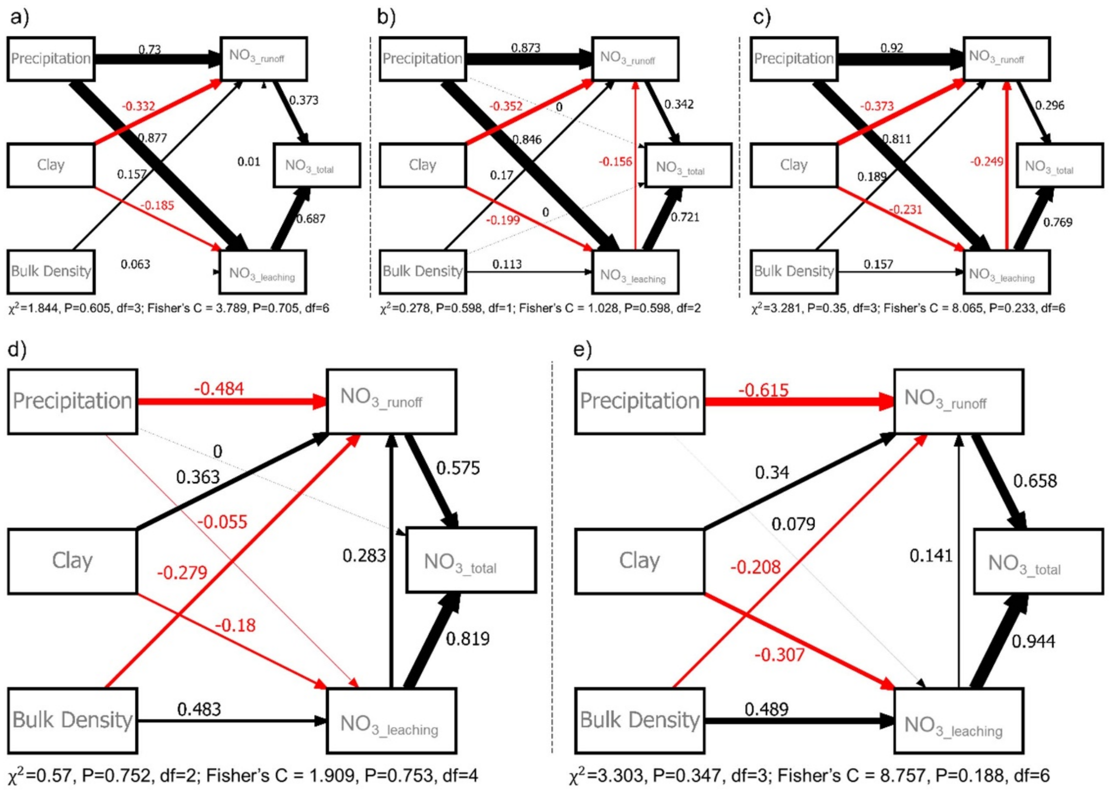

Figure 3. Piecewise structural equation models (SEM) of precipitation and soil (i.e. clay content and bulk density) as predictors of nitrate leaching ($NO_{3\_leaching}$), runoff (NO_{3_runoff}) and total losses (NO_{3_total}). Standardized path estimates are provided next to each path with line thickness scaled based on the magnitude of the estimate. Black and red arrows indicate positive and negative relationships ($P < 0.05$), respectively. (a) CT, (b) RTI, (c) NT, (d) RTI vs. CT (the differences between RTI and NT scenarios), and (e) NT vs. CT.

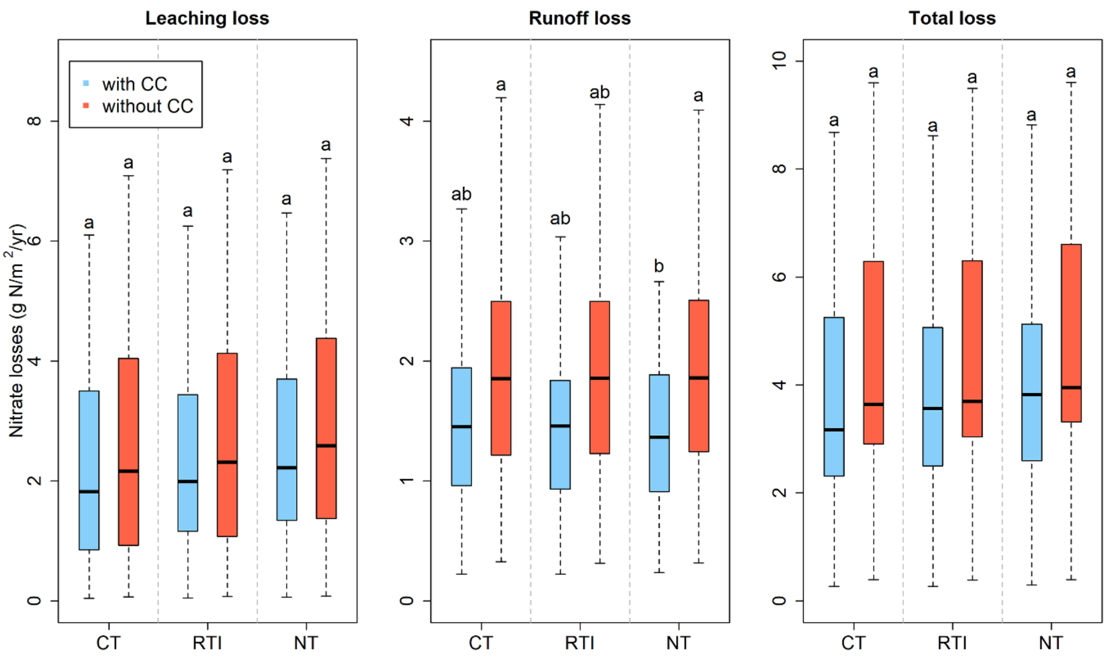

Figure 4. Annual nitrate losses through drainage and runoff, as well as the total losses under different simulation scenarios at the site level during 1979–2018 (CC: cover crop; NT: no-tillage; RTI: reduced tillage intensity; CT: conventional tillage). The black mid-lines of boxes represent the median responses during the period, the hinges of boxes indicate the first and third quartiles, and the whiskers extend both to the minimum and maximum values within 1.5 times the interquartile range of the distribution. Different letters indicate that differences in the means between treatments were significant (ANOVA test, $P < 0.05$).

3.4. Reduction in nitrate losses caused by cover crop

We conducted scenario simulations at an Iowa site (table S1) as an example to explore the combined effects of cover crop (i.e. cereal rye) and tillage (i.e. CT, RTI, and NT) on nitrate losses. The results showed that adding cover crops into the cropping system significantly reduced nitrate runoff in the NT scenario, with annual nitrate runoff changing from 1.95 g N m^{-2}to 1.43 g N m^{-2} (figure 4). Nitrate leaching and total nitrate losses were not significantly affected by cover crops, although a decreasing trend caused by cover crops was observed in all tillage scenarios (figures 4 and S7).

4. Discussion

Previous meta-analysis studies showed that NT results in greater nitrate leaching (11.1%, 95% CI [1.3%, 21.9%]) but less nitrate runoff (43.9%, 95% CI [25.6%, 57.7%]) than the tilled cropping systems (figure 5). Our simulated results in the US Midwest aligned with these findings that NT increased nitrate leaching and reduced nitrate runoff (figure 2(b)). Overall, the NT scenario led to a ~32.5% increase in nitrate leaching and a ~15.2% decrease in nitrate runoff compared to the CT scenario in the Midwest during the simulation period. The meta-analyses that were based on globally collected observational data do not accurately represent the diverse soil and climate conditions across the Midwest. Nitrate leaching accounts for the largest N loss pathways in the Midwest (USDA 2017), and an increase in drainage can result in more nitrate leaching. Our SEM also demonstrated that nitrate leaching contributed more to the total nitrate losses compared to nitrate runoff in the Midwest. In addition, meta-analysis studies have revealed that nitrate concentration in leachate and runoff water tended to be lower and higher, respectively, under NT than under CT systems (figure 5). These results suggested that NT increased drainage volume, reduced runoff volume, and changes in soil water fluxes play a key role in determining nitrate leaching and runoff (Cameron *et al* 2013).

Water is the carrier and driving force for nitrate leaching and runoff (Wang and Li 2019). The precipitation amount is closely related to and explains the largest variations in nitrate leaching in rainfed agricultural areas (Tamagno *et al* 2022). Our simulations showed that annual precipitation was positively associated with both nitrate runoff and leaching regardless of the tillage regime in the study region (figures 3 and S4). However, changes in tillage intensity can alter the partition of water fluxes among different pathways, and therefore affect nitrate runoff and leaching (Daryanto *et al* 2017, Huang *et al* 2021). The reduction in runoff under NT/RTI can be attributed to surface crop residue retention, which protects soil from raindrop impacts on surface sealing (Kumar *et al* 2012) and acts as a physical barrier preventing horizontal water movement (Sun *et al* 2015). Crop residue coverage can intercept a certain amount of water, which lowers evaporation and allows more infiltration (Baumhardt and Lascano 2022, Kozak

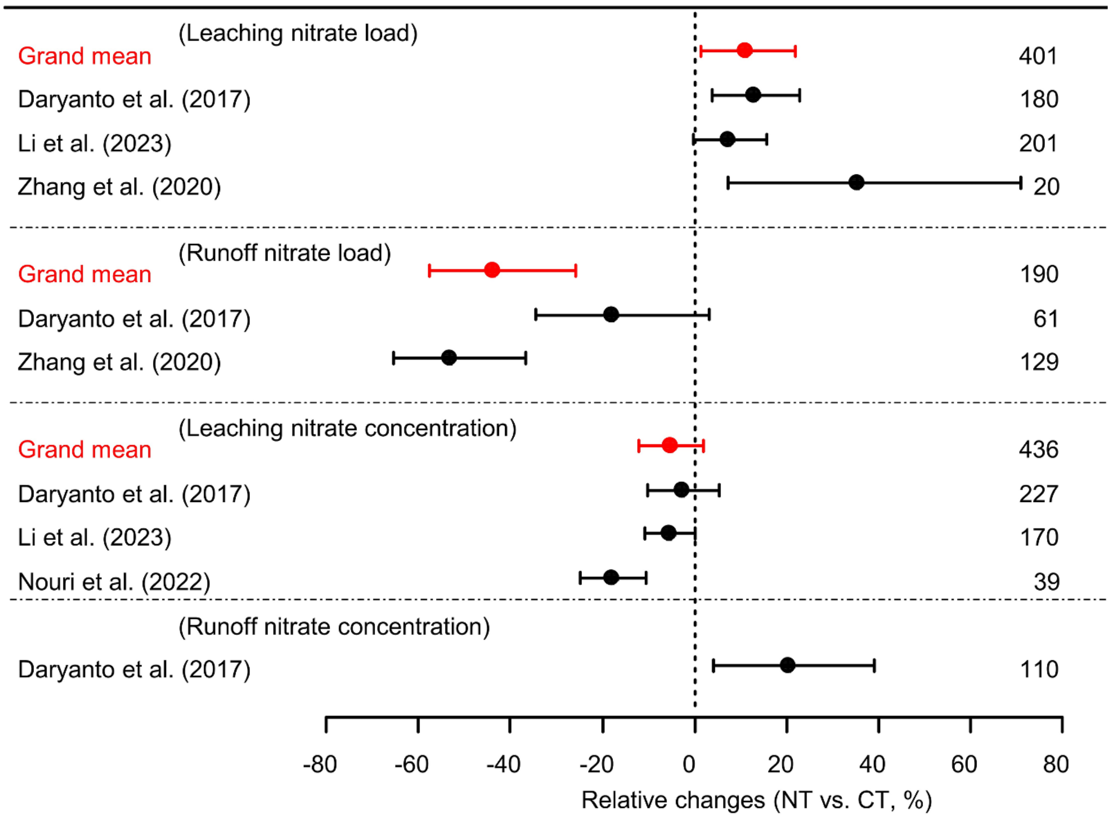

Figure 5. The effects of no-tillage (NT), as compared with conventional tillage (CT), on nitrate runoff and leaching through a second-order meta-analysis (see supplementary, section 4, for more details). The numbers on the right side are the total number of experiments used.

et al 2007). With less soil disturbance, NT/RTI can increase macro-aggregation (Grandy and Robertson 2007). Macropores may develop from decaying roots and soil fauna (Blanco-Canqui and Ruis 2018) and facilitate soil preferential flow and infiltration. The higher drainage volumes under NT/RTI vs. CT had been broadly realized in the Midwest region (Randall and Iragavarapu 1995, Syswerda *et al* 2012, Hess *et al* 2018) and globally (Meisinger *et al* 2015, Spiess *et al* 2020, Zhang *et al* 2020). Other modeling studies have also captured the increase in drainage volume with decreasing tillage intensity (Jiang *et al* 2014, Hess *et al* 2020, Pan *et al* 2023).

It should be noted that the infiltration processes are of paramount importance in sub-humid/humid climates like the US Midwest, where the mean annual precipitation exceeds crop potential evapotranspiration (Baumhardt and Lascano 2022). In the Midwest, the principal and more pronounced pathway for N losses is through subsurface water flows, as opposed to N loss through surface runoff (USDA 2017). Therefore, more N loss could be expected due to increased subsurface water flow even if surface runoff decreased. Our simulation results confirmed the hypothesis that NT/RTI led to an overall increase in nitrate losses in the Midwest due to the increased nitrate leaching outweighing the decreased nitrate runoff. Similarly, using the SPARROW model, Roland *et al* (2022) showed a similar trend of nitrate losses influenced by reducing tillage intensity in the Midwest. They observed that a 50% increase in conservation tillage implementation resulted in an overall increase in N losses; in contrast, a decrease in the adoption rate of conservation tillage led to a decrease in N loss. However, they did not compare changes between these two nitrate loss pathways. In contrast, in paddy rice systems where surface runoff is the main problem, Jiang *et al* (2014) reported an overall lower nitrate loss under conservation tillage compared with CT due to the decreased nitrate runoff exceeding the increased nitrate leaching.

The effects of reducing tillage intensity on nitrate leaching and runoff vary widely depending on climate, soil, and management practices (Daryanto *et al* 2017, Spiess *et al* 2020 Baumhardt and Lascano 2022). Our simulations showed that when averaged across dry and wet years, respectively, NT/RTI tended to increase the total nitrate losses more in dry years or relatively dry areas than during wet years or relatively wet areas, although the gaps in both nitrate leaching and runoff between NT/RTI and CT were amplified with higher precipitation amount in the Midwest (figure S6). Our results agreed with the findings that compared to CT, NT/RTI increases nitrate leaching more in dry years than that in wet years (Daryanto *et al* 2017). A rainfall simulation experiment in the Midwest reported that rainfall intensification increased nitrate leaching more in CT than in NT, likely due to greater rates of deep percolation under CT and rapid macropore flow bypassing nitrate in soil matrix under NT (Hess *et al* 2020). However, Miranda-Vélez *et al* (2022) suggested that only a fraction of soil nitrate can be bypassed by macropore flow in NT soils due to the slow diffusion of nitrate from macropores to soil matrix. The SEM results agreed with the argument that precipitation influences nitrate leaching more strongly compared to soil or management factors (Shahhosseini *et al* 2019, Tamagno *et al* 2022). But precipitation had a weak correlation with NT/RTI-induced increase in nitrate leaching. However, NT/RTI-induced decrease in nitrate runoff would be more pronounced with increasing precipitation (figures 3 (d) and (e)). Considering that precipitation rate and intensity are anticipated to increase in this region (Feng *et al* 2016), the trade-offs between decreased nitrate runoff and increased nitrate leaching associated with NT/RTI will present a key challenge for mitigation practices.

Soil texture is an important factor that affects soil water flow and nitrate leaching (van Es *et al* 2020). It has been reported that NT is more effective in reducing nitrate leaching in coarse-textured soils than in fine-textured soils (Daryanto *et al* 2017), likely due to increased soil organic matter and, consequently, improved water retention and nutrient use efficiency, particularly in coarse-textured soils with low water-holding capacity. Our study agreed with this finding as the SEM showed that higher clay content was associated with a small increase in nitrate leaching caused by NT/RTI in the Midwest. In addition, NT/RTI-induced increase in nitrate leaching was found to be more significant with the increase in soil bulk density, suggesting that reducing tillage intensity might alleviate soil penetration resistance. Blanco-Canqui and Ruis (2018) revealed that soil bulk density, penetration resistance, and wet aggregate stability under medium-textured soils could be most responsive to tillage because organic matter interacts more favorably with medium-textured soils than soils dominated with clay or sand particles.

Winter cover crops, specifically non-legume species like cereal rye, have been widely recognized to reduce nitrate leaching from cropland (Teixeira *et al* 2016, Thapa *et al* 2018). It is suggested that cover crops control nitrate leaching mainly via N uptake rather than flow regulation and exhibit a higher potential for reducing nitrate leaching in the presence of CT compared to RTI and NT (Nouri *et al* 2022). However, our simulations at the Iowa site showed that cover crop had insignificant effects on nitrate leaching regardless of tillage scenarios but reduced nitrate runoff under NT. In addition, the simulated drainage and runoff volume were similar between cover crop treatments (figure S8). In other studies, similar drainage volumes were also observed among cover crop and tillage treatments in Iowa (Waring *et al* 2020, O'Brien *et al* 2022). These studies found that the reduction in nitrate leaching due to cover crops was primarily due to a decrease in nitrate concentration in drainage water. As shown in the simulated results, the contrasting changing trend of drainage volume and nitrate leaching load suggested that cover crop may lower nitrate concentration in the leachate.

This study explored the long-term effects of reducing tillage intensity on nitrate losses. While the overall model performance is satisfactory, it is worth acknowledging several limitations when interpreting the results of this study. The lack of spatially explicit tillage information at the grid level and simplification of tillage types may introduce some uncertainties in the simulation results. For example, we reconstructed historical tillage maps based on data from the Conservation Technology Information Center's (CTIC) National Crop Residue Management Survey (1989–2004) and Operational Tillage Information System (2005–2018) at the 8-digit hydrologic unit watershed. The tillage information of missing years during the study period was assumed to be the same as the nearest year. As tillage is generally rotational (Kurkalova and Tran 2017), this approach may not accurately characterize tillage dynamics, especially when CTIC did not report data in some even years during 1989–2004.

Other data sources, such as USDA's ARMS, collect data on only one or two targeted crops in a given year, with each crop typically surveyed about every 4 years. It has been reported that the CTIC data showed lower growth in conservation tillage in the US than the ARMS did during the early 2000s (Horowitz *et al* 2010). The NRI-CEAP Cropland Survey data covers all crops in a survey year but is available only for a limited geographic area. Therefore, collaborative community efforts are needed to further develop and refine spatiotemporally explicit tillage datasets to improve the accuracy of model simulations. It should be noted that our assumption that long-term continuous tillage with one tillage method in the three ideal simulation scenarios may not reflect real-world practices. For instance, long-term continuous NT is very challenging and may not be an agronomic and environmental panacea in all circumstances (Blanco-Canqui and Wortman 2020). Some studies advocated strategic tillage like occasional tillage in NT systems, which could alleviate soil stratification and slow evolution of weed resistance in continuous NT systems (Renton and Flower 2015, Wang *et al* 2023). Nevertheless, a wide variety of factors could affect farmers' decision on the adopting a tillage method, such as their perspective on soil health, risk, and profitability (Ogiereiakhi and Woodward 2022). This study only considered the ideal conditions and sought to explore the possible environmental consequences under these conditions. As more detailed information about tillage and rotation practices is available, further simulations can better address the complexities of real-world farming decisions.

Our model might slightly overestimate the effects of reducing tillage intensity on nitrate leaching. For example, it does not consider the bypass effect caused by macropore flows, which could be more pronounced under conservation tillage (Miranda-Vélez *et al* 2022). However, this bypass effect has not been well understood and remains controversial in the literature. Future experiments and observations are urgently needed to address this knowledge gap. In addition, the model assumes nitrate losses through water are solely determined by water flux and nitrate concentration in the soil matrix, without accounting for variations in nitrate concentrations between runoff and drainage water. This simplification might introduce uncertainties in estimating nitrate losses. Beyond the estimated effects on nitrate losses via water fluxes, it is important to acknowledge that NT/RTI may have further environmental effects not explored in this study. For example, a recent study showed that NT might reduce N_2O emissions in the Kentucky region with a humid climate and well-aerated soils (Huang *et al* 2022). A thorough understanding of tillage intensity effects on the N cycle is urgently needed to maximize its potential benefits on agroecosystems in the context of climate change.

The combined implementation of multiple practices could result in complex effects on mitigating nitrate losses. While the interaction between NT/RTI and cover crop in relation to nitrate leaching was not significant, both practices independently contribute to reducing nitrate runoff. The hypothesis that combining NT/RTI with the cover crop can offset the potential disadvantage of NT/RTI alone in terms of increased nitrate leaching was not fully supported. Some uncertainties could be associated with the single-site simulations. In addition, the investigation of cover crop effects on nitrate leaching was limited to one crop type, i.e. cereal rye, in this study, but our objective was to assess the nitrate leaching mitigation potential of a more diverse group of cover crops recognized for N scavenging capacity, and under different tillage scenarios. However, cover crop types substantially affect soil structure, hydraulic properties, and soil nitrate contents (Koudahe *et al* 2022). Therefore, the combined effect of NT/RTI and cover crops could yield multifaceted outcomes. It should be noted that weed resistance may persist or grow with reducing tillage intensity (Renton and Flower 2015, Maheswari 2021), which could bring other environmental consequences. Future studies should aim to provide more comprehensive data and address the knowledge gap regarding the interactions among multiple management practices in order to better understanding their combined effects on reducing nitrate losses and promoting environmental health.

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available from the authors upon reasonable request.

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