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RESEARCH ARTICLE

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Response of nitrate leaching to no-tillage is dependent on soil, climate, and management factors: A global meta-analysis

Jinbo Li[1,2] | Wei Hu[1,2] | Henry Wai Chau[1,3] | Mike Beare[1,2] | Rogerio Cichota[2] | Edmar Teixeira[2] | Tom Moore[2] | Hong Di[1] | Keith Cameron[1] | Jing Guo[4] | Lingying Xu[5]

[1]Department of Soil and Physical Sciences, Faculty of Agriculture and Life Science, Lincoln University, Lincoln, New Zealand

[2]The New Zealand Institute for Plant and Food Research Limited, Lincoln, New Zealand

[3]Lethbridge Research and Development Centre, Agriculture and Agri-Food Canada, Lethbridge, Alberta, Canada

[4]Manaaki Whenua – Landcare Research, Lincoln, New Zealand

[5]State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China

Correspondence
Wei Hu, The New Zealand Institute for Plant and Food Research Limited, Canterbury Agriculture and Science Centre, Private Bag 4704, Christchurch Mail Centre, Christchurch 8140, New Zealand.
Email: wei.hu@plantandfood.co.nz

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Abstract

No tillage (NT) has been proposed as a practice to reduce the adverse effects of tillage on contaminant (e.g., sediment and nutrient) losses to waterways. Nonetheless, previous reports on impacts of NT on nitrate (NO_3^-) leaching are inconsistent. A global meta-analysis was conducted to test the hypothesis that the response of NO_3^- leaching under NT, relative to tillage, is associated with tillage type (inversion vs non-inversion tillage), soil properties (e.g., soil organic carbon [SOC]), climate factors (i.e., water input), and management practices (e.g., NT duration and nitrogen fertilizer inputs). Overall, compared with all forms of tillage combined, NT had 4% and 14% greater area-scaled and yield-scaled NO_3^- leaching losses, respectively. The NO_3^- leaching under NT tended to be 7% greater than that of inversion tillage but comparable to non-inversion tillage. Greater NO_3^- leaching under NT, compared with inversion tillage, was most evident under short-duration NT (<5 years), where water inputs were low (<2 mm day^{-1}), in medium texture and low SOC (<1%) soils, and at both higher (>200 kg ha^{-1}) and lower (0–100 kg ha^{-1}) rates of nitrogen addition. Of these, SOC was the most important factor affecting the risk of NO_3^- leaching under NT compared with inversion tillage. Globally, on average, the greater amount of NO_3^- leached under NT, compared with inversion tillage, was mainly attributed to corresponding increases in drainage. The percentage of global cropping land with lower risk of NO_3^- leaching under NT, relative to inversion tillage, increased with NT duration from 3 years (31%) to 15 years (54%). This study highlighted that the benefits of NT adoption for mitigating NO_3^- leaching are most likely in long-term NT cropping systems on high-SOC soils.

KEYWORDS
drainage, no tillage, NO_3^- leaching, review, soil organic carbon

1 | INTRODUCTION

About 50%–70% of nitrogen (N) fertilizer applied in agricultural systems is lost to the environment (Cassman et al., 2002; Coskun et al., 2017; Ladha et al., 2005). Nitrate (NO_3^-) leaching is regarded as one of the main loss pathways, as nitrate is mobile and easily transported to ground water through the soil profile when drainage occurs (Coskun et al., 2017; Wang et al., 2019). Previous studies suggested that NO_3^- leaching losses accounted for about 8%–19% of the total N applied (Lin et al., 2001; Sebilo et al., 2013). These losses not only reduce soil fertility and crop yield (Cameron et al., 2013), but also degrade water quality (Rivett et al., 2008; Stuart et al., 2011) and put human health at risk (Cameron et al., 2013; Liu, Peng, et al., 2021). Thus, appropriate management strategies are urgently needed to reduce NO_3^- leaching.

The use of no tillage (NT) has been proposed as a means of decreasing NO_3^- leaching (Spiess et al., 2020). However, the reported impacts of NT on NO_3^- leaching are inconsistent. Compared with tillage, NT has been shown to increase (Huang, Liang, et al., 2015), decrease (Spiess et al., 2020; Zhang et al., 2020), or have no impacts (Meisinger et al., 2015) on NO_3^- leaching. For the sake of brevity, we refer to "tillage" here to represent all forms of tillage (i.e., inversion tillage and non-inversion tillage). A previous meta-analysis showed that, on average, NT increased NO_3^- leaching in corn, soybean, and wheat systems compared with tillage (Daryanto et al., 2017). Their study highlighted that the effect of NT on NO_3^- leaching differed depending on soil texture, water input, crop type, fertilizer type, and duration of NT. For example, it was reported that NT increased NO_3^- leaching in drylands (aridity index [rainfall/potential evapotranspiration] <0.65), but decreased NO_3^- leaching in non-drylands (aridity index >0.65). However, the Daryanto et al. (2017) meta-analysis did not consider other factors such as how NT compares with different forms of tillage and the role of soil organic carbon (SOC) content, which may affect the response of NO_3^- leaching to NT. It remains unclear what soil, climate, and management factors most strongly affect the risk of NO_3^- leaching under NT compared to different forms of tillage.

Most previous meta-analyses of NT practices have tended to compare NT with all forms of tillage combined, without distinguishing the impacts of different tillage forms (Briones & Schmidt, 2017; Zhao et al., 2022). Non-inversion tillage generally involves less disturbance of the soil than inversion tillage (Morris et al., 2010). Some previous studies have shown that non-inversion tillage (also termed reduced tillage) has little or no significant effects on soil physical properties (e.g., bulk density and wet aggregate stability) compared with NT (Abdollahi et al., 2017; Blanco-Canqui et al., 2017; de Moraes et al., 2016; Reichert et al., 2017). Soil physical properties affect storage and transport of water and N in soils, and hence soil water drainage and NO_3^- leaching. Therefore, we expect the difference in NO_3^- leaching between NT and inversion tillage to be greater than that between NT and non-inversion tillage. SOC affects both soil physical (e.g., soil aggregates) (Kong et al., 2005) and chemical (e.g., mineralization) (Alvarez & Alvarez, 2000) properties. Increasing SOC was found to significantly decrease NO_3^- leaching (Kanthle et al., 2016), but it is unknown whether SOC content influences the response of NO_3^- leaching to NT relative to that of tillage. For example, SOC content may affect the response of NO_3^- leaching to NT by decoupling some key N cycling processes (e.g., N protection in aggregates, N immobilization, and N uptake) compared to tillage.

Despite numerous studies having reported both area-scaled NO_3^- leaching and crop yields under different cultivation systems (Spiess et al., 2020; Waring et al., 2020), it remains unknown how yield-scaled NO_3^- leaching (kg NO_3^-/ kg produce) responds to NT. In the context of sustainable agriculture, where both the environment and food production are crucial, yield-scaled NO_3^- leaching may be more informative than area-scaled NO_3^- leaching. Daryanto et al. (2017) attributed the greater NO_3^- leaching under NT to increased drainage due to an increase in macropores; however, it remains unclear what the relative contributions of drainage or nitrate concentration are to NO_3^- leaching under NT compared with tillage. Therefore, a more comprehensive meta-analysis was required to identify the major factors affecting the response of NO_3^- leaching to NT relative to different forms of tillage and to identify the conditions (e.g., soil, climate, and management practices) where a reduction in NO_3^- leaching from NT may be possible.

In this study, we tested the hypothesis that the response of NO_3^- leaching to NT relative to tillage is context specific. In particular, we aimed to (1) evaluate how NO_3^- leaching under NT cropping compares to that of inversion and non-inversion tillage practices and (2) determine to what extent these effects are influenced by soil properties (SOC content, soil texture), water input (as a climate factor), and management factors (e.g., NT duration, crop type, and nitrogen fertilizer inputs). We also applied the results of these analyses to evaluate the potential impacts of NT adoption on the risk of NO_3^- leaching at a global scale.

2 | MATERIALS AND METHODS

2.1 | Data collection

Data were collected from the Web of Science and Google Scholar databases up to December 2021. The search terms "tillage" and "nitrate leaching" resulted in 633 publications. Studies had to meet the following criteria to be included in the final dataset: (1) NO_3^- leaching must have been measured under field conditions or modeled using field data; (2) NT was compared with inversion tillage and/or non-inversion tillage. NT refers to both NT and direct drilling where no soil cultivation is applied. Inversion tillage includes those practices that create high inversion and high mixing of soil, such as produced by moldboard ploughing, and non-inversion tillage refers to those practices that result in shattering and aeration of topsoil, such as produced by chisel ploughing (Briones & Schmidt, 2017) (Table 1); (3) means and replicates of NO_3^- leaching were reported; (4) NO_3^- leaching measurement covered at least one entire crop growing season (from sowing to harvest); and (5) the deepest measurement of

TABLE 1 Categorical variables in the meta-analysis and the levels within each variable that define the groups.

Variable	Levels	Parameters	References or comments
Tillage type	Inversion tillage	Moldboard plough, plough, and rotary tillage	Briones and Schmidt (2017)
	Non-inversion tillage	Chisel plough, strip tillage, and ridge tillage	
SOC content	Low	<1%	Kallenbach and Grandy (2011); 0–30 cm
	Medium	1%–3%	
	High	>3%	
Soil texture	Fine	Clay, sandy clay, and silty clay	Omondi et al. (2016); 0–30 cm
	Medium	Silt, silt loam, silty clay loam, loam, sandy clay loam, and clay loam	
	Coarse	Sand, loamy sand, and sandy loam	
NT duration	Short term	<5 years	Briones and Schmidt (2017)
	Mid term	5–10 years	
	Long term	>10 years	
Water input	Low	<2 mm day^{-1}	Classification is made to ensure similar sample size of area-scaled NO_3^- leaching for each group
	Medium	2–3 mm day^{-1}	
	High	>3 mm day^{-1}	
Nitrogen input	Low	0–100 kg ha^{-1}	Kallenbach and Grandy (2011)
	Medium	100–200 kg ha^{-1}	
	High	>200 kg ha^{-1}	
Crop type	Grain	Wheat, barley	Maize was separated from grain as it has high water and nitrogen demand
	Maize	Maize	
	Soybean	Soybean	
	Others	Fallow, ley, forage rape, cotton, etc.	

leaching was used if multiple depths were reported. Data from a total of 724 observations (362 pairs) at 29 sites and 44 scientific papers met these criteria. Among these, 201 pairs compared NO_3^- leaching between NT and inversion tillage, and 161 pairs compared NO_3^- leaching between NT and non-inversion tillage. These observations were mainly from studies conducted in Europe and North America (Figure S1). Multiple observations (e.g., multiple years and multiple treatments) from the same publication were treated as independent data points because these observations were subjected to different treatments and cover distinct environmental conditions. In addition, this approach has been shown to increase the statistical power of meta-analysis by reducing the error variance of effect sizes resulting from an increased number of independent observations (Lajeunesse & Forbes, 2003; Nouri et al., 2022).

In addition, drainage volumes, NO_3^- concentration of leachate samples, soil properties (soil texture and SOC content of top 30 cm), water input (as a climate variable), and management practices (tillage type, NT duration, nitrogen input, and crop type) were also recorded to identify the most influential factors affecting the response of NO_3^- leaching to tillage systems (Table 1). Water input represents a climate factor because of the dominant effect of rainfall on total water input during the measurement period (i.e., rainfall accounts for 89% of total water input on average; $R^2 = .88$). The yield-scaled NO_3^- leaching (kg kg^{-1}) was calculated by dividing the area-scaled NO_3^- leaching (kg ha^{-1}) by the crop yield (kg ha^{-1}). Total water input (mm) during the sampling period was calculated as the sum of precipitation and irrigation amounts divided by days during the sampling period. The published data from graphs were extracted using GetData software (http://getdata-graph-digitizer.com).

2.2 | Data analysis

The random effects model was used to explore variables that might explain the response of NO_3^- leaching to NT by calculating the weighted effect size for each variable. The numerical factors (e.g., NT duration, nitrogen input, water input, and SOC) were categorized according to previous studies (Table 1). In this study, the response ratio (RR) was calculated as the ratio between the outcome (e.g., area-scaled NO_3^- leaching) of treatment (NT) and that of the control (inversion-tillage, non-inversion tillage, or both). The RR of individual observations was natural logarithm transformed (lnRR) to ensure normality and treat deviations in the numerator and denominator more equally (Hedges et al., 1999):

$$\ln RR_i = \ln \frac{\chi_i^t}{\chi_i^c} = \ln(\chi_i^t) - \ln(\chi_i^c) \quad (1)$$

where $\ln RR_i$ is the effect size of the corresponding parameters from *i*th comparisons, and χ_i^t and χ_i^c the *i*th means of corresponding parameters in the treatment (NT) and control (reference) group (inversion tillage, non-inversion tillage, or both), respectively.

We calculated the weighted effect sizes from individual $\ln RR_i$ by giving greater weight to observations with higher accuracy (smaller variance [v_i] of $\ln RR_i$). The weighted effect sizes were calculated as:

$$\overline{\ln RR} = \frac{\sum_{i=1}^{m} w_i \times \ln RR_i}{\sum_{i=1}^{m} w_i} \tag{2}$$

where m is the number of comparisons in the group, w_i the weight of corresponding comparisons, which was calculated as the reciprocal of the variance (v_i) of $\ln RR_i$, written as:

$$w_i = \frac{1}{v_i} = \frac{1}{\left(\frac{(SD_i^t)^2}{n_i^t \times (\chi_i^t)^2} + \frac{(SD_i^c)^2}{n_i^c \times (\chi_i^c)^2} + \tau^2\right)} \tag{3}$$

where SD_i^t (or SD_i^c) and n_i^t (or n_i^c) are the standard deviation (SD) and the number of replicates of the ith observation for the treatment (or control) data. τ^2 is between-study variance and was estimated by the restricted maximum likelihood method (Veroniki et al., 2016). SD values were computed from standard error (SE) if SD was unavailable, using:

$$SD = SE \times \sqrt{n} \tag{4}$$

where n is the number of replicates. The missing SDs were imputed using the method of Bracken (1992).

The SE ($s(\overline{\ln RR})$) and 95% confidence interval (95% CI) of $\overline{\ln RR}$ were computed as:

$$s(\overline{\ln RR}) = \sqrt{\frac{1}{\sum_{i=1}^{m} w_i}} \tag{5}$$

$$95\%\,CI = \overline{\ln RR} \pm 1.96 s(\overline{\ln RR}) \tag{6}$$

The $\overline{\ln RR}$, $s(\overline{\ln RR})$, and 95% CI of relevant variables were calculated using the "rma" function of the "metafor" package in R (Viechtbauer, 2010). The variables of interest in the treatment (i.e., NT) were defined to be significantly greater (>0) or less (<0) than the control (i.e., tillage) if the 95%CI for weighted response ratio $\overline{\ln RR}$ of corresponding variables did not overlap with zero. To facilitate the interpretation, $\overline{\ln RR}$ was converted to relative change (*RC*) in percentage (%), using:

$$RC = \left(e^{\overline{\ln RR}} - 1\right) \times 100\% \tag{7}$$

The corresponding 95% CI of RC was computed analogously by combining Equations (6) and (7). The *RC* reflects the difference in outcome (e.g., area-scaled NO_3^- leaching) between the treatment (NT) and control (inversion-tillage, non-inversion tillage, or both), expressed as a percent of the control.

Random-forest analysis was implemented to determine the main factors affecting the response of area-scaled NO_3^- leaching to NT (Wang et al., 2021). The key factors affecting yield-scale NO_3^- leaching were not identified because of the relatively small number of comparisons (n = 99) that reported yield-scale NO_3^- leaching data. This method assesses the importance of factors by calculating the increase in the prediction error (mean squared errors) associated with random permutations of each factor while keeping other factors unchanged (Liaw & Wiener, 2002). Where factor permutation did not change the prediction error, the related factors were considered unimportant (Liaw & Wiener, 2002). The random-forest analysis was conducted using the *R* packages "randomforest" and "rfPermute" (Archer & Archer, 2016).

The risk of area-scaled NO_3^- leaching from NT relative to inversion tillage was estimated globally based on the main predictors (i.e., soil texture, SOC, water input, and NT duration) using the best-fit regression model. The best-fit model was identified from the model selection analysis using the "rma.glmulti" function in "metafor" package (Hurvich & Tsai, 1993; Viechtbauer & Viechtbauer, 2015). In this model, lnRR of area-scaled NO_3^- leaching was the response variable, and the fixed effects of main predictors were analyzed, with the variance (v_i) being $\ln RR_i$ of area-scaled NO_3^- leaching. The original numerical factor data were used to develop a regression equation. The model selection analysis is widely employed in meta-analysis, as it generates all possible models involving these variables (Feng & Zhu, 2019; Su, Feng, et al., 2021). The best-fit model was selected based on the corrected Akaike information criterion (AIC_c) value (please refer to Text S1 and Table S1 for the details). Global maps of the risk of area-scaled NO_3^- leaching under NT cropping were generated under various NT duration scenarios (i.e., 3, 8, and 15 years) based on the baseline maps of the main predictors. We used mean annual precipitation, soil texture (calculated from soil particle size distribution), and the SOC dataset as the baseline maps because the results of random forest analyses showed that these were the main factors affecting the response of NO_3^- leaching to NT. The mean annual precipitation data were collected from WorldClim2 database (Fick & Hijmans, 2017) and soil particle size distribution and SOC data were collected from SoilGrids (Hengl et al., 2017). Prior to calculation, each map of predictors was re-sampled at a consistent resolution (please refer to Text S1 for the details). Analyses were conducted with ArcGIS Desktop 10.5.

3 | RESULTS

3.1 | Influence of tillage type

The lnRR of area-scaled and yield-scaled NO_3^- leaching were both normally distributed (Figure S2). On average, area-scaled NO_3^- leaching was 4% greater (p = .13) under NT than all forms of tillage (i.e., both inversion and non-inversion tillage) (Figure 1a). In contrast, yield-scaled NO_3^- leaching was 14% greater under NT than under tillage (Figure 1b), owing to a lower (−8%) crop yield in NT (Figure 1 e). The higher NO_3^- leaching associated with NT was consistent with the greater drainage (10%) (Figure 1c), which was partially offset by a lower NO_3^- concentration in the leachate (−6%) (Figure 1d).

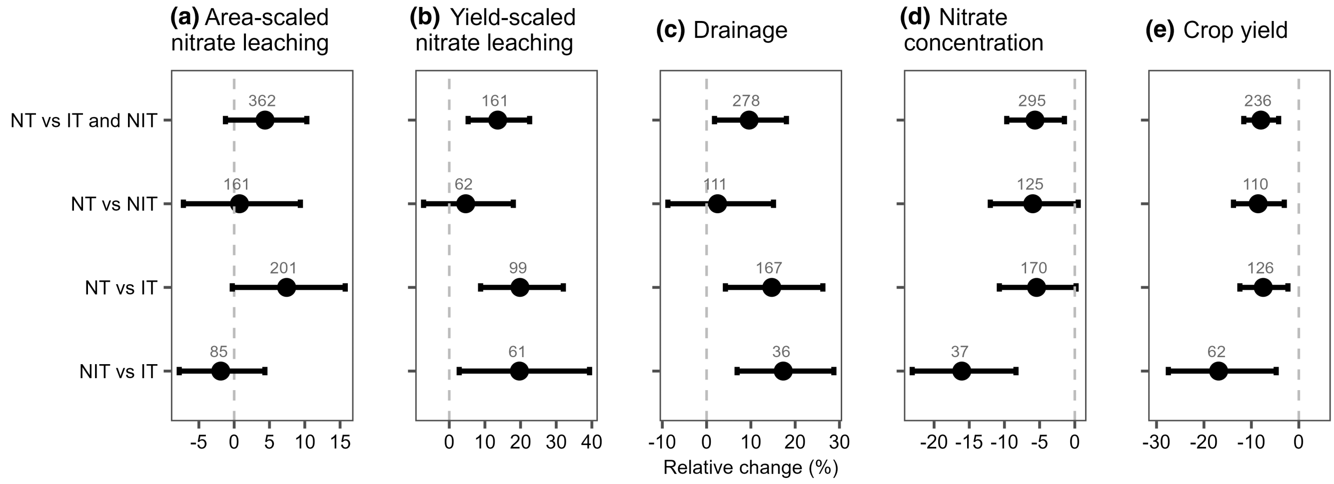

FIGURE 1 Relative change in (a) area-scaled NO_3^- leaching, (b) yield-scaled NO_3^- leaching, (c) drainage volume, (d) NO_3^- concentration of leachate samples, and (e) crop yield for different tillage type comparisons. NT, no tillage; NIT, non-inversion tillage; IT, inversion tillage. The sample size for each category is shown above the mean relative change. Error bars are 95% confidence intervals. The effects are significant at $p<.05$ where error bars do not overlap zero.

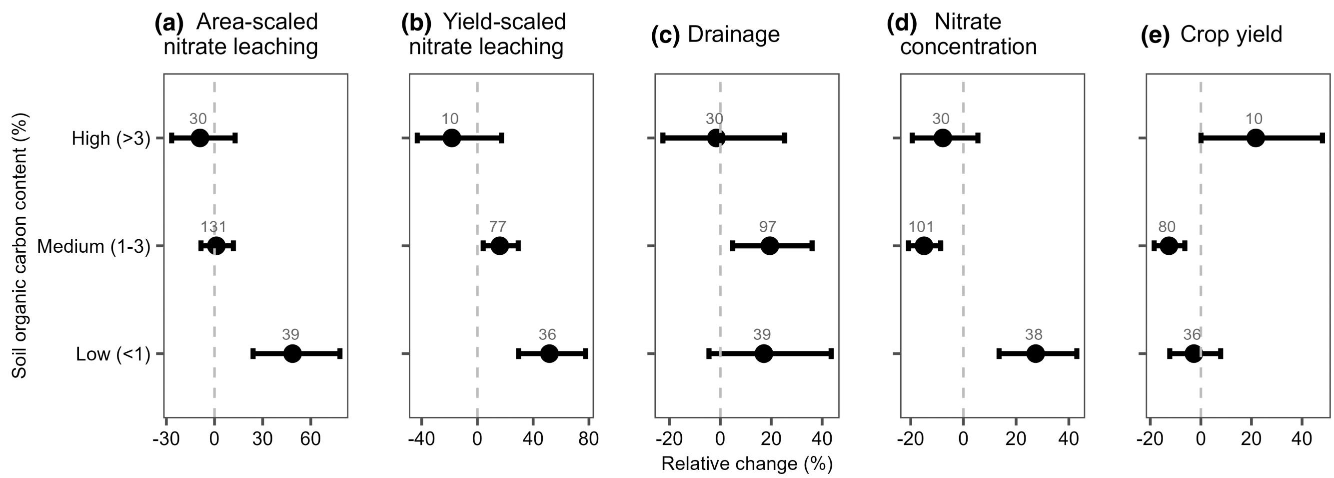

FIGURE 2 Relative change in (a) area-scaled NO_3^- leaching, (b) yield-scaled NO_3^- leaching, (c) drainage volume, (d) NO_3^- concentration of leachate samples, and (e) crop yield in no-till (NT) compared with inversion tillage, segregated by different soil organic carbon contents. The sample size for each category is shown above the mean relative change. Error bars are 95% confidence intervals. The effects are significant at $p<.05$ where error bars do not overlap zero.

Separating data by different tillage types indicated that NO_3^- leaching under NT was significantly greater than under inversion tillage, but comparable to that of non-inversion tillage. For example, on average, NT had 20% greater yield-scaled NO_3^- leaching than inversion-tillage, while the difference between NT and non-inversion tillage was not significant (Figure 1b). Similar results were also found for drainage (Figure 1c). It is notable that the differences in NO_3^- leaching and drainage between non-inversion tillage and inversion tillage were also similar to those between NT and inversion tillage. For example, non-inversion tillage, in comparison to inversion tillage, resulted in 20% greater drainage and yield-scaled NO_3^- leaching (Figure 1b,c).

Since there were no statistically significant differences in NO_3^- leaching or drainage between NT and non-inversion tillage, subsequent analyses focused solely on the comparison between NT and inversion tillage.

3.2 | Factors affecting NO_3^- leaching under NT relative to inversion tillage

3.2.1 | Influence of SOC

In soils with low SOC content (<1%), NT resulted in approximately 50% greater area- and yield-scaled NO_3^- leaching than inversion tillage (Figure 2a,b). The differences decreased as SOC content increased. In contrast, in soils with a high SOC content (>3%), NT resulted in slightly lower area- and yield-scaled NO_3^- leaching than inversion tillage. Similar effects of NT on drainage (Figure 2c) and NO_3^- concentration (Figure 2d) were observed as with NO_3^- leaching. In contrast to the overall effects of NT on NO_3^- concentration (Figure 1d), on average, NT resulted in a 27% higher NO_3^- concentration than inversion tillage in low SOC soils, but a lower NO_3^- concentration than inversion tillage in soils with SOC >1% (Figure 2d).

3.2.2 | Influence of soil texture

The effects of NT on NO_3^- leaching were found to vary with soil texture (Figure 3). In soils with medium texture, on average, NT produced greater area-scaled (17%) and yield-scaled NO_3^- leaching (23%) than inversion tillage (Figure 3a,b). In coarse-textured soils, no significant effects of NT on area-scaled NO_3^- leaching were observed, whereas yield-scaled NO_3^- leaching was 25% greater with NT than with inversion tillage (Figure 3a,b). While NT resulted in 34% less area-scaled NO_3^- leaching compared with inversion tillage in fine-textured soils, the small sample size (n = 15) makes it difficult to draw a firm conclusion (Figure 3a). NT tended to produce lower drainage and NO_3^- concentrations than inversion tillage in fine-textured soils, whereas in coarse-textured soils, NT resulted in greater drainage (30%) but lower NO_3^- concentrations (−16%) in leachates than inversion tillage.

3.2.3 | Influence of NT duration

Short duration NT (<5 years since conversion from tillage), on average, resulted in significantly greater area-scaled (15%) and yield-scaled NO_3^- leaching (32%) than inversion tillage (Figure 4a,b). However, the effects of NT on area-scaled NO_3^- leaching were not significant for either medium (5–10 years) or long (>10 years) duration NT compared with inversion tillage effects. The effect of NT on drainage was similar to the effect on NO_3^- leaching (Figure 4c), that is, short-term NT (<5 years) resulted in greater drainage than inversion tillage, while long-term NT produced slightly lower drainage than inversion tillage. NT over more than 5 years tended to result in 14–16% lower NO_3^- concentrations in leachates than inversion tillage. While short-term NT resulted in 10% lower crop yield than inversion tillage, no significant yield penalties were found with medium- to long-term use of NT.

3.2.4 | Influence of water input

When water input was low (<2 mm day^{-1}), NT tended to produce greater NO_3^- leaching than inversion tillage (Figure 5a,b). For example, on average, NT resulted in 15% greater (p = 0.07) area-scaled and 39% greater yield-scaled NO_3^- leaching than inversion tillage under low water input (<2 mm day^{-1}) (Figure 5a,b). In contrast, the effects of NT on NO_3^- leaching were insignificant under medium and high water input, although the NO_3^- concentration in NT leachates was significantly lower (−16%) under medium water input (2–3 mm day^{-1}) (Figure 5d). NT produced lower relative yields (−16%) than inversion tillage where water inputs were low (<2 mm day^{-1}), but there were no significant differences where water inputs were medium (2–3 mm day^{-1}) or high (>3 mm day^{-1}) (Figure 5e).

3.2.5 | Influence of nitrogen input

Overall, under both low (0–100 kg ha^{-1}) and high (>200 kg ha^{-1}) rates of N input, NT tended to result in greater NO_3^- leaching than inversion tillage (Figure 6a,b). For example, on average, NT produced significantly greater yield-scaled NO_3^- leaching under high (39%) and low (29%) nitrogen inputs (Figure 6a,b). The effects of NT on drainage were not related to nitrogen input (Figure 6c). Moreover, NT resulted in significantly lower nitrate concentrations (−13%) at medium N application rates and lower crop yield (−20%) at low N application rates (Figure 6e).

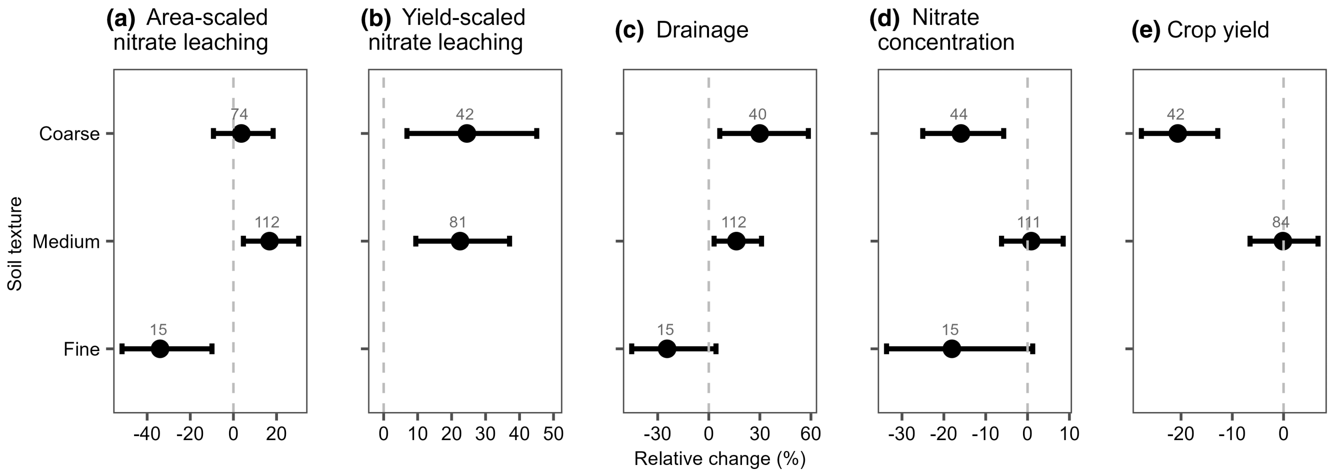

FIGURE 3 Relative change in (a) area-scaled NO_3^- leaching, (b) yield-scaled NO_3^- leaching, (c) drainage volume, (d) NO_3^- concentration of leachate samples, and (e) crop yield in no-till (NT) compared with inversion tillage, segregated by soil texture. The sample size for each category is shown above the mean relative change. Error bars are 95% confidence intervals. The effects are significant at $p < .05$ where error bars do not overlap zero.

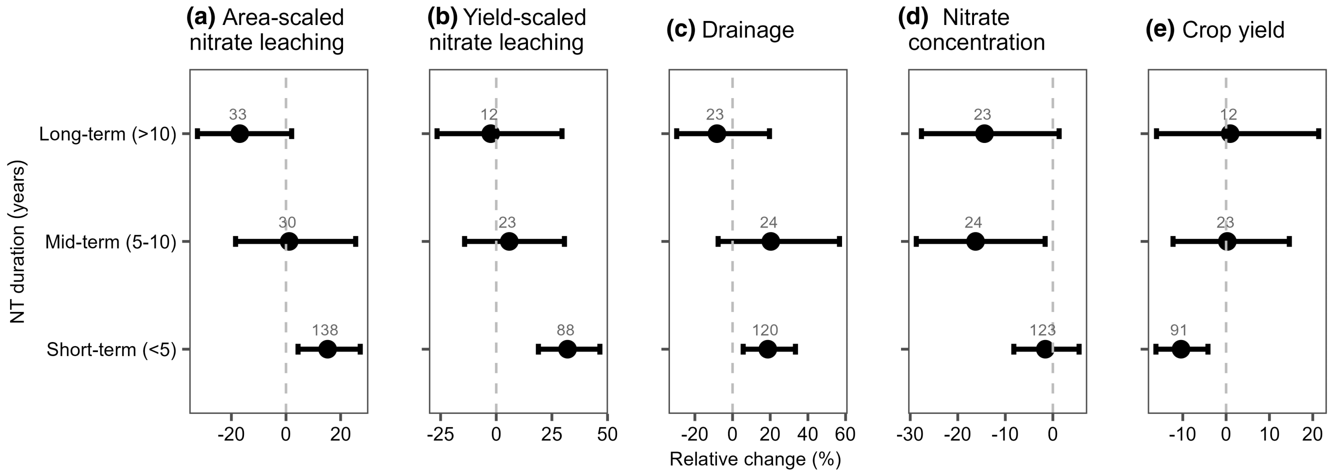

FIGURE 4 Relative change in (a) area-scaled NO_3^- leaching, (b) yield-scaled NO_3^- leaching, (c) drainage volume, (d) NO_3^- concentration of leachate samples, and (e) crop yield in no-till (NT) compared with inversion tillage segregated by NT duration. The sample size for each category is shown above the mean relative change. Error bars are 95% confidence intervals. The effects are significant at $p < .05$ where error bars do not overlap zero.

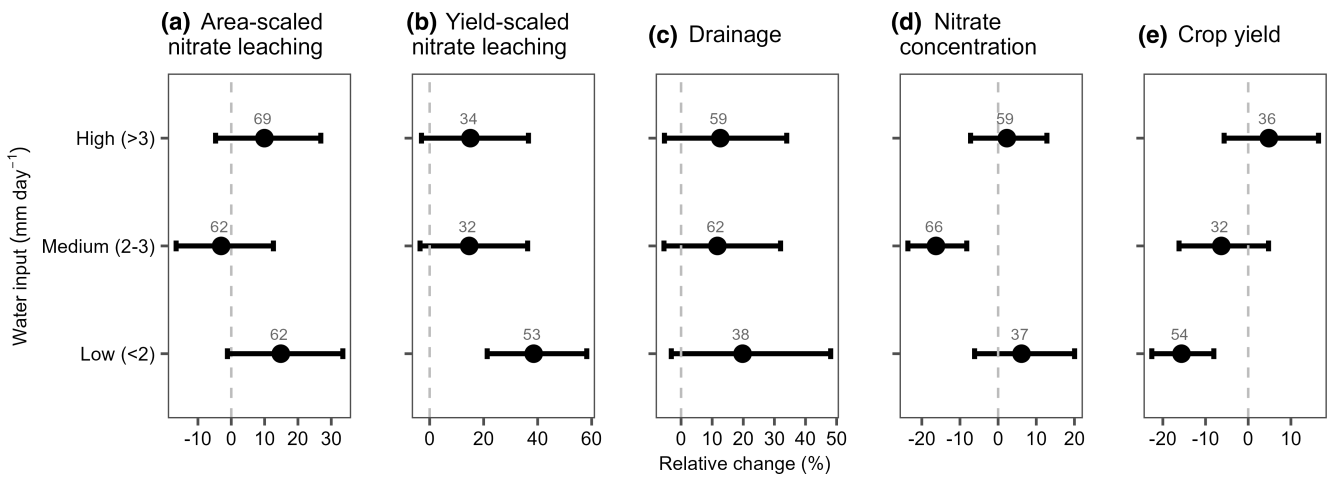

FIGURE 5 Relative change in (a) area-scaled NO_3^- leaching, (b) yield-scaled NO_3^- leaching, (c) drainage volume, (d) NO_3^- concentration of leachate samples, and (e) crop yield in no-till (NT) compared with inversion tillage segregated by water input. The sample size for each category is shown above the mean relative change. Error bars are 95% confidence intervals. The effects are significant at $p < .05$ where error bars do not overlap zero.

3.2.6 | Influence of crop type

While NT tended to produce greater area-scaled NO_3^- leaching than inversion tillage for soybean (Figure 7a), NT resulted in significantly greater yield-scaled NO_3^- leaching for most crop types except soybean (Figure 7b). In general, the effects of crop type on the response of drainage to NT were similar to those on area-scaled NO_3^- leaching (Figure 7c).

3.3 | Relative importance of factors affecting the response of area-scaled NO_3^- leaching to NT

SOC was the most important factor affecting area-scaled NO_3^- leaching under NT compared with inversion tillage (Figure 8). In addition, soil texture, water input, and NT duration also significantly affected the response of area-scaled NO_3^- leaching to NT. The effects of crop type and nitrogen input were not statistically significant.

4 | DISCUSSION

4.1 | NT effects on NO_3^- leaching and potential mechanisms

This study confirmed the findings of a previous study (Daryanto et al., 2017) that NT results in greater NO_3^- leaching losses than tilled cropping systems. However, the present study also determined that the significantly greater NO_3^- leaching losses associated with NT are restricted to comparisons with inversion tillage, and that there were no significant differences between NT and non-inversion tillage, in part due to their similar effects on soil properties (Blanco-Canqui & Ruis, 2018). Compared with non-inversion tillage, NT has been

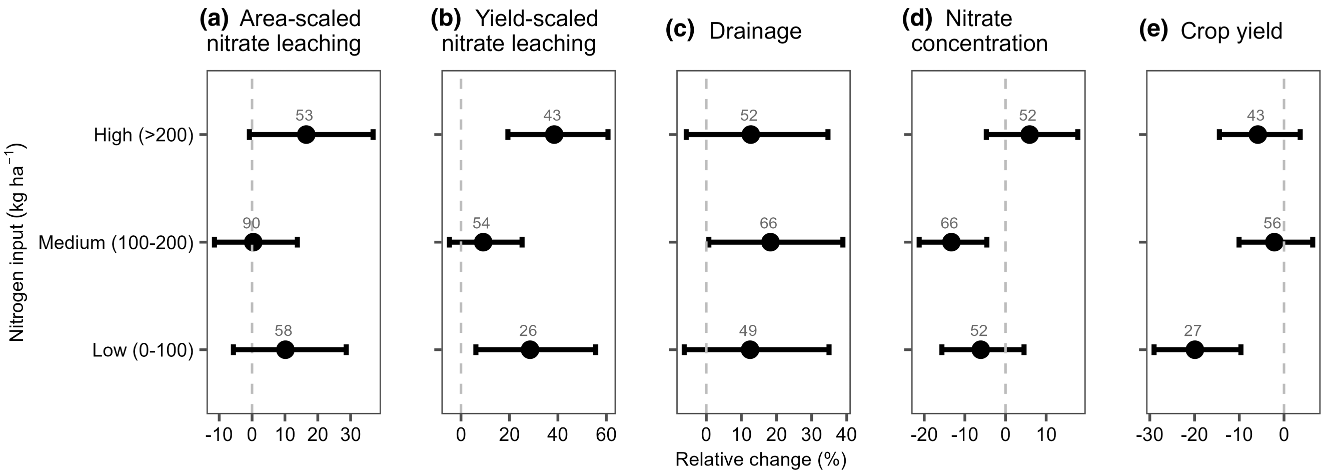

FIGURE 6 Relative change in (a) area-scaled NO_3^- leaching, (b) yield-scaled NO_3^- leaching, (c) drainage volume, (d) NO_3^- concentration of leachate samples, and (e) crop yield in no-till (NT) compared with inversion tillage segregated by nitrogen input. The sample size for each category is shown above the mean relative change. Error bars are 95% confidence intervals. The effects are significant at $p < .05$ where error bars do not overlap zero.

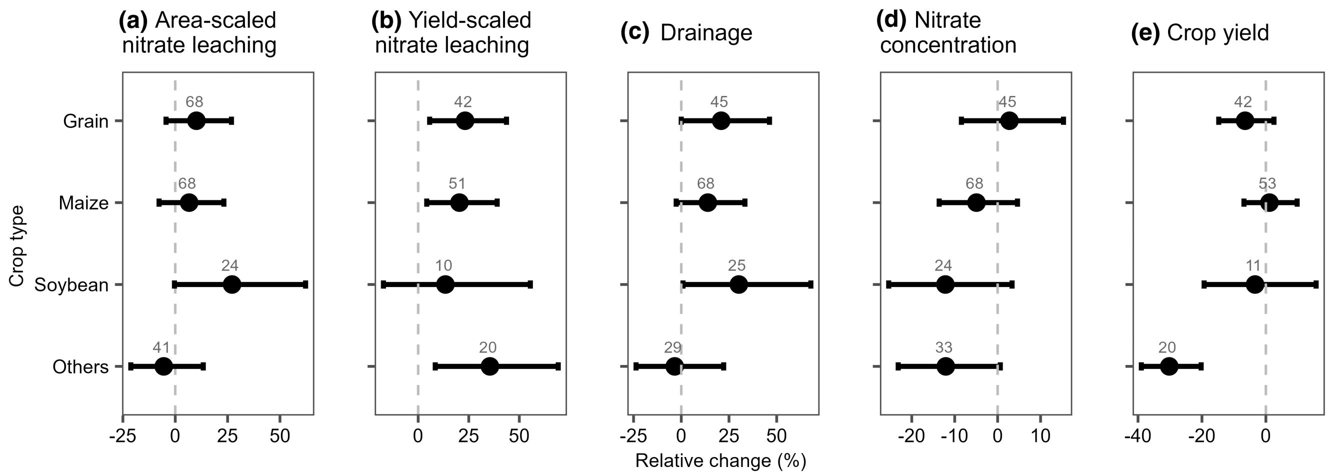

FIGURE 7 Relative change in (a) area-scaled NO_3^- leaching, (b) yield-scaled NO_3^- leaching, (c) drainage volume, (d) NO_3^- concentration of leachate samples, and (e) crop yield in no-till (NT) compared with inversion tillage segregated by crop type. The sample size for each category is shown above the mean relative change. Error bars are 95% confidence intervals. The effects are significant at $p < .05$ where error bars do not overlap zero.

reported to have little effect on soil bulk density (Blanco-Canqui et al., 2017), aggregate stability (Abdollahi et al., 2017), macroporosity (Reichert et al., 2017), or infiltration rates (de Moraes et al., 2016). This also partly explains why the comparison of yield-scaled NO_3^- leaching between NT and inversion tillage is similar to that between non-inversion tillage and inversion tillage (Figure 1b). The relative change in NO_3^- leaching under NT compared with inversion tillage was not correlated with the absolute NO_3^- leaching (Figure S3). This indicates that greater relative differences are not primarily associated with small absolute amounts of NO_3^- leaching. In addition, this study highlighted that the greater NO_3^- leaching associated with NT was magnified when it was normalized by yield. This was associated with yield penalties from NT compared with tillage, particularly in short-term (<5 years) evaluations of NT conversions, as reported in previous meta-analyses (Pittelkow et al., 2015; Su, Gabrielle, & Makowski, 2021).

In the context of eco-efficient and sustainable agriculture, the effects of management practices on the environment and on production are gaining increasing attention. Several previous studies have also used yield-scaled estimates of environmental impacts to compare the effects of NT to tilled cropping systems (Pittelkow et al., 2014; van Kessel et al., 2013). Our study highlights that trade-offs such as increased risk of NO_3^- leaching must be considered, particularly in the initial years of NT implementation and in low-SOC soils, when converting cropping systems to conservation tillage practices.

NO_3^- leaching is a product of drainage and the NO_3^- concentration in the drainage water. It has previously been suggested that NO_3^- leaching is affected more by NO_3^- concentration than by drainage volume because NO_3^- concentration varies more between tillage systems than drainage (Spiess et al., 2020). This study, however, showed that the global effect of NT on NO_3^- leaching

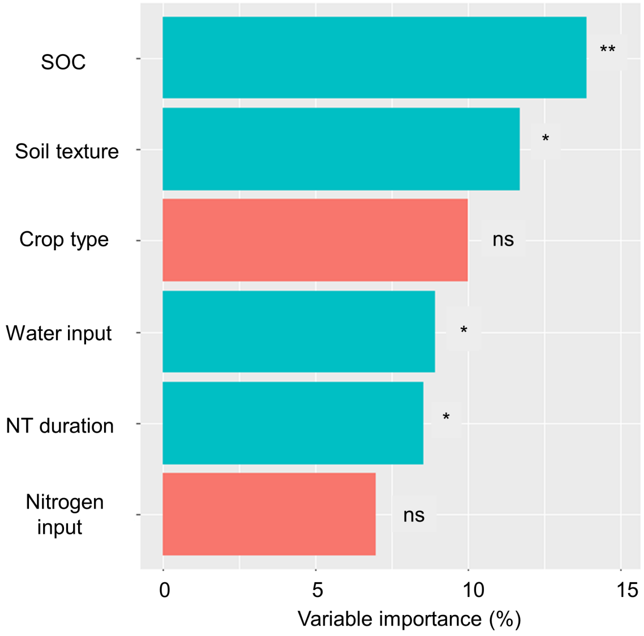

FIGURE 8 Importance of variables for predicting the effect size (lnRR) of area-scaled NO_3^- leaching identified by random forest analysis. Variable importance is the percentage increase in mean square error of the random forests model when the data for that variable were randomly permuted (ns: $p > .05$, $^*p < .05$, $^{**}p < .01$).

was primarily associated with its effect on drainage, rather than NO_3^- concentration (Figure 1). Furthermore, the relative change in NO_3^- leaching was more strongly correlated with drainage (R^2 = .46) than with NO_3^- concentration (R^2 = .12) (Figure S4). Therefore, globally, the effect of NT on NO_3^- leaching, compared to inversion tillage, was mainly attributed (or more sensitive) to differences in drainage. This also implies that to mitigate nitrate leaching at the global scale more attention should be given to (i) reducing drainage under NT and (ii) reducing NO_3^- concentration in drainage water under inversion tillage. The higher NO_3^- concentrations in drainage water under inversion tillage may be partly associated with enhanced N mineralization, which may be attributed to faster rates of crop residue decomposition (Beare et al., 1992; Lupwayi et al., 2006) and the release of aggregate-protected organic matter (Beare, Hendrix, Cabrera, & Coleman, 1994; Six et al., 2000). Numerous strategies have been developed to mitigate the risk of NO_3^- leaching losses by lowering soil NO_3^- concentrations. These include, for example, growing cover crops (Carey et al., 2016; Nouri et al., 2022) and applying fertilizer using best management practices (e.g., plastic mulch, a better fertilizer placement, and split applications) (Ruidisch et al., 2013). Further research is needed to identify under which conditions NO_3^- leaching is more sensitive to drainage, and how to reduce NO_3^- leaching by reducing drainage losses.

Greater drainage, and consequently NO_3^- leaching, has been attributed to NT's increased risk of macropore flow from bio-pores (Daryanto et al., 2017; Spiess et al., 2020). While this may be the case for specific studies (Miranda-Vélez et al., 2022; Singh & Kanwar, 1991), it may not hold at the global scale. A recent global meta-analysis showed that NT typically results in higher microporosity, and lower macroporosity and saturated hydraulic conductivity than inversion tillage (Mondal & Chakraborty, 2022). Therefore, macropore flow may not be an important factor affecting the risk of NO_3^- leaching in many NT cropping systems. In contrast, greater macropore flow under NT would be expected to result in more drainage water bypassing mobile soil nitrogen residing in the soil matrix, which would lead to reduced rather than increased NO_3^- leaching in NT systems (Miranda-Vélez et al., 2022). It is widely reported that NT soils often have greater soil water content than tilled soils (De Vita et al., 2007; Jemai et al., 2013; Page et al., 2019). This has been attributed to higher water-holding capacity due to increased microporosity (Mondal & Chakraborty, 2022), lower soil evaporation due to changes in pore size distribution (Yi et al., 2022) and higher plant residue cover (De Vita et al., 2007), and lower water uptake (i.e., transpiration) due to reduced crop growth and yield (Figure 1e) (Guan et al., 2015). Higher soil water content tends to lower the capacity of the soil to store additional water before triggering drainage, and this is likely to be the main reason for greater drainage and NO_3^- leaching under NT relative to tillage (Lu et al., 2021; Yi et al., 2022). Therefore, proper management of water inputs and soil water content (e.g., reducing irrigation inputs) is crucial to reducing drainage and nutrient leaching losses related to NT in cropping systems.

4.2 | Factors affecting response of NO_3^- leaching to NT

The response of NO_3^- leaching to NT was most strongly affected by SOC. Greater NO_3^- leaching loss under NT primarily occurred in soils with low SOC (<1%), whereas less NO_3^- leaching occurred in soils with high SOC (>3%) (Figure 2). Interestingly, the greater NO_3^- leaching loss under NT in low-SOC soils was associated with both greater drainage and higher NO_3^- concentrations. The effects of SOC content on NO_3^- concentrations under NT may be related to the following factors associated with SOC-rich soils: (1) greater aggregate-protected C and N; (2) greater immobilization of N due to accelerated microbial activities (Zuber & Villamil, 2016); and (3) higher crop N uptake. These effects are expected to be more pronounced under NT systems since NT generally enhances macroaggregates and aggregate stability (Liu, Wu, et al., 2021), soil water conditions (Page et al., 2019), and carbon sequestration (Beare, Hendrix, & Coleman, 1994; Luo et al., 2010). Previous studies have reported that, compared to tilled soils, NT soils have greater aggregate-protected C and N, which contributes to the physical protection of organic matter from microbial decomposition (Beare, Hendrix, Cabrera, & Coleman, 1994; Mikha & Rice, 2004; Oorts et al., 2007), and this effect was more obvious in higher SOC soils (Liu, Wu, et al., 2021). It is also evident that nitrogen immobilization increases with the increase in soil organic matter content because of a more active microbial community (Barrett & Burke, 2000). In addition, in contrast to low- and medium-SOC soils, there is some evidence that NT may result in higher crop yields compared to tilled crops in high-SOC soils (Figure 2e) (Huang, Zhou, et al., 2015), which may be accompanied by an increase in crop N uptake and a decrease in residual soil nitrate available for leaching. Likewise, these higher crop yields under NT are expected to contribute to higher evapotranspiration and hence reduced drainage, while the opposite is true in low- and medium-SOC soils (<3%) (Figure 2). The results of this study suggest the potential for NT adoption in high-SOC soils to increase crop yields and mitigate NO_3^- leaching risk. Note that it remains unclear if increasing SOC content at a given site could result in lower NO_3^- leaching risk under NT. Future research is needed to verify if NO_3^- leaching risk under NT can be mitigated by companion practices that increase SOC content, such as cover crops and biochar applications (Bai et al., 2019).

Our meta-analysis also revealed that greater NO_3^- leaching losses under NT compared with inversion tillage were also associated with medium-textured soils, short-term NT duration, and relative low water input agricultural production systems (relative dry climate). As discussed above, NT-induced increases in soil microporosity and soil water content may be the main causes for the greater amount of drainage and NO_3^- leaching loss. For example, compared with tillage, NT has been shown to increase microporosity in medium-textured soils more than in coarse- or fine-textured soils (Mondal & Chakraborty, 2022). Previous research has shown that NT soils have higher bulk density and soil penetration resistance than tillage soils in the first few years, and that the differences also diminish with time (Blanco-Canqui & Ruis, 2018). The microporosity of soils is typically higher in those with higher bulk density and greater penetration resistance (Houlbrooke & Laurenson, 2013; Yi et al., 2022). This suggests that the increase in microporosity under NT mainly occurs in the short term, and the differences tend to decrease over time (Blanco-Canqui & Ruis, 2018). Although NT adoption in higher SOC soils is more likely to reduce the NO_3^- leaching risk, it remains unclear if the reduced NO_3^- leaching risk under long-term NT is attributable to an increase in SOC content (Kan et al., 2021). The inconsistent effects of NT duration on the relative changes in SOC under NT compared to tilled soils reported in previous meta-analyses (Das et al., 2022; Kan et al., 2021; Li et al., 2020; Nunes et al., 2020; Peixoto et al., 2020), and the poor correlation between NT duration and SOC in the current study (Figure S5), suggest that the influence of NT duration on the NO_3^- leaching risk may not be associated with changes in SOC content. Greater soil water content under NT relative to that under tillage was more prevalent in drier climates (De Vita et al., 2007). The greater NO_3^- leaching losses under NT compared with inversion tillage in areas with low water input, as reported in this study, is consistent with Daryanto et al. (2017) who reported that NT has greater NO_3^- leaching risk relative to tillage mainly in dry years and dryland production systems.

Our meta-analysis also found that there was less NO_3^- leaching under NT than under inversion tillage in fine-textured soils, which may be attributed in part to the higher SOC content of fine soils (Figure S6) (Burke et al., 1989). The analysis also showed that NT had greater NO_3^- leaching under low (0–100 kg ha^{-1}) and high rates (>200 kg ha^{-1}) of nitrogen application. This may have been due to poor crop establishment and low crop N uptake, as indicated by the significant crop yield decline at low application rates in NT systems (Figure 6e) (Pittelkow et al., 2015), and higher NO_3^- concentration at higher application rates (>200 kg ha^{-1}) (Figure 6d). NT had greater area-scaled NO_3^- leaching losses in soybean systems (Figure 7a). The reason for this is unclear, but the greater NO_3^- leaching losses are consistent with greater drainage in soybean systems. Although the data from this study were insufficient to assess the interactions between different factors influencing the response of NO_3^- leaching to NT, our results suggest the potential for important interactions between factors that need to be investigated further. For example, short-term NT in soils with low SOC resulted in relatively greater NO_3^- leaching losses compared with inversion tillage, whereas long-term NT was associated with a reduction in area-scaled NO_3^- leaching in medium (RC = −24%) and high (RC = −22% with one sample only) SOC soils (Figure S7).

4.3 | Risk of area-scaled NO_3^- leaching from NT relative to inversion tillage at a global scale

The AICc index identified the best-fit regression equation for the effect size (lnRR) of area-scaled NO_3^- leaching:

$$\ln RR = 0.27 - 0.13 \times SOC - 0.02 \times \text{NT duration} + 0.03 \times \text{Water input} - 0.03(\text{fine}-\text{textured soils}) + 0.13(\text{medium}-\text{textured soils}) \quad (R^2 = 10.4\%) \tag{8}$$

The equation shows that SOC, NT duration, water input, and soil texture explain 10% of total variations in the effect size (lnRR) of area-scaled NO_3^- leaching at the global scale.

The regression equation (Equation 8) was applied to the cropping land at the global scale to gain a preliminary understanding of the risk of NO_3^- leaching from the adoption of NT (Figure 9). Note that limited variations in effect size (or relative change) of area-scaled NO_3^- leaching from NT explained by these variables were partly due to the limited number of datasets, hence relatively large estimation uncertainties may exist. For this reason, no changes in NO_3^- leaching from NT are assumed when the relative changes are in the range of −5 to +5%; also by considering that 5% has usually been set as the threshold of non-significant change in geoscience (e.g., Hu & Si, 2014; Peterson & Wicks, 2006); and a change in NO_3^- leaching from NT relative to intensive tillage is assumed when relative changes are greater than 5% or less than <−5%. More paired comparisons of NO_3^- leaching under various tillage systems and conditions, particularly over the long term, are required to create a more robust dataset for model development and associated predictions. However, this study's regression equation clearly captured that NT tends to significantly ($p < .05$) decrease NO_3^- leaching relative to inversion tillage in high-SOC soils and under long NT duration (Table S2).

In Europe and Oceania, NT is predicted to result in less NO_3^- leaching than inversion tillage on average, while in other continents,

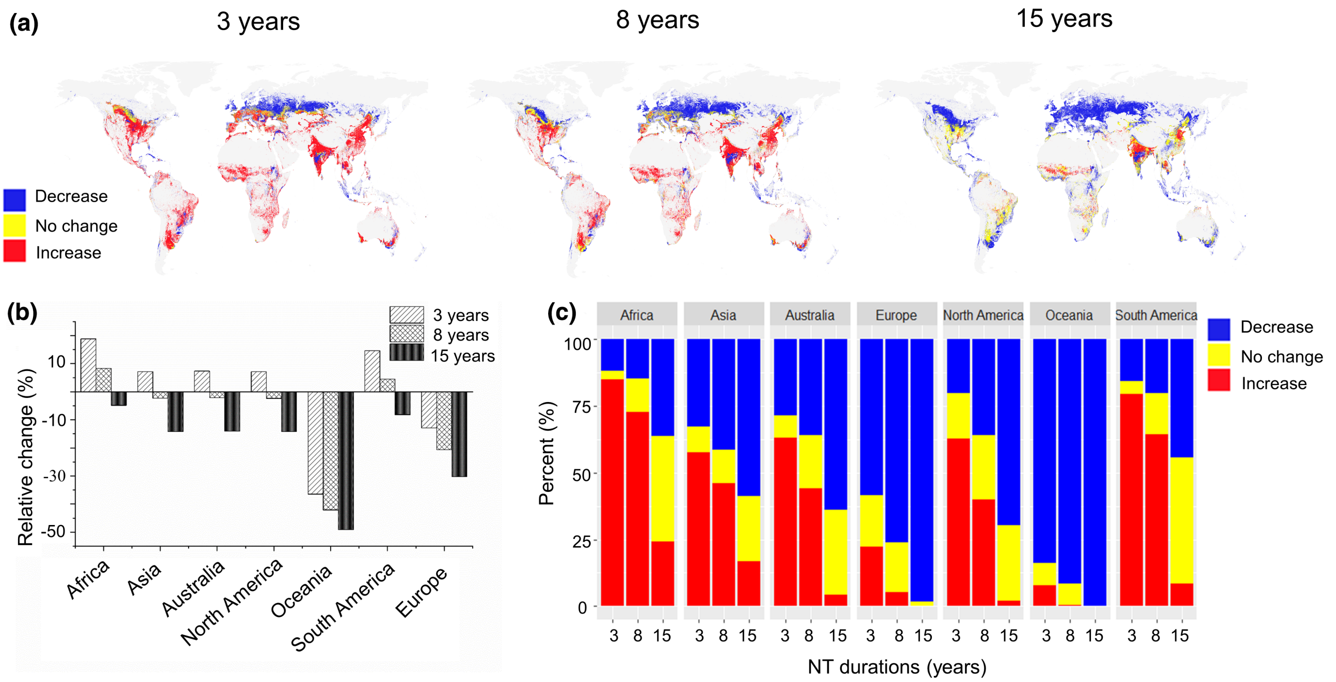

FIGURE 9 (a) Global maps of the relative change of area-scaled NO_3^- leaching under no-tillage (NT) relative to inversion tillage under three different NT duration scenarios (3, 8, and 15 years). Decrease, no change, and increase refer to relative change of NO_3^- leaching in NT relative to inversion tillage with <−5%, −5–5%, and >5%, respectively; (b) mean value of the percentage change in area-scaled NO_3^- leaching under NT relative to inversion tillage under three NT duration scenarios (3, 8, and 15 years) on different continents; (c) percentages of three different risk levels under different NT duration scenarios on different continents.

NT is predicted to result in greater NO_3^- leaching (Figure 9a). For example, our modeled predictions suggest that short-term (3 year) NT will result in greater area-scaled NO_3^- leaching than tillage on 63% of cropland in North America, but much less (22%) in Europe (Figure 9c). Correspondingly, the average relative change in area-scaled NO_3^- leaching with NT relative to inversion tillage was −13% (13% less) and +7% (7% more) in Europe and North America, respectively (Figure 9b). Furthermore, our model also projects that the risk of NO_3^- leaching decreases with increasing NT duration. It was estimated that the percentage of global cropping land with reduced risk of area-scaled NO_3^- leaching under NT relative to inversion tillage was 31%, 42%, and 54% under NT duration of 3, 8, and 15 years, respectively. While short duration NT (<3 years) in North America could increase area-scaled NO_3^- leaching by 7%, it is predicted to decrease area-scaled NO_3^- leaching by 16% after 15 years. Similarly, the relative change in area-scaled NO_3^- leaching decreased from +15% to −10% from 3 years' NT duration to 15 years' NT duration in South America. Therefore, the benefit of NT in reducing nitrate leaching relative to inversion tillage may be achievable in the long term. However, at this stage, the temporal changes in absolute NO_3^- leaching under NT over the long term are unclear because data are lacking. Continuously improving soil structure and companion practices that are beneficial for reducing drainage and NO_3^- concentration should be the key to mitigating NO_3^- leaching.

Finally, it is important to note that the data obtained for this study are heavily weighted toward North American and European crop production systems, while suitable data from other significant areas of NT cropping (e.g., South America and Australia) were not available. These gaps need to be filled in the future to verify the applications of this study on a global basis.

5 | CONCLUSIONS

Our meta-analysis confirmed that, on average, cropland recently converted to NT increased the risk of NO_3^- leaching, but the effects were significant only where NT was compared with inversion tillage. The NT effect was magnified when the NO_3^- leaching was scaled by yield relative to area. Globally, on average, greater NO_3^- leaching with NT was mainly attributed to greater drainage, rather than greater NO_3^- concentration in the drainage water, highlighting the importance of regulating hydrological conditions for mitigating NO_3^- leaching losses under NT systems. This study indicated the importance of SOC and other factors (e.g., soil texture, water input, and NT duration) in affecting the response of NO_3^- leaching to NT relative to inversion tillage. A preliminary analysis using a regression equation developed from the data and presented in global maps showed the variations in risk of NO_3^- leaching to NT under different NT duration scenarios. This study also highlighted that adopting NT in regions with high SOC soils could yield the greatest benefits in terms of reducing NO_3^- leaching losses with NT, relative to inversion tillage, especially in the longer term.

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CONFLICT OF INTEREST STATEMENT

We declare that we have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in figshare at https://doi.org/10.6084/m9.figshare.21914964.

ORCID

Jinbo Li https://orcid.org/0000-0001-8632-3297
Wei Hu https://orcid.org/0000-0002-5911-178X
Henry Wai Chau https://orcid.org/0000-0002-9411-9816
Mike Beare https://orcid.org/0000-0003-0027-3757
Rogerio Cichota https://orcid.org/0000-0002-1618-986X
Edmar Teixeira https://orcid.org/0000-0002-4835-0590
Tom Moore https://orcid.org/0000-0002-8373-627X
Hong Di https://orcid.org/0000-0002-6966-0299
Keith Cameron https://orcid.org/0000-0002-7631-1636
Jing Guo https://orcid.org/0000-0001-9469-4813
Lingying Xu https://orcid.org/0000-0001-7528-3509

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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