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META-ANALYSIS

The role of conservation agriculture practices in mitigating N_2O emissions: A meta-analysis

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Abstract

Conservation agriculture is often assumed to reduce soil N_2O emissions. Yet, studies analyzing the specific effect of conservation agriculture practices on N_2O emissions give contradictory results. Herein, we synthesized a comprehensive database on the three main conservation agriculture practices (cover crops, diversified crop rotations, and no-till and/or reduced tillage (NT/RT)) to elucidate the role of conservation practices on N_2O emissions. Further, we used a random meta-forest approach to identify the most important predictors of the effects of these practices on soil N_2O emissions. Averaged across all comparisons, NT/RT significantly decreased soil N_2O emissions by 11% (95% CI: –19 to –1%) compared to conventional tillage. The reductions due to NT/RT were more commonly observed in humid climates and in soils with an initial carbon content < 20 g kg^{-1}. The implementation of cover crops and diversified crop rotations led to variable effects on soil N_2O emissions. Cover crops were more likely to reduce soil N_2O emissions at neutral soil pH, and in soils with intermediate carbon (~20 g kg^{-1}) and nitrogen (~3 g kg^{-1}) contents. Diversified crop rotations tended to increase soil N_2O emissions in temperate regions and neutral to alkaline soils. Our results provide a comprehensive predictive framework to understand the conditions in which the adoption of various conservation agriculture practices can contribute to climate change mitigation. Combining these results with a similar mechanistic understanding of conservation agriculture impacts on ecosystem services and crop production will pave the way for a wider adoption globally of these management practices.

Keywords Cover crops · Diversified crop rotations · No-till · Reduced tillage · Nitrous oxide · Agricultural management practices

1 Introduction

Conservation agriculture is a farming concept promoting maintenance of permanent soil cover (e.g., cover crops), crop diversification (e.g., different crops in rotation), and minimum soil disturbance (e.g., no-till and/or reduced tillage [NT/RT]) (Giller et al. 2015; Northrup et al. 2021). The main goals of these farming concepts are to promote soil and water conservation and increase soil carbon (C) storage (González-Sánchez et al. 2012; Knapp and van

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der Heijden 2018; Rusinamhodzi et al. 2011). However, the effects of these practices on soil nitrous oxide (N_2O) emissions remain controversial (Basche et al. 2014; Lemke et al. 1998; Sainju 2015). Since N_2O is a powerful greenhouse gas (GHG) accounting for ~6% of current anthropogenic climate change (IPCC 2014), it is critical to resolve the role of conservation practices on N_2O emissions (Johnson et al. 2005). Nitrous oxide is predominantly emitted from agricultural soils and is mostly attributed to denitrification processes, but nitrification can also contribute strongly to soil N_2O emissions (Reay et al. 2012). The 100-year global warming potential of N_2O is 273 times that of carbon dioxide (IPCC 2021). Therefore, the potential benefits of these practices for climate change mitigation due to higher soil C storage can be offset by small increases in soil N_2O emissions (Lugato et al. 2018).

Cover crops can offer many ecosystem benefits, such as weed suppression, improved soil fertility, and decreased nutrient leaching and soil erosion relative to no cover crops (Akhtar et al. 2018; Poeplau and Don 2015; Thapa et al. 2016). Although cover crops can enhance environmental quality and soil health through increased soil C and nitrogen (N) cycling (Abalos et al. 2022a; Muhammad et al. 2019), they have highly variable effects on soil N_2O emissions. A meta-analysis by Basche et al. (2014) stated that the cover crop types (that is, legume or non-legume), biomass production, lignin content, and residue C/N ratios are the main factors driving the N_2O emission variability. However, the relative importance of these factors was not identified. Furthermore, the role played by climatic and soil parameters is still largely unknown but is needed to understand the conditions in which cover crops can be used as an agricultural practice that also mitigates climate change.

Globally, cropping systems range from monocultures to complex crop rotations, which have many varied crops sequentially planted (Chen et al. 2020b; Tenuta et al. 2019). Increased crop diversification can induce complex changes in soil properties affecting the abundance and function of N_2O-producing soil microbial communities (Adviento-Borbe et al. 2006; Banerjee et al. 2016; Tiemann et al. 2015). For example, several studies found that diversified crop rotations can increase soil N_2O emissions (e.g., Alvarez et al. 2012; Mosier et al. 2006; Sainju et al. 2012), and this can be due to stimulation of nitrifying and denitrifying bacterial abundance (Linton et al. 2020). Conversely, Snyder et al. (2009) found that a corn-soybean-wheat (*Triticum aestivum* L.) rotation had lower soil N_2O emissions in comparison to a continuous corn cropping for the entire rotation. Similarly, other studies found that more diverse crop rotations lowered soil N_2O emissions compared to mono-crop planting (Adviento-Borbe et al. 2007; Jacinthe and Dick 1997; Johnson et al. 2010). This is especially evident when all phases of the rotation are considered so that a 'rotational average' is compared with less diverse rotations (Drury et al. 2014a, b, 2021). Despite their potential for N_2O mitigation, the effects of diverse crop rotations have not been quantitatively synthesized.

The implementation of conservation tillage (NT/RT) is widely promoted globally among many diverse crop rotations and cropping systems to increase soil organic C, conserve soil water, enhance soil fertility, and reduce soil erosion, relative to conventional tillage (Rochette et al. 2008; Snyder et al. 2009; Venterea et al. 2005). Yet, from a climate change mitigation perspective, NT/RT effects on soil N_2O emissions have been intensively debated and are highly variable among individual studies (Abdalla et al. 2013; Powlson et al. 2012; Rochette et al. 2008; van Kessel et al. 2013; Zhao et al. 2016). Previous studies on the impact of adopting NT/RT reported that soil N_2O emissions were increased (Ball et al. 1999; Sainju 2015; Zhang et al. 2016), decreased (Drury et al. 2006, 2012; Gregorich et al. 2008; Mosier et al. 2006), or did not change (Lemke et al. 1998). A meta-analysis revealed that the effects of NT/RT on soil N_2O emissions may be time- and climate-dependent, with NT/RT only leading to N_2O reductions in dry climates and after more than 10 years after the implementation (van Kessel et al. 2013). The higher availability of studies since the meta-analysis of van Kessel et al. (2013) and the development of new statistical tools may allow us to better understand the robustness of these patterns. For example, a random-meta-forest analysis is a recently developed tool that can simultaneously assess various kinds of non-numeric and numeric variables, helping handle many potential predictors and their interactions (Abalos et al. 2022b; Chen et al. 2020a; Terrer et al. 2019). Therefore, it can be used to identify the main factors by which NT/RT (and cover crops and diversified crop rotations) regulates soil N_2O emissions and rank their relative importance.

Our objective was to synthesize the results of studies measuring the effects of cover crops, diversified crop rotations and NT/RT on soil N_2O emissions relative to no cover crops, mono-cropping and conventional tillage, respectively. A random-meta-forest approach was used to explore the main drivers of the effects of these conservation agriculture practices on soil N_2O emissions. We hypothesized that the links between soil properties, climatic and management factors can be unfolded to develop a predictive framework of the effects of conservation agriculture practices on soil N_2O emissions. Our study is the first to 1) concurrently test the effects of the three main conservation agriculture practices on soil N_2O emissions; and 2) incorporate a wide variety of soil, experimental and environmental predictors affecting responses of soil N_2O emissions to these practices.

2 Materials and methods

2.1 Data compilation

The dataset in this meta-analysis was constructed by using Scopus, Google Scholar (Google Inc., Mountain View, CA, USA; http://scholar.google.com/) and Web of Science (WOS; http://apps.webofknowledge.com/) following a screening of applicable studies within the Managing Agricultural Greenhouse Gases Network (MAGGnet) (Liebig et al. 2016). We searched peer-reviewed articles evaluating the effects of conservation agriculture practices that included cover crops, diversified crop rotations and NT/RT on soil N_2O emissions. For each study, we noted whether cover crops, diversified crop rotations, and NT/RT were compared with no cover crops, mono-cropping as well as conventional tillage, respectively. The keywords used for the paper selection were: (1) "cover crops" OR "reduced tillage" OR "rotations" OR "no-till" OR "zero tillage", OR "conservation tillage", AND (2) "nitrous oxide" OR "greenhouse gas" OR "N_2O" OR "GHG", AND (3) "soil" OR "land". The publications were included in this meta-analysis if they met the following criteria: (a) all factors (e.g., fertilization, soil properties and climatic parameters) were similar for cover crops, diversified crop rotations and NT/RT and the corresponding control treatments, (b) studies reported the experimental design and the details of recent history, (c) results were obtained under field conditions, and (d) the mean and the number of replications (*n*) were available. Moreover, standard deviation (*SD*) or standard error (*SE*) values were collected from articles when possible. Missing variances were calculated using the average coefficient of variation (*CV*) across the data set (van Groenigen et al. 2017). If the *SD* values were not reported in the studies, they were calculated from reported *SE* values, or *CV* according to the following equations:

$$SD = SE \times \sqrt{n} \tag{1}$$

$$SD = mean \times CV \tag{2}$$

For each study in our data set, we also tabulated details on the experimental and environmental variables: climate variables [mean annual temperature (MAT), mean annual precipitation (MAP)], site location [latitude and longitude], elevation, soil pH, soil organic C, soil total N, soil clay content, soil C:N ratios, experiment duration (in years), and annual fertilizer rate (<150 kg N ha^{-1} yr^{-1}, 150–200 kg ha^{-1} yr^{-1} and >200 kg N ha^{-1} yr^{-1}). When published data were only presented graphically, WebPlotDigitizer (https://automeris.io/WebPlotDigitizer/) was used to extract data. There were a number of studies where some of the supporting information was not listed in the published manuscript with the soil N_2O emissions data. In these cases, we contacted corresponding authors and requested the missing information. For the remaining missing values, we extracted MAT and MAP from WorldClim 2.1 (https://www.worldclim.org/), and soil clay content, soil pH, soil organic carbon (C), and soil total nitrogen (N) from SoilGrid 2.0 (https://soilgrids.org/). Soil C:N was calculated as the ratio of soil organic C and soil total N. Mean values of annual potential evapotranspiration for each study site were extracted from the Global Aridity Index geodatabase (https://cgiarcsi.community/data/global-aridity-and-pet-database/). Aridity Index (AI) was calculated as the ratio of MAP to mean annual potential evapotranspiration. Study sites with an AI <0.65 were categorized as 'dry', whereas study areas with a higher AI were categorized as 'humid' (UNEP 1997). Moreover, for cover crops, studies were divided into three categories (cash crops, cover crops, or both) based on the phase of the rotation in which the soil N_2O emissions were measured. Cover crop types were grouped into legume and non-legume. For the diversified crop rotations, the results are also analyzed according to the phase in the crop rotation (entire rotation or only when the corresponding monoculture crop was present in the rotation) in which the soil N_2O emissions were measured. The final database included 97 direct comparisons between cover crops and no cover crops, 33 direct comparisons between diversified crop rotations and mono-cropping, and 151 direct comparisons between NT/RT and conventional tillage. The geographical distribution of the studies is presented in Fig. 1. The articles and the number of comparisons within each article that were included in the analysis and related information such as experiment duration and climate are listed in Table S1.

2.2 Statistical analyses

We assessed the effects of cover crops, diversified crop rotations and NT/RT on soil N_2O emissions by calculating the natural log-transformed response ratio (*lnR*) (Hedges et al. 1999):

$$\ln R = \ln\left(\frac{X_{\mathrm{Treatment}}}{X_{Control}}\right) = \ln\left(X_{\mathrm{Treatment}}\right) - \ln\left(X_{Control}\right) \tag{3}$$

where $X_{Treatment}$ refers to the cumulative mean value of soil N_2O emissions in cover crops, diversified crop rotations, and NT/RT, $X_{Control}$ is the cumulative mean value of soil N_2O emissions in the corresponding control treatment (that is, no cover crops, mono-cropping, or conventional tillage).

The variance (v_i) of *lnR* was calculated as:

$$v_i = \left(\frac{SD^2_{Treatment}}{n_{Treatment}X^2_{Treatment}}\right) + \left(\frac{SD^2_{Control}}{n_{Control}X^2_{Control}}\right) \tag{4}$$

where $SD_{Treatment}$ is the standard deviation in cover crops, diversified crop rotations, and NT/RT, $SD_{Control}$ is the standard deviation values in the corresponding control treatment, $n_{Treatment}$ and $n_{Control}$ are the replicate numbers in cover crops, diversified crop rotations, or NT/RT and the corresponding

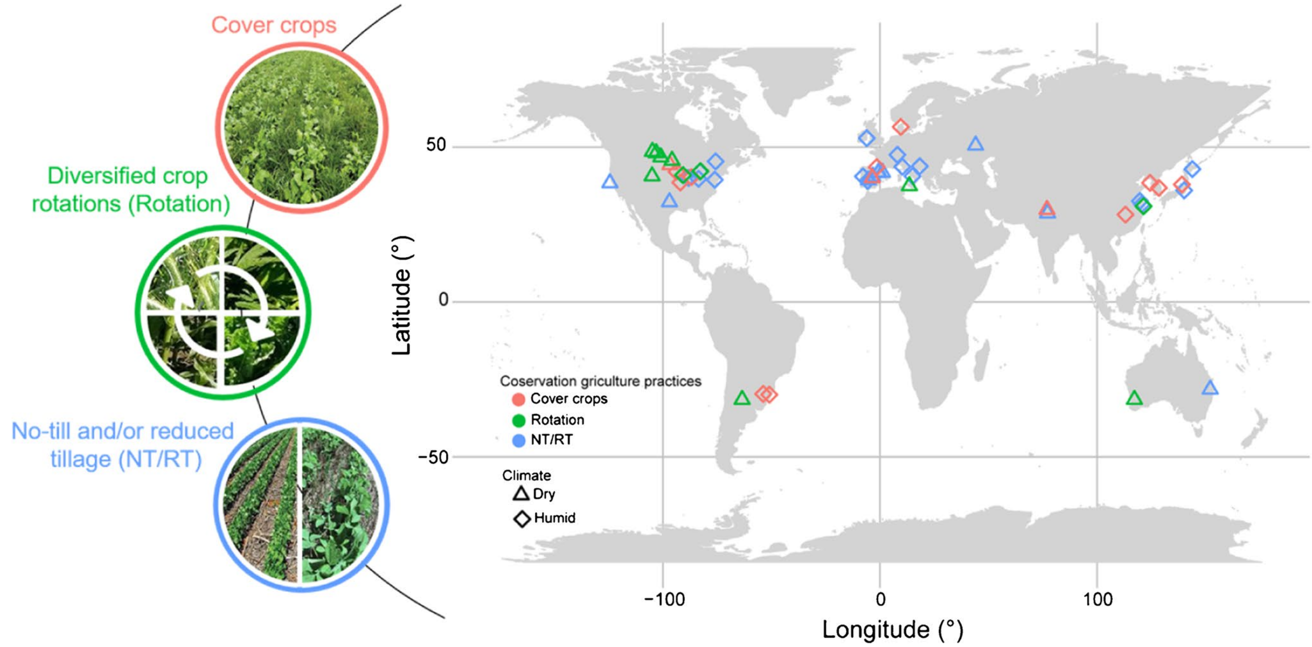

Fig. 1 Distribution of conservation agriculture practices included in the meta-analysis. Different shapes indicate climate (dry and humid), and different colors refer to the type of conservation agriculture practice. Rotation, diversified crop rotations; NT/RT, no-till and/or reduced tillage.

control treatment, and $X_{Treatment}$ and $X_{Control}$ are cumulative values for soil N_2O emissions for cover crops, diversified crop rotations, or NT/RT and the corresponding control treatment, respectively.

A weighted mixed-effects model was performed using the '*rma.mv*' function in the R package '*metafor*' (Abalos et al. 2022b; Chen et al. 2020a; Viechtbauer 2010). To ensure the independence of each observation, 'publication' and 'observation' were set as random factors in the mixed-effects models. The results were shown as percentage changes to ease interpretation [i.e., ($e^{\ln R}$-1) × 100]. The effects of cover crops, diversified crop rotations, and NT/RT were considered significant if the 95% confidence intervals (CIs) did not overlap with zero. Moreover, a random-forest model selection was used to identify the most important predictors (soil properties, weather factors and management practices) of the effects of cover crops, diversified crop rotations and NT/RT on soil N_2O emissions in the dataset. We incorporated available predictors in a bootstrapped random-forest meta-analysis with recursive preselection using the '*metaforest*' package of R (Terrer et al. 2019; Van Lissa 2017; Zhang et al. 2022). Based on partial dependence plots (Figs. S1, S2 and S3), the reciprocal transformations were used for nonlinear predictors. The most important predictors (13 for cover crops, 12 for diversified crop rotations, and 11 for NT/RT) were included in a mixed-effects meta-regression model with the '*metafor*' package of R (Terrer et al. 2016; Viechtbauer 2010). Finally, quadratic and linear meta-regressions were fitted to show the best model describing the links between the most important predictors and *lnR*. The optimal regression model was selected by Akaike information criterion (AIC; quadratic and linear models were considered), and the best model with lower AIC was retained.

3 Results

Averaged across the whole data set, NT/RT significantly decreased soil N_2O emissions by 10.6% (95% CI = −18.9 to −1.4%; Fig. 2a). In contrast, cover crops (mean effect size = 3.3%; 95% CI = –14.8% to 25.2%) and diversified crop rotations (mean effect size = 1.6%; 95% CI = −27.8% to 43.0%) had no significant effects on soil N_2O emissions due to a very large variability across the study sites (Fig. 2a). The responses of soil N_2O emissions ($lnR\text{-}N_2O$) were normally distributed for cover crops and the implementation of NT/RT, but not for diversified crop rotations (Fig. 2b).

Our random-meta-forest method identified soil pH, soil total N, and soil organic C as the most important predictors of the effects of cover crops on soil N_2O emissions (Fig. 3a). Cover crops-derived soil N_2O emissions were lowest at neutral soil pH (AIC=152, n=97; Fig. 3b), soil total N of ~3 g kg^{-1} (AIC=151, n=97; Fig. 3c), and soil organic C of ~20 g kg^{-1} (AIC=152, n=97; Fig. 3d). An absence of variation in predicted cover crop effects across cover crop types and climatic conditions reflected the lower predictive power of these factors (Fig. S1).

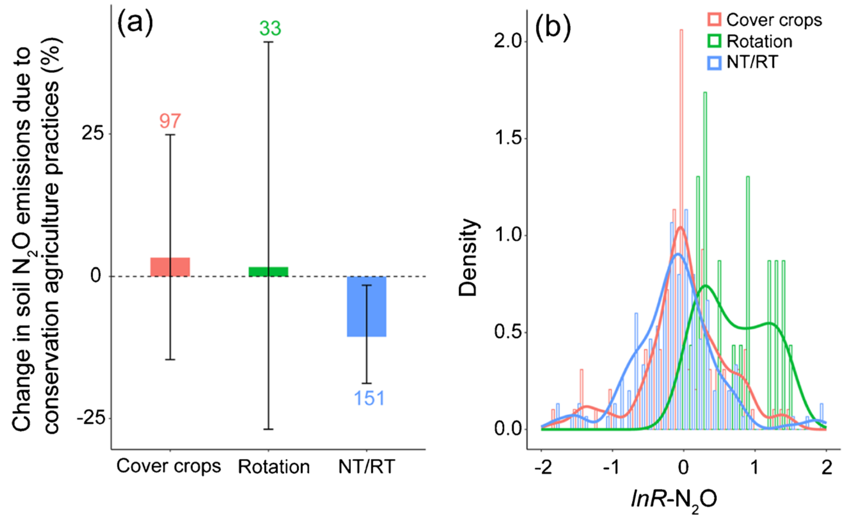

Fig. 2. **a** Effects of cover crops, diversified crop rotations (rotation), and no-till and/or reduced tillage (NT/RT) on soil N_2O emissions. (**b**) Distribution of log-transformed response ratios of soil N_2O emissions (*lnR*-N_2O) to cover crops, diversified crop rotations and NT/RT practices. Error bars refer to bootstrap 95% confidence intervals (CIs). The numbers are sample sizes. The fitted curves are from the estimated Gaussian distribution in frequency.

Among 11 potential predictors, MAT, soil pH, and soil clay content were the primary modulators of the responses of soil N_2O emissions to diversified crop rotations vs mono-cropping (Fig. 4a). Soil N_2O emissions from diversified crop rotations reached a maximum at the MAT values of 13–15℃ (AIC=82, n=33; $p< .05$) and at soil pH values of 7–8 (AIC=85, n=33; $p < .05$) compared to N_2O emissions from mono-cropping (Figs. 4b, c). Soil N_2O emissions from diversified crop rotations were reduced at increasing values of soil clay content (Fig. 4d). Partial dependence plots showed the weaker predictive power of other factors (i.e., soil total N, experiment duration, MAP, climate, fertilizer rate, and rotation crop) for the effects of diversified crop rotations on soil N_2O emissions (Fig. S2).

Our random-forest meta-analysis showed that the most important predictors of NT/RT effects on soil N_2O emissions in our dataset were initial soil organic C, MAP, and soil C:N ratios (Fig. 5a). Soil N_2O emissions from NT/RT increased with increasing values of soil organic C (AIC= 274, n=151; p=0.20; Fig. 5b) but decreased with increasing

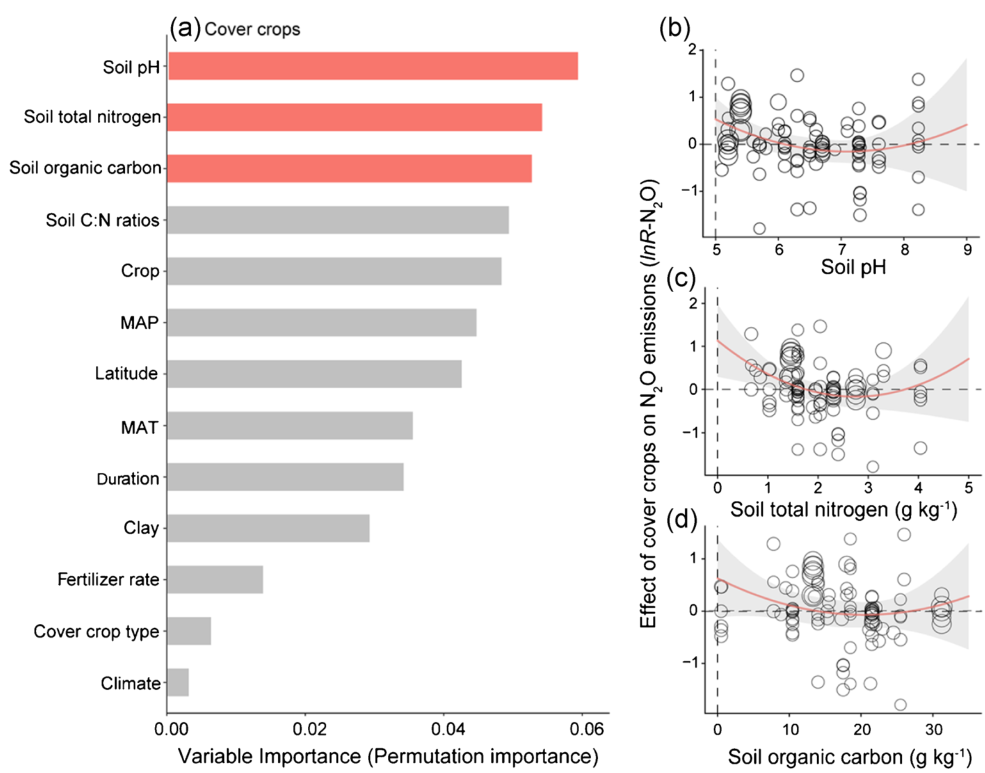

Fig. 3 **a** Variable importance of the factors regulating the impacts of cover crops on soil N_2O emissions based on the random-meta-forest approach. (**b**, **c**, and **d**) Meta-analytic scatterplots between the effects of cover crops on soil N_2O emissions and the most important predictors of these effects (soil pH, soil total nitrogen, and soil organic carbon). The optimal regression model was chosen by Akaike Information Criterion (AIC). Crop: the phase of the rotation in which the soil N_2O emissions were measured (cash crops, cover crops, or both of them); MAP: mean annual precipitation; MAT: mean annual temperature; Cover crop types: legume and non-legume; Climate: humid and dry; Fertilizer rate: <150 kg N ha^{-1} yr^{-1}, 150–200 kg N ha^{-1} yr^{-1} and >200 kg N ha^{-1} yr^{-1}.

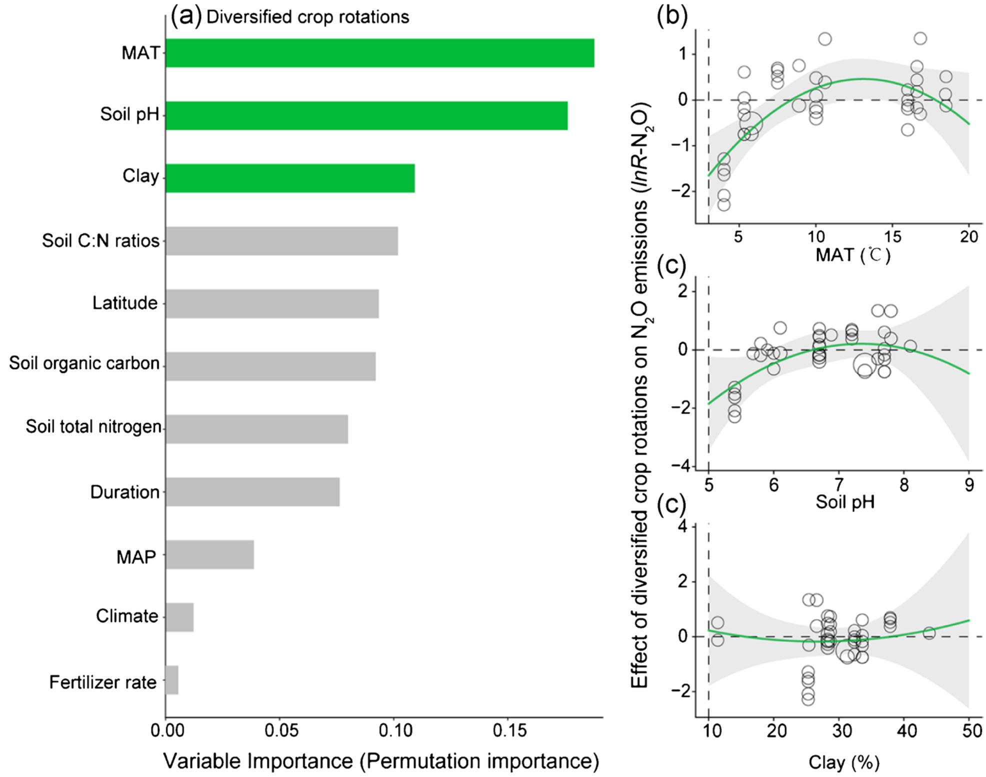

Fig. 4 **a** Variable importance of the factors regulating the impacts of diversified crop rotations on soil N_2O emissions based on the random-meta-forest approach. (**b**, **c**, and **d**) Meta-analytic scatterplots between the effects of diversified crop rotations on soil N_2O emissions and the most important predictors of these effects (MAT, soil pH, and soil clay content). The optimal regression model was chosen by Akaike Information Criterion (AIC). MAP: mean annual precipitation; MAT: mean annual temperature; Climate: humid and dry; Fertilizer rate: <150 kg N ha^{-1} yr^{-1}, 150–200 kg N ha^{-1} yr^{-1} and >200 kg N ha^{-1} yr^{-1}.

MAP (AIC=268, n=151; p=0.01; Fig. 5c). Soil N_2O emissions from NT/RT increased with soil C:N ratios, reaching a maximum at ~10–12 (Fig. 5d). Soil N_2O emissions responses to NT/RT were not well predicted by climate and fertilizer rate (Fig. S3).

Cover crops tended to reduce soil N_2O emissions as the N fertilizer rate applied to the cash crops increased (Fig. 6). Cover crop effects on soil N_2O emissions did not differ between cover crop types (legume or non-legume) or climate regimes (dry or humid). When separated by crop rotation phase in which the soil N_2O emissions were measured, the increases in soil N_2O emissions in cover crop studies were significant when only the cover crop phase was included, but not when measurements also included the cash crop phase (Fig. 6). No significant diversified crop rotation effects were found after separating the data set by fertilizer rate (<150 kg N ha^{-1} yr^{-1}, 150–200 kg ha^{-1} $yr^{-1}$and >200 kg N ha^{-1} yr^{-1}), climate regime (dry or humid), or period in the rotation when soil N_2O emissions were measured (entire rotation compared to a monoculture crop or only when the same crop in the rotation as the monoculture crop are compared). For NT/RT, the reductions of soil N_2O emissions were only significant in humid climates. No significant NT/RT effect was found when separated by fertilizer rate.

4 Discussion

4.1 Effects of cover crops on soil N_2O emissions

Our meta-analysis found that cover crops increased, decreased or had neutral effects on soil N_2O emissions (Fig. 2a), confirming the trends observed in previous studies (Basche et al. 2014; Poeplau and Don 2015; Shan and Yan 2013). We found that the effects were modulated by specific management practices, N fertilizer rate and edaphoclimatic factors. Cover crops tended to increase soil N_2O emissions mainly during the cover crop phase of the rotation (Fig. 6), and this could be explained by the C supply from rhizodeposition through actively growing root systems, promoting denitrification (Abdalla et al. 2013; Mitchell et al. 2013; Webb et al. 2000). Moreover, we found that the capacity of cover crops to reduce soil N_2O emissions increased as N fertilizer rate to the previous cash crop rises (Fig. 6). This could be because cover crops can utilize the residual soil N in the late fall, which would reduce N_2O emissions from both nitrification and denitrification (Abdalla et al. 2019; Drury et al. 2014b). Our finding of no significant effects of cover crop types (legume vs non-legume) on soil N_2O emissions is inconsistent with Muhammad et al. (2019), who reported higher soil N_2O emissions with legume cover

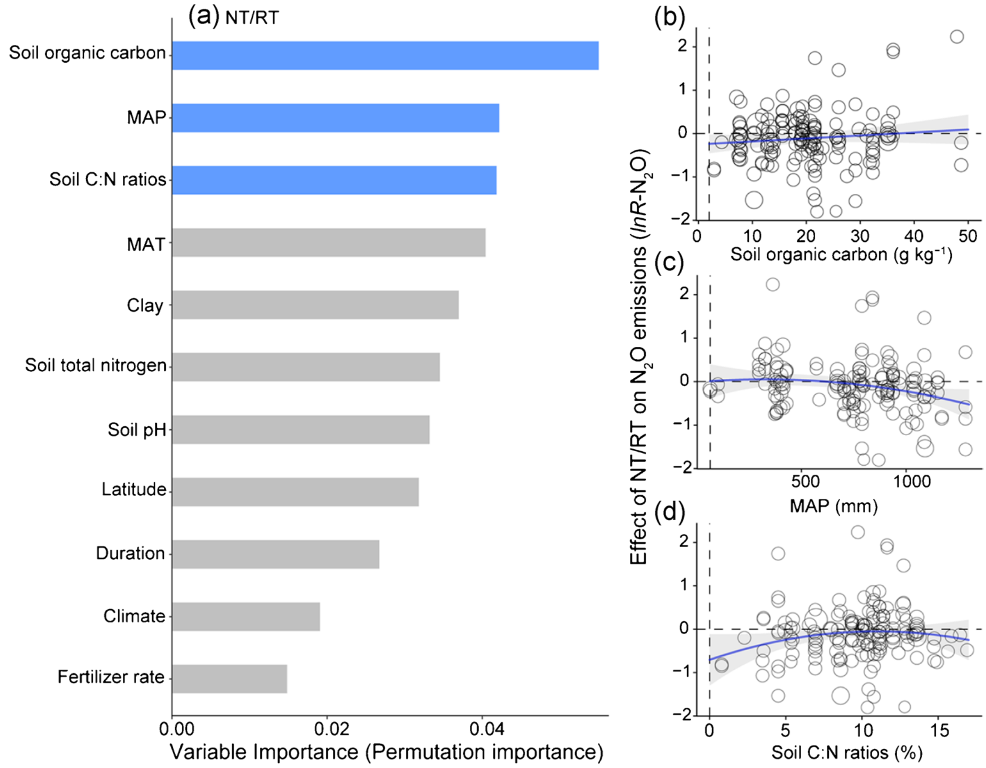

Fig. 5 **a** Variable importance of the factors regulating the impacts of no-till and/or reduced tillage (NT/RT) on soil N_2O emissions based on the random-meta-forest approach. (**b**, **c**, and **d**) Meta-analytic scatterplots between the effects of no-till and/or reduced tillage on soil N_2O emissions and the most important predictors of these effects (soil organic carbon, MAP, and soil C:N ratios). The optimal regression model was chosen by Akaike Information Criterion (AIC). MAP: mean annual precipitation; MAT: mean annual temperature; Climate: humid and dry; Fertilizer rate: <150 kg N ha^{-1} yr^{-1}, 150–200 kg N ha^{-1} yr^{-1} and >200 kg N ha^{-1} yr^{-1}.

crops than with non-legume cover crops. The lack of difference between cover crop types in our study supports the notion that legumes have a high capacity to self-regulate in terms of N input via N_2 fixation (De Notaris et al. 2021), and therefore their effects on N cycling (including soil N_2O emissions and nitrate leaching) are similar to those of non-legume cover crops. Additional field studies are warranted to clarify the potential differences between cover crop types in terms of N_2O emissions, including other plant functional groups and more detailed trait-based approaches.

Soil pH, soil total N and soil organic C were strong predictors of the effect of cover crops on soil N_2O emissions (Fig. 3a). Cover crops-derived N_2O emissions were lowest at neutral soil pH (Fig. 3b). The reason may be that neutral soil pH values stimulate cover crop biomass production, which can decrease N_2O emissions by increasing plant N uptake thereby lowering soil mineral N availability for nitrifiers and denitrifiers, and also due to higher plant water uptake, which could decrease soil moisture content below the optimum for N_2O production (Abalos et al. 2020; Zhang et al. 2022). Cover crops were more likely to reduce soil N_2O emissions from soils with intermediate soil N and soil organic C contents. In soils with low C and N contents, cover crops can trigger N_2O by increasing the availability of C and N through root exudation and plant biomass decomposition. In soils with high C and N contents, a more diverse and abundant microbiome may be able to decompose the cover crop biomass more efficiently (Jian et al. 2020), and greater abundance of N-cycling microorganisms can increase the amount of N_2O produced (Zhang et al. 2021).

4.2 Effects of diversified crop rotations on soil N_2O emissions

Diversified crop rotations are a broad category often with a mixture of different agronomic practices, and the effects may depend on what crops are used to diversify, as well as the fertilization and tillage practices required for each of those crops (Venter et al. 2016; Zhao et al. 2020). In addition, in many diversified rotations total N_2O emissions from the entire rotation sequence can be lower because there are fewer phases that receive mineral N fertilizer (Drury et al. 2021; MacWilliam et al. 2018; Zhao et al. 2022). However, we did not find differences in soil N_2O emissions according to the period in the rotation in which soil N_2O emissions were measured. Despite this high variation, our study was able to identify the main factors determining when diversified crop rotations may be able to reduce soil N_2O emissions. Mean annual temperature was the best predictor of the effects of diversified crop rotation on soil N_2O emissions, with emission reductions mainly observed at low MAT values (Fig. 4a). Diversified crop rotations can promote the growth of nitrifying and denitrifying communities (Linton et al. 2020), and stimulate soil N_2O emissions by providing a higher quantity, quality, and chemical diversity of C inputs (Zhao et al. 2020). It is possible that these effects are less

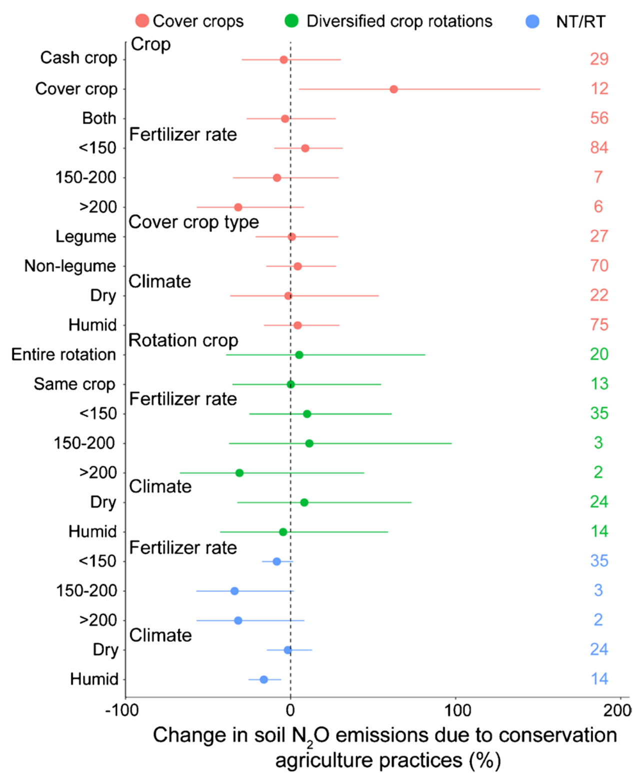

Fig. 6 Effect of cover crops, diversified crop rotations, and no-till and/or reduced tillage (NT/RT) on soil N_2O emissions as a function of N fertilizer rate and climate. For the cover crops, the results are also shown as a function of the cover crop type, and crop of the phase of the rotation in which the soil N_2O emissions were measured. For the diversified crop rotations, the results are also shown as a function of the phase in the crop rotation (entire rotation or only when the corresponding monoculture crop was present in the rotation) in which the soil N_2O emissions were measured. Error bars represent bootstrap 95% confidence intervals (CIs). Error bars represent 95% confidence intervals, and the numbers refer to sample size.

clear when N_2O production processes and microbial mineralization are limited by low temperatures (Aulakh et al. 1992; Behnke et al. 2018; Chen et al. 2022; Johnson et al. 2011, 2012; Smith et al. 2011; Snyder et al. 2009). Another possibility is that, since complex rotations can increase soil moisture (Linton et al. 2020; Zhao et al. 2020), they might have increased soil N_2O emissions in warmer and drier sites. In Mediterranean climates for example, nitrification can be the main contributor to N_2O emissions because soil water-filled pore space does not exceed 60% often (Ardenti et al. 2022; Bateman and Baggs 2005; Perego et al. 2016) and therefore slight increases in soil moisture induced by complex rotations can stimulate N_2O emissions.

Soil pH and soil clay content were important predictors of soil N_2O emissions from diversified crop rotations (Fig. 4a). Increases in soil N_2O emissions with more complex rotations were observed at neutral soil pH values, perhaps because soil acidity constrains the potential changes in soil microbial communities induced by diversified rotations. The relationship between soil clay content and *lnR*-N_2O is difficult to explain, and the patterns are less clear (Fig. 4d), suggesting that a confounding variable may be behind these effects. Indeed, we found that soil clay content was positively correlated with soil pH for this dataset (Spearman's rank correlation coefficient = 0.49), and therefore the role of soil clay content should be interpreted with caution. The sample size for the extremes of clay content was small in this analysis, which could bias the results. More field studies are needed to rigorously explore the response of soil N_2O emissions to diversified crop rotations as affected by soil clay content.

4.3 Effects of NT/RT on soil N_2O emissions

Consistent with previous meta-analyses (Mei et al. 2018; van Kessel et al. 2013), the implementation of NT/RT significantly decreased soil N_2O emissions (Fig. 2a). In contrast, a recent meta-analysis conducted by Shakoor et al. (2021) stated that NT significantly increased soil N_2O emissions by 12%. We found that the N_2O reductions induced by NT were positively related to the MAP (Fig. 5c), implying N_2O mitigation was more commonly found in humid climates (Fig. 6), which is supported by Mei et al. (2018) and van Kessel et al. (2013). As indicated by the latter authors, the higher soil moisture content promoted by NT/RT might not be sufficient to increase soil N_2O emissions from denitrification in regions where soil moisture content is already high due to abundant rainfall (humid climates); conversely, NT/RT can further stimulate nitrification, heterotrophic denitrification and/or nitrifier denitrification by increasing the soil water filled-pore space under dry climates (Cox et al. 1990; Dobbie and Smith 2003; Palma et al. 1997).

Our analysis using the random-meta-forest method showed that soil organic C and soil C:N ratios had strong predictive power regarding soil N_2O emissions after NT/RT implementation, which is consistent with other meta-analyses (Shakoor et al. 2021). Reductions in soil N_2O emissions from NT/RT in soil with low C content may be mediated by changes in soil physical conditions, as NT/RT can increase soil organic matter content (Ogle et al. 2012). Increasing soil organic matter can progressively improve soil structure, which could suppress the formation of anaerobic microsites conducive to soil N_2O production (Ussiri et al. 2009; Malhi et al. 2006). Such soil organic matter increases are more likely to be observed in soils with lower initial C content relative to soils with greater soil C concentration (Huang et al. 2018).

4.4 The way forward

Using a yield-scaled approach can be a valuable tool to reconcile the targets of increasing food production while reducing agricultural GHG emissions. This methodology should be considered in future meta-studies to understand the feasibility of conservation agriculture practices, since their potential effects on crop yields are highly uncertain. For example, while diversified crop rotations tend to increase crop yield (Zhao et al. 2020), NT/RT can reduce it, depending on climatic and soil factors (Huang et al. 2018; Pittelkow et al. 2015; van Kessel et al. 2013; Wang et al. 2018). The impact of cover crops on yield is particularly variable, and depends on the cover crop species, the termination timing, and the method of termination, among others management practices (Abdalla et al. 2019; Tonitto et al. 2006; Valkama et al. 2015; Wang et al. 2021).

Conservation agriculture practices can increase agroecosystem complexity (Abalos et al. 2019; Grandy et al. 2022), providing an opportunity to transition into more biologically based agroecosystems that rely more on internal N cycling and less on external N inputs, and this could be better assessed in future synthesis work by normalizing N_2O emission (and ammonia volatilization, nitrate leaching, nitric oxide and N_2 emissions) based on N application. This emission factor approach (IPCC 2021) can be a way to account for the differences in N fertilizer rates due to e.g., the extra N provided by biological N fixation with legumes, or for reduced N losses with cover crops (i.e., N quota), providing a clearer picture of the wider implications of conservation agriculture practices for N cycling.

5 Conclusion

We conducted a global meta-analysis to understand the impacts of conservation agriculture practices (cover crops, diversified crop rotations and NT/RT) on soil N_2O emissions. Conservation agriculture can promote ecosystem multi-functionality by enhancing regulating and supporting services, including biodiversity preservation, soil and water quality, and climate mitigation (Wittwer et al. 2021). However, our results show that climate benefits may be sometimes compromised under specific edaphoclimatic conditions due to potential increases in soil N_2O emissions. Only conservation tillage (NT/RT) appeared to mitigate soil N_2O emissions consistently across the three main conservation agriculture practices included in this analysis. However, NT/RT can jeopardize crop production if not adopted in combination with cover crops and longer rotations (Pittelkow et al. 2015) as expected according to the principles of conservation agriculture. This is particularly the case under wet and cool soil conditions in humid regions, which may delay emergence and reduce cash crop yields (Allam et al. 2021; Morugán-Coronado et al. 2020). In these situations, alternative conservation tillage practices such as zone or strip tillage may represent a better option to manage the cover crops under reduced tillage (Drury et al. 2006, 2012).

We found that the large variation in the response of soil N_2O emissions to cover crops and diversified crop rotations could be well predicted by specific soil and climatic factors. Accordingly, our results provide a roadmap of the regions of the world in which the adoption of specific conservation agriculture practices will help mitigate climate change more efficiently.

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Authors' contributions Conceptualization was conducted by DA, JC, CD. Data curation was conducted by ZW, DA and CD. YL conducted the statistical analysis and produced all graphs. Formal analysis and methodology of the meta-analysis data was conducted by YL, JC, and DA. Writing (original draft preparation) was conducted by YL, DA, CD, and JC. ML, JJ, and ZW gave intensive feedback on the first draft. All authors contributed to the writing (editing and review) and approved the final version of the manuscript.

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Data availability The data will be available from Figshare once the manuscript is published.

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Declarations

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