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Synthesizing the evidence of nitrous oxide mitigation practices in agroecosystems

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Synthesizing the evidence of nitrous oxide mitigation practices in agroecosystems

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E-mail: diego.gradosb@agro.au.dk**Keywords:** agricultural soils, nitrous oxide, greenhouse gas, mitigation, evidence synthesis, meta-analysisSupplementary material for this article is available [online](#)**Abstract**

Nitrous oxide (N₂O) emissions from agricultural soils are the main source of atmospheric N₂O, a potent greenhouse gas and key ozone-depleting substance. Several agricultural practices with potential to mitigate N₂O emissions have been tested worldwide. However, to guide policymaking for reducing N₂O emissions from agricultural soils, it is necessary to better understand the overall performance and variability of mitigation practices and identify those requiring further investigation. We performed a systematic review and a second-order meta-analysis to assess the abatement efficiency of N₂O mitigation practices from agricultural soils. We used 27 meta-analyses including 41 effect sizes based on 1119 primary studies. Technology-driven solutions (e.g. enhanced-efficiency fertilizers, drip irrigation, and biochar) and optimization of fertilizer rate have considerable mitigation potential. Agroecological mitigation practices (e.g. organic fertilizer and reduced tillage), while potentially contributing to soil quality and carbon storage, may enhance N₂O emissions and only lead to reductions under certain pedoclimatic and farming conditions. Other mitigation practices (e.g. lime amendment or crop residue removal) led to marginal N₂O decreases. Despite the variable mitigation potential, evidencing the context-dependency of N₂O reductions and tradeoffs, several mitigation practices may maintain or increase crop production, representing relevant alternatives for policymaking to reduce greenhouse gas emissions and safeguard food security.

1. Introduction

Increasing atmospheric concentrations of nitrous oxide (N₂O) is a major driver of climate change and stratospheric ozone depletion (Ravishankara *et al* 2009, IPCC 2021). Agriculture is the primary anthropogenic source of N₂O, contributing globally about 3.8 (2.5–5.8) Tg N yr⁻¹ or 22% to the atmospheric N₂O budget (Tian *et al* 2020). Direct soil N₂O emissions from agroecosystems account for 61% of anthropogenic emissions (Tian *et al* 2020). Due to the projected increases in food demand (van Dijk *et al* 2021), agricultural land area, and fertilizer use, the

associated N₂O emissions are expected to rise over the coming decades (Reay *et al* 2012, Davidson and Kanter 2014). Climate change may further exacerbate N₂O emissions from agricultural soils (Montzka *et al* 2011, Bowles *et al* 2018). This daunting picture challenges stated policy goals to curb greenhouse gas (GHG) emissions from agriculture, such as the Paris Agreement (United Nations Framework Convention on Climate Change 2015, Clark *et al* 2020). However, active management of agroecosystems offers opportunities for N₂O mitigation without jeopardizing (perhaps even increasing) food production (Smith *et al* 2008, Snyder *et al* 2009).

N₂O emission reductions are best achieved by altering the environmental factors that promote N₂O production and release (most prominently soil aeration, soil N content, C availability, and soil pH), by inhibiting biochemical pathways during which N₂O is produced using soil additives, or by precise N management to minimize excess soil N inputs (Paustian *et al* 2016). A wide range of mitigation practices for N₂O abatement has been proposed and tested at field-scale (Snyder *et al* 2014). Biochar (Dawar *et al* 2021), organic amendments (Li *et al* 2021, Ruangcharus *et al* 2021), conservation tillage (Arango and Rice 2021, Pelster *et al* 2021), and enhanced-efficiency fertilizers (Friedl *et al* 2020, Nishimura *et al* 2021), among others, have been assessed worldwide, with contrasting results. For instance, while biochar amendments frequently reduce N₂O emissions (Schmidt *et al* 2021), the effects of organic amendments are equivocal (Lazcano *et al* 2021).

As a result of the burgeoning of laboratory and field-scale experiments, several meta-analyses synthesizing empirical results from individual mitigation practices have been published in recent years (e.g. Akiyama *et al* 2010, Cayuela *et al* 2014, Zhang *et al* 2020a). While meta-analyses may differ in scope, methods, and geographic scale, they are comparable when they assess the same response (i.e. soil N₂O emission) for an intervention type (i.e. mitigation practice). However, results from meta-analyses regarding the same mitigation practice do not always confirm each other due to the variability of the experimental results and data collection procedures (e.g. databases, sample size, language, and quality criteria). In this context, combining a systematic review (i.e. high-level review using rigorous and explicit accountable research methods; Gough *et al* 2017) and second-order meta-analysis (i.e. meta-analysis of meta-analyses; Hunter and Schmidt 2004) provides a robust framework to integrate and synthesize cumulative evidence-based knowledge of N₂O mitigation practices. Specifically, second-order meta-analysis allows to consolidate research quantitatively by assimilating and gauging meta-analyses grounded on diverse designs, samples, and variables for high-level generalization (Castellanos and Verdú 2012) and to ascertain true effects (i.e. non-artifactual, by pooling the effects sizes to obtain a larger sample size that reduces uncertainties) for multiple meta-analyses, even when they report contrasting results (Schmidt and Oh 2013, Tamburini *et al* 2020). Therefore, this tool can be used to advance our understanding of the variability and performance of N₂O mitigation practices. The fast-growing number of studies assessing N₂O mitigation practices and synthesis-based research allows to simultaneously compare the N₂O mitigation potential of prominent mitigation practices, thus enabling a robust ranking of their mitigation efficiency. This information is crucial to guide policymaking to reduce GHG emissions from

agricultural soils and identify mitigation measures requiring further research before implementation.

The objective of this study was to understand the effect of various mitigation practices on N₂O emissions. Therefore, we conducted a narrative and quantitative synthesis of published meta-analyses focused on N₂O emissions from agricultural soils. Specifically, we conducted a systematic review combined with a second-order meta-analysis of 27 meta-analyses, including 41 effect sizes (obtained from 1119 primary studies and 3700 pairwise comparisons).

2. Material and methods

2.1. Protocol and reporting

The initial protocol of the study was pre-registered on the Open Science Framework before data collection and analysis (<https://doi.org/10.17605/osf.io/2fjhw>). The reporting guidelines suggested in ROSES (Reporting standards for Systematic Evidence Synthesis; Haddaway *et al* 2018) were followed where applicable (figure S1). Data processing, analysis, and figure generation were executed using R v.4.0.3 (R Core Team 2020).

2.2. Systematic review

2.2.1. Literature search strategy

A systematic search combined with a semi-automatic co-occurrence network (Grames *et al* 2019) was performed to identify published meta-analyses. We used ISI Web of Science and SCOPUS databases and the search engine Google Scholar. Our search covered all articles having titles, abstracts, or keywords in English, with no restrictions on publication type. The cut-off date was May 2021. Further details of the literature search (e.g. keywords) can be found in Supplementary information S1.

2.2.2. Eligibility criteria

After removing duplications (figure S1), the articles were screened by title and abstract to meet the eligibility criteria. The fundamental eligibility criterion was that the study should be a meta-analysis focused on at least one mitigation practice for N₂O emission from agroecosystems (tables S1 and S2). This step resulted in 142 articles. Additional eligibility criteria were considered during full-text screening: (a) Meta-analyses needed to assess the impact of mitigation practices on agricultural soils in peer-reviewed publications. For instance, if a meta-analysis reported effect sizes for different land uses or ecosystem types, only those referring to agricultural soils were retained (e.g. Wang *et al* 2021). (b) Systems comparisons were excluded if pairwise comparisons of the mitigation practice were not performed. (c) Regional and national level meta-analyses were included (e.g. Aguilera *et al* 2013, Gao *et al* 2021) due to their extensive geographical scope. However, meta-analyses with small regional scope (i.e. region within a country)

were not considered (e.g. Xu *et al* 2017) due to limited sample size. (d) The studies had to provide clear information regarding what was considered treatment and control. (e) The effect size of the mitigation practice was calculated using formal meta-analytic methodologies. (f) The precision of the effect size had to be indicated (i.e. standard error or confidence interval). (g) Meta-analyses in which primary studies were fully considered in more recent meta-analyses were excluded (e.g. Akiyama *et al* 2010). (h) The list of primary studies had to be provided. Authors were contacted when the complete list of references was unavailable from the publication (e.g. Huang *et al* 2018). Removal of duplicates and screening of articles were performed using CADIMA (Kohl *et al* 2018). After this step, the database consisted of 57 articles (figure S1).

2.2.3. Considerations of statistical independence

The use of the same primary studies in different meta-analyses focused on the same N₂O mitigation practice can be a source of non-independence among meta-analyses. To overcome this type of pseudoreplication, we quantified the overlap percentage between primary studies (figure S2). This resulted in one additional eligibility criterion: (i) only meta-analyses with less than 30% overlap of primary studies were retained in the database (Tamim *et al* 2011, Tamburini *et al* 2020). When the 30% percentage was exceeded, the rationale for deciding what study should be retained was that meta-analyses with a higher number of primary studies and rigorous methodology were preferred (i.e. high-quality studies according to table S2; see section 2.2.5). A total of 28 articles were considered statistically independent (27 in English and 1 in Chinese). The visualization for assessing statistical independence (figure S2) was implemented using the R-package tidygraph 1.2.0 (Pedersen 2020).

2.2.4. Data extraction and effect sizes

Study identification characteristics (e.g. title, author, and publication year), contextual information (e.g. mitigation practice and geographical range), methodological procedures (e.g. literature search strategy and experimental scale), and data analysis features (e.g. statistical model, effect size type, and precision indicator) were extracted from the meta-analyses. Data from text and tables were directly obtained from the study, while data from figures were extracted using Engauge Digitizer v12.1 (Mitchell *et al* 2019). If a study reported sub-group analysis but not the overall effect size of the N₂O mitigation practice, we calculated the overall effect size with a meta-analytic fixed-effect model, which pools the partial effect sizes of the sub-group analyses (e.g. Xia *et al* 2017, Wang *et al* 2021). Sampling error variance was estimated using the commonly reported 95% confidence intervals

(CIs) assuming a normal distribution (Castellanos and Verdú 2012). We transformed all the effect sizes (e.g. response ratio and percentage of change) to a standard metric (i.e. log response ratio—lnRR). However, we removed one study because we were unable to transform the mean difference to lnRR without the original data (Aliyu *et al* 2021). The sign of the effect sizes was reversed when the contrast was against the mitigation practice instead of the control treatment. The final dataset included 27 meta-analysis studies (*n*) encompassing 41 effect sizes (*k*) based on 1119 primary studies (*m*) with 3700 pairwise comparisons (*l*) (Supplementary data).

The N₂O mitigation practices were (table S1): biochar, crop residue removal instead of crop residue retention, use of organic fertilizer instead of synthetic fertilizer, use of cover crops instead of fallow soil between cash crops, diversified crop rotation instead of crop monoculture, optimization of fertilizer rate (i.e. according to total *N* crop requirement) compared to conventional application rates, increased fertilizer application frequency compared to single fertilizer application, deep fertilization instead of superficial fertilizer application, slow- or controlled release fertilizer, nitrification inhibitor, urease inhibitor, combination of nitrification and urease inhibitors, lime amendment, no-tillage or reduced tillage compared to conventional tillage, and drip irrigation compared to traditional irrigation techniques such as sprinkler or furrow irrigation. The proposed mechanisms by which these practices may mitigate N₂O emissions are summarized based on the systematic review in Supplementary information S2.

2.2.5. Methodologic quality of the meta-analyses

The quality of meta-analyses can differ widely due to methodological aspects by which primary studies are selected, the meta-analytic model used, and how results are reported (Nakagawa *et al* 2017, Gurevitch *et al* 2018, Pigott and Polanin 2020). To account for this potential bias, we calculated a quality index (see Tamim *et al* 2011, Beillouin *et al* 2021) based on 11 methodological criteria: (a) definition of the experimental (i.e. mitigation practice) and control treatment, (b) literature search strategy, (c) number of databases and search engines used, (d) number of original studies included, (e) eligibility criteria to select primary studies, (f) statistical model, (g) average effect size and precision indicator, (h) weighting procedure, (i) publication bias assessment, (j) availability of heterogeneity indicators, and (k) sensitivity assessment. Further description for each category is provided in Supplementary information table S2. Meta-analyses were ranked for each criterion with a high score (2) or low score (1). The theoretical maximum value is 22. The sum of the scores defined the general quality, which was used in further analysis (see section 2.3.2).

2.3. Second-order meta-analysis

2.3.1. Statistical model

The impact of the N₂O mitigation practices was assessed with a multi-level mixed meta-regression model with a categorical predictor (i.e. moderator) using the extracted overall effect sizes and corresponding variance from every meta-analysis (i.e. not the effect sizes derived from individual pairwise observations included in each meta-analysis). The form of the statistical model was:

$$\hat{\theta}_{ik} = \theta + \beta D_g + w_i + u_{ik} + e_{ik} \quad (1)$$

with $w_i \sim N(0, \sigma_B^2)$, $u_{ik} \sim N(0, \sigma_W^2)$, $e_{ik} \sim N(0, v_{ik})$

where $\hat{\theta}_{ik}$ is the estimate of the true effect size θ (intercept) based on the k th effect size of the i th meta-analysis, β is the regression coefficient (representing the effect size difference) of the categorical predictor D_g (mitigation practice), w_i is the random effect accounting for the variance between meta-analyses (σ_B^2), u_{ik} is the random effect accounting for the variance within meta-analysis (σ_W^2) and e_{ik} is the sampling error with variance v_{ik} . The model was fitted without intercept to obtain the parameter estimates ($\hat{\theta}_{ik}$) for each level of the categorical predictor.

The meta-analysis was weighted by the inverse of the sampling variance of the effect sizes. The following nested random effect was assumed: meta-analysis ID encompassing the effect sizes extracted from the same meta-analysis, and effect size ID representing the residual/within-meta-analysis variance. Model parameters were calculated using the restricted maximum likelihood estimator (Viechtbauer 2005). Estimates were transformed to percentages of change to ease interpretation. Estimates are presented with their 95% CIs in square brackets throughout, and statistical significance was assumed when CIs did not span zero. Moreover, 95% prediction intervals (PIs) were reported. CIs represent the range of the average true effect to be found, and PIs the range in which 95% of effects are expected to occur in similar future (or unknown) studies (IntHout *et al* 2016, Kim *et al* 2021). Significance tests of the estimates and the CIs were computed assuming a z -distribution. The omnibus test of moderators (Q_M) was reported. The percentage of heterogeneity explained by the moderator was estimated using R^2_{marginal} (Nakagawa and Schielzeth 2013). The meta-analysis was fitted using the R-package metafor v.3.0–2 (Viechtbauer 2010). Results of the main effect model were graphically represented as lookalike forest graphics (i.e. orchard plots) using the R-package orchaRd v.0.0.0.9000 (Nakagawa *et al* 2020).

2.3.2. Publication bias and sensitivity analysis

Publication bias was explored with Funnel plots and Egger's Regression tests (Sterne *et al* 2006, Sterne and Egger 2006). We fitted multi-level mixed

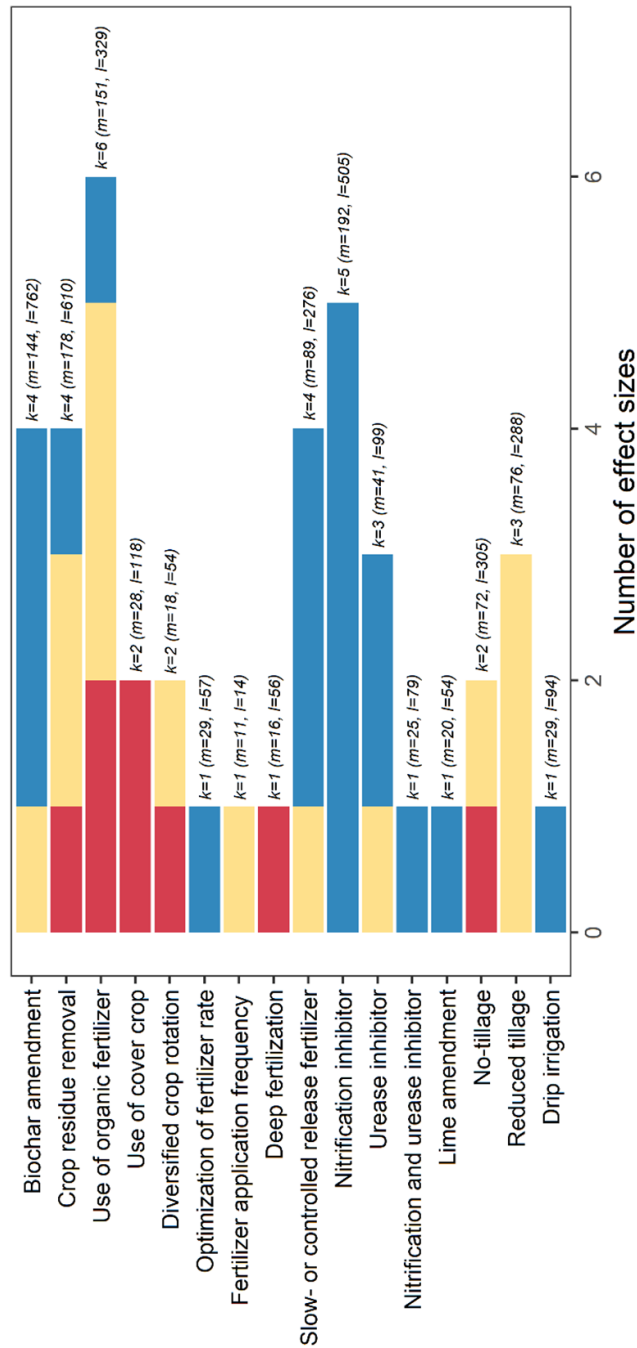
meta-regression models, including the standard error and sample size as moderators separately. The potential presence of bias was identified based on the significant deviation of the model intercept from zero. Similarly, influential studies were identified based on the leverage (i.e. hat values) extracted from the hat matrix and potential outliers based on the standardized residuals (Viechtbauer 2020). Studies with large influence were those with two times the average leverage (Habeck and Schultz 2015), whereas possible outliers were those studies with high standardized residuals. Meta-regressions including continuous moderators were plotted with the R-package ggplot2 v.3.3.5 (Wickham 2016).

We used two different approaches as a sensitivity analysis to test the robustness of the multi-level mixed meta-regression model. We used a conservative estimation with the Knapp-Hartung adjustment (Knapp and Hartung 2003, van Aert and Jackson 2019) based on a t -distribution. This adjustment controls for the uncertainty in the estimate of between-study heterogeneity affecting the calculation of the standard error, the hypothesis tests, and CI using the Satterthwaite adjustment. To incorporate the quality of the meta-analyses, a quality effects model was fitted (Doi *et al* 2015). Consequently, the weights of the effect sizes were compensated by the rescaled quality index (based on the highest index) obtained for each meta-analysis, thereby reducing the weight of low-quality studies.

3. Results

3.1. Systematic review

We found that 46% of the effect sizes showed significant N₂O reductions across the mitigation practices, while 34% showed neutral responses and 20% significant increases in N₂O emissions (figure 1). Among all the mitigation practices, the use of organic fertilizer ($k = 6$ effect sizes), nitrification inhibitor ($k = 5$), biochar amendment ($k = 4$), and crop residue removal ($k = 4$) were the most frequently assessed. Nitrification inhibitors ($k = 5$), biochar amendment ($k = 3$), and slow- or controlled release fertilizer ($k = 3$) reported a high number of effect sizes with significant N₂O reductions compared to other potential mitigation practices. However, the use of nitrification inhibitors was the only practice consistently showing N₂O reductions across all meta-analyses (figure 1). Less explored (e.g. optimization of fertilizer rate or high fertilizer application frequency) and more recent meta-analyzed N₂O mitigation practices (e.g. lime amendment and drip irrigation) resulted in single effect sizes (figure 1). Most of the meta-analyses had a global scope (70%), followed by the country scale (China with 16%) (figure S4(A)). The overall quality score of the meta-analyses was relatively high, ranging from 14 to 22 (figure S4(B)), with a median of 18 (theoretical maximum value = 22).



Response ■ Significant increase ■ No change ■ Significant reduction

Figure 1. The number and direction of effect sizes for every N₂O mitigation practice included in our synthesis. *k* indicates the number of effect sizes, *m* the number of primary studies, and *I* the number of pairwise comparisons.

3.2. Second-order meta-analysis

The efficiency of the mitigation practices for curbing N₂O emissions was highly variable (test of moderator $Q_M = 208$ ($p < 0.0001$)); the moderator explained 83% of heterogeneity ($R^2_{\text{marginal}} = 0.829$). Considerable N₂O reductions were found for biochar amendment (−26.6%), optimization of fertilizer rate (−31.2%), slow- or controlled release fertilizer (−33.0%), nitrification inhibitors (−44.1%), urease inhibitors (−22.5%), combined use of nitrification and urease inhibitors (−49.4%), and drip irrigation (−26.5%). The use of greater frequency of fertilizer application (−5.4% [−26.9 to +22.3%]), crop residue removal (−2.6% [−14.2 to +10.6%]), and lime amendment (−9.0% [−30.8 to +19.7%]) led to mixed results, though across all studies minor reductions in N₂O emissions were observed. The use of organic fertilizer (+4.8% [−7.2 to +18.4%]), diversified crop rotation (+8.6% [−17.1 to +42.3%]), deep fertilization (+18.6% [−6.9 to +51.1%]), no-tillage (+11.7% [−8.9 to +37.0%]) or reduced tillage (+3.7% [−11.1 to +21.0%]) resulted in marginal increases in N₂O emissions as compared to standard practices. The use of cover crops increased N₂O emission by +36.7% (figure 2).

There was no clear evidence of publication bias for the second-order meta-analysis. Based on the standard error fit (intercept = −0.207, $p = 0.001$; $R^2_{\text{marginal}} = 0.088$), effect sizes tended to become marginally smaller as standard error increased (figure S5(A)). Nevertheless, there was no evidence of publication bias derived from the sample size fit (intercept = −0.061, $p = 0.386$; $R^2_{\text{marginal}} = 0.046$); effect sizes tended to become marginally smaller as sample size (i.e. number of pairwise comparisons) increased (figure S5(B)). Influential studies were only identified for mitigation practices based on a single meta-analysis (figure S6); an effect size with high standardized residual (belonging to diversified crop rotation under paddy soil conditions) was identified (figure S6). The two approaches of the sensitivity analysis showed that our results are robust, as all the different models yielded similar effect sizes to our primary model (table S3).

4. Discussion

Several technology-driven solutions showed substantial N₂O mitigation potentials across meta-analyses (figure 2). These included biochar, slow- or controlled release fertilizers, nitrification inhibitors, and urease inhibitors. Drip irrigation and the combination of both inhibitor types, also reduced N₂O emissions, based on one effect size each. The main goal behind the development of these technologies was originally not to mitigate N₂O emissions. Biochar was valued for its capacity to retain C in the long term, thereby potentially increasing soil C sequestration (Wu *et al* 2019). Enhanced-efficiency

fertilizers were developed to achieve better synchronicity between N release and crop uptake, thereby increasing uptake efficiency while simultaneously reducing nitrate leaching (slow- or controlled release fertilizer and nitrification inhibitors) or ammonia (NH₃) volatilization (urease inhibitors) (Akiyama *et al* 2010, Timilsena *et al* 2015, Li *et al* 2018). Drip irrigation is widely used as an irrigation practice for optimizing water supply to high-value crops (e.g. vegetables, grain crops; Vallejo *et al* 2014, Zhang *et al* 2020b, Qasim *et al* 2021), thus increasing crop water use efficiency as compared to flood or sprinkler irrigation (van der Kooij *et al* 2013); 20% of cropland worldwide is irrigated, contributing to 40% of the world food production (The United Nations World Water Development 2014). Although there are potential tradeoffs linked to certain technology-driven options that need to be considered (e.g. nitrification inhibitors may increase NH₃ volatilization; Li *et al* 2005, Pan *et al* 2016, Wu *et al* 2021), our results suggest that these management practices can achieve substantial N₂O reductions from agricultural soils.

As opposed to the technology-driven options, agroecological practices tended to increase N₂O emissions (figure 2). Examples of these practices are the use of organic fertilizer, diversifying crop rotations, reduced/no-tillage, and the use of cover crops. Despite the potential adverse impact on N₂O, these practices (not primarily conceived to abate N₂O emissions) are linked to a wide range of beneficial effects, including enhanced soil biodiversity (Liu *et al* 2016, Venter *et al* 2016, Chen *et al* 2020, Kim *et al* 2020), lower weed infestation (Osipitan *et al* 2019), increased nutrient retention (McDaniel *et al* 2014, Chen *et al* 2018, Wei *et al* 2021), reduced water pollution (Thapa *et al* 2018), reduced soil erosion (Sun *et al* 2015), and other ecosystem services (Iverson *et al* 2014, Lichtenberg *et al* 2017). From a GHG balance perspective, reduced/no-tillage may increase soil organic carbon (SOC), although this topic remains widely debated (e.g. Baker *et al* 2007, Powlson *et al* 2014, Bai *et al* 2019). Cover crops may increase soil C storage by 6%–16% (Bai *et al* 2019, Jian *et al* 2020). Therefore, a unidimensional view focused on reducing soil N₂O emissions does not capture the multifunctional benefits of agroecological interventions (Guenet *et al* 2021).

Most agroecological practices had a highly variable effect on N₂O emissions, highlighting the need to better understand under which pedoclimatic and management conditions such practices may lead to N₂O mitigation instead of stimulation. For instance, the N₂O mitigation of organic amendments is primarily determined by their physicochemical characteristics and N-fertilizer substitution rate (Ren *et al* 2017, Zhang *et al* 2020a). Most of the available meta-analyses focused on solid manure, whereas only one evaluated the effect of replacing synthetic fertilizers with livestock slurry with regard to soil N₂O

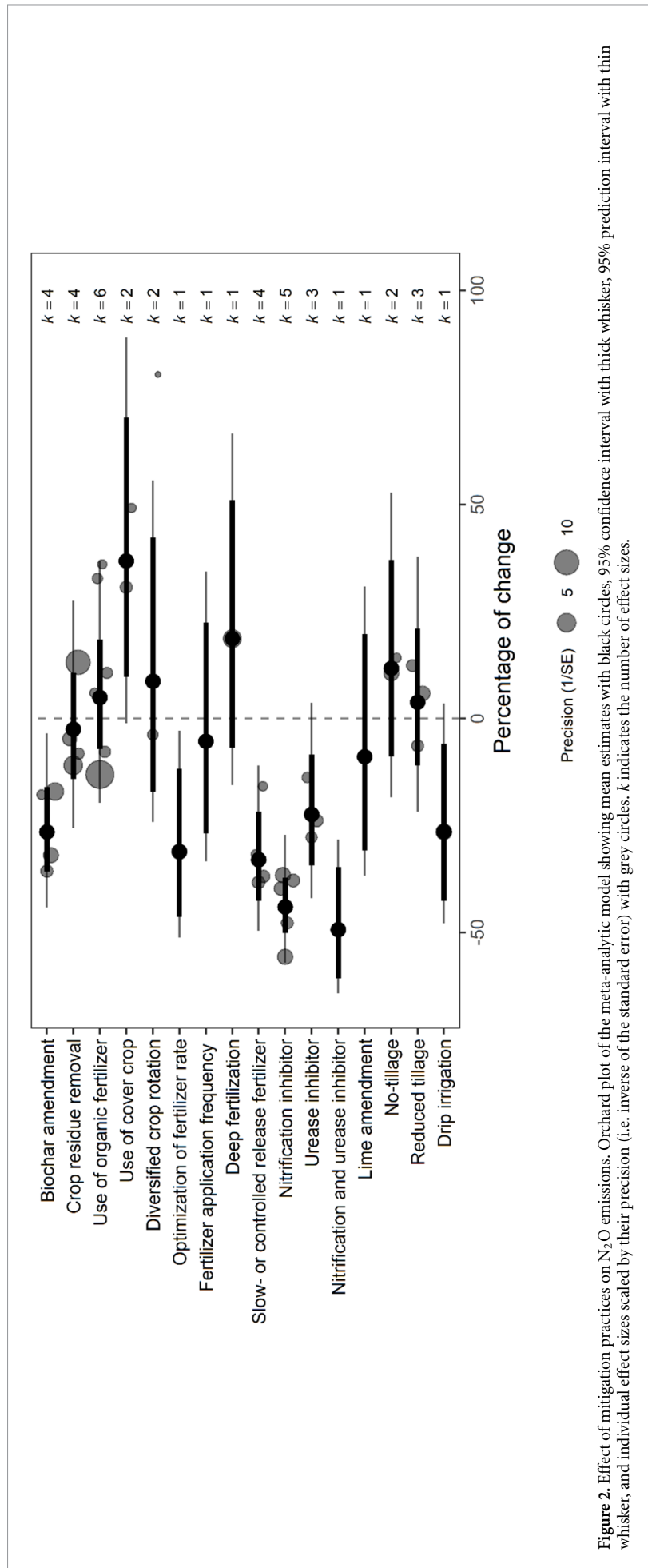


Figure 2. Effect of mitigation practices on N₂O emissions. Orchard plot of the meta-analytic model showing mean estimates with black circles, 95% confidence interval with thick whisker, 95% prediction interval with thin whisker, and individual effect sizes scaled by their precision (i.e. inverse of the standard error) with grey circles. *k* indicates the number of effect sizes.

emissions (Aguilera *et al* 2013). Crop diversification may reduce N₂O emissions depending on the specific crops within the rotation and fertilization schemes (Ijaz *et al* 2019). However, understanding crop diversification effects is challenging due to crop-specific confounding variables (e.g. timing and rate of fertilizer application, different rooting depths) and methodological constraints (e.g. continuous N₂O measurements over multiple years are required). These reasons may explain the limited number of effect sizes and corresponding primary sources for this management option (figure 1). Even though conservation tillage practices (i.e. reduced/no-tillage) may increase N₂O emissions, they could potentially decrease N₂O emissions in dry areas over time (van Kessel *et al* 2013, Mei *et al* 2018). The effect of cover crops on N₂O emissions varies with cover crop species (e.g. legume and non-legume), termination date, and soil incorporation (Basche *et al* 2014). It is necessary to update meta-analytic results with the burgeoning primary studies considering the temporal (including non-growing season) and geographical effects on N₂O release, especially for diversified crop rotation and cover crops.

While optimized fertilizer rate according to crop needs showed important N₂O reductions, increasing the frequency of fertilizer applications, crop residue removal, and lime application reduced N₂O emissions only marginally. This may be because the N₂O mitigation potential of these practices is highly context-dependent. Crop residue removal may only reduce N₂O emissions when the residues are immature and have a low C/N ratio (Chen *et al* 2013, Essich *et al* 2020, Abalos *et al* 2022); rainfall distribution determines the efficacy of split fertilizer application (Abalos *et al* 2017, Song *et al* 2022); lime-induced N₂O abatement may only occur when the soil pH is below a critical value, defined by the liming material and application rate (Wang *et al* 2021). Better matching of crop N need and N supply through optimization of fertilizer rate offers significant opportunities for N₂O emission reductions (Davidson and Kanter 2014), and it can be combined with technology-driven solutions and agroecological practices. However, predicting crop N need is difficult due to variable soil and weather conditions, with increasing variability of environmental conditions induced by climate change (Hénault *et al* 2012, Reay *et al* 2012, Kanter *et al* 2016). Therefore, our results imply that these practices must be assessed on a case-by-case basis and at farm or regional scale before recommending their adoption for N₂O mitigation.

Several policies and regulations aimed at curbing agricultural N₂O and other GHG emissions have been launched recently, most of which require drastic emission reductions in the near future (Rogelj *et al* 2016, Clark *et al* 2020). For instance, Ireland

(agriculture contributes to 37% of GHG emissions; Environmental Protection Agency 2021) committed to decreasing agricultural GHG emissions by 22%–33% compared to 2017 levels by 2030 (Department of the Environment, Climate and Communications 2021). Denmark's agricultural sector, contributing 25% of the national total GHG emissions, with N₂O emissions accounting for 45% (Nielsen *et al* 2021), pledged to reduce GHG emissions by 55%–65% below 1990 levels by 2030 (Ministry of Finance 2021). Considering that the overall range of N₂O mitigation potential for the technology-driven solutions was 22%–49% (figure 2), our results indicate that adopting a portfolio of strategies for N₂O mitigation at the field level may strongly contribute to achieve these mitigation targets despite the variability. Furthermore, since N₂O emissions can dominate the GHG balance of agricultural soils (Li *et al* 2005, Lugato *et al* 2018, Autret *et al* 2019), failing to incorporate N₂O mitigation practices into environmental initiatives (e.g. carbon farming practices; Tang *et al* 2016, Oldfield *et al* 2022) may hinder efforts to obtain GHG emissions reductions. Policy efforts should address the economic and social constraints limiting the adoption of mitigation practices (Smith *et al* 2007).

Although agriculture is a crucial sector for the reduction of anthropogenic GHG emissions (Wollenberg *et al* 2016, Frank *et al* 2018, Tian *et al* 2019, 2020, IPCC 2021), only 131 countries (covering 72% of global GHG emissions) are discussing, have announced, or have adopted net-zero targets (Höhne *et al* 2021). One of the reasons limiting international commitments may be the perceived potential tradeoffs between GHG mitigation and food production (Frank *et al* 2017). However, several N₂O mitigation practices do not compromise biomass or food production. Many of them tend to enhance crop yields (see table S4 for references), including biochar (9%–28% increase in yield) in tropical regions predominantly, deep fertilization (4%–11%), drip irrigation (12%), optimization of fertilizer rate (1%), increased frequency of fertilizer application (6%), lime amendment (36%), nitrification inhibitors (4%–10%), urease inhibitors (5%–10%), and the combined use of inhibitors (1%–9%). The use of slow- or controlled released fertilizers has uncertain effects on crop production, whereas yield decline can sometimes be observed with high substitution rate of synthetic fertilizer by organic sources (no effect to 14% reduction), reduced/no-tillage (no effect to 6% reduction), and crop residue removal (reduction 5%–8%). There is no consensus on the impact of cover crops on yield, while diversified crop rotation may have a positive effect (20%) (table S4). Efforts to reduce N₂O emissions from agricultural soils could simultaneously improve food security. Therefore, they should represent a priority in policy agendas,

providing a tool to overcome barriers to implementation (Snyder *et al* 2009, Kanter *et al* 2020).

A systematic review allows to identify knowledge gaps. In addition, a second-order meta-analysis can advance our understanding of differences and similarities among N₂O mitigation practices by aggregating results across numerous meta-analyses grounded on hundreds of studies with thousands of pairwise comparisons. This approach can gauge the true between-meta-analyses variability of mean effect size values, and use this information to improve estimation accuracy for each first-order meta-analytic mean estimate (Schmidt and Oh 2013). For certain management practices, our second order meta-analysis synthesizes a relatively low number of original meta-analyses, which in some cases are based on relatively small datasets. However, we contend that also in these cases, a second-order meta-analysis provides important advantages over first-order meta-analyses. First, by combining data from more than one meta-analysis, we increase statistical power. This is especially important in those cases when the number of available studies is relatively low. Second, our standardized approach ensures that overall treatment effects are directly comparable and are not affected by artifacts related to differences in methodological approaches between individual first-order meta-analyses. Yet, certain shortcomings can arise from this generalization. Due to the nature of the method and the specific factors controlling each N₂O mitigation strategy, further moderator analyses (e.g. temporal dynamics, experimental scale, management practices, pedoclimatic features, and land use) are unfeasible. This limits the capacity of this methodology to provide region-specific recommendations as effects may depend on pedoclimatic conditions or field management, which can be better identified in first-order meta-analyses. To complement our results and guide the implementation of the N₂O mitigation practices, the assessment of yield-scaled emissions (e.g. van Groenigen *et al* 2010) would be valuable.

Our synthesis exposes critical research gaps to be filled in future studies. Due to the nature of meta-analyses, the N₂O reductions are mainly shown for individual mitigation practices, but many of the examined practices may be combined at the field scale, leading to synergistic or antagonistic effects on N₂O emissions (e.g. Fuertes-Mendizábal *et al* 2019, Pokharel and Chang 2021). There is a need to explore and document such interactions, including the tradeoffs and long-term effects of potential mitigation practices for designing cropping systems to minimize N emissions while enhancing production without compromising soil functions or services (Power 2010, Bommarco *et al* 2013, Greiner *et al* 2017, Bünemann *et al* 2018). Novel strategies with possible N₂O mitigation capacity (and their interactions with more assessed mitigation practices) have not been

sufficiently studied to be meta-analytically studied. Some examples are intercropping (Pappa *et al* 2011, Huang *et al* 2019), biological nitrification and denitrification inhibitors (Subbarao *et al* 2009, Bardon *et al* 2014), silicate additions (Vicca *et al* 2021), and inoculants for legumes (Bakken and Frostegård 2020).

5. Conclusions

We present a second-order meta-analysis of the effects of management practices on N₂O emissions from agricultural soils. Despite the intrinsic variability of N₂O mitigation practices, technology-driven solutions (enhanced-efficiency fertilizers, biochar, and drip irrigation) and fertilizer rate optimization may substantially reduce emissions in agroecosystems. These practices may favorably be implemented because they often increase crop production. On the contrary, certain agroecological practices (e.g. use of organic fertilizer) may exacerbate N₂O release if they are not carefully managed. Our exhaustive evidence synthesis provides a state-of-the-art overview of the potential for N₂O abatement of the main available mitigation strategies.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.17605/osf.io/2fjhw>.

Code availability statement

The code to reproduce the findings of this study is openly available at the following URL/DOI: <https://doi.org/10.17605/osf.io/2fjhw>. The synthesized data after curation is provided (Supplementary data).

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Author contribution

Conceptualization, D G and D A; Methodology, D G and D A; Software, D G; Formal Analysis, D G and D A; Data Curation, D G; Writing—Original Draft,

D G, K B B; J C, K J G, J E O, J W G, and D A; Writing—Review & Editing, D G, K B B; J C, K J G, J E O, J W G, and D A; Supervision, D A; Funding Acquisition, D A.

Conflicts of interest


The authors declare no conflict of interest.

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