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## LETTER

## Synthesizing the evidence of nitrous oxide mitigation practices in agroecosystems

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Jørgen Eivind Olesen<sup>1</sup> , Jan Willem van Groenigen<sup>5</sup> and Diego Abalos<sup>1</sup> <sup>1</sup> Department of Agroecology, iClimate, Aarhus University, 8830 Tjele, Denmark<sup>2</sup> Pioneer Center Land-CRAFT, Department of Agroecology, Aarhus University, Aarhus C 8000, Denmark<sup>3</sup> Institute of Meteorology and Climate Research, Atmospheric Environmental Research, Karlsruhe Institute of Technology, 82467 Garmisch-Partenkirchen, Germany<sup>4</sup> Department of Geography, College of Life and Environmental Sciences, University of Exeter, EX4 4QE Exeter, United Kingdom<sup>5</sup> Soil Biology Group, Wageningen University and Research, 6708PB Wageningen, The Netherlands

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E-mail: [diego.gradosb@agro.au.dk](mailto: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 (N<sub>2</sub>O) emissions from agricultural soils are the main source of atmospheric N<sub>2</sub>O, a potent greenhouse gas and key ozone-depleting substance. Several agricultural practices with potential to mitigate N<sub>2</sub>O emissions have been tested worldwide. However, to guide policymaking for reducing N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O decreases. Despite the variable mitigation potential, evidencing the context-dependency of N<sub>2</sub>O 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 (N<sub>2</sub>O) is a major driver of climate change and stratospheric ozone depletion (Ravishankara *et al* 2009, IPCC 2021). Agriculture is the primary anthropogenic source of N<sub>2</sub>O, contributing globally about 3.8 (2.5–5.8) Tg N yr<sup>-1</sup> or 22% to the atmospheric N<sub>2</sub>O budget (Tian *et al* 2020). Direct soil N<sub>2</sub>O 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 N<sub>2</sub>O emissions are expected to rise over the coming decades (Reay *et al* 2012, Davidson and Kanter 2014). Climate change may further exacerbate N<sub>2</sub>O 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 N<sub>2</sub>O mitigation without jeopardizing (perhaps even increasing) food production (Smith *et al* 2008, Snyder *et al* 2009).

N<sub>2</sub>O emission reductions are best achieved by altering the environmental factors that promote N<sub>2</sub>O production and release (most prominently soil aeration, soil N content, C availability, and soil pH), by inhibiting biochemical pathways during which N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O mitigation practices. The fast-growing number of studies assessing N<sub>2</sub>O mitigation practices and synthesis-based research allows to simultaneously compare the N<sub>2</sub>O 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 N<sub>2</sub>O emissions. Therefore, we conducted a narrative and quantitative synthesis of published meta-analyses focused on N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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  $\theta$  (intercept) based on the  $k$ th effect size of the  $i$ th meta-analysis,  $\beta$  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 ( $\sigma_B^2$ ),  $u_{ik}$  is the random effect accounting for the variance within meta-analysis ( $\sigma_W^2$ ) 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  $R^2_{\text{marginal}}$  (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

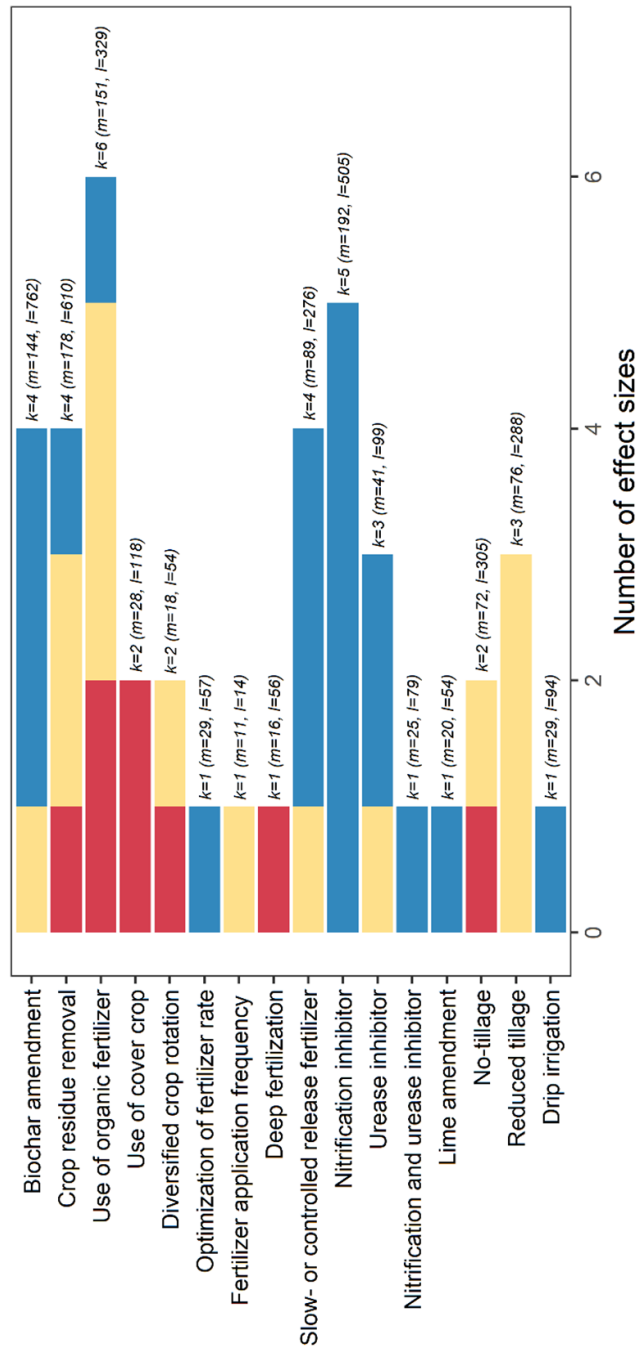
meta-regression models, including the standard error and sample size as moderators separately. The potential presence of bias was identified based on the significant deviation of the model intercept from zero. Similarly, influential studies were identified based on the leverage (i.e. hat values) extracted 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 N<sub>2</sub>O reductions across the mitigation practices, while 34% showed neutral responses and 20% significant increases in N<sub>2</sub>O 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 N<sub>2</sub>O reductions compared to other potential mitigation practices. However, the use of nitrification inhibitors was the only practice consistently showing N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O emissions as compared to standard practices. The use of cover crops increased N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O emissions, based on one effect size each. The main goal behind the development of these technologies was originally not to mitigate N<sub>2</sub>O 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 (NH<sub>3</sub>) 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 NH<sub>3</sub> volatilization; Li *et al* 2005, Pan *et al* 2016, Wu *et al* 2021), our results suggest that these management practices can achieve substantial N<sub>2</sub>O reductions from agricultural soils.

As opposed to the technology-driven options, agroecological practices tended to increase N<sub>2</sub>O 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 N<sub>2</sub>O, these practices (not primarily conceived to abate N<sub>2</sub>O 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 N<sub>2</sub>O emissions does not capture the multifunctional benefits of agroecological interventions (Guenet *et al* 2021).

Most agroecological practices had a highly variable effect on N<sub>2</sub>O emissions, highlighting the need to better understand under which pedoclimatic and management conditions such practices may lead to N<sub>2</sub>O mitigation instead of stimulation. For instance, the N<sub>2</sub>O 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 N<sub>2</sub>O

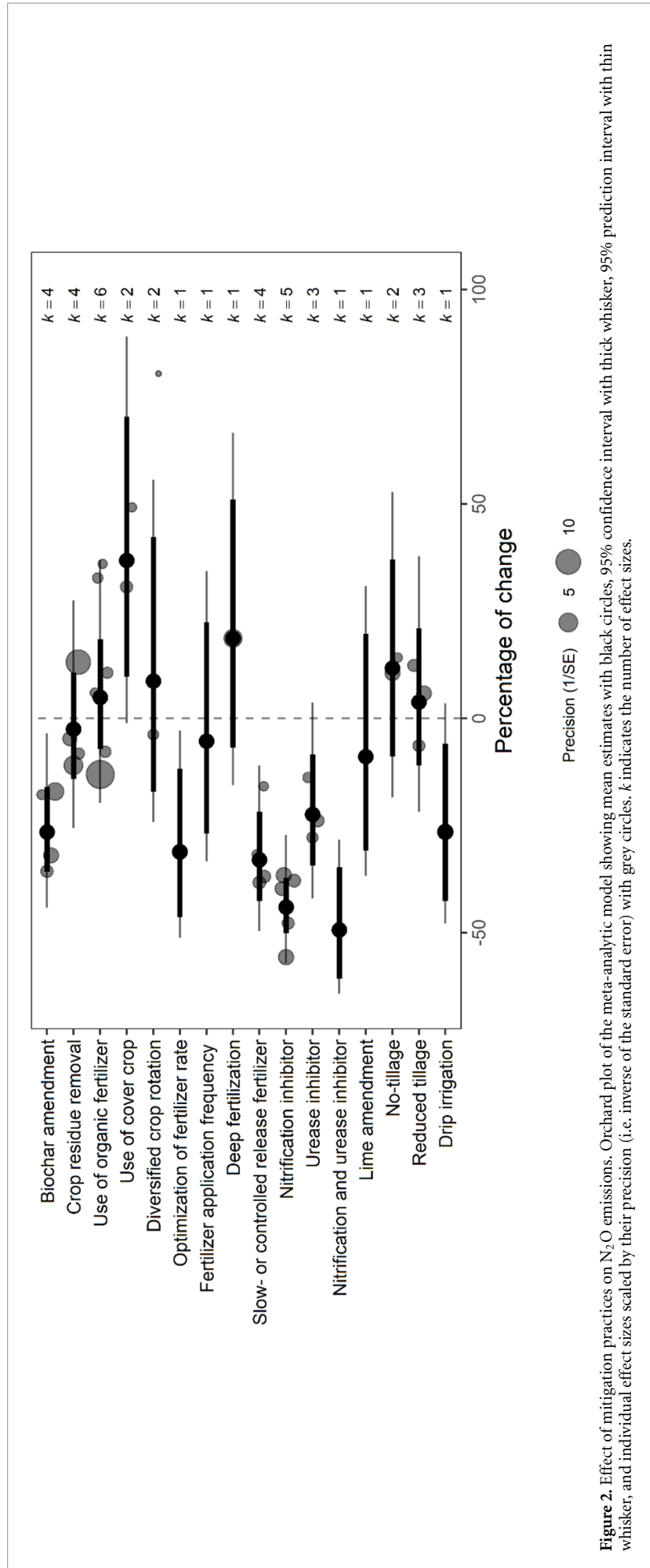


Figure 2. Effect of mitigation practices on N<sub>2</sub>O emissions. Orchard plot of the meta-analytic model showing mean estimates with black circles, 95% confidence interval with thick whisker, 95% prediction interval with thin whisker, and individual effect sizes scaled by their precision (i.e. inverse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



emissions (Aguilera *et al* 2013). Crop diversification may reduce N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O emissions, they could potentially decrease N<sub>2</sub>O emissions in dry areas over time (van Kessel *et al* 2013, Mei *et al* 2018). The effect of cover crops on N<sub>2</sub>O 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 N<sub>2</sub>O release, especially for diversified crop rotation and cover crops.

While optimized fertilizer rate according to crop needs showed important N<sub>2</sub>O reductions, increasing the frequency of fertilizer applications, crop residue removal, and lime application reduced N<sub>2</sub>O emissions only marginally. This may be because the N<sub>2</sub>O mitigation potential of these practices is highly context-dependent. Crop residue removal may only reduce N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O mitigation.

Several policies and regulations aimed at curbing agricultural N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O mitigation potential for the technology-driven solutions was 22%–49% (figure 2), our results indicate that adopting a portfolio of strategies for N<sub>2</sub>O mitigation at the field level may strongly contribute to achieve these mitigation targets despite the variability. Furthermore, since N<sub>2</sub>O emissions can dominate the GHG balance of agricultural soils (Li *et al* 2005, Lugato *et al* 2018, Autret *et al* 2019), failing to incorporate N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O 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 N<sub>2</sub>O emissions from agricultural soils. Despite the intrinsic variability of N<sub>2</sub>O 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 N<sub>2</sub>O release if they are not carefully managed. Our exhaustive evidence synthesis provides a state-of-the-art overview of the potential for N<sub>2</sub>O 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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## References

- Abalos D et al 2022 Predicting field N<sub>2</sub>O emissions from crop residues based on their biochemical composition: a meta-analytical approach *Sci. Total Environ.* **812** 152532
- Abalos D, Sanz-Cobena A, Andreu G and Vallejo A 2017 Rainfall amount and distribution regulate DMPP effects on nitrous oxide emissions under semiarid Mediterranean conditions *Agric. Ecosyst. Environ.* **238** 36–45
- Aguilera E, Lassaletta L, Sanz-Cobena A, Garnier J and Vallejo A 2013 The potential of organic fertilizers and water management to reduce N<sub>2</sub>O emissions in Mediterranean climate cropping systems. A review *Agric. Ecosyst. Environ.* **164** 32–52
- Akiyama H, Yan X and Yagi K 2010 Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N<sub>2</sub>O and NO emissions from agricultural soils: meta-analysis *Glob. Change Biol.* **16** 1837–46
- Aliyu G, Luo J, Di H J, Liu D, Yuan J, Chen Z, He T and Ding W 2021 Yield-scaled nitrous oxide emissions from nitrogen-fertilized croplands in China: a meta-analysis of contrasting mitigation scenarios *Pedosphere* **31** 231–42
- Arango M A and Rice C W 2021 Impact of nitrogen management and tillage practices on nitrous oxide emissions from rainfed corn *Soil Sci. Soc. Am. J.* **85** 1425–36
- Autret B, Beaudoin N, Rakotovololona L, Bertrand M, Grandeau G, Gréhan E, Ferchaud F and Mary B 2019 Can alternative cropping systems mitigate nitrogen losses and improve GHG balance? Results from a 19-yr experiment in Northern France *Geoderma* **342** 20–33
- Bai X, Huang Y, Ren W, Coyne M, Jacinthe P-A, Tao B, Hui D, Yang J and Matocha C 2019 Responses of soil carbon sequestration to climate-smart agriculture practices: a meta-analysis *Glob. Change Biol.* **25** 2591–606
- Baker J M, Ochsner T E, Venterea R T and Griffis T J 2007 Tillage and soil carbon sequestration—what do we really know? *Agric. Ecosyst. Environ.* **118** 1–5
- Bakken L R and Frostegård Å 2020 Emerging options for mitigating N<sub>2</sub>O emissions from food production by manipulating the soil microbiota *Curr. Opin. Environ. Sustain.* **47** 89–94
- Bardon C, Piola F, Bellvert F, Haichar F E Z, Comte G, Meiffren G, Pommier T, Puijalón S, Tsafack N and Poly F 2014 Evidence for biological denitrification inhibition (BDI) by plant secondary metabolites *New Phytol.* **204** 620–30
- Basche A D, Miguez F E, Kaspar T C and Castellano M J 2014 Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis *J. Soil Water Conserv.* **69** 471–82
- Beillouin D, Ben-Ari T, Malézieux E, Seufert V and Makowski D 2021 Positive but variable effects of crop diversification on biodiversity and ecosystem services *Glob. Change Biol.* **27** 4697–710
- Bommarco R, Kleijn D and Potts S G 2013 Ecological intensification: harnessing ecosystem services for food security *Trends Ecol. Evol.* **28** 230–8
- Bowles T M, Atallah S S, Campbell E E, Gaudin A C M, Wieder W R and Grandy A S 2018 Addressing agricultural nitrogen losses in a changing climate *Nat. Sustain.* **1** 399–408
- Bünemann E K et al 2018 Soil quality—a critical review *Soil Biol. Biochem.* **120** 105–25
- Castellanos M C and Verdú M 2012 Meta-analysis of meta-analyses in plant evolutionary ecology *Evol. Ecol.* **26** 1187–96
- Cayuela M L, van Zwieten L, Singh B P, Jeffery S, Roig A and Sánchez-Monedero M A 2014 Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis *Agric. Ecosyst. Environ.* **191** 5–16
- Chen H, Dai Z, Veach A M, Zheng J, Xu J and Schadt C W 2020 Global meta-analyses show that conservation tillage practices promote soil fungal and bacterial biomass *Agric. Ecosyst. Environ.* **293** 106841
- Chen H, Li X, Hu F and Shi W 2013 Soil nitrous oxide emissions following crop residue addition: a meta-analysis *Glob. Change Biol.* **19** 2956–64
- Chen Y, Camps-Arbestain M, Shen Q, Singh B and Cayuela M L 2018 The long-term role of organic amendments in building soil nutrient fertility: a meta-analysis and review *Nutr. Cycling Agroecosyst.* **111** 103–25
- Clark M A, Domingo N G G, Colgan K, Thakrar S K, Tilman D, Lynch J, Azevedo I L and Hill J D 2020 Global food system emissions could preclude achieving the 1.5° and 2 °C climate change targets *Science* **370** 705–8
- Davidson E A and Kanter D 2014 Inventories and scenarios of nitrous oxide emissions *Environ. Res. Lett.* **9** 105012
- Dawar K, Rahman S U, Fahad S, Alam S S, Khan S A, Dawar A, Younis U, Danish S, Datta R and Dick R P 2021 Influence of variable biochar concentration on yield-scaled nitrous oxide emissions, wheat yield and nitrogen use efficiency *Sci. Rep.* **11** 16774
- Department of the Environment, Climate and Communications 2021 Climate action plan 2021 (available at: [www.gov.ie/en/publication/6223e-climate-action-plan-2021/](http://www.gov.ie/en/publication/6223e-climate-action-plan-2021/)) (Accessed 13 December 2021)
- Doi S A R, Barendregt J J, Khan S, Thalib L and Williams G M 2015 Advances in the meta-analysis of heterogeneous clinical trials II: the quality effects model *Contemp. Clin. Trials* **45** 123–9
- Environmental Protection Agency 2021 Greenhouse gas emissions from agriculture (available at: [www.epa.ie/our-services/monitoring-assessment/climate-change/ghg/agriculture/#](http://www.epa.ie/our-services/monitoring-assessment/climate-change/ghg/agriculture/#)) (Accessed 13 December 2021)
- Essich L, Nkebiwe P M, Schneider M and Ruser R 2020 Is crop residue removal to reduce N<sub>2</sub>O emissions driven by quality or quantity? A field study and meta-analysis *Agriculture* **10** 546
- Frank S et al 2017 Reducing greenhouse gas emissions in agriculture without compromising food security? *Environ. Res. Lett.* **12** 105004
- Frank S et al 2018 Agricultural non-CO<sub>2</sub> emission reduction potential in the context of the 1.5 °C target *Nat. Clim. Change* **9** 66–72
- Friedl J, Scheer C, Rowlings D W, Deltedesco E, Gorfer M, De Rosa D, Grace P R, Müller C and Keiblinger K M 2020 Effect of the nitrification inhibitor 3,4-dimethylpyrazole

- phosphate (DMPP) on N-turnover, the N<sub>2</sub>O reductase-gene nosZ and N<sub>2</sub>O:N<sub>2</sub> partitioning from agricultural soils *Sci. Rep.* **10** 2399
- Fuertes-Mendizábal T *et al* 2019 Biochar reduces the efficiency of nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) mitigating N<sub>2</sub>O emissions *Sci. Rep.* **9** 2346
- Gao J, Luo J, Lindsey S, Shi Y, Sun Z, Wei Z and Wang L 2021 Benefits and risks for the environment and crop production with application of nitrification inhibitors in China *J. Soil Sci. Plant Nutr.* **21** 497–512
- Gough D, Oliver S and Thomas J 2017 Introducing systematic reviews *An Introduction to Systematic Reviews* (London: SAGE) pp 1–19
- Grames E M, Stillman A N, Tingley M W, Elphick C S and Freckleton R 2019 An automated approach to identifying search terms for systematic reviews using keyword co-occurrence networks *Methods Ecol. Evol.* **10** 1645–54
- Greiner L, Keller A, Grêt-Regamey A and Papritz A 2017 Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services *Land Use Policy* **69** 224–37
- Guenet B *et al* 2021 Can N<sub>2</sub>O emissions offset the benefits from soil organic carbon storage? *Glob. Change Biol.* **27** 237–56
- Gurevitch J, Koricheva J, Nakagawa S and Stewart G 2018 Meta-analysis and the science of research synthesis *Nature* **555** 175–82
- Habeck C W and Schultz A K 2015 Community-level impacts of white-tailed deer on understory plants in North American forests: a meta-analysis *AoB Plants* **7** plv119
- Haddaway N R, Macura B, Whaley P and Pullin A S 2018 ROSES reporting standards for systematic evidence syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps *Environ. Evid.* **7** 1–8
- Hénault C, Gossel A, Mary B, Roussel M and Léonard J 2012 Nitrous oxide emission by agricultural soils: a review of spatial and temporal variability for mitigation *Pedosphere* **22** 426–33
- Höhne N *et al* 2021 Wave of net zero emission targets opens window to meeting the Paris Agreement *Nat. Clim. Change* **11** 820–2
- Huang J, Sui P, Gao W and Chen Y 2019 Effects of maize-soybean intercropping on nitrous oxide emissions from a silt loam soil in the North China Plain *Pedosphere* **29** 764–72
- Huang Y, Ren W, Wang L, Hui D, Grove J H, Yang X, Tao B and Goff B 2018 Greenhouse gas emissions and crop yield in no-tillage systems: a meta-analysis *Agric. Ecosyst. Environ.* **268** 144–53
- Hunter J E and Schmidt F L 2004 General technical issues in meta-analysis *Methods of Meta-Analysis: Correcting Error and Bias in Research Findings* (London: SAGE) pp 371–433
- Ijaz M, Nawaz A, Ul-Allah S, Rizwan M S, Ullah A, Hussain M, Sher A and Ahmad S 2019 Crop diversification and food security *Agronomic Crops: Volume 1: Production Technologies* ed M Hasanuzzaman (Singapore: Springer) pp 607–21
- Int'Hout J, Ioannidis J P A, Rovers M M and Goeman J J 2016 Plea for routinely presenting prediction intervals in meta-analysis *BMJ Open* **6** e010247
- IPCC 2021 Climate change 2021: the physical science basis *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (Cambridge: Cambridge University Press) (<https://doi.org/10.1017/9781009157896>)
- Iverson A L, Marín L E, Ennis K K, Gonthier D J, Connor-Barrie B T, Remfert J L, Cardinale B J, Perfecto I and Wilson J 2014 Do polycultures promote win-wins or trade-offs in agricultural ecosystem services? A meta-analysis *J. Appl. Ecol.* **51** 1593–602
- Jian J, Du X, Reiter M S and Stewart R D 2020 A meta-analysis of global cropland soil carbon changes due to cover cropping *Soil Biol. Biochem.* **143** 107735
- Kanter D R, Ogle S M and Winiwarter W 2020 Building on Paris: integrating nitrous oxide mitigation into future climate policy *Curr. Opin. Environ. Sustain.* **47** 7–12
- Kanter D R, Zhang X, Mauzerall D L, Malyshev S and Shevliakova E 2016 The importance of climate change and nitrogen use efficiency for future nitrous oxide emissions from agriculture *Environ. Res. Lett.* **11** 094003
- Kim B, Moran N P, Reinhold K and Sánchez-Tójar A 2021 Male size and reproductive performance in three species of livebearing fishes (*Gambusia* spp.): a systematic review and meta-analysis *J. Anim. Ecol.* **90** 2431–45
- Kim N, Zabaloy M C, Guan K and Villamil M B 2020 Do cover crops benefit soil microbiome? A meta-analysis of current research *Soil Biol. Biochem.* **142** 107701
- Knapp G and Hartung J 2003 Improved tests for a random effects meta-regression with a single covariate *Stat. Med.* **22** 2693–710
- Kohl C, McIntosh E J, Unger S, Haddaway N R, Kecke S, Schiemann J and Wilhelm R 2018 Online tools supporting the conduct and reporting of systematic reviews and systematic maps: a case study on CADIMA and review of existing tools *Environ. Evid.* **7** 1–17
- Lazcano C, Zhu-Barker X and Decock C 2021 Effects of organic fertilizers on the soil microorganisms responsible for N<sub>2</sub>O emissions: a review *Microorganisms* **9** 983
- Li C, Frolking S and Butterbach-Bahl K 2005 Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing *Clim. Change* **72** 321–38
- Li G, Schwenke G D, Hayes R C, Lowrie A J, Lowrie R J, Poile G J, Oates A A, Xu B and Rohan M 2021 Can legume species, crop residue management or no-till mitigate nitrous oxide emissions from a legume-wheat crop rotation in a semi-arid environment? *Soil Tillage Res.* **209** 104910
- Li T *et al* 2018 Enhanced-efficiency fertilizers are not a panacea for resolving the nitrogen problem *Glob. Change Biol.* **24** e511–e521
- Lichtenberg E M *et al* 2017 A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes *Glob. Change Biol.* **23** 4946–57
- Liu T, Chen X, Hu F, Ran W, Shen Q, Li H and Whalen J K 2016 Carbon-rich organic fertilizers to increase soil biodiversity: evidence from a meta-analysis of nematode communities *Agric. Ecosyst. Environ.* **232** 199–207
- Lugato E, Leip A and Jones A 2018 Mitigation potential of soil carbon management overestimated by neglecting N<sub>2</sub>O emissions *Nat. Clim. Change* **8** 219–23
- McDaniel M D, Tiemann L K and Grandy A S 2014 Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis *Ecol. Appl.* **24** 560–70
- Mei K, Wang Z, Huang H, Zhang C, Shang X, Dahlgren R A, Zhang M and Xia F 2018 Stimulation of N<sub>2</sub>O emission by conservation tillage management in agricultural lands: a meta-analysis *Soil Tillage Res.* **182** 86–93
- Ministry of Finance 2021 Aftale om grøn omstilling af dansk landbrug [Agreement on green conversion of Danish agriculture] (available at: <https://fm.dk/media/25215/aftale-om-groen-omstilling-af-dansk-landbrug.pdf>) (Accessed 13 December 2021)
- Mitchell M *et al* 2019 Engauge digitizer software (available at: <http://markummitcheh.github.io/engauge-digitizer>) (Accessed 19 August 2021)
- Montzka S A, Dlugokencky E J and Butler J H 2011 Non-CO<sub>2</sub> greenhouse gases and climate change *Nature* **476** 43–50
- Nakagawa S, Lagisz M, O'Dea R E, Rutkowska J, Yang Y, Noble D W A and Senior A M 2020 The orchard plot: cultivating a forest plot for use in ecology, evolution, and beyond *Res. Synth. Methods* **12** 4–12
- Nakagawa S, Noble D W A, Senior A M and Lagisz M 2017 Meta-evaluation of meta-analysis: ten appraisal questions for biologists *BMC Biol.* **15** 18

- Nakagawa S, Schielzeth H and O'Hara R B 2013 A general and simple method for obtaining  $R^2$  from generalized linear mixed-effects models *Methods Ecol. Evol.* **4** 133–42
- Nielsen O-K et al 2021 Denmark's national inventory report 2021. Emission inventories 1990–2019—Submitted under the United Nations framework convention on climate change and the Kyoto protocol. Aarhus University, DCE—Danish Centre for Environment and Energy *Scientific Report No. 437* p 944 (available at: <http://dce2.au.dk/pub/SR437.pdf>) (Accessed 13 December 2021)
- Nishimura S, Sugito T, Nagatake A and Oka N 2021 Nitrous oxide emission reduced by coated nitrate fertilizer in a cool-temperate region *Nutr. Cycling Agroecosyst.* **119** 275–89
- Oldfield E E, Eagle A J, Rubin R L, Rudek J, Sanderman J and Gordon D R 2022 Crediting agricultural soil carbon sequestration *Science* **375** 1222–5
- Osipitan O A, Dille J A, Assefa Y, Radicetti E, Ayeni A and Knezevic S Z 2019 Impact of cover crop management on level of weed suppression: a meta-analysis *Crop Sci.* **59** 833–42
- Pan B, Lam S K, Mosier A, Luo Y and Chen D 2016 Ammonia volatilization from synthetic fertilizers and its mitigation strategies: a global synthesis *Agric. Ecosyst. Environ.* **232** 283–9
- Pappa V A, Rees R M, Walker R L, Baddeley J A and Watson C A 2011 Nitrous oxide emissions and nitrate leaching in an arable rotation resulting from the presence of an intercrop *Agric. Ecosyst. Environ.* **141** 153–61
- Paustian K, Lehmann J, Ogle S, Reay D, Robertson G P and Smith P 2016 Climate-smart soils *Nature* **532** 49–57
- Pedersen T L 2020 tidygraph: a tidy API for graph manipulation
- Pelster D E, Chantigny M H, Royer J, Angers D A and Vanasse A 2021 Reduced tillage increased growing season  $N_2O$  emissions from a fine but not a coarse textured soil under the cool, humid climate of eastern Canada *Soil Tillage Res.* **206** 104833
- Pigott T D and Polanin J R 2020 Methodological guidance paper: high-quality meta-analysis in a systematic review *Rev. Educ. Res.* **90** 24–46
- Pokharel P and Chang S X 2021 Biochar decreases the efficacy of the nitrification inhibitor nitrpyrin in mitigating nitrous oxide emissions at different soil moisture levels *J. Environ. Manage.* **295** 113080
- Power A G 2010 Ecosystem services and agriculture: tradeoffs and synergies *Phil. Trans. R. Soc. B* **365** 2959–71
- Powlson D S, Stirling C M, Jat M L, Gerard B G, Palm C A, Sanchez P A and Cassman K G 2014 Limited potential of no-till agriculture for climate change mitigation *Nat. Clim. Change* **4** 678–83
- Qasim W, Xia L, Lin S, Wan L, Zhao Y and Butterbach-Bahl K 2021 Global greenhouse vegetable production systems are hotspots of soil  $N_2O$  emissions and nitrogen leaching: a meta-analysis *Environ. Pollut.* **272** 116372
- R Core Team 2020 *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing)
- Ravishankara A R, Daniel J S and Portmann R W 2009 Nitrous oxide ( $N_2O$ ): the dominant ozone-depleting substance emitted in the 21st century *Science* **326** 123–5
- Reay D S, Davidson E A, Smith K A, Smith P, Melillo J M, Dentener F and Crutzen P J 2012 Global agriculture and nitrous oxide emissions *Nat. Clim. Change* **2** 410–6
- Ren F, Zhang X, Liu J, Sun N, Wu L, Li Z and Xu M 2017 A synthetic analysis of greenhouse gas emissions from manure amended agricultural soils in China *Sci. Rep.* **7** 8123
- Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K and Meinshausen M 2016 Paris Agreement climate proposals need a boost to keep warming well below 2 °C *Nature* **534** 631–9
- Ruangcharu C, Kim S U, Yoo G-Y, Choi E-J, Kumar S, Kang N and Hong C O 2021 Nitrous oxide emission and sweet potato yield in upland soil: effects of different type and application rate of composted animal manures *Environ. Pollut.* **279** 116892
- Schmidt F L and Oh I-S 2013 Methods for second order meta-analysis and illustrative applications *Organ. Behav. Hum. Decis. Process.* **121** 204–18
- Schmidt H, Kammann C, Hagemann N, Leifeld J, Bucheli T D, Sánchez Monedero M A and Cayuela M L 2021 Biochar in agriculture—a systematic review of 26 global meta-analyses *Glob. Change Biol. Bioenergy* **13** 1708–30
- Smith P et al 2007 Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture *Agric. Ecosyst. Environ.* **118** 6–28
- Smith P et al 2008 Greenhouse gas mitigation in agriculture *Phil. Trans. R. Soc. B* **363** 789–813
- Snyder C S, Bruulsema T W, Jensen T L and Fixen P E 2009 Review of greenhouse gas emissions from crop production systems and fertilizer management effects *Agric. Ecosyst. Environ.* **133** 247–66
- Snyder C S, Davidson E A, Smith P and Venterea R T 2014 Agriculture: sustainable crop and animal production to help mitigate nitrous oxide emissions *Curr. Opin. Environ. Sustain.* **9–10** 46–54
- Song X, Wei H, Rees R M and Ju X 2022 Soil oxygen depletion and corresponding nitrous oxide production at hot moments in an agricultural soil *Environ. Pollut.* **292** 118345
- Sterne J A C, Becker B J and Egger M 2006 The Funnel plot *Publication Bias in Meta-Analysis* (West Sussex: Wiley) pp 73–98
- Sterne J A C and Egger M 2006 Regression methods to detect publication and other bias in meta-analysis *Publication Bias in Meta-Analysis* (West Sussex: Wiley) pp 99–110
- Subbarao G V et al 2009 Evidence for biological nitrification inhibition in *Brachiaria* pastures *Proc. Natl Acad. Sci. USA* **106** 17302–7
- Sun Y, Zeng Y, Shi Q, Pan X and Huang S 2015 No-tillage controls on runoff: a meta-analysis *Soil Tillage Res.* **153** 1–6
- Tamburini G, Bommarco R, Wanger T C, Kremen C, van der Heijden M G A, Liebman M and Hallin S 2020 Agricultural diversification promotes multiple ecosystem services without compromising yield *Sci. Adv.* **6** eaba1715
- Tamim R M, Bernard R M, Borokhovski E, Abrami P C and Schmid R F 2011 What forty years of research says about the impact of technology on learning: a second-order meta-analysis and validation study *Rev. Educ. Res.* **81** 4–28
- Tang K, Kragt M E, Hailu A and Ma C 2016 Carbon farming economics: what have we learned? *J. Environ. Manage.* **172** 49–57
- Thapa R, Mirsky S B and Tully K L 2018 Cover crops reduce nitrate leaching in agroecosystems: a global meta-analysis *J. Environ. Qual.* **47** 1400–11
- The United Nations World Water Development 2014 The United Nations world water development report 2014 (available at: [www.unesco.org/new/en/natural-sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact-24-irrigated-land/](http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact-24-irrigated-land/)) (Accessed 13 December 2021)
- Tian H et al 2019 Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: magnitude, attribution, and uncertainty *Glob. Change Biol.* **25** 640–59
- Tian H et al 2020 A comprehensive quantification of global nitrous oxide sources and sinks *Nature* **586** 248–56
- Timilsena Y P, Adhikari R, Casey P, Muster T, Gill H and Adhikari B 2015 Enhanced efficiency fertilisers: a review of formulation and nutrient release patterns *J. Sci. Food Agric.* **95** 1131–42
- United Nations Framework Convention on Climate Change—Paris Agreement 2015 (available at: [https://unfccc.int/sites/default/files/english\\_paris\\_agreement.pdf](https://unfccc.int/sites/default/files/english_paris_agreement.pdf)) (Accessed 13 December 2021)
- Vallejo A, Meijide A, Boeckx P, Arce A, García-torres L, Aguado P L and Sanchez-martin L 2014 Nitrous oxide and methane emissions from a surface drip-irrigated system combined with fertilizer management *Eur. J. Soil Sci.* **65** 386–95

- van Aert R C M and Jackson D 2019 A new justification of the Hartung-Knapp method for random-effects meta-analysis based on weighted least squares regression *Res. Synth. Methods* **10** 515–27
- van der Kooij S, Zwarteveen M, Boesveld H and Kuper M 2013 The efficiency of drip irrigation unpacked *Agric. Water Manage.* **123** 103–10
- van Dijk M, Morley T, Rau M L and Saghay Y 2021 A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050 *Nat. Food* **2** 494–501
- van Groenigen J W, Velthof G L, Oenema O, Van Groenigen K J and Van Kessel C 2010 Towards an agronomic assessment of N<sub>2</sub>O emissions: a case study for arable crops *Eur. J. Soil Sci.* **61** 903–13
- van Kessel C, Venterea R, Six J, Adviento-Borbe M A, Linquist B and van Groenigen K J 2013 Climate, duration, and N placement determine N<sub>2</sub>O emissions in reduced tillage systems: a meta-analysis *Glob. Change Biol.* **19** 33–44
- Venter Z S, Jacobs K and Hawkins H-J 2016 The impact of crop rotation on soil microbial diversity: a meta-analysis *Pedobiologia* **59** 215–23
- Vicca S *et al* 2021 Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes? *Glob. Change Biol.* **28** 711–26
- Viechtbauer W 2005 Bias and efficiency of meta-analytic variance estimators in the random-effects model *J. Educ. Behav. Stat.* **30** 261–93
- Viechtbauer W 2010 Conducting meta-analyses in R with the metafor package *J. Stat. Softw.* **36** 1–48
- Viechtbauer W 2020 Model checking in meta-analysis *Handbook of Meta-Analysis* (Florida: Chapman and Hall/CRC) pp 219–54
- Wang Y, Yao Z, Zhan Y, Zheng X, Zhou M, Yan G, Wang L, Werner C and Butterbach-Bahl K 2021 Potential benefits of liming to acid soils on climate change mitigation and food security *Glob. Change Biol.* **27** 2807–21
- Wei Z, Hoffland E, Zhuang M, Hellegers P and Cui Z 2021 Organic inputs to reduce nitrogen export via leaching and runoff: A global meta-analysis *Environ. Pollut.* **291** 118176
- Wickham H 2016 *Ggplot2: Elegant Graphics for Data Analysis* (2016) (New York: Springer)
- Wollenberg E *et al* 2016 Reducing emissions from agriculture to meet the 2 °C target *Glob. Change Biol.* **22** 3859–64
- Wu D, Zhang Y, Dong G, Du Z, Wu W, Chadwick D and Bol R 2021 The importance of ammonia volatilization in estimating the efficacy of nitrification inhibitors to reduce N<sub>2</sub>O emissions: a global meta-analysis *Environ. Pollut.* **271** 116365
- Wu P, Ata-Ul-Karim S T, Singh B P, Wang H, Wu T, Liu C, Fang G, Zhou D, Wang Y and Chen W 2019 A scientometric review of biochar research in the past 20 years (1998–2018) *Biochar* **1** 23–43
- Xia L, Lam S K, Chen D, Wang J, Tang Q and Yan X 2017 Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis *Glob. Change Biol.* **23** 1917–25
- Xu C, Han X, Bol R, Smith P, Wu W and Meng F 2017 Impacts of natural factors and farming practices on greenhouse gas emissions in the North China Plain: a meta-analysis *Ecol. Evol.* **7** 6702–15
- Zhang X, Fang Q, Zhang T, Ma W, Velthof G L, Hou Y, Oenema O and Zhang F 2020a Benefits and trade-offs of replacing synthetic fertilizers by animal manures in crop production in China: a meta-analysis *Glob. Change Biol.* **26** 888–900
- Zhang X, Xiao G, Li H, Wang L, Wu S, Wu W and Meng F 2020b Mitigation of greenhouse gas emissions through optimized irrigation and nitrogen fertilization in intensively managed wheat-maize production *Sci. Rep.* **10** 5907