



# Assessing the impacts of tillage, cover crops, nitrification, and urease inhibitors on nitrous oxide emissions over winter and early spring

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## Abstract

There are increasing demands to reduce greenhouse gas emissions from agricultural soils worldwide. A significant portion of these emissions occur in cold regions during soil's freezing and thawing. Focusing on over-winter cropland nitrous oxide (N<sub>2</sub>O) emissions, a review of 21 relevant peer-reviewed studies with a total of 88 comparisons was conducted to quantify the efficacy of field management practices (no-till, cover crops (CCs), nitrification, and urease inhibitors (NI + UI)) in reducing emissions. We also assessed these mitigation practices' efficacy across soil types and between cold humid and cold dry areas. The ratio of non-growing season emissions to full-year N<sub>2</sub>O emissions reported in the studies used in this review ranged between 5 and 91%. No-till significantly reduced N<sub>2</sub>O emissions by 28%, and this effect was more pronounced in drier climates. NI + UI also significantly reduced over-winter emissions by 23% compared to conventional fertilizers, and this effect was more evident in medium-textured soils than coarse soils. CCs showed an overall reduction potential of 18%; however, this effect was not significant. This review showed that under the CC practice, N<sub>2</sub>O emissions were reduced overall in humid climates but increased in drier climates, while no-till and NI + UI practices effectively reduced over-winter emissions in both dry and humid winter regions and all soil types.

**Keywords** Nitrous oxide · Over-winter · Tillage · Cover crops · Nitrification and urease inhibitors

## Introduction

Agricultural soils emit trace gases that increase atmospheric concentrations of nitrous oxide (N<sub>2</sub>O), a greenhouse gas that contributes to global climate change (Davidson and Kanter 2014). Studies investigating N<sub>2</sub>O emissions from agricultural soils have vastly focused on growing season. Nonetheless, the contribution of over-winter N<sub>2</sub>O emissions to annual emissions that occur in mid-high to high latitude regions, such as Canada and the Mid-West US where soil freezing and thawing occur over a 5-month period, could reach up to 90% (Risk et al. 2014). The bulk of over-winter emissions mostly occurs in the early spring partly due to the anaerobic conditions created during the thawing of soils enhancing N<sub>2</sub>O production (Chantigny et al. 2016; Ejack and Whalen 2021; Risk et al. 2014; Wagner-Riddle et al. 2007).

Understanding the factors including substrate availability, snow cover, freeze–thaw dynamics, soil temperature, soil type, and moisture conditions that impact the magnitude of over-winter emissions is becoming the focus of recent studies (Chen et al. 2016; Smith et al. 2010; Zhe et al. 2018).

Appropriate agronomic management practices could help achieve a reduction in over-winter emissions. These practices include those tailored towards minimizing the substrates available for emission during the spring thaw such as the use of nitrification inhibitors during fall manure application and incorporation of cover crops. The use of nitrification inhibitors to prevent oxidation of NH<sub>4</sub><sup>+</sup> to NO<sub>3</sub><sup>-</sup> has been suggested as an effective method for reducing N<sub>2</sub>O losses, especially from fall-applied manure, which carries N mostly in the form of ammonium (NH<sub>3</sub>) or organic N (Dong et al. 2018; Vallejo et al. 2001; VanderZaag et al. 2011; Zhang et al. 2018). Apart from lowering substrate availability, practices that can alter soil temperature or moisture, such as the presence of cover crop and no-tillage, have been shown to lessen over-winter emissions (Congreves et al. 2017; Preza-Fontes et al. 2020; Wagner-Riddle et al. 2007). The use of non-legume cover crops (CC) as a mitigation practice for

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N<sub>2</sub>O emissions is centered on the hypothesis that cover-crops will absorb more moisture and NO<sub>3</sub><sup>-</sup> from the soil, lowering their levels and resulting in reduced N<sub>2</sub>O emissions (Shackelford et al. 2019). The major difference between legume CC and non-legume CC is that while legume CC can fix nitrogen from the atmosphere to the soil, non-legume CC cannot, but can absorb large quantities of N from the soil. Having a vegetation cover atop the soil can also slow down the thawing of frozen soils and lower the freeze–thaw cycles, thereby reducing emission rates (Chen et al. 2020). Tillage could affect emissions through its influence on soil aeration, structure, temperature, moisture content, microbial activity, and gas diffusion through the subsoil to the surface (Gregorich et al. 2015; Signor and Cerri 2013). No-till field management could reduce N<sub>2</sub>O emissions by lowering freezing intensity and soil moisture (Wagner-Riddle et al. 2007). However, the efficacy of no-till and the use of non-legume cover crops remains under debate as some studies have also reported no consistent effects of these practices (Behnke and Villamil 2019; Elmi et al. 2003; Thomas et al. 2017). It is essential to clarify the controversies since farmers' and policymakers' willingness to adopt and implement recommended strategies will depend on data-driven evidence of reduced emissions, without hampering farm productivity.

Meta-analyses have been used to investigate the efficacy of agronomic practices including tillage, cover crops, and nitrification and urease inhibitors in mitigating N<sub>2</sub>O emissions. Earlier meta-analyses studies focusing majorly on growing season N<sub>2</sub>O losses showed no significant differences in N<sub>2</sub>O emissions between CT and no-till or reduced tillage (NT/RT) (Decock 2014; Feng et al. 2018; Six et al. 2004; van Kessel et al. 2013). Other studies reported significantly greater emissions by 12% (Shakoor et al. 2021) and 10% (Huang et al. 2018) in NT/RT treatments compared to CT. Concerning nitrification and urease inhibitors, previous meta-analysis studies have shown that the use of the inhibitors could reduce N<sub>2</sub>O losses by up to 44% (Feng et al. 2016; Qiao et al. 2015; Thapa et al. 2016; Yang et al. 2016). Investigating the overall effect of cover crops on N<sub>2</sub>O emissions, Basche et al. (2014) showed that 60% of the 106 observations utilized in their meta-analysis study positively affected N<sub>2</sub>O emissions, while 40% indicated negative effects.

Although these meta-analysis studies quantified the above management practices' effectiveness on N<sub>2</sub>O emissions, they mainly included individual studies that reported growing season emissions and have not adequately accounted for the sizeable N<sub>2</sub>O losses that occur over winter. For instance, only 14% of the observations used by Decock (2014) were all year round measurement. We still do not have a clear overview of these strategies' effectiveness in mitigating the considerable N<sub>2</sub>O losses that occur over-winter. Accordingly, this work is aimed to review studies to quantify the effectiveness of nitrification and urease inhibitors, tillage,

and cover crops in reducing non-growing season N<sub>2</sub>O emissions in cold temperate regions. We also assessed the efficacy of these mitigation practices across soil types and aridity zones (cold-dry vs. cold-humid areas).

## Mechanism of over-winter N<sub>2</sub>O emissions

The potential mechanism of over-winter N<sub>2</sub>O emissions in this study is discussed for two distinct periods: the freezing period and the spring-thaw period. The frozen soil reduces the microbial activities it harbors, although it does not completely inhibit them. After the initial lysis of some microbial cells that may occur at subzero temperatures (Maljanen et al. 2007), soil microorganisms gradually acclimatize to low temperatures (Smith et al. 2010). The relatively warm soil under snow cover further supports a level of their activities. For instance, decomposition of soil organic matter occurs during the freezing period, evidenced by the low rates of CO<sub>2</sub> accumulation (Maljanen et al. 2007). However, the CO<sub>2</sub> fluxes were lower compared to the fluxes observed during pre-freezing period. Likewise, mineralization of organic N also takes place, as shown by high levels of ammonium (NH<sub>4</sub><sup>+</sup>) in these same soils (Maljanen et al. 2007). However, a significant concomitant increase in NO<sub>3</sub><sup>-</sup> is not always observed following the soil thaw (Chen et al. 2016; Maljanen et al. 2007). This condition has been attributed to low levels of nitrifying bacteria found in the soil, as a result of their greater susceptibility to cold temperatures (Smith et al. 2010) or the possible rapid denitrification of NO<sub>3</sub><sup>-</sup> — generated from a portion of the accumulated NH<sub>4</sub><sup>+</sup> — to N<sub>2</sub>O and N<sub>2</sub> (Maljanen et al. 2007; Zhe et al. 2018). Contrary to the effect of cold temperature on nitrifier populations that made their detection in mid-winter difficult, cold temperatures have a lesser effect on the denitrifier community and did not hamper their detection (Smith et al. 2010). Gases produced in the freezing period are trapped in the soil, given that ice blocks the pores of soil surface, resulting in increased concentrations of N<sub>2</sub>O and CO<sub>2</sub> in the soil over time. However, partial release of such trapped gases can sometimes occur during the freezing period through cracks caused by increases in temperature and slight thawing of the soil (Teepe et al. 2001).

In early spring during the soil thaw, the ice barriers that trapped gases begin to give away, causing the physical release of these gases (Burton and Beauchamp, 1994; Teepe et al. 2001). As the soil thaws further, the frozen subsoil melts, enhancing soil drainage, thereby creating the aerobic topsoil required for nitrification of available NH<sub>4</sub><sup>+</sup>. Although more N<sub>2</sub>O is produced in the deeper soil layers over the freezing period, as evidenced by its greater concentrations at these depths, as well as the depletion of NH<sub>4</sub><sup>+</sup> and organic N, a substantial proportion of these N<sub>2</sub>O molecules

are converted to  $N_2$  by the time they reach the surface (Wagner-Riddle et al. 2008). One study by Van Groenigen et al. (2005) showed that while the subsoil is characterized by depleted  $\delta^{15}N$  indicating  $N_2O$  production, the topsoil consumed  $N_2O$ , as shown by a greater  $\delta^{15}N$ . Consumption of  $N_2O$  is generally typical for soils which are anoxic and rich in OM, but have depleted  $NO_3^-$ . This depletion of  $NO_3^-$  in the subsoil usually occurs at the onset of thawing, resulting in greater  $N_2$  than  $N_2O$  fluxes (Ludwig et al. 2006). In addition, more recent studies suggest the release of trapped gases and newly produced  $N_2O$  occurs at the onset of thawing. Such newly produced  $N_2O$  fluxes could be up to five times the amount observed during the release of trapped gases (Risk et al. 2014). De novo production results from favorable conditions for nitrification or denitrification processes during thawing. Identified as the principal source of  $N_2O$  emitted during the thawing process, the denitrification process requires anaerobic conditions, nitrates, and simple C compounds (Priemé and Christensen 2001; Sehy et al. 2004; van Groenigen et al. 2005). Anaerobic conditions are enhanced by a frozen subsoil which hinders drainage while creating saturated soil conditions (Nyborg et al. 1997). Additionally, the thaw period, characterized with high soil moisture from the snow melt, also enhances anaerobic conditions. The C and N required for denitrification could arise from the death of microbes due to freeze–thaw stresses, as well as residual C and N available in the soil (Chen et al. 2020; Pelster et al. 2013; Teepe et al. 2001).

A few studies have evaluated the role of nitrifiers and denitrifiers on over-winter  $N_2O$  emissions. Using PCR-DGGE analysis, Smith et al. (2010) observed significant changes in the diversity of the nitrifier and denitrifier populations observed between the pre- and post-spring thaw period. While this method only observes changes in dominant microbial populations compared to amplicon-sequencing or metagenomics, the authors alluded that these variations in microbial community composition suggest that microbes must be active immediately after spring thaw. Significant  $N_2O$  flushes that occurred during the thaw in their study were primarily attributed to denitrification. Similarly, Ludwig et al. (2004) used  $^{15}N$  as a tracer to show that denitrification contributed 83% of  $N_2O$  production in organic soils immediately after the soil began to thaw. A microcosm study (Sharma et al. 2006) observed an apparent increase in denitrifying bacteria and a larger amount of nitrate reductase (*napA*) and nitrite reductase (*nirS*) gene copies soon after the soil thaw began, followed by a decrease in gene copies. Their study concluded that the release of spring  $N_2O$  fluxes was influenced by increased microbial activities and the expression of denitrifying genes. Using next-generation sequencing, Bent et al. (2016) showed over-winter  $N_2O$  fluxes to relate to community composition of the denitrification genes (*nirS/nirK* and *nosZ*) in a

residue-retained field, and both nitrifiers (bacterial *amoA*) and denitrifiers (*nirK* and *nosZ*) in a residue-removed field. However, a recent study has suggested that although changes in the nitrifier and denitrifier populations were observed during the winter period, these variations in the abundance of functional genes were not correlated with the changes in over-winter  $N_2O$  fluxes (Yin et al. 2019). The lack of consensus on the role of denitrifiers in spring thaw  $N_2O$  fluxes may stem from the detection limits of these sequencing methods. Additionally, these studies rely on gene copy numbers as a parameter for denitrifying activity, which does not directly translate to expression since these genes may be present in dormant species' DNA (Nannipieri et al. 2020). Thus, future investigations could utilize an improved PCR primer set (Zhang et al. 2021) developed for better detection of denitrifying genes as well as metatranscriptomics to determine denitrifying activity. Furthermore, studies could use  $^{15}N$  analysis of site preference to understand the role of denitrifying and nitrifying genes on over-winter  $N_2O$  emissions.

## Magnitude of over-winter $N_2O$ emissions

Table 1 provides the summary of the studies used for the review in the present study. It shows the magnitude of the non-growing season  $N_2O$  emissions from the various studies, also expressed as a percentage of total annual emissions. Additionally, it includes the major treatments of the studies and the measurement period of the over-winter fluxes. More details of the data can be found in the supplementary data (S1). In this review (21 studies with a total of 88 comparisons), the ratio of the non-growing season to full-year  $N_2O$  emissions ranged between 5 and 91%, highlighting high variation and the significance of these emissions. The over-winter flux measurement varied among studies. For example, in the North Atlantic region of the USA and Canada, and the Mid-West US, snow cover appears in early December, and peaks between February and early March, with the spring melt occurring within 2–3 weeks between late March and early April (Chantigny et al. 2016). Some of the studies started earlier or ended later to capture the entire winter and early spring period. As snow accumulation varies from year to year, the timing and intensity of winter-time soil fluxes may vary, as would the temporal occurrence and magnitude of peak fluxes.

## Mitigation potential of no-till/reduced tillage

Using the meta-analysis approach, we quantified the effectiveness of mitigation practices in reducing non-growing season  $N_2O$  emissions in cold temperate regions (more

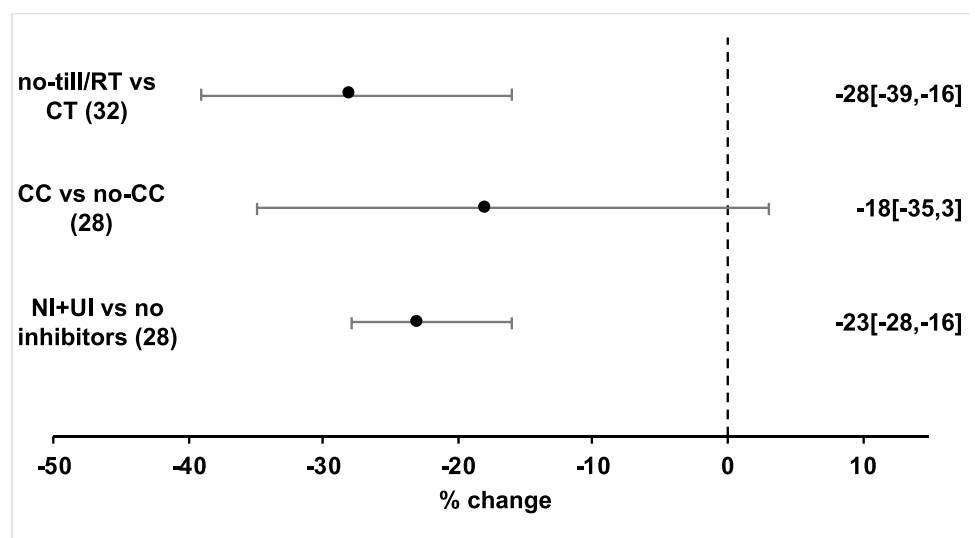
**Table 1** Summary of the studies used in the meta-analysis

Treatment			N <sub>2</sub> O emissions (kg N ha <sup>-1</sup> )			Measurement period	Source	
Tillage	Crop cover	Nitrification inhibitors	Annual	Non-growing season	100 • $\frac{\text{Over-winter}}{\text{Annual}}$	Number of comparisons		
✓	✓		–	1.8	–	Dec–May	4	Behnke and Villamil (2019)
✓			1.9	1.4	77	Jan–April	2	Congreves et al. (2017)
✓			3.3	2.9	88	Nov–April	5	Wagner-Riddle et al. (2007)
✓			2.8	2.6	91	Mar–April	12	Lemke et al. (1999)
✓			0.9	0.3	30	Dec–March	2	Ussiri et al. (2009)
✓			0.8	0.2	22	Nov–April	1	Mutegi et al. (2010)
✓	✓		–	3.9	–	Sep–May	2	Petersen et al. (2011)
✓			–	0.6	–	Oct–April	4	Ferrari Machado et al. (2021)
	✓		12.1	7.2	59	Oct–May	2	Jarecki et al. (2009)
	✓			0.03		Mar–April	8	Hung et al. (2021)
	✓		1.9	1.1	57	Jul–April	4	Preza-Fontes et al. (2020)
	✓		–	0.4	–	Sep–June	4	Thomas et al. (2017)
	✓		–	27.1	–	Feb–May	4	Dietzel et al. (2011)
		✓	6.2	5.2	84	Mar–April	4	Lin et al. (2017)
		✓	8.8	4.1	47	Nov–April	2	Pfab et al. (2012)
		✓	5.3	2.5	48	Nov–April	2	Parkin and Hatfield (2010)
		✓	0.8	0.2	22.1	Oct–March	4	Halvorson and Del Gross (2012)
		✓	2.6	0.1	5.4	April–May	1	Asgedom et al. (2014)
		✓	1.1	0.8	72.2	Oct–April	6	Dong et al. (2018)
		✓	2.3	1.3	56.4	Nov–April	6	Ferrari Machado et al. (2020)
		✓	–	0.5	–	Oct–June	3	Ding et al. (2015)

details of the method can be found in the [supplementary information](#)). In the winter and early spring, the effect of no-till/reduced tillage (NT/RT) compared with conventional tillage (CT) was  $-28\%$  (95% confidence interval =  $-39$  to  $-16\%$ ), indicating a significant reduction of N<sub>2</sub>O emissions (Fig. 1; Table 2). Under the tillage practice, dry areas

emitted significantly lower emissions than the humid areas (35% less), while soil texture did not significantly affect N<sub>2</sub>O emissions (Fig. 2; Table S2). Although among the studies there were years when no-till did not reduce N<sub>2</sub>O emissions over winter, in some other cases, studies reported that mean N<sub>2</sub>O fluxes under NT were one to six times lower than in CT

**Fig. 1** Forest plot (random effects model) indicating the overall effect size estimates of management practices: no-till/reduced tillage (RT) vs. tillage treatments; cover crops (CCs) vs. no cover crops (no-CCs); nitrification and urease inhibitors (NI+UI) vs. no inhibitors, on over-winter N<sub>2</sub>O emissions. Numbers in the bracket indicate the number of observations utilized in the analysis. The center circle represents the summary estimate. Confidence intervals are also reported. CI crossing the null (zero) line indicates no significant change in effect or that both treatments show equivalent effects



**Table 2** List of management practices, environmental conditions, and percent change in N<sub>2</sub>O emissions

Practice	Conditions	% change
<b>No-till</b>	Overall	▼*28%
	Climate	
	Humid	▼*18%
	Dry	▼*47%
	Soil type	
	Coarse	▼*41%
	Medium	▼*19%
	Fine	-
<b>Cover crop</b>	Overall	▼18%
	Climate	
	Humid	▼26%
	Dry	△41%
	Soil type	
	Coarse	▼43%
	Medium	▼2%
	Fine	-
<b>NI + UI inhibitors</b>	Overall	▼*23%
	Climate	
	Humid	▼*31%
	Dry	▼*18%
	Soil type	
	Coarse	▼*12%
	Medium	▼*28%
	Fine	-

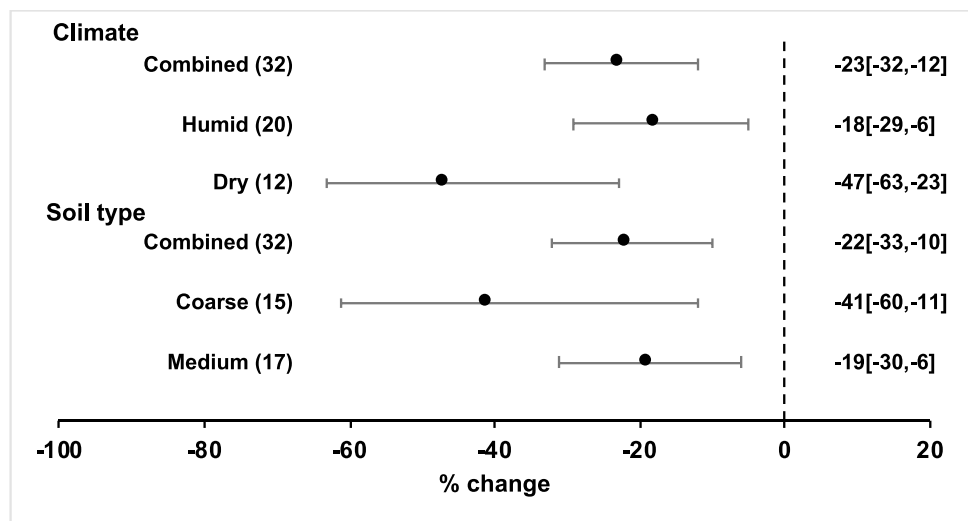
Arrow pointing downwards indicates a decreasing change in N<sub>2</sub>O emissions due to the treatment effect, while the arrow pointing upwards shows an increasing change

\*Statistically significant change

plots (Congreves et al. 2017; Lemke et al. 1999; Wagner-Riddle et al. 2007). The micrometeorological method used in gas emission measurements in some studies (Congreves et al. 2017; Wagner-Riddle et al. 2007), allowing for more frequent sampling, would have accorded the researchers a greater chance of capturing distinct peak fluxes.

The lower N<sub>2</sub>O emissions under NT/RT can be attributed to the combined insulating effects of crop residues and snow cover that lowers the cumulative degree hours below 0 °C, an indicator of freezing intensity and duration (Wagner-Riddle et al. 2007). Wagner-Riddle et al. (2007) also suggested that crop residues that are retained on NT/RT plots can effectively trap snow. Due to their low heat of diffusivity, snow and residues insulate the soil and decrease the transfer of heat from the soil to the atmosphere, resulting in higher soil temperature in RT/NT than in CT (Wagner-Riddle et al. 2007). Under CT, soil temperatures varied over a wider range, increasing the degree of freezing than under NT/RT plots. The magnitude of over-winter N<sub>2</sub>O emissions has been linked to the number of degree hours below 0 °C. An exponential to plateau relationship model defined this link and showed that N<sub>2</sub>O emissions increased exponentially with cumulative freezing degree days until a plateau was reached (Wagner-Riddle et al. 2017). The wider temperature variation reported for CT (vs. NT/RT) soils (Wagner-Riddle et al. 2007; Smith et al. 2010) could lead to greater microbes' die-off. When freezing stresses kill off some soil microbes, microbial polymers return to the soil C pool, while amino acids and other organic monomers are returned to the dissolved organic nitrogen (DON) pool (Schimel and Bennett 2004). Living microbes in the frozen soil's liquid film then utilize these substances to stimulate N<sub>2</sub>O emissions (Chen et al. 2020; Pelster et al. 2013). Additionally,

**Fig. 2** Forest plot (random effects model) indicating subgroup (climate and soil type) effects of no-tillage/reduced tillage (no-till/RT) vs. tillage treatments (CT). Confidence intervals are also reported. CI crossing the null (zero) line indicates no significant change in effect or that both treatments show equivalent effects





Ferrari Machado et al. (2021) suggested that higher  $N_2O$  emission under CT may have been induced by mechanisms potentially resulting from lower temperatures such as the breakdown of soil aggregates and subsequent release of previously protected soil organic C. Lower temperatures could therefore cause an exponential rise in  $N_2O$  fluxes for a few days resulting from the death of microbes and subsequent release of  $NO_3^-$  (Larsen et al. 2002; Maljanen et al. 2007; Sharma et al. 2006). This observation was also confirmed by Smith et al. (2010) who suggested that the soil's lower nutrient availability in NT/RT plots due to lower freezing intensity could lower  $N_2O$  emissions than CT plots. Smith et al. (2010) also implied that the significant differences in the composition of nitrifier and denitrifier communities observed soon after spring thaw could explain the differences in emissions between the CT and NT/RT treatments.

The difference in the establishment period of NT/RT from CT is an important factor to consider when investigating the effect size of NT/RT practice on  $N_2O$  emissions. Six et al. (2004) showed that the potential to reduce  $N_2O$  emissions with NT is only achieved with long-term NT practice. Elevated  $N_2O$  emissions from newly adopted NT/RT plots slowly diminish due to the development of macropores, improved soil structure and aeration status, and decreased formation of anaerobic microsites. Studies have shown that the elevated  $N_2O$  emissions observed under NT/RT only occurred within the first 10 years following the shift from CT to NT/RT, after which a significant reduction in  $N_2O$  emissions was observed under NT/RT (Six et al. 2004; Feng et al. 2018; van Kessel et al. 2013). In our meta-analysis, 62% of the tillage studies had  $\geq 10$  years of NT/RT and this could be one of the reasons for the significant reduction in  $N_2O$  emissions observed under NT/RT.

This review revealed that relatively drier areas such as the low annual precipitation areas in Western Canada or China's moist continental climate with dry winter periods emitted significantly lower emissions than the humid winter areas (35% less). Elevated soil moisture during the winter and especially in the spring thaw period favors the denitrification process (Maljanen et al. 2007), the main process contributing to freeze–thaw  $N_2O$  emissions. Antecedent fall moisture conditions have also been shown to affect spring thaw  $N_2O$  emissions, with a greater fall water-filled pore space (WFPS) leading to greater spring fluxes (Chen et al. 2016; Li et al. 2012; Pri  m   and Christensen 2001). Following a distinctly wet field growing season, Chen et al. (2016) observed relatively high subsequent spring thaw  $N_2O$  fluxes. These elevated spring emissions, accounting for up to 49% of the non-growing season fluxes, were attributed to the soil's high moisture condition, which led to a rise in soil WFPS to 54%, compared to the 28% measured in a previous drier year when no significant thaw emissions were observed. A confirmatory lab experiment within the

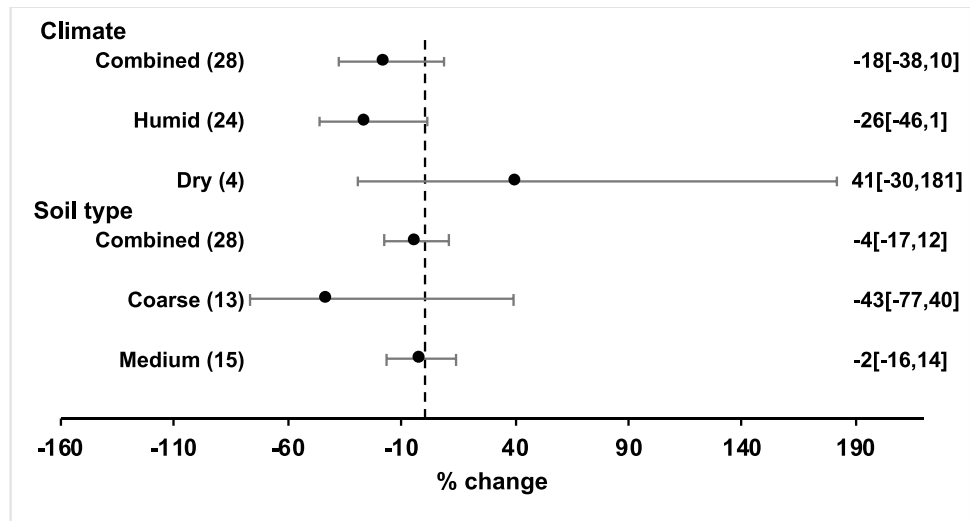
same study showed that freeze–thaw cycles did not induce distinct fluxes at a 20% WFPS, but that emissions increased by an order of magnitude at a WFPS of 80% (Chen et al. 2016). Subsequent to a dry antecedent fall and low winter air temperatures, Li et al. (2012) measured limited spring thaw emissions — 6.6% of annual emissions, in contrast to about 70% from the previous wetter and warmer preceding fall and winter. Dry fall soil conditions and the presence of less unfrozen water during the winter would have limited denitrification. Therefore, dry areas which are likely to have lower antecedent (fall) soil moisture prior to the soil freezing up in the winter could emit significantly lower spring thaw emissions than humid areas.

Although our meta-analysis showed that soil texture did not significantly impact the emissions (Fig. 2; Table S2), coarse soils tended to lower emissions more than medium soils under tillage practices. This observation reveals that the lower  $N_2O$  levels observed may be partially associated with soil texture influence on soil moisture since coarse soils have lower WFPS than medium soils. Water-filled pore space and soil moisture affect growing season emissions. For instance, Linn and Doran (1984) showed NT/RT fields to have a greater average water-filled pore space (WFPS = 62%) than CT fields (WFPS = 44%), leading them to relate the greater emissions to anaerobic metabolism occurring in the NT/RT plots. However, the influence of soil texture on WFPS under tillage practices was not significant over the winter period as soils would tend to be saturated, no matter the soil type.

## Mitigation potential of cover crops

In our meta-analysis, the effect of cover crop treatment across the trials was  $-18\%$  (95% CI =  $-35$  to  $3\%$ ) (Fig. 1; Table 2). This result indicates that although cover crops showed a tendency to reduce emissions overall ( $-18\%$ ), the change in their effect on over-winter  $N_2O$  emissions compared to the absence of a cover crop was not significantly different. In humid regions, the use of CCs significantly resulted in lower emissions (89% less) than in the dry areas, while soil texture did not significantly affect  $N_2O$  emissions (Fig. 3; Table S2). This finding concurs with Basche et al. (2014) findings that cover crops did not significantly affect direct  $N_2O$  emissions during the winter period. Their study also showed a significantly positive impact for data points measured during the decomposition of the cover crops compared to the impact during the cover crop growth period, which showed no significant difference. Although CCs can assimilate  $NO_3^-$  over winter, they have also been observed to produce elevated  $N_2O$  concentrations in the rhizosphere by drawing on a supply of labile C and N generated by decomposing tissues and living roots (Thomas et al. 2017; Wertz

**Fig. 3** Forest plot (random effects model) indicating subgroup (climate and soil type) effects of cover crop (CC) vs. no cover crop treatments (no-CC). Confidence intervals are also reported. CI crossing the null (zero) line indicates no significant change in effect or that both treatments show equivalent effects



et al. 2016). Therefore, while CCs have a better potential to mitigate  $N_2O$  emissions by depleting  $NO_3^-$ , this potential could be countered by the production of denitrification substrates in the cover crops' root zone.

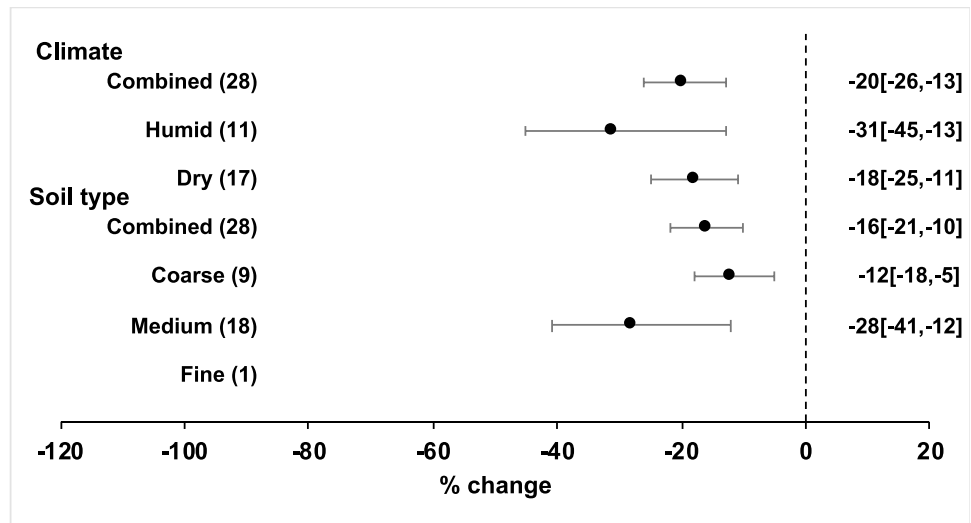
The capacity of cover crops to reduce over-winter  $N_2O$  emissions through the assimilation of  $NO_3^-$  largely depends on whether the cover crop is adequately established before the winter. This could be why a clear distinction was observed between the humid and dry climates in our meta-analysis. In cold and dry areas, cover crops sometimes develop poorly, suffer winter-kill, and cannot produce spring biomass. This situation was the case in a study by Behnke and Villamil (2019) where  $N_2O$  emissions ( $1.64 \text{ kg N ha}^{-1}$ ) in the first 2 years of their study, when the cover crop was poorly established, were significantly larger than emissions ( $0.32 \text{ kg N ha}^{-1}$ ) observed in the last 2 years, which had warmer temperatures and early November precipitation. Similarly, Dietzel et al. (2011) found that after a harsh winter, a winter rye cover crop (vs. the absence of a cover crop) had no significant effect on over-winter  $N_2O$  emissions; however, after the following year's milder winter, the cover crop resulted in lower  $N_2O$  fluxes. When simulated in growth chambers compared to field conditions where CC did not reduce over-winter  $N_2O$  emissions, Jarecki et al. (2009) observed that cover crops resulted in  $N_2O$  reduction due to better growing conditions in the growth chambers, which allowed for the development of roots, faster growths, and N uptake. Our analysis showed that although not significantly different, emissions under the CC practice were lower in coarse soils than in medium soils. We adduce that the ease of plant growth in coarse soils, which facilitates good plant establishment, may explain why lower  $N_2O$  emissions were observed in coarse soils. These observations point to the potential influence of CC developmental status on their overall impact on over-winter emissions.

Although cover crops tend to reduce spring thaw emissions in humid climates, and when their roots are well established, they have been observed to cause a significant increase in the growing season  $N_2O$  emissions after the following crop has been planted and fertilizer applied (Mitchell et al. 2013; Preza-Fontes et al. 2020). This increase in  $N_2O$  emissions is likely due to the denitrification substrates produced in the cover crops' rhizosphere, as well as the decomposition and subsequent release of  $N_2O$  when CCs are incorporated into the soil. Consequently, to improve N efficiency in CC plots, fertilizer inputs should be reduced after plowing (Guardia et al. 2016). The selected studies show no consensus about the cover crops' effects on either spring thaw or growing season  $N_2O$  emissions (Iqbal et al. 2015; Parkin et al. 2016). However, cover crops have other benefits, including reducing  $NH_3$ ,  $NO_3^-$ , DOC, and suspended solids in leachate (Gillette et al. 2018; Smukler et al. 2012). Cover crops also increase soil organic C sequestration (Basche et al. 2014) and enhance microbial abundance (Kim et al. 2020).

### Mitigation potential of nitrification and urease inhibitors

Our analysis on nitrification and urease inhibitors' (NI+UIs') effect on over-winter  $N_2O$  emissions shows a summary result of  $-23\%$  (95% CI =  $-28$  to  $-16\%$ ) (Fig. 1; Table 2), indicating that on average, NI+UI significantly reduced  $N_2O$  emissions. Under NI+UI, no significant difference was observed in  $N_2O$  emissions between humid and dry climates, although emissions were lower in humid areas. However, soil texture significantly impacted emissions under NI+UI (Fig. 4; Table S2). This effect was more evident in medium-textured soils than in coarse soils.

**Fig. 4** Forest plot (random effects model) indicating subgroup (climate and soil type) effects of nitrification and urease inhibitors (NI + UI) vs. no inhibitors. Confidence intervals are also reported. CI crossing the null (zero) line indicates no significant change in effect or that both treatments show equivalent effects. Only data for groups with more than one study is presented



This meta-analysis result concurs with a modelling study (Grant et al. 2020) which showed that nitrification inhibitors (NI) could reduce  $N_2O$  emissions from fall-applied slurry by up to 33%. Our review included various types of NI and UI — 3,4-dimethyl pyrazole phosphate (DMPP), nitrapyrin, dicyandiamide (DCD), N-(n-butyl) thiophosphoric triamide (NBPT), hydroquinone (HQ). It has been shown that some inhibitor types could be more effective in reducing  $N_2O$  emissions than others. For instance, Lin et al. (2017) revealed that the reduction coefficients for DMPP and nitrapyrin were 81% and 57%, respectively. Ding et al. (2015) also showed that DCD achieved more  $N_2O$  reduction (78.6%) than NBPT (50%).

Our findings together with earlier meta-analysis that focused majorly on the growing season (Feng et al. 2016; Qiao et al. 2015; Thapa et al. 2016; Yang et al. 2016) all agree that the use of NI + UI to prevent oxidation of  $NH_4^+$  to  $N_2O$  is an effective method for reducing  $N_2O$  losses. The significantly lower over-winter  $N_2O$  emissions observed with NI + UI application could result from low soil temperatures during winter since the efficacy of NI + UI for reducing  $N_2O$  emissions has been shown to depend on temperature. For instance, in their study of UK soils, McGeough et al. (2016) measured 89-, 37-, and 18-day DCD inhibitors half-lives ( $t_{1/2}$ ) in soils at 5 °C, 15 °C, and 25 °C, respectively. Similarly, Kelliher et al. (2008) found DCD inhibitors'  $t_{1/2}$  values in the soil to be 110 days at 5 °C, compared to 20 days at 25 °C. NI + UI's more prolonged efficacy at colder temperatures ensures the NI stays effective, particularly during the spring thaw period when N loss potential is typically high.

We further separated fall fertilizer + inhibitor application studies (Ding et al. 2015; Lin et al. 2017; Parkin and Hatfield 2010) from the rest of the inhibitor studies to investigate the effect size of fall application vs. prior spring application. We found that fall and prior spring application of inhibitors

significantly reduced over-winter emissions by 12 and 14%, respectively. Fall-applied inhibitors likely remained active by the following spring given their shorter duration and the low temperature during winter, explaining their effectiveness in significantly lowering over-winter  $N_2O$  emissions. However, the reason for the effectiveness of inhibitors applied in prior spring remains unclear given that the inhibitors should have degraded by the winter season. Additionally, it is hypothesized that the use of inhibitors, causing more N uptake by plants, could lower the C:N ratio in residues after harvest (Grant et al. 2020; Pfab et al. 2012). Ferrari Machado et al. (2020) suggested that the carryover effect of inhibitor treatments increasing soil N levels could be negligible after observing low  $N_2O$  fluxes during both the growing and non-growing seasons compared to the conventional N sources. Other researchers have attributed lower over-winter emissions in NI + UI plots to the reduction of denitrifying bacteria rather than  $NO_3^-$  availability, since  $NO_3^-$  levels were the same as those found in conventional plots (Pfab et al. 2012). However, a contradictory finding shows a NI such as DMPP to have significantly reduced  $NH_4^+$  oxidation on grasslands, though it showed no adverse effect on the denitrifier community's growth and activity (Duan et al. 2017). More studies are needed to understand the carryover effect of spring-applied inhibitors on over-winter  $N_2O$  emissions. Further research could focus on the effect of inhibitors on the microbial community.

The result of our meta-analysis showed that soils with medium texture significantly influenced the efficacy of NI + UI in reducing  $N_2O$  emissions more than coarse soils (Fig. 4). Medium-textured soils have larger surface area which allows the soil to hold more water. NI + UI's effectiveness has been tied to WFPS, Lin et al. (2017) showing a wetter site to exhibit a noticeable beneficial effect of NI compared to a less wet site. This scenario was due to



increased  $N_2O$  production in the control plots resulting from high soil WFPS compared with the lower  $N_2O$  production in NI plots where fall-added NIs prevented the oxidation of manures. This impact of WFPS on NI + UI's efficacy may also be the reason for the lower  $N_2O$  emissions observed in humid areas compared to dry areas. Similarly, Lin and Hernandez-Ramirez (2020) observed a greater NI efficacy in soils with increasing moisture content when the potential for  $N_2O$  production was high. However, after a few days, when WFPS surpassed field capacity, NI's potential to reduce  $N_2O$  emissions from the soil diminished. This reduced efficiency was possibly due to the complete denitrification of  $NO_3^-$  to  $N_2$  in control plots leading to lower  $N_2O$  emissions or the lapsing of NI effectiveness in NI treatment plots, giving rise to the possible oxidation of  $NH_4^+$  to  $N_2O$ . Increasing NI rates has been recommended to ensure NI's continued efficacy in soils with high moisture content. For instance, the most efficient NI rates were achieved by increasing the nitrapyrin rate by 25% as soil moisture increased from 60 to 80% WFPS (Lin and Hernandez-Ramirez 2020).

However, caution must be applied interpreting these results as NI + UI efficacy to inhibit  $NO_3^-$  production may also be affected by other soil properties, including organic matter, clay content, soil Cu, and total N (McGeough et al. 2016). For instance, NI's lower inhibitory efficiency has been reported to result from high rates of adsorption by clay and SOC (Zhu et al. 2019). Therefore, it may be the case that there are variations in environmental and soil factors such as moisture, temperature, substrate availability, and management decisions such as timing, quantity, and placement of the NI + UI, that could affect the efficacy of NI + UI. Further studies investigating how the combination of these factors interacts with various NI rates over winter are needed. Given the potential trade-offs of NI application, including an increase in  $NH_3$  emissions and possible NI contamination, it is essential that studies also account for volatilization and N-leaching in addition to  $N_2O$  measurements. Overall, NI + UI practice significantly reduces both over-winter and growing season  $N_2O$  emissions. NI + UIs have also been shown to increase NUE use by 13% and boost yield by an average of 7.5%, and by adopting NI + UI practice, farmers could potentially gain up to US\$6 per ha (Kanter and Searchinger 2018).

## Conclusions

Occurring predominantly at the onset of the winter freezing period and in early spring when the soil begins to thaw, over-winter  $N_2O$  emissions make up a significant portion (up to 91%) of annual cropland emissions. We discussed the overall efficacy of nitrification and urease inhibitors (NI + UI), no-till, and cover crops (CCs) to mitigate emissions. We show that while no-till and the use of NI + UI significantly reduced

over-winter  $N_2O$  emissions by 28% and 23%, respectively, the use of CCs overall did not cause any significant change in the emissions. Although CCs have the potential to mitigate  $N_2O$  emissions by assimilating  $NO_3^-$  over winter, the production of denitrification substrates in the cover crops' root zone could hinder this potential. This review revealed that cold-dry soil conditions, such as in Western Canada, could prevent CCs from being fully established in some years, hampering this management practice's effectiveness for reducing  $N_2O$  emissions in these regions. To effectively mitigate the significant freeze–thaw emissions, we recommend the enactment of policies that will encourage farmers' adoption of NI + UI in addition to other management practices such as no-till and the use of cover crops. We highlight the need for more extensive research focusing on the effect of the interaction of soil and climate conditions with field practices on the magnitude of emissions. Further studies could focus on the roles of denitrifying and nitrifying genes on over-winter  $N_2O$  emissions.

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**Author contribution** Kosoluchukwu C. Ekwunife curated data, performed the analysis, and wrote the paper. Chandra A. Madramootoo outlined scope of the study and reviewed and edited all drafts. Naeem A. Abbasi curated data and provided technical comments. All authors read and approved the final manuscript.

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**Data availability** The datasets generated and analyzed during this study are included in the manuscript. Any queries for the datasets can be directed to the corresponding author.

**Code availability** The R software package *metafor* 2.4–0 was used for all analyses performed in this study. The code can be made available by the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors declare no competing interests.

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