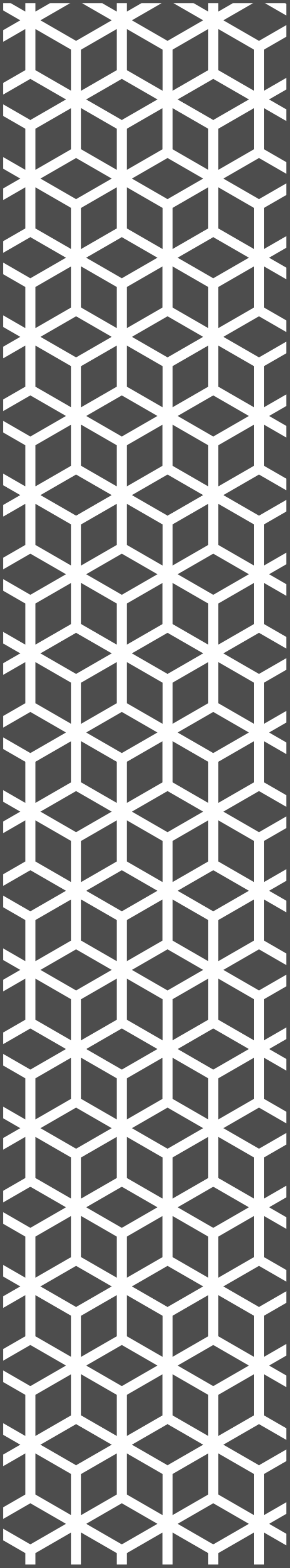

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Opportunities & Challenges for Meeting Fertilizer Based Emission Reduction Target

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OPPORTUNITIES & CHALLENGES FOR MEETING FERTILIZER BASED EMISSION REDUCTION TARGET

Working Paper.
May 20, 2022.

Joshua Bourassa[1*], Luc Fourner[2], Elena Vinco[1]

1: Simpson Centre, The School of Public Policy, University of Calgary, Calgary, AB, Canada
2: Department of Agribusiness and Agricultural Economics, University of Manitoba, Winnipeg, MB, Canada

* Corresponding author: Joshua.Bourassa@ucalgary.ca

Abstract

Increasing pressure to expand output while maintaining or decreasing input and land use has placed farmers in a difficult position. The increase in fertilizer use to support growing yields and soil deficiencies in Canada lead to a significant spike in nitrous oxide emissions over the past 18 years. In 2020, the federal government of Canada introduced the first emission reduction target specific to the agricultural sector, aiming for a 30 percent reduction of inorganic fertilizer-based emissions by 2030. Agriculture and Agri-Foods Canada released a discussion paper in 2022, supplementing the federal government's target with practical strategies and recommendations for farmers to adopt with associated changes and trade-offs, in order to reach the target. This systemic review of meta-analytical studies based explores the potential impact of 4R stewardship adoption and other mitigation strategies, including biochar, irrigation, and the use of legumes in crop rotation, on N_2O emissions in Western Canada. Results were mixed, likely due to the interrelationships between environmental and soil factors in the nitrogen and hydrological cycles. Overall, enhanced efficiency fertilizers were identified as the most advantageous and applicable practices, with less applicable practices like biochar and micro irrigation also reducing N_2O emissions. In order to improve N_2O emission measurements and reflect the adoption of all mitigation strategies, Canada's N_2O accounting methodology should be updated before the 2030 target deadline.

Keywords: *Greenhouse gas, Fertilizer, N2O, Canadian Agriculture, Crop Production, NIR, IPCC*

Near-Term Nitrous Oxide Reduction Options:

Opportunities & Challenges for Meeting Fertilizer Based Emission Reduction Target

Greenhouse gas emissions from the Canadian agricultural sector have increased by 5.6 percent since 2005, reaching a high of 69 Mt CO_2 equivalent (CO2e) in 2020 (Environment and Climate Change Canada, 2022b). Agricultural emissions can be divided into three broad categories: animal production, crop production, and on-farm fuel use, each comprising of 50, 31, and 20 percent of total agricultural emissions, respectively. While emissions originating from animal production decreased since 2005, and on-farm fuel use emissions remained relatively unchanged, emissions from crop production have nearly doubled, increasing from 12 to 21 Mt CO2 eq. The spike in emissions from crop production can be primarily attributed to increased use of inorganic nitrogen fertilizer, which rose by 89 percent between 2005 and 2020, accounting for 73 percent of the increase in direct N_2O emissions attributed to crop production (Environment and Climate Change Canada, 2022a), demonstrated in Figure 1. In response to growing emissions from crop production, the federal government proposed introducing Canada's first emission reduction target for the agricultural sector (Agriculture and Agri-Food Canada, 2022). The plan aims to reduce inorganic fertilizer-based emissions by 30 percent of 2020 levels by 2030, resulting in a reduction of approximately 3.8 Mt CO_2 eq based on 2019 estimates. To meet this target by 2030, Canadian farmers will need to adopt the latest best management practices and embrace emerging technologies. This report synthesizes near-term mitigation options currently available to producers, and adoption-related agronomic benefits or shortfalls. To identify potential emission reduction opportunities, a systematic review of meta-analytical studies was conducted covering the period from 2010 to April 2022. A total of 31 papers explored the effectiveness of 4R Nutrient Stewardship[1] (4R), irrigation, biochar, and the use of legumes in crop rotations on reducing emissions. Lastly, this report discusses how these mitigation efforts are integrated into the Intergovernmental Panel on Climate Change (IPCC) framework and Canadian specific emission methodology.

Background

Nitrous oxide is a potent greenhouse gas and an ozone-depleting substance with a 100-year global warming potential of approximately 298 times that of CO_2 (Environment and Climate Change Canada, 2022c). It is the third most emitted greenhouse gas in Canada, after carbon dioxide (CO_2) and methane (CH_4), and accounts for approximately 5 percent of total emissions, measured in CO_2 equivalent (CO_2e). Agricultural production accounts for 76 percent of total N_2O emissions, with 17 percent originating from animal production and the remainder from crop production (Environment and Climate Change Canada, 2022a). Nitrous oxide emissions from crop production occur as a result of biochemical processes in agricultural soils (Environment and Climate Change Canada, 2022b). They are classified as direct or indirect emissions. Direct emissions are a result of biochemical reactions within the soil called nitrification and denitrification. Nitrification occurs when soil microorganisms convert ammonium (NH_4^+) to nitrate (NO_3^-), a form of bioavailable nitrogen for plants. Denitrification is the conversion of nitrate to nitrogen gas (N_2).

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[1] 4R is a framework designed to aid farmers in managing crop inputs by applying the right fertilizer source at the right rate, at the right time, and at the right place in order to meet economic, environmental and sustainability goals (Agriculture and Agri-Food Canada, 2022).

Indirect emissions are classified into two groups: volatilization, and leaching and runoff (Environment and Climate Change Canada, 2022b). Volatilization occurs when ammonium (NH_4^+) is converted to ammonia gas (NH_3) and commonly occurs when nitrogen fertilizer is surface applied. Leaching and runoff occur when nitrates (NO_3^-) leach or runoff and are subsequently lost to the environment. Nitrification, denitrification, volatilization, leaching, and runoff are naturally occurring processes in the nitrogen cycle. Cycle imbalance is likely with the addition of nitrogen fertilizers or the incorporation of crop residues, resulting in excess soil nitrogen level and high N_2O emissions. In 2020, 58 per cent of direct N_2O emissions from agricultural soils were attributed to the use of inorganic nitrogen fertilizer, 10 percent from organic fertilizers, and 25 percent from the incorporation of crop residues (Environment and Climate Change Canada, 2022a).

As seen in Figure 2, significant increases in crop production-based emissions between 2005 and 2020 were observed in all regions of Canada and ranged between 11 percent in Atlantic Canada and 103 percent in Manitoba (Environment and Climate Change Canada, 2022c). Across Alberta, Saskatchewan, Manitoba and Ontario, the four largest emitting provinces, emissions from crop production increased by 84 percent. While these increased are considerable, it is important to place these changes in a broader context of agricultural production in Canada. Growing demand in conjunction with economic pressures has propelled farmers to increase output while maintaining or shrinking land use (Statistics Canada, 2022a), prompting increased use of nitrogen fertilizer and subsequent increased N_2O emissions.

The federal government proposed its first agriculture specific emission reduction target in its 2020 Strengthened Climate Plan, aiming to reduce greenhouse gas emissions from the agricultural sector and reverse current emission trends (Environment and Climate Change Canada, 2020). The proposed target sought to reduce fertilizer-based emissions by 30 percent of 2020 levels by 2030. This target was estimated to reduce emissions by 3.8 Mt of CO_2 eq (Agriculture and Agri-Food Canada, 2022), leading to a reduction of 5 per cent of total agricultural emissions and 0.5 per cent of total Canadian emissions (Environment and Climate Change Canada, 2021b). Additional supplementary information about the target was provided in a 2022 Agriculture and Agri-Food Canada (AAFC) paper (Agriculture and Agri-Food Canada, 2022). Direct and indirect emissions from inorganic fertilizer were the main focus of reduction initiatives, while emissions from organic fertilizers, such as manure, or emissions originating from fertilizer production, were not included. The AAFC paper highlighted several near-term mitigation strategies to meet the emission target. The strategies primarily focused on adopting 4R nutrient stewardship and the sustainable use of fertilizer in crop production, as well as the adoption of conservation tillage, improving field drainage, and increased use of legumes in rotation. The paper also briefly discussed the importance of emission measurements, reporting, and data.

Developing and approving the use of a comprehensive methodology that directly accounts for near-term mitigation strategies is critical to ensure emission targets are met. For example, the IPCC Tier 1 methodology used by most Annex I parties to the United Nations Framework Convention on Climate Change uses a set emission factor of 1 percent, meaning that for every 1 kg of nitrogen applied, 0.01 kg of N_2O-N is emitted (IPCC, 2006). While this is a relatively easy and transparent way to estimate emissions, many of the practices discussed within the AAFC paper would not reduce emissions according to current accounting methodology. Strategies proposed by the AAFC paper would influence both emission factor calculations and activity data, While the IPCC methodology only uses activity data (fertilizer use) to measure emissions (Environment and Climate Change Canada, 2022b; IPCC, 2006). Additionally, a set emission factor fails to account for climatic differences between regions, resulting in differing emission levels despite identical practices. Improvements on the 2006 Guidelines were provided in the 2019 Refinement, in which disaggregated emission factors were provided, specifying emission factors based on climate (tropical, temperate, boreal), rainfall (wet, dry), use of irrigation, and type of fertilizer (inorganic, organic, or mixed) (IPCC, 2019). Despite the improvements, broad-based emission factors, such as a single emission factor for dry temperate climates, still fail to account for substantial regional differences and do not go far enough to account for specific management practices that potentially result in significant emission reductions.

The methodology currently used in Canada addresses some of the major concerns of the IPCC Tier 1 approach. This method estimates localized emission factors at an Eco-district level (Environment and Climate Change Canada, 2022b). A base emission factor for each of 405 Eco-districts in which agricultural production takes place is first estimated as a function of precipitation, potential evaporation, topography, and soil texture. The base emission factors can be modified to account for specific management practices, crop types, and fertilizer types, improving emission factor estimate accuracy. Despite these improvements, many of the near-term measures presented within the AAFC discussion paper, particularly around adopting 4R practices, are not directly accounted. Fertilizer timing, placement, or the use of enhanced efficiency fertilizer are not considered in the current methodology's framework. Changes in emissions are only partially accounted through additional soil testing and nitrogen credits (i.e., reduced fertilizer use). Given the current methodology, adopting many of these near-term strategies would result in little to no change in emission reporting, further complicating and convoluting the way forward in meeting the emission reduction targets. Methodology shortcomings were acknowledged in the AAFC paper, and improvements are likely to continue as data becomes more readily available (Agriculture and Agri-Food Canada, 2022). Recent updates to the methodology introduced in 2022 lead to substantial decreases in both the emission factors and emission levels, see Figure 4 and Figure 5

(Environment and Climate Change Canada, 2021a, 2022b). For Canadian producers to effectively meet the target without sacrificing large production decreases, further updates are still required.

METHODS

A systematic review of meta-analytical studies covering peer-reviewed papers published between 2010 and April 2022 was conducted. The review was carried out using the CAB Abstracts, Environment Complete, Web of Science, and Scopus databases. The original search string used was: "N2O *OR* nitrous oxide *OR* GHG *OR* greenhouse *AND* soil *OR* agriculture *OR* crop *OR* farm *AND* mitigate* *OR* prevent* *OR* reduc* *AND* meta-analysis". Subsequent searches were also conducted to ensure management practices of interest were included, focusing on fertilizer[2], conservation tillage[3], irrigation[4], and rotation[5]. Papers were further restricted to those published in peer-reviewed journals and published in English. Three hundred ninety-eight unique articles were identified from the keyword searches and were further screened based on the following criteria:

1. The meta-analysis was not country-specific (except for in the case of North American production).
2. The meta-analysis was focused on grain crops commonly grown in Canada or was not crop-specific.
3. The meta-analysis provided an estimate of the effect of adopting a practice with the value presented on N_2O, area-scaled N_2O, or yield-scaled N_2O emissions.

Of the 398 papers reviewed, 30 meta-analytical studies and one review of meta-analytical studies met all criteria. The studies covered nitrogen source, nitrogen application rate, timing, nitrogen placement,

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[2] Search string is as follows: "fertil* or urea and N2O or nitrous oxide or GHG and meta-analysis"
[3] Search string is as follows: "no-till or reduced or conservation and till* and N2O or nitrous oxide or GHG and meta-analysis"
[4] Search string is as follows: "irrigat* and N2O or nitrous oxide or GHG and meta-analysis"
[5] Search string is as follows: "irrigat* and N2O or nitrous oxide or GHG and meta-analysis"

adoption of conservation tillage, use of biochar, irrigation, cover cropping, and rotation, see Table 1. Each study's response ratio and associated error terms were extracted using WebPlotDigitizer (version 4.5).

The average effects sizes of the management practices and technologies were estimated using the natural logarithm of the response ratio ($LnRR$) using Equation 1 (Pustejovsky, 2018)

$$lnRR = ln\left(\frac{\bar{X}_t}{\bar{X}_C}\right) = ln(\bar{X}_t) - ln(\bar{X}_c) \qquad (1)$$

where $\bar{X}_t$ is the mean value of the treatment and $\bar{X}_C$ is the mean value of the control. To aid in the interpretation of the $LnRR$, the value was converted to percent change between the treatment and control value using Equation 2 (Pustejovsky, 2018).

$$\%Change = 100 * (e^{LnRR} - 1) \qquad (2)$$

Once converted, a weighted mean and standard deviation were estimated for each management practice identified within the literature review. A series of range plots, using a 95 percent confidence interval, were generated to interpret the findings. Significant results can be identified when the estimated confidence interview does not intersect with zero.

Results and Discussions

This report sought to synthesize a wide body of literature to better understand the potential effects of near-term Best Management Practices (BMP) on N_2O emission reductions. Thirty-one meta-analytical studies were included in the database, with observations covering 10 management practices. This section provides an exploratory look at the effects of the BMPs on emissions and yields. The review's findings are also compared to the AAFC discussion paper and other recent academic literature.

Enhanced Efficiency Nitrogen Fertilizers

Enhanced efficiency nitrogen fertilizers (EENFs) prolong nitrogen availability by reducing nitrogen loss (Heard, n.d.). They can be categorized into two broad groups based on the mechanism used to increase availability. The first group of EENFs are stabilized nitrogen fertilizers (SNFs), which use urease or nitrification inhibitors (UI and NI, respectively) to temporarily protect against ammonia volatilization (UI) or denitrification and leaching (NI). The inhibitors can be applied individually or combined, referred to as double inhibitors (DI) (CropWatch, 2019). The second type of EENFs are controlled released nitrogen fertilizers (CRNF). CNRF protect against nitrogen loss by coating the fertilizer in a polymer or resin, releasing nitrogen as the coating around the fertilizer breaks down over time (Nutrien, n.d.).

As seen in Figure 6, EENFs were effective at reducing N_2O emissions. The estimated average reduction was 29 percent, similar to estimates provided by AAFC (2022) and Young et al. (2021). Both types of EENFs, SNFs and CRNFs, were effective, with an average reduction estimated to be 37 and 19 percent (Figures 7 and 8). Significant differences in effectiveness were observed when comparing inhibitor types. Urease inhibitors were less effective than NIs at reducing N_2O emissions. However, since urease inhibitors' main function is to inhibit the production of NH_3 gas and not directly inhibit nitrification or denitrification (CropWatch, 2019), this result was expected. Conversely, less effective UIs were observed to reduce N_2O emissions. As seen in Figure 9, EENFs were effective across various management practices, soil types, and in humid and arid environments. Three important findings can be observed in Figure 9. First, EENFs appear effective in reducing emissions from irrigated cropping systems. Irrigation is highly important for production in many semi-arid regions of Western Canada (Statistics Canada, 2022b), but increased soil moisture leads to significant increases N_2O production. Second, EENFs are more effective with the adoption of other 4R BMPs (placement and time), but are still effective at reducing emissions in combination with traditional practices, allowing for increased flexibility when making production decisions. Lastly, EENFs were effective when applied to conservation tillage systems, a practice with high adoption rates in Western Canada (Statistics Canada, 2022c).

As seen in Figure 6, EENFs were found to significantly increase yields compared to conventional inorganic fertilizers, creating a potential win-win scenario where cost of adoption can be offset, or partially offset, by increased yields. Low current adoption rates despite compatibility with a variety of management practices suggests costs may still outweigh expected benefits of implementation (Agriculture and Agri-Food Canada, 2022). Improvements to current carbon offsets or development of other supplementary programs may facilitate rapid emission reductions once incentives are in place. Along with the challenge of increasing adoption is the challenges quantification. Canadian methodology does not currently account for the use of EENFs. A recent review of 42 national inventory report found only three countries had separate emission factors for their use (Bourassa & Vinco, 2022). Canada's methodology has the flexibility incorporate the use of EENFs without significant changes to the model's structures. This flexibility was highlighted to recent changes to emission estimates from organic fertilizers which applies an adjustment factor to the estimated emission factor to account for differences in nitrogen source (Environment and Climate Change Canada, 2022b).

Organic Fertilizers

The AAFC discussion paper identified increased use of organic fertilizers, such as manure, biosolids, and anaerobic digestate, as a potential near-term mitigation strategy (Agriculture and Agri-Food Canada, 2022). The paper estimated N_2O reductions between 10 and 20 percent, contrary to this review's findings. This review identified seven meta-analytical papers that examined the effect of switching from inorganic to organic fertilizer sources. The individual results ranged from -7 to 40 percent changes in emissions, see Figure 10. The weighted average of the results was not significant, with a mean value of 15.6 percent and a confidence interval between -3 and 34 percent. While not significant, some evidence suggests an increase in N_2O emissions in switching between nitrogen sources. For example, in Young et al. (2021), the response ratio average is a 23 percent increase in N_2O emissions. The effects of organic fertilizer on yield were not found to be significant, but the mean average value, -6.3 percent, was similar to Young et al. (2021) findings of 5.6 percent, which may suggest a potential yield increase with adoption. Additionally, high variability in manure nitrogen content, and variability in nitrogen availability after application, would require additional testing to ensure the right rate is being applied at the right time, further complicating this practice. The results of this review suggest the substitution of inorganic nitrogen fertilizer for organic fertilizer sources does not appear to be an effective mitigation strategy.

Despite some apparent drawbacks as a mitigation strategy, organic sources do have some advantages, particularly around meeting emission targets. First, it is a productive use of animal waste. Second, it is a stable nitrogen source and available longer than other nitrogen sources once incorporated (Shaji et al., 2021). Third, organic sources can be mixed with inhibitors which have been found to be effective at reducing emissions (Wilson & Vetsch, 2019). Lastly, emissions attributed to organic fertilizer are not accounted for within the emission reduction target, leading to a substantial reduction from an emission accounting perspective (Agriculture and Agri-Food Canada, 2022; Environment and Climate Change Canada, 2022b).

Biochar Application

Soil amended with biochar (charcoal) was found to be the most effective practice at reducing N_2O emissions in this review. Biochar has been used in many traditional agricultural systems, particularly in South America where it’s use goes back over 2,500 years (United States Biochar Initiative, 2021). Historically, biochar was used to improve soil health and increase crop yields, and is being investigated further as a way to increase carbon sequestration and mitigate greenhouse gas emissions. Biochar is produced when organic matter is burned in a low oxygen environment. While traditional methods of production produce significant amount of CO_2, biochar produced in a closed system using modern techniques has minimal environmental impact and can be used as a renewable energy source.

Within this review, biochar amended soil reduced N_2O emissions by an average of 38 percent and increased yields by an average of 14 percent compared to systems without biochar application, see Figure 11. A promising near term-mitigation strategy, adoption of biochar may be difficult, given variability in effectiveness at different rates, and differences in composition when derived from various sources. Further complicating potential adoption, production and application of biochar is a multistep process, potentially impacting effectiveness, and emission reduction outcomes at several stages. First, biochar needs to be incorporated in the soil, possibly reversing some of the benefits of conservation tillage in Western Canada. Second, the effectiveness of biochar is highly dependent on the feed stock, see Figure 12. Woody and non-woody biomass derived biochar were most effective, while biochar derived from manure and other biosolids were not found to significantly reduce N_2O emissions. Application rates also greatly affected capacity to mitigate nitrous oxide emissions. Application at rates under 10 tonnes per hectare (t ha^{-1}) was not found to significantly reduce emissions. As seen in Figure 12, significant reductions were observed at application rates greater than 10 t ha^{-1}, and most effective at rates above 40 t ha^{-1}, likely a significant barrier to widespread implementation. While this practice is not likely to see extensive adoption for field crop production in the Canadian Prairies, it could be an effective mitigation strategy for organic production, where woody biomass for biochar production is more readily available in certain areas.

Conservation Tillage

Tillage, an important step in the preparation of soil for planting, is a mechanical process which loosens the soil to prepare the seedbed (Hofmann, 2008). Conventional tillage often involves incorporating the previous year‘s crop residue into the soil. While this practice clears the field and can be an effective weed management strategy, susceptibilities to wind, water erosion, and moisture loss are increased. Conservation tillage primarily seeks to protect against erosion by leaving some crop residue on the soil surface. At a minimum, conservation tillage requires at least 30 percent of crop residue to remain on the soils surface, however; significantly more is retained in systems like no-till, which involves direct seeding into the crop residue (Bergtold et al., 2020). In Western Canada, adoption of no-till is high; 88 percent of seeded acres in Alberta utilize.

Conservation tillage promotes several environmental benefits, including reduced erosion, increased soil health, improved moisture retention, and increased soil organic matter (Bergtold et al., 2020). It is also highlighted within the AAFC discussion paper as a potential near-term N_2O mitigation option. Additionally, the adoption of conservation tillage is one of the few practices directly accounted for within the national methodology for its effect on direct N_2O emissions, however; its effects vary by region, and can promote N_2. This review found limited research demonstrating the effectiveness of conservation tillage in reducing N_2O emissions.

Overall, the estimated weighted average was found to be significant, increasing emissions by an average of 7 percent, as seen in Figure 13. Complicating this discussion further, Young et al, (2021) found significant increases in N_2O emissions and decreases in yield in their meta-analytical synthesis. Disaggregated results, also presented in Figure 14, did not identify any limited scenarios in which conservation tillage significantly reduced N_2O. One possible explanation is the relationship between N_2O and soil moisture, as conservation tillage systems increase moisture retention, thus stimulating N_2O emissions. However, given that soil moisture is a potential limiting factor in Western Canada and other environmental benefits of conservation tillage, adoption may be a beneficial trade off.

Other 4R BMPs

Limited results exploring the effects of other 4R practices (rate, place, and time) on N_2O emissions and yield were identified in the review. The lack of studies may be a result of difficulty finding suitable comparisons for a generalized meta-analytical study. Applying the right source, at the right rate, time, and place, are highly interdependent factors, and also depend on other management practices, the environment, and specific crops, therefore possibly limiting the effectiveness of this type of analysis. To provide a more rounded discussion and to make the discussion more applicable to Western Canada, several recent field studies conducted in Western Canada and the Northern Great Plains were included in the discussion for comparison.

Selecting the right application rate is an optimization problem farmers face. If the selected rate is too low, productivity is constrained, decreasing farm income. On the other hand, overapplying fertilizer may only marginally increase productivity, while also increasing input cost and decreasing profitability. Also, soils with excess nitrogen are prone to increased nitrogen loss. To maximize income and reduce environmental impacts, BMPs related to rate often focus on a combination of increased soil testing and variable rate application so fertilizer application is most advantageous. These practices are highlighted in the AAFC discussion paper, recommending annual soil testing for spring application accompanied by variable rate application, and accounting for nitrogen credits when determining application rates. Both management practices focus on preventing nitrogen over-application, with the benefit of reducing excess soil nitrogen, thereby reducing nitrogen available to be emitted as N_2O. Within this review, only two papers directly examined application rate effects on emissions and yield. Both yield and N_2O emissions increased as fertilizer application increased; however, yield increased at a diminishing rate. Yangjin et al. (2021) found that reductions in application rate (<25%) could result in significant emissions reduction without significantly reducing yield. Their findings suggest that current application rates are likely above-recommended levels and farmers may see financial benefits by reducing fertilizer use. Similar results were found by Young et al. (2021); both N_2O emissions and yields decreased with decreased nitrogen application, but the magnitude of the change was significantly larger for N_2O, -8.6 compared with -3.4 percent, respectively. Canada's current methodology accounts for changes in application rates to an extent. The approach uses a combination of estimated recommended rates which are then adjusted by annual fertilizer sales within the province (Environment and Climate Change Canada, 2021a). Reduction of fertilizer sales within the province linked to increased soil testing, variable rate application, or better accounting of nitrogen credits, would translate into reduced emissions in national reporting. As estimates are made at the Eco-district level, changes made to application rates at the field level may not be fully quantified.

Best Management Practices for nitrogen placement recommends applying fertilizer below the surface (Fertilizer Canada, n.d.). Subsurface application ensures easier access to the plant root zone for quick fertilizer utilization and reduces risk of nutrient loss through run off and ammonia volatilization. This practice was also recommended in the AAFC discussion paper, with current high rates of adoption in western Canada, and estimates potential N_2O reductions to be between 5 to 15 (Agriculture and Agri-Food Canada, 2022). Findings from Young et al. (2021) also appear to support the AAFC discussion paper reduction estimates, observing an average emission reduction of 14 percent. Further evidence was found in Gao et al. (2017) which conducted multiple field trials in Manitoba. Using the reported emissions presented in the paper, the average difference between banding and broadcast incorporation was -21 percent.

This review only identified two meta-analytical studies that explored the effectiveness of deep placement (>5 cm) on N_2O emissions. In Han (2017), subsurface application was not found to lead to significant emission reductions across the 23 treatments included in the estimate. Chen (2021) found significant increases in N_2O emissions with the adoption of deep placement but also significant increases in yields and a decrease in emission intensity. Fertilizer placement is not explicitly accounted for within Canada's national emission methodology for either direct or indirect emissions. However, some effects maybe be captured if adoption results in a decrease of fertilizer use and consequently reflected in provincial fertilizer sales.

The AAFC discussion paper highlighted three management practices related to timing (Agriculture and Agri-Food Canada, 2022). First, the paper recommended spring fertilizer application as opposed to fall application, a practice mainly applicable in Western Canada with potential to reduce emissions by 5 to 15 percent. The second practice highlighted using a split application, identified as being mainly applicable in Eastern Canada with potential to reduce emissions by 15 to 35 percent. Lastly, the paper highlighted fertigation, which is mainly applicable to production in Western Canada, with potential to reduce emissions by 15 to 25 percent, further discussed in following section. Several recent studies conducted in Western Canada explored the effects of timing on N_2O emissions. In Owens et al. (2020), emission comparisons between applying 100 percent of nitrogen fertilizer pre-planting for winter wheat with a split application of 30 percent replanting and 70 percent in the late fall, or 30 percent preplanning and 70 percent at growth stage 4 were compiled. Across the eight comparisons available, the average difference between split application and a single application was found to be -8 percent. When comparing the effectiveness of different timing for the second application, applying in late fall increased emissions by 6 percent while applying at GS4 decreased cumulative emissions by 22 percent. Thilakarathna et al. (2020), examined the effectiveness of different fertilizer types and application times. Across the seven comparisons, the average effect of springtime application compared to the fall was found to be -18 percent.

This review identified two papers exploring the effects of fertilizer timing on N_2O emissions. Han et al. (2017) compared fall application to a delayed application and found no significant differences across 34 treatments. Similarly, Abalos et al. (2016) found non-significant results comparing fall to spring fertilizer application and planting to side dressed application times. When evaluating timing effects on yield, significant differences were not observed between fall and spring, but an increase in yield was observed when comparing planting to side dressed. Differences between the AAFC estimates and those of the meta-analytical studies included in the review highlight some of the challenges in untangling the interrelatedness of 4R BMPs and may oversimplify some of the practices. For example, the Canola Council of Canada provides a general description of 4R practices related to timing (The Canola Council of Canada, 2022). While spring or early summer applications are recommended, banding fertilizer in the fall, or top-dressing nitrogen in the summer are also acceptable practices. Alberta’s Nitrous Oxide Emission Reduction Protocol (NERP), requires spring, split applications, or fall application once soil temperatures cool below 10 degrees Celsius (Government of Alberta, 2015). While there are several recommended timings, it is generally recommended not to apply nitrogen in the winter or when the soil is frozen as it is more prone to loss (The Canola Council of Canada, 2022). Currently Canada’s emission methodology does not account for timing, unless timing results in reduced fertilizer sales.

Irrigation

Irrigation poses a unique challenge for agricultural systems in meeting emission reduction targets. On one hand, irrigation is a key component to climate change adaptation for the agricultural sector, particularly in Western Canada were the frequency and severity of droughts are expected to increase with time (Natural Resource Canada, 2021). On the other hand, irrigation leads to significantly higher N_2O emissions as a result of substantial increases in soil moisture. If total irrigated land is to increase, large increases in nitrous oxide emissions should also be expected. While significant work done to quantify emissions from irrigated land has been conducted work is still needed is still needed (Environment and Climate Change Canada, 2021a, 2022b). For example, in David et al. (2018) estimated emissions using the Canadian methodology significantly overestimated emissions compared to field level measurements, while this is partially addressed in the 2022 National Inventory Report assumptions around target soil moisture levels may still need to be adjusted.

AAFC recommends the use of fertigation to reduce N_2O emissions from irrigated systems (Agriculture and Agri-Food Canada, 2022). Fertigation is the process of applying fertilizer with water through the irrigation system, allowing incremental but more frequent application of nitrogen throughout the growing season (Chai et al., 2020). This review was unable to find any meta-analytical studies that estimated the effects of fertigation on N_2O emissions. Recent field studies conducted in Western Canada by Gao et al. (2017) and Chai et al. (2020) support recommendations around the use of fertigation. Gao et al. (2017) observed lower average emission levels of approximately 43 percent when fertigation was used compared to a single broadcast application of urea. Chai et al. (2020) compared the use of fertigation at differing rate and with different crop type, using the reported values an average difference was estimated to be 16 percent.

A second potential related mitigation strategy was identified from this review. Drip irrigation is a type of micro-irrigation system aimed at applying water directly base of the plant (surface drip irrigation) or to the root size (sub surface drip irrigation) to meet moisture needs while reducing water consumption (Statistics Canada, 2016). While micro-irrigation is common in fruit and vegetable production in Canada, it has seen little adoption for field crops (Statistics Canada, 2021); however, it is becoming more commercially available and can be adapted to larger scale (Kalinowski, 2021). Both Kuang et al. (2021) and Yangjin et al. (2021) found significant emission reductions with drip irrigation, with an average effect size of -32 percent, see figure 16.

Cover Crops and Rotation

Cover crops provide a number of ecological benefits including reduced soil erosion, increased water availability, and improved soil health (Clark, 2019). As a mitigation strategy, the type of crop grown effects how and when emissions are reduced. Legume cover crops fix nitrogen within the soil which in turn reduces nitrogen requirements for subsequent crops potentially reducing N_2O emissions in subsequent years if nitrogen credits are accounted for. Non-legume crops scavenge excess nutrients in the soil from previous crops and can reduce non-growing season emissions. The use of cover crops as a mitigation option was not highlighted in the AAFC discussion document but was frequently discussed as an ecological-based mitigation strategy throughout the reviews. Three meta-analytical studies, Basche (2014), Han et al. (2017) and Muhammad et al. (2019) were included within this review, with varying results between studies. In Han et al. (2017), average effect of cover crops on N_2O emissions was not found to be significant, but it was found that the length of the study had a significant effect on results. For example, studies that only measured over the cover-crop growing season found significant reductions in N_2O emissions; however, after accounting for the full growing season, the use of cover crops were no longer found to have a significant effect. In Bashe et al.

(2014), results were further disaggregated by crop type. Both legume and non-legume crops were observed to significantly increase N_2O emissions; however, the increase in emissions was significantly lower for non-legume crops (8 percent), compared with legume crops (487 percent, reported LNRR value of 1.77). In Muhammad et al. (2019), results were also disaggregated by crop type, with non-legume crops found to significantly reduce N_2O emissions by an average of 36 percent while legume cover crops increased N_2O by an average of 60 percent. For comparison, Young et al. (2021) found emissions were reduced by the inclusion of cover crops by an average of -5 percent but did not differentiate by crop type.

The increased use of legumes in crop rotations would have multiple effects on N_2O emissions. First legumes have significantly lower nitrogen requirements compared with non-legume crops reducing total nitrogen use within the growing season. Second, as legume fix nitrogen, less nitrogen inputs would be required in the subsequent year further reducing N_2O emissions (Agriculture and Agri-Food Canada, 2022). Limited examples of the effects of crop rotation on N_2O emissions were provided within the review one two papers, Decock (2014) and Han et al. (2017) provided comparison. In Decock (2014) corn-corn rotations were compared with corn-soybean rotations and no significant differences were found. In Han et al. (2017) simple rotations were compared with diverse rotations, and no significant differences were found. Significant reductions in emissions were found in the case of Young et al. (2021), which compared simple to diverse rotations, and the average reduction was found to be -4 percent which had a similar magnitude to Han et al (2017), see figure 16. In a recent field study conducted by Liu et al. (2021) wheat-wheat rotations were compared with different legume – wheat rotations over a four-year period and found that legume type effected N_2O emissions. Emissions reductions were observed in pea – wheat and faba bean – wheat rotations while increases were observed in the case chickpea – wheat and lentil wheat rotations. Macwilliam et al.

(2018), supports the approach presented in the AAFC discussion paper, namely the inclusion of legumes needs to be accompanied by additional soil to properly account for nitrogen credits if reductions are to be observed.

Conclusion

Reduction of direct and indirect fertilizer emissions remains at the forefront of N_2O-based emission reduction initiatives in Canada, with an ambitious goal of reducing 2020 emission levels by 30 percent by 2030. Despite the goals outlines in Canada's 2020 Strengthened Climate Plan, supplemented by different strategies highlighted in the supplementary AAFC paper, it is clear that a "one-size-fits-all" solution cannot be implemented, as adoption of different Best Management Practices are more or less feasible depending on multiple factors. The complexities related to the nitrogen cycle and environmental interdependencies complicate application feasibility and expected efficacy of mitigation strategies.

Through the systematic review process, fertilizer application approaches from 38 different peer-reviewed research articles were compiled and extracted to determine different practices effects on N_2O reduction, and how these reductions would be reflected in national emission reports. Results across studies were mixed, with conflicting results between papers and insignificant effects of practices. Overall, enhanced efficiency fertilizers were identified as the most advantageous best management practice for adoption. Results from trials utilizing enhanced efficiency fertilizers demonstrated the most consistent results in reducing N_2O emissions without negatively impacting yield or other production measures. Biochar and fertigation were also identified as promising practices, however widespread use and application is limited. Depending on farm operations and existing infrastructure, irrigation, and therefore fertigation, cannot be easily implemented, with high costs and workforce required for installation. Benefits in N_2O reductions in biochar use were a result of massive application rates, which might only be feasible in certain geographic and operational contexts. Going forward, updating N_2O emission accounting methodology to include emissions reduction practices will be critical to ensure accurate measurements and properly reflect progression towards Canada's emission reduction target.

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Tables

Table 1

Papers Included in the Systematic Review

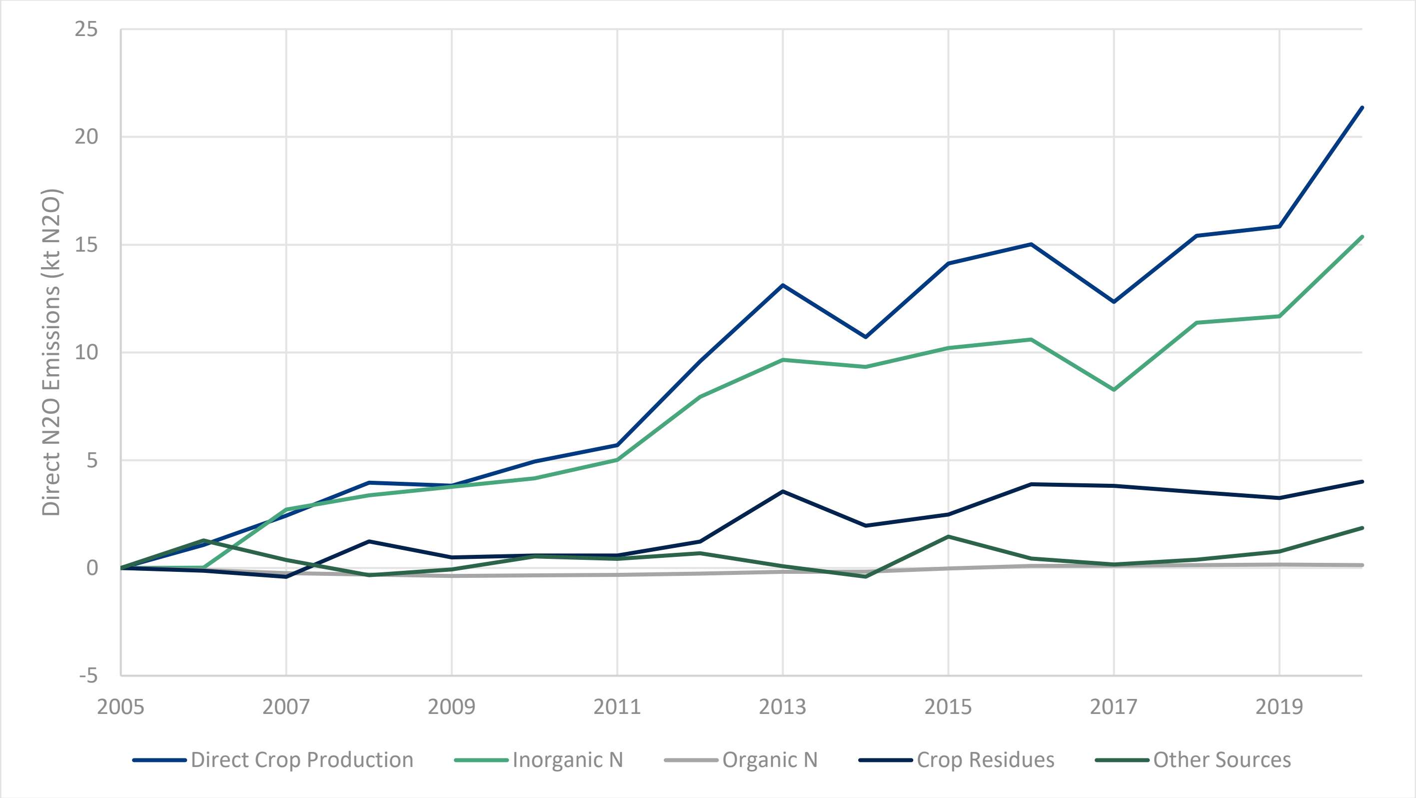
EENF	CRNF	SNF	Organic Fertilizer	Conservation Tillage	Biochar	Other
Yangjin et al. (2021)	Abalos et al. (2016)	Abalos et al. (2016)	Abalos et al. (2016)	Decock, 2014	Borchard et al. (2019)	Abalos et al. (2016)
	Akiyama et al. (2010)	Akiyama et al. (2010)	Decock (2014)	Feng et al.(2018)	Cayuela et al. (2014)	Basche et al. (2014)
	Decock (2014)	Decock (2014)	O'Brien & Hatfield (2019)	Huang et al. (2018)	Cayuela et al. (2015)	Chen et al. (2021)
	Eagle et al. (2017)	Eagle et al. (2017)	Phillips et al. (2009)	Mei et al., 2018	Xu et al. (2021)	Decock (2014)
	Feng et al. (2016)	Feng et al. (2016)	Xia et al. (2017)	Phillips et al., 2009	Yangjin et al. (2021)	Han et al. (2017)
	Phillips et al. (2009)	Qiao et al. (2015)	Yangjin et al. (2021)	Shakoor et al. (2021)	Zhang et al. (2020)	Kuang et al. (2021)
	Thapa et al. (2016)	Thapa et al. (2016)	Zhou et al. (2017)	vanKessel et al., (2013)		Muhammad et al. (2019)
	Yang et al. (2021)	Wu et al. (2021)		Yangjin et al., (2021)		Yangjin et al. (2021)
	Zhang et al. (2019)	Yang et al. (2016)				

Note.

Figures

Figure 1

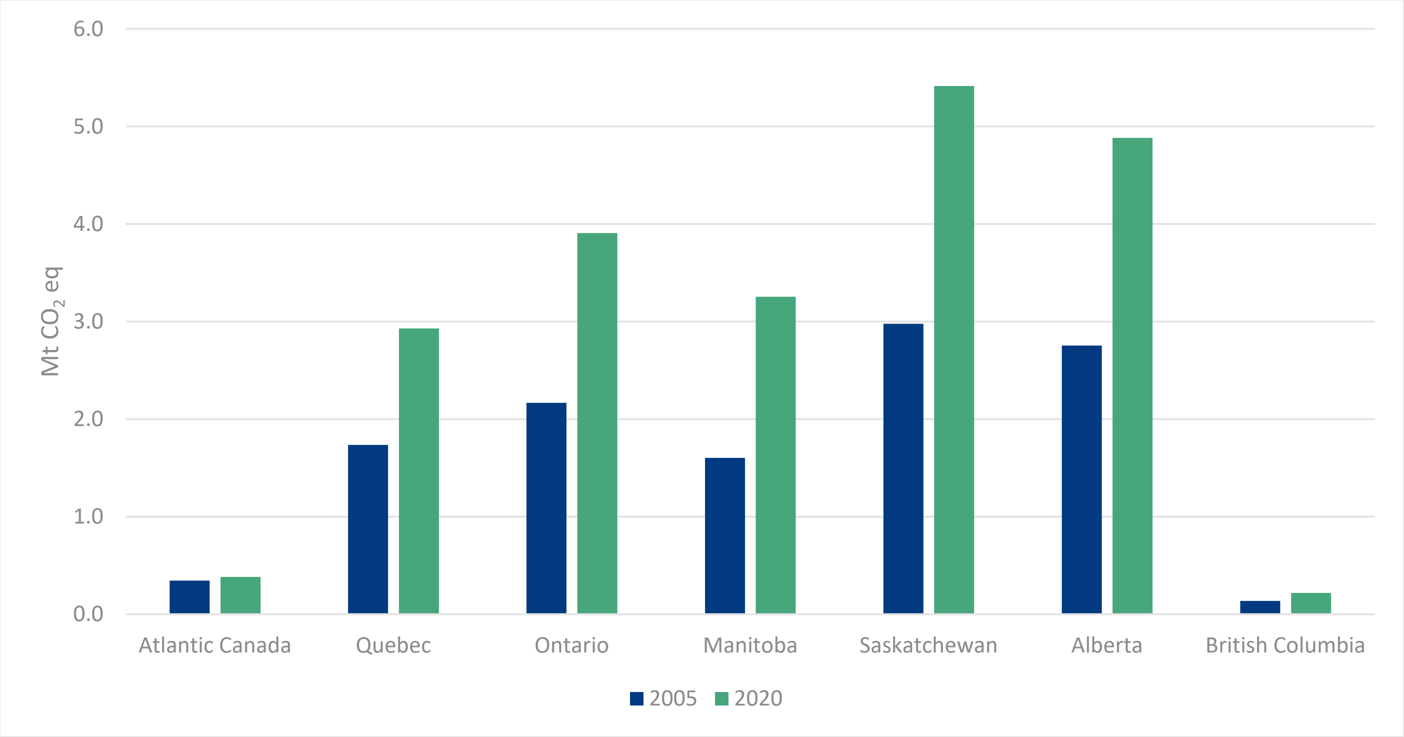
Change in Direct N$_2$O Emissions from Agricultural Soils since 2005



Note. Data used in this figure was collected from Table 3.D of the 2022 Common Reporting Format Tables, as part of Canada's 2022 National Inventory Submission. https://unfccc.int/sites/default/files/resource/can-2022-crf-14apr22.zip

Figure 2

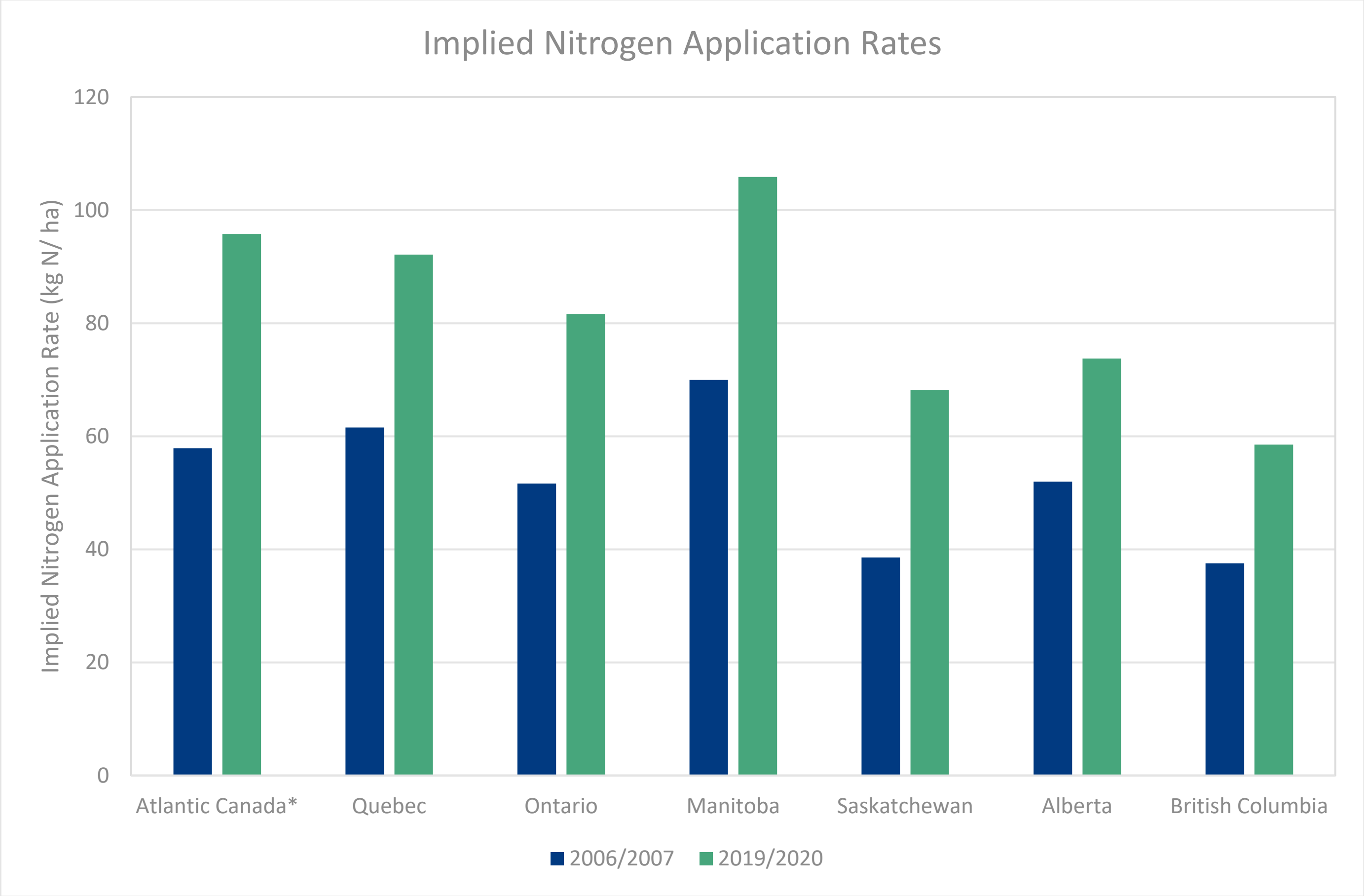
Crop Production Based Emissions by Province



Note. Emissions from crop production follow the Canadian Economic Sector method of emission classification but uses the same methodology as the IPCC classification. Data Source: Data used in this figure was collected from Annex 12, Tables 2 through 11 of Canada's 2022 National Inventory Report Part 3. https://unfccc.int/sites/default/files/resource/can-2022-nir-14apr22.zip

Figure 3

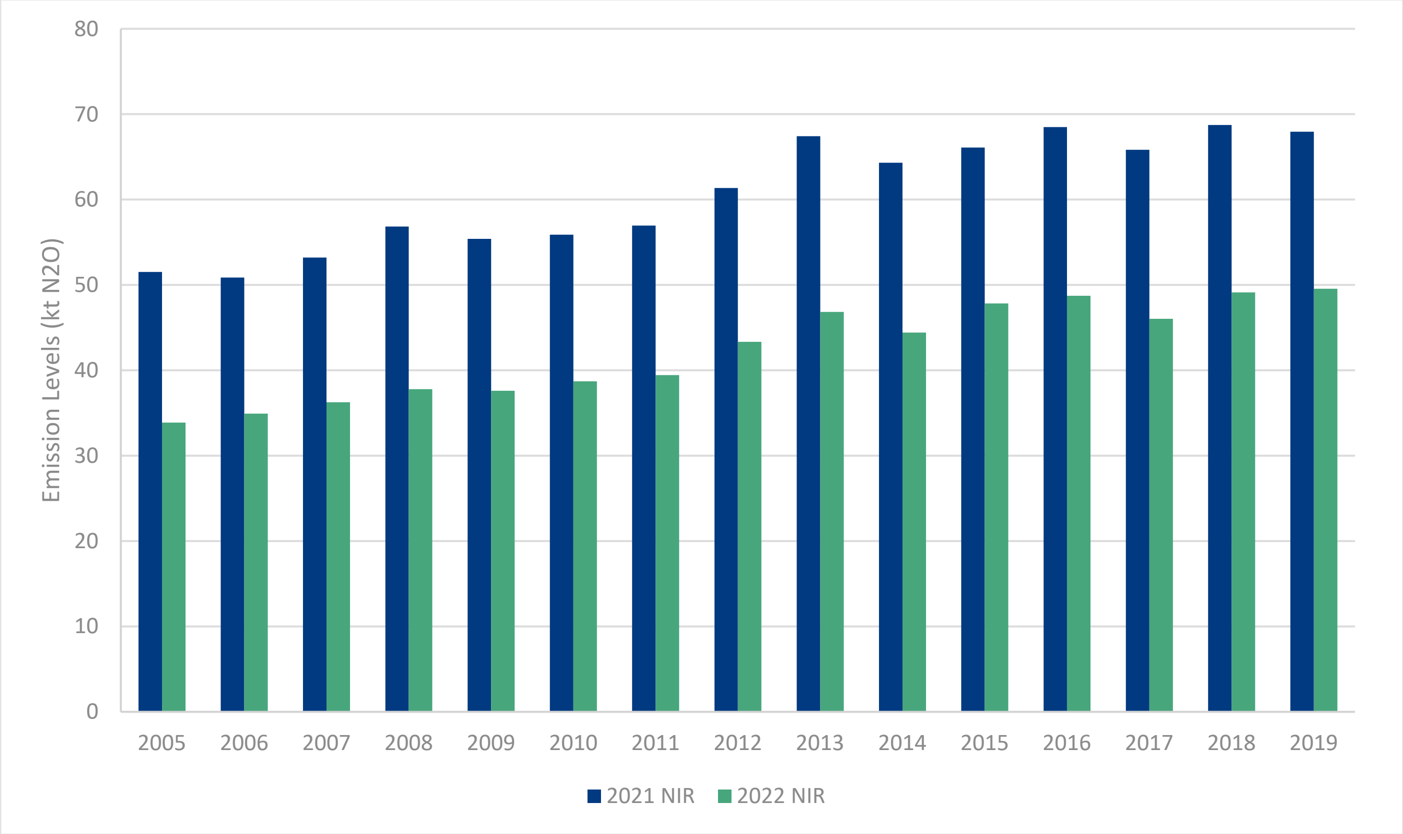
Implied Nitrogen Application Rates by Province



Note. Implied nitrogen application rate was estimated by dividing nitrogen fertilizer shipments for fertilizer year 2006/2007 and 2019/2020 by total area of farms reported in the 2016 Census of Agriculture. The estimate for Atlantic Canada is an aggregation of all four Atlantic provinces. Data Source: Statistics Canada. Table 32-10-0039-01 Fertilizer shipments to Canadian agriculture markets, by nutrient content and fertilizer year, cumulative data (x 1,000) DOI: https://doi.org/10.25318/3210003901-eng and Statistics Canada. Table 32-10-0153-01 Land use, Census of Agriculture historical data DOI: https://doi.org/10.25318/3210015301-eng.

Figure 4.

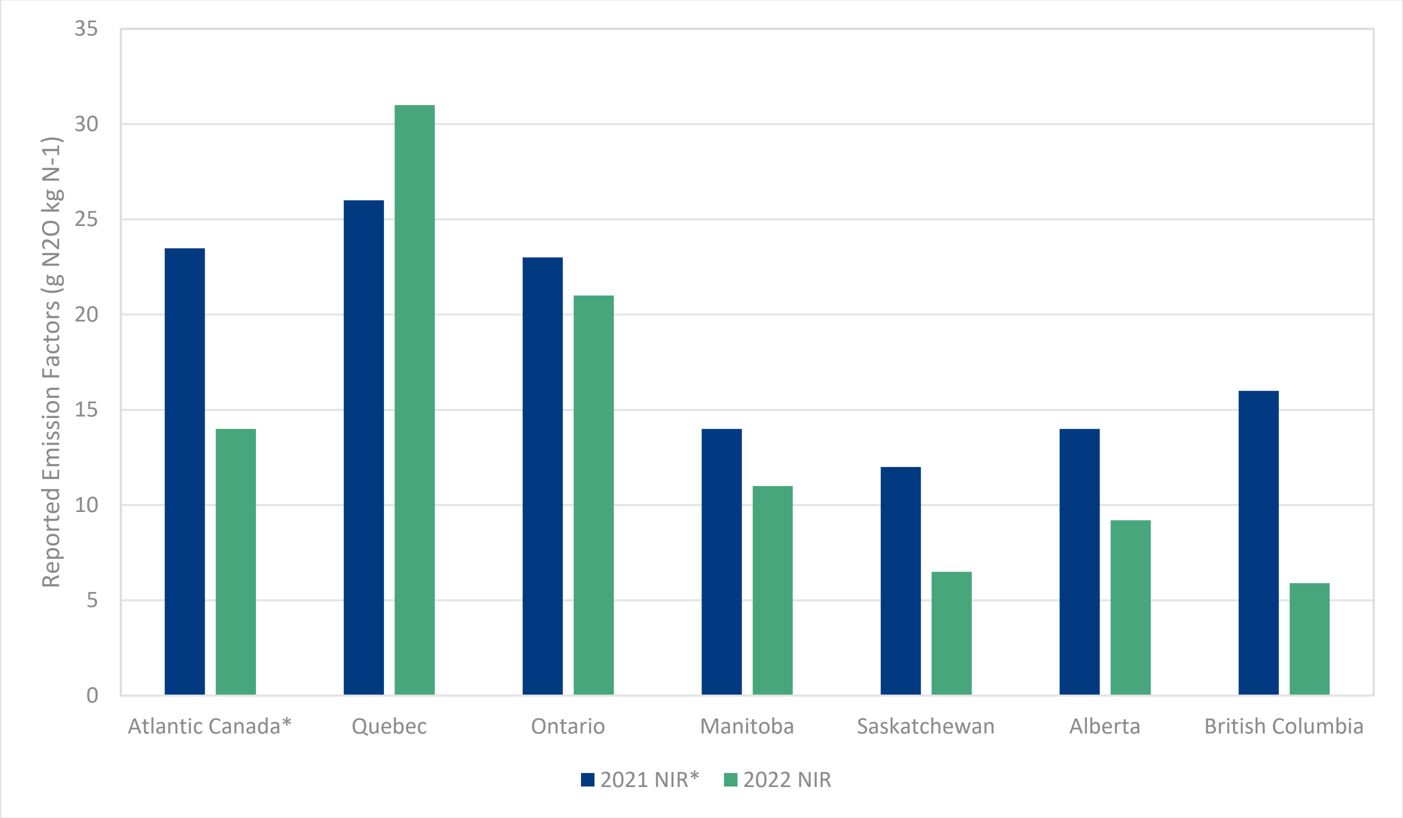
Effects of Changing Methodology on Direct N_2O emissions from Managed Soils



Note. Figure 4 provides a comparison of the reported total direct N_2O emissions from agricultural soils before and after the change in methodology and corresponding recalculation introduced in the 2022 National Inventory Submission. Data Source: Data was collected from Table 3.D in the 2021 and 2022 Common Reporting Format Tables for years 2005 to 2019, https://unfccc.int/sites/default/files/resource/can-2022-crf-14apr22.zip and https://unfccc.int/sites/default/files/resource/can-2021-crf-12apr21.zip.

Figure 5.

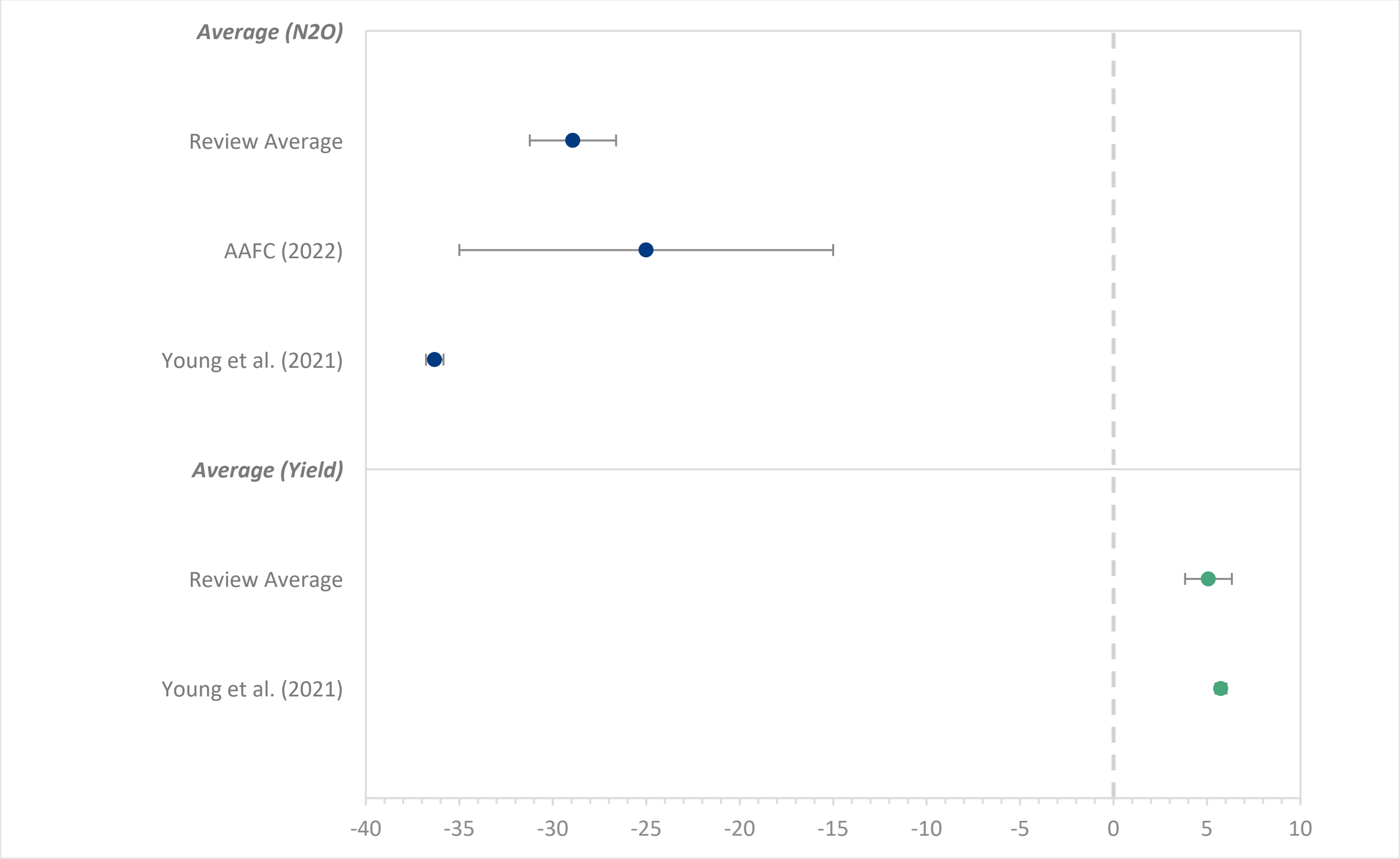
Effects of Changing Methodology on Average Emission Factors



Note. Figure 5 provides a comparison of the average provincial emission factor as reported in Annex 6.4 Table 20 of Part 2 of the 2021 and 2022 National Inventory Reports. For the 2021 National Inventory Report average emission factors were provided for each Atlantic province; the value presented in this figure is the average of the provincial emission factors weighted by total area of farmland as reported in the 2016 Census of Agriculture.

Figure 6

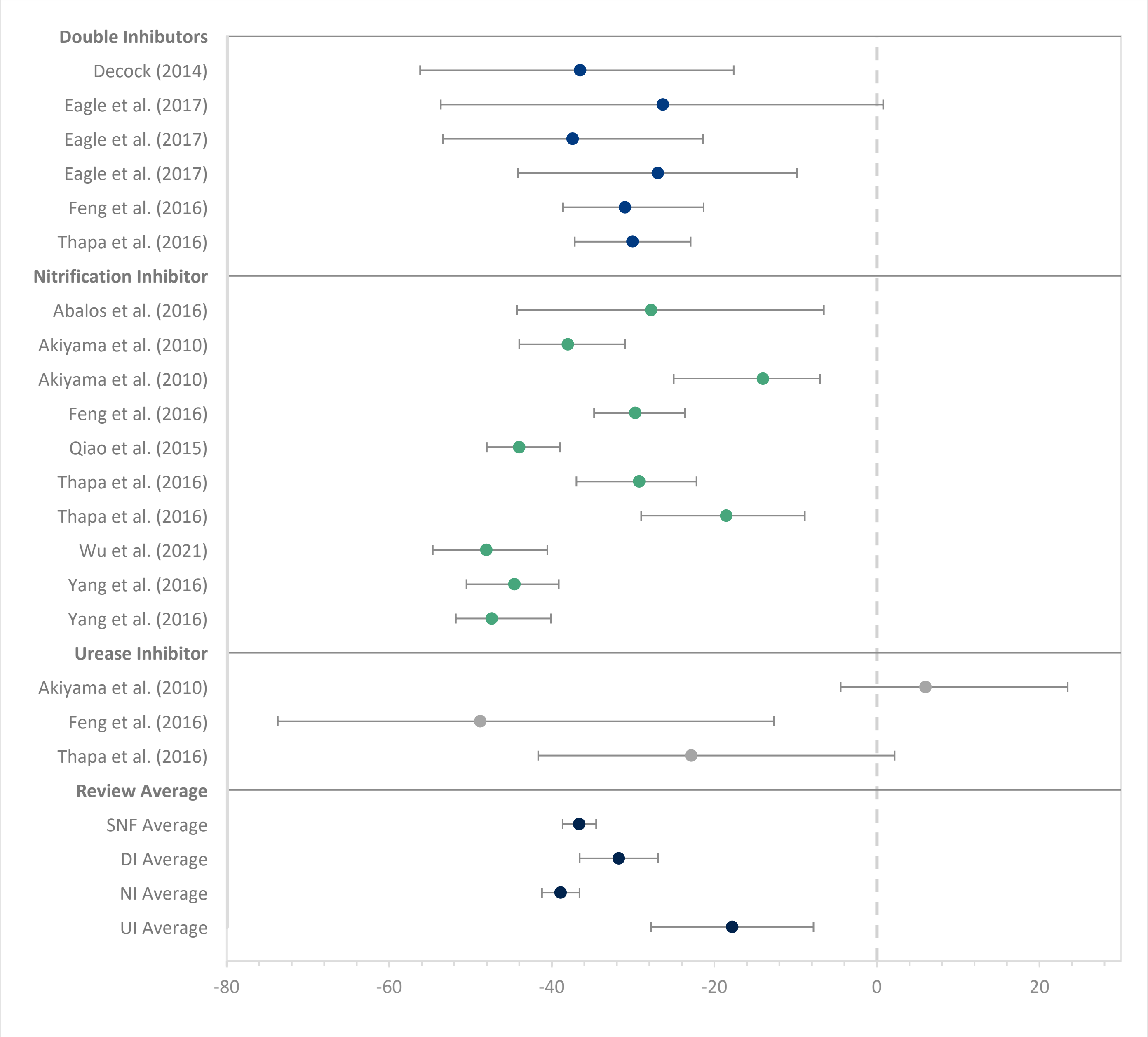
Effects of Enhanced Efficiency Fertilizer on N_2O Emissions and Yield



Note. Individual study results and estimated weighted mean of the effect of EENFs on N_2O emissions and Yield. Significant findings can be identified if the confidence interval does not intersect zero indicated by the dashed line. In the case of AAFC (2022), the depicted CI is based on the reported potential range, with the mean value presented as the midpoint.

Figure 7

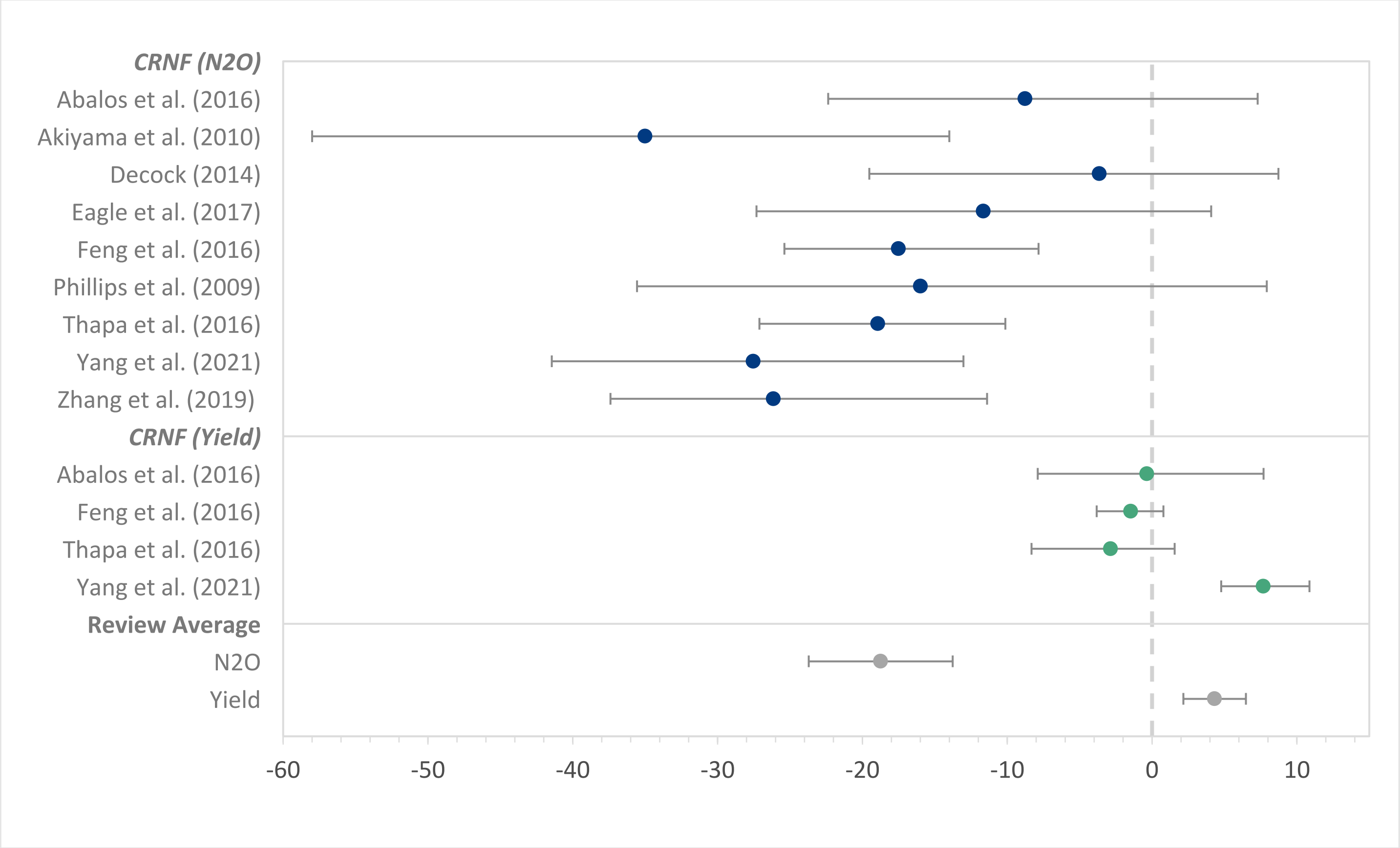
Effects of Stabilized Nitrogen Fertilizer on N_2O Emissions



Note. Individual study results and estimated weighted mean of the effect of SNFs on N_2O emissions. Significant findings can be identified if the confidence interval does not intersect zero, indicated by the dashed line.

Figure 8

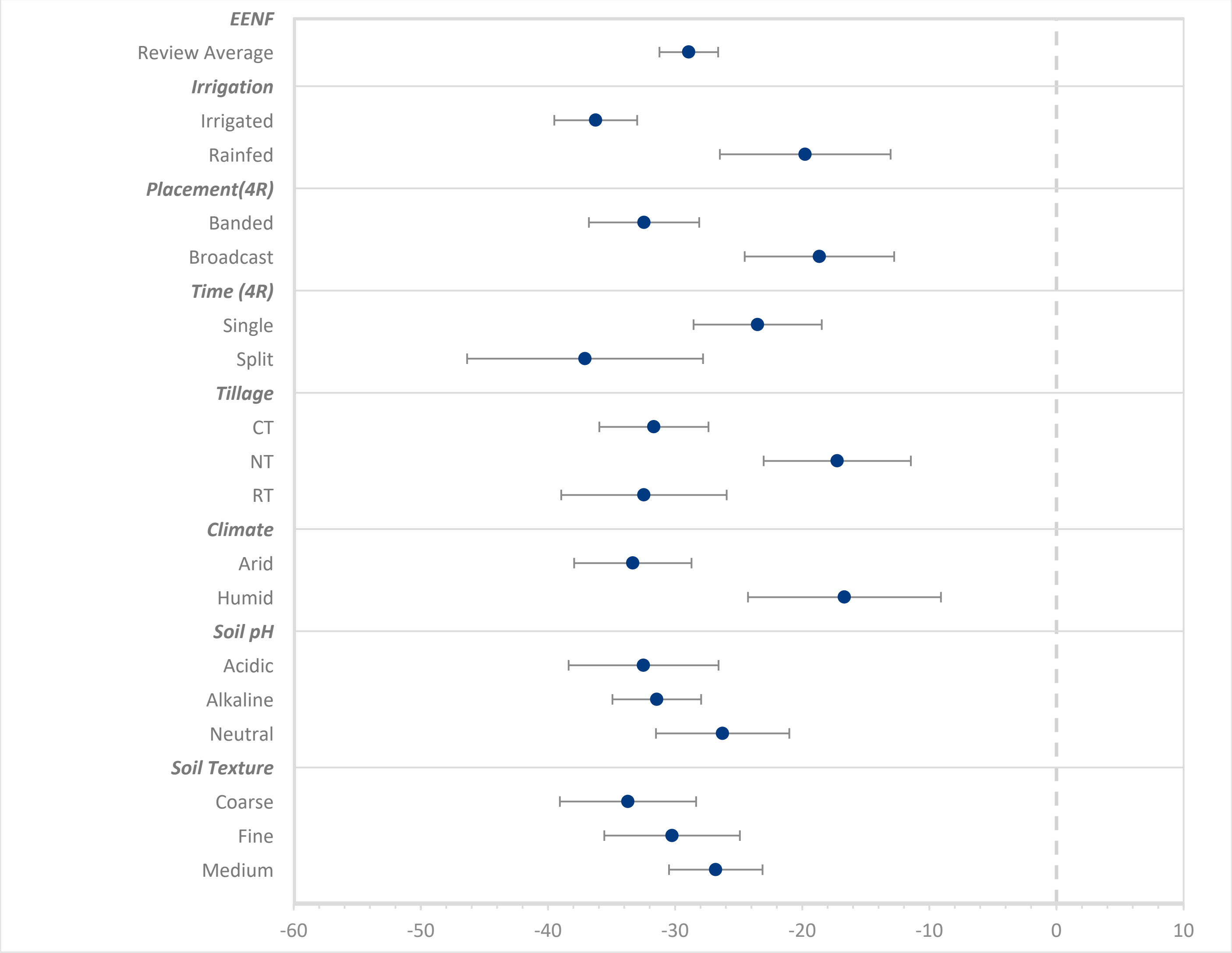
Effects of Controlled Release Nitrogen Fertilizer on N_2O Emissions



Note. Individual study results and estimated weighted mean of the effect of CRNFs on N_2O emissions. Significant findings can be identified if the confidence interval does not intersect zero, indicated by the dashed line.

Figure 9

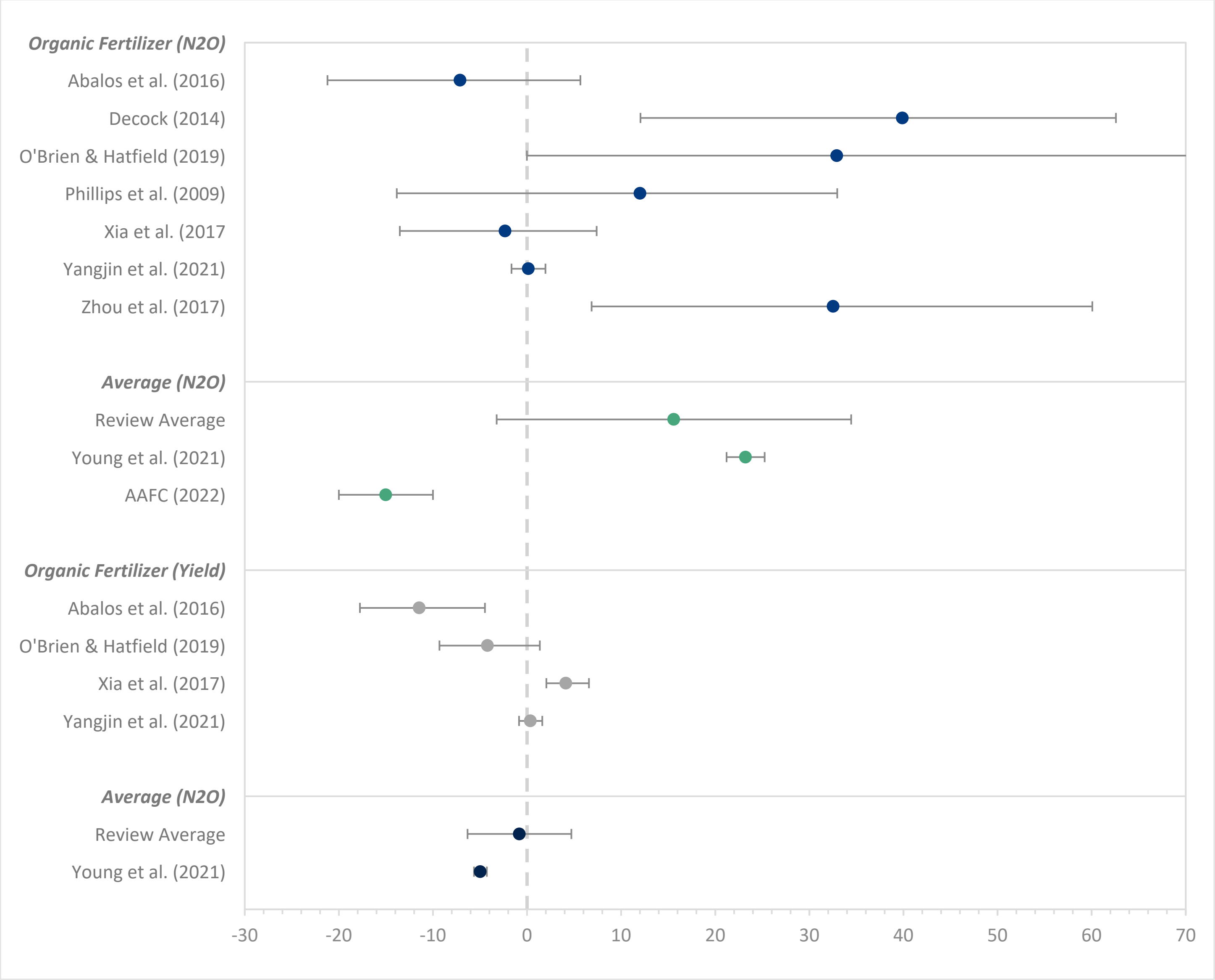
Disaggregated Effects on Enhanced Efficiency Nitrogen Fertilizer on N_2O emissions



Note. Weighted mean and 95% CI of the effects of EENFs on N_2O emissions in various conditions and management practices. Significant findings can be identified if the confidence interval does not intersect zero, indicated by the dashed line.

Figure 10

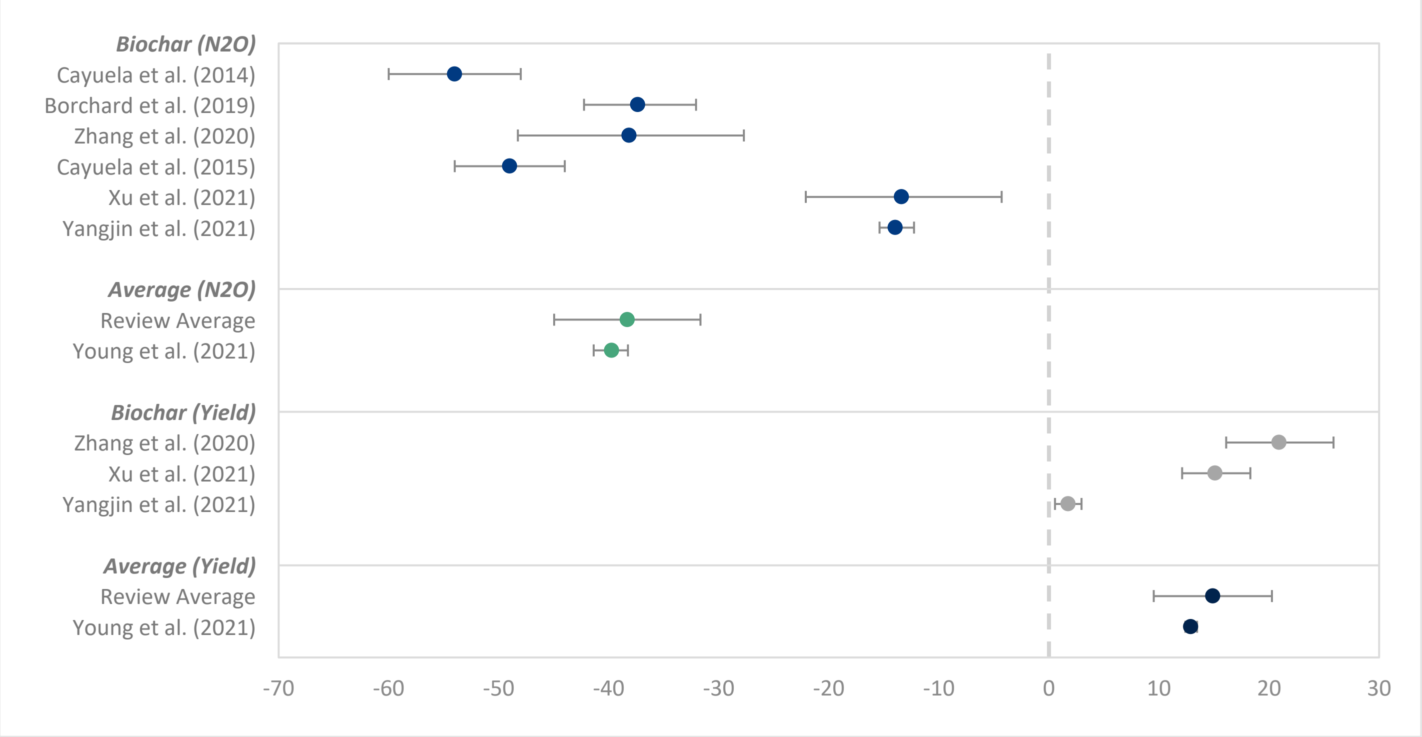
Effects of Organic Fertilizer on N_2O Emissions and Yield



Note. Individual study results and estimated weighted mean of the effect of organic fertilizers on N_2O emissions and yield. Significant findings can be identified if the confidence interval does not intersect zero, indicated by the dashed line. In the case of AAFC (2022), the depicted CI is based on the reported potential range, with the mean value presented as the midpoint.

Figure 11.

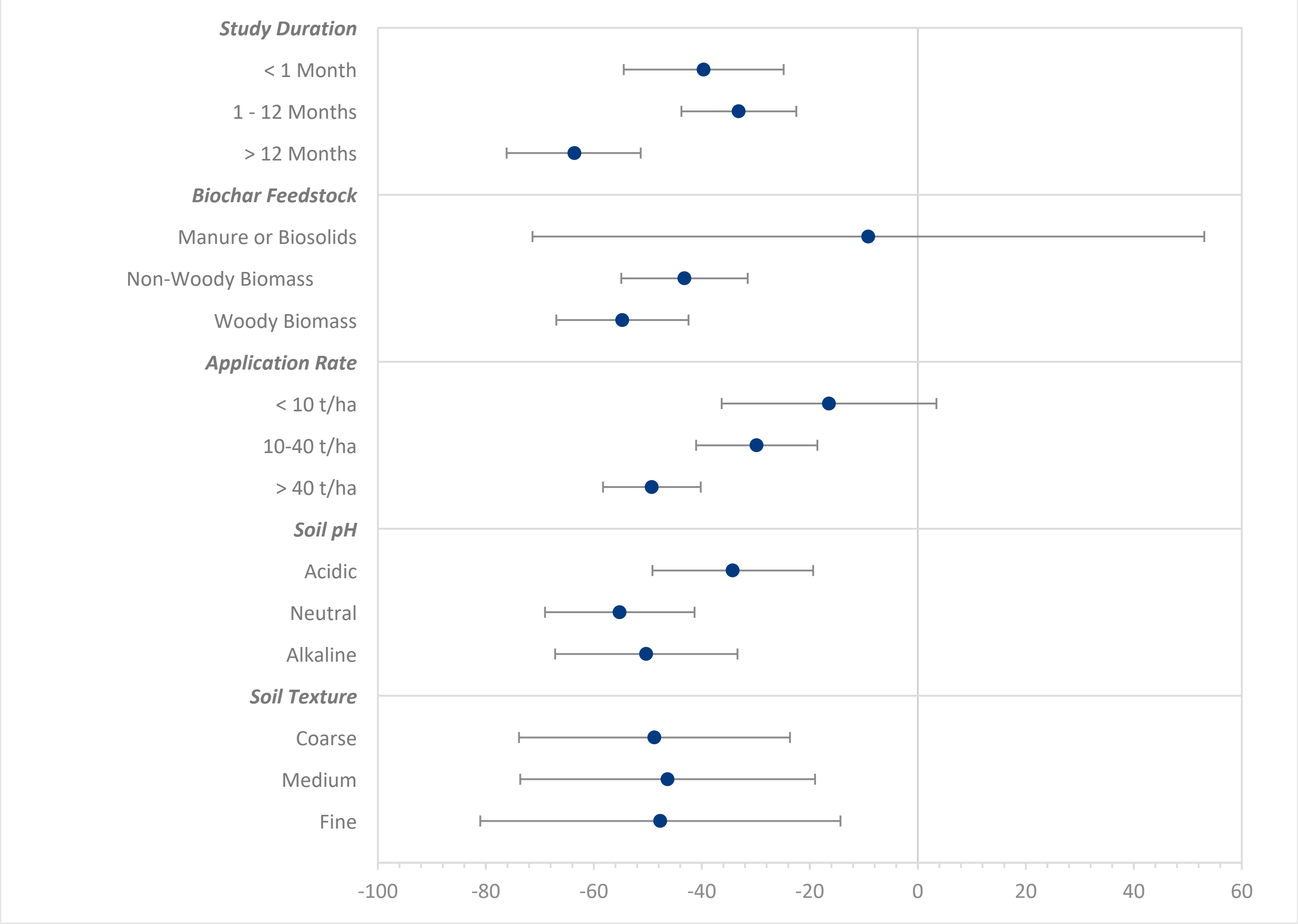
Effects of Biochar on N_2O emissions and Yield



Note. Individual study results and estimated weighted mean of the effect of biochar application on N_2O emissions and yield. Significant findings can be identified if the confidence interval does not intersect zero, indicated by the dashed line. In the case of AAFC (2022), the depicted CI is based on the reported potential range, with the mean value presented as the midpoint.

Figure 12

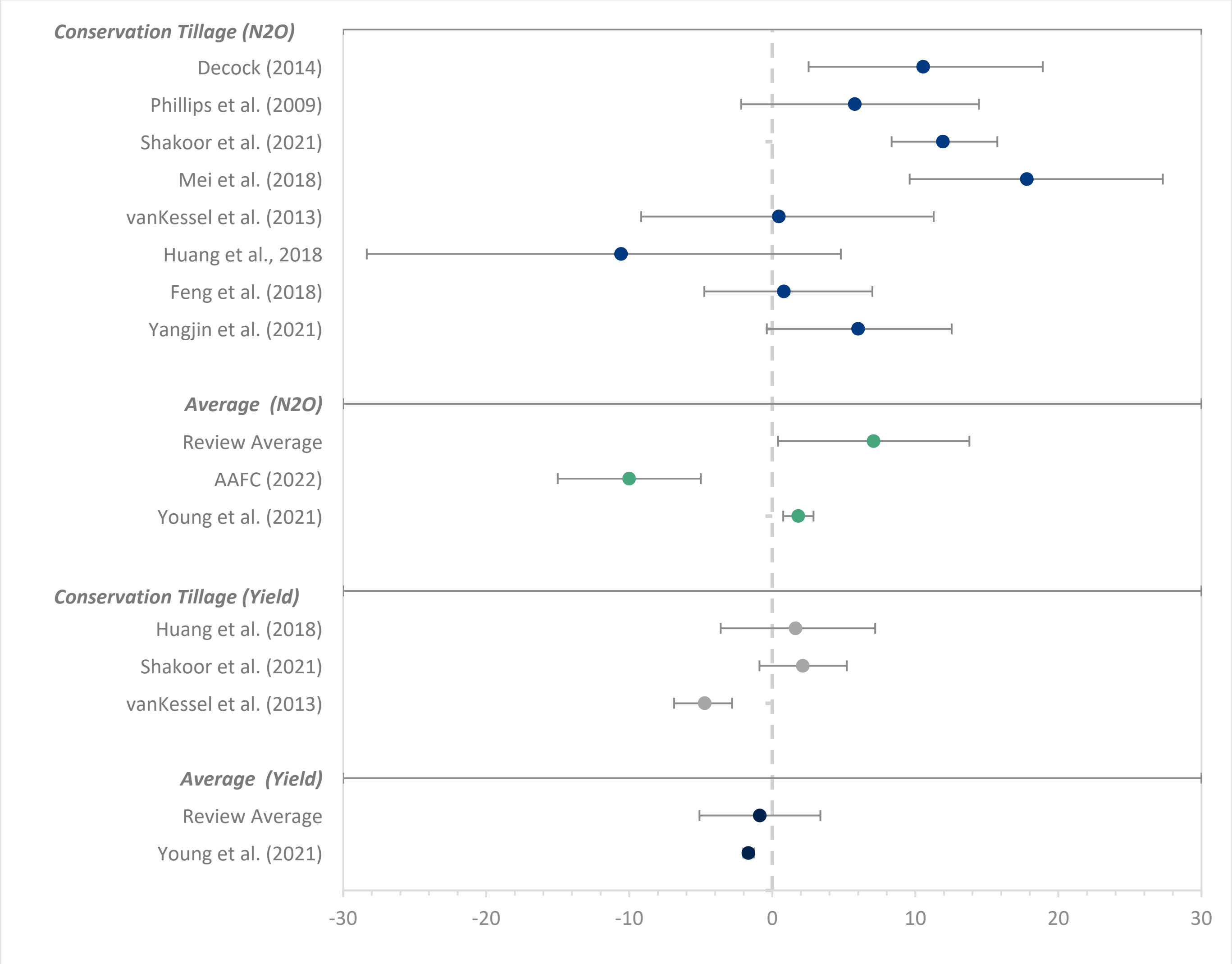
Disaggregated Effects on Biochar on N_2O Emissions



Note. Weighted mean and 95% CI l of the effects of biochar application on N_2O emissions in various conditions and management practices. Significant findings can be identified if the confidence interval does not intersect zero, indicated by the dashed line.

Figure 13

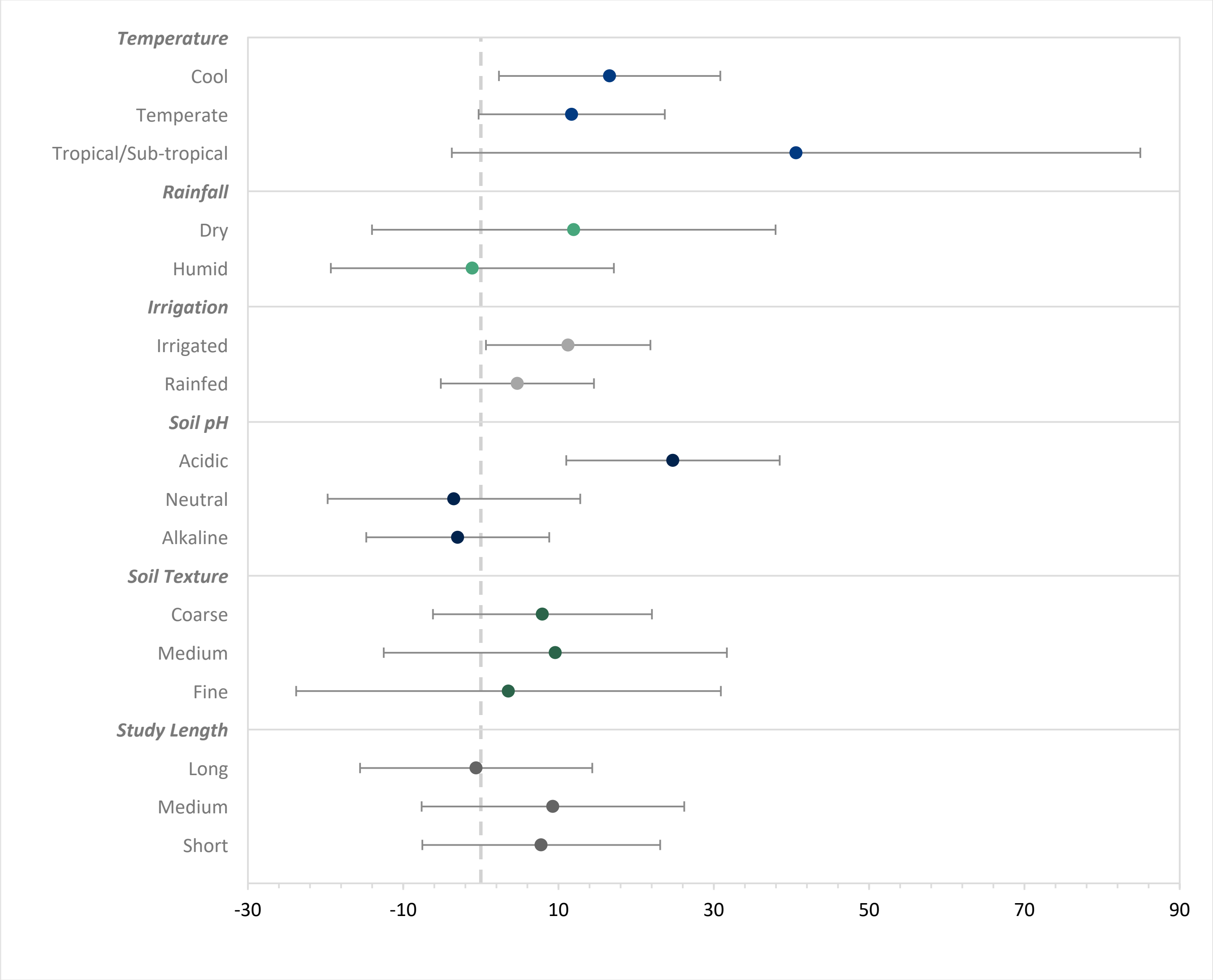
Effects of Conservation tillage on N_2O emissions and Yield



Note. Individual study results and estimated weighted mean of the effect of conservation tillage on N_2O emissions and yield. Significant findings can be identified if the confidence interval does not intersect zero, indicated by the dashed line. In the case of AAFC (2022), the depicted CI is based on the reported potential range, with the mean value presented as the midpoint.

Figure 14

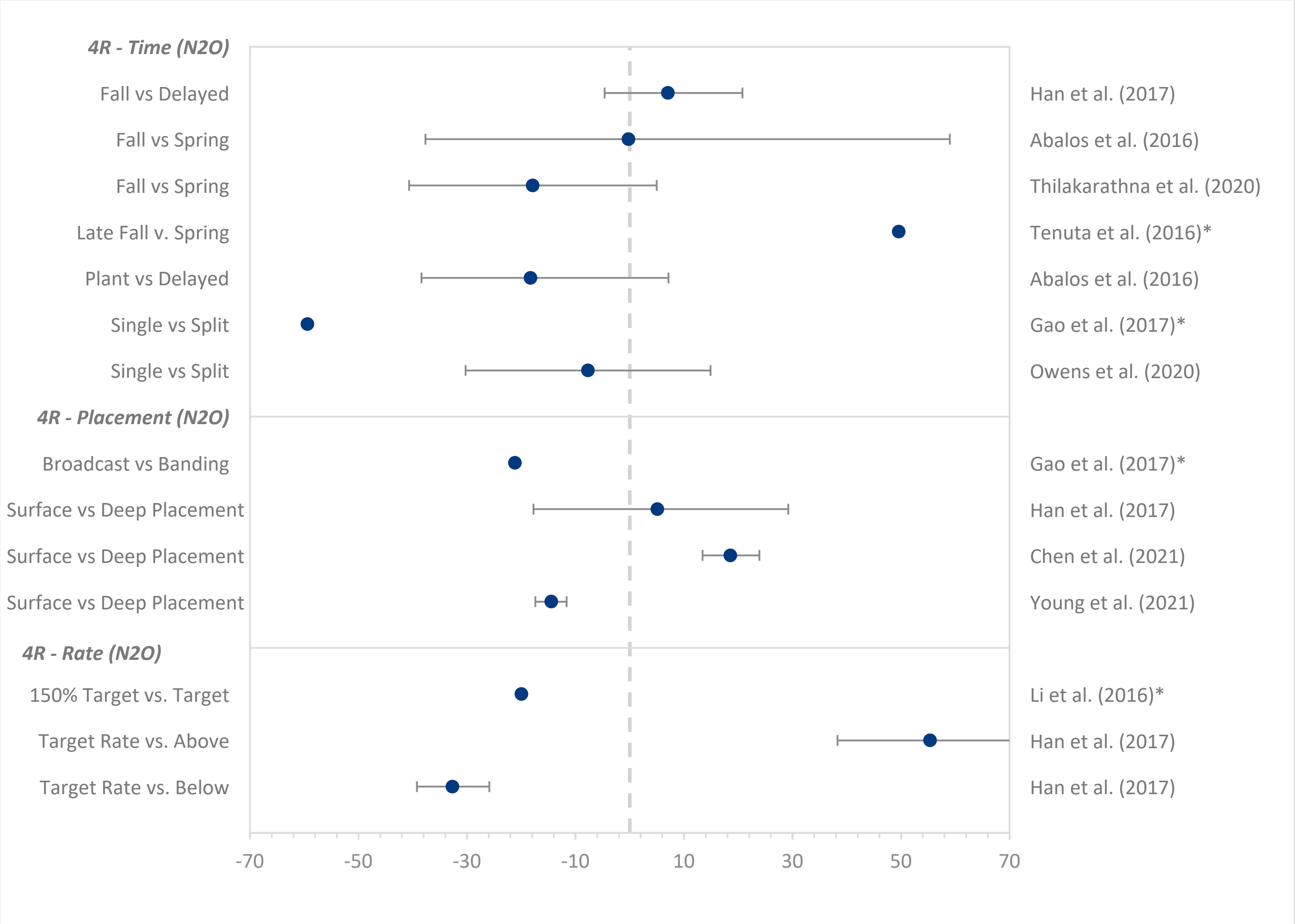
Disaggregated Effects of Conservation Tillage on N_2O emissions



Note. Weighted mean and 95% CI l of the effects of conservation tillage on N_2O emissions in various conditions and management practices. Significant findings can be identified if the confidence interval does not intersect zero, indicated by the dashed line.

Figure 15

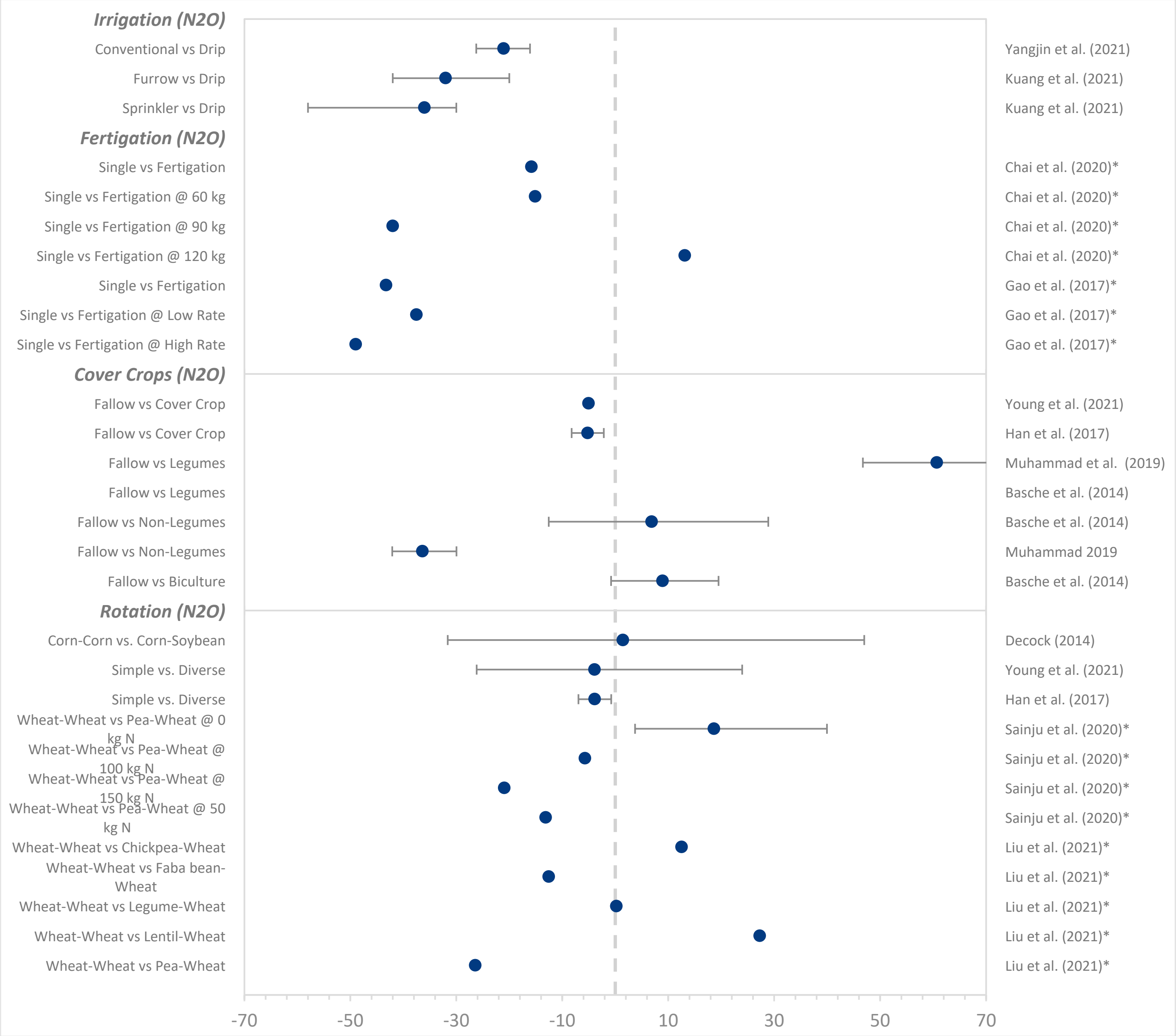
Effects of 4R Nutrient Stewardship on N_2O emissions



Note. Individual study results of the effect of 4R (excluding Source) on N_2O emissions and yield. Significant findings can be identified if the confidence interval does not intersect zero, indicated by the dashed line. (*) Indicates individual field trials conducted in Western Canada but are not included within the systematic review.

Figure 16

Other Practices Effects on N_2O Emissions



Note. Individual study results of the effect of 4R (excluding Source) on N_2O emissions and yield. Significant findings can be identified if the confidence interval does not intersect zero indicated by the dashed line. (*)

Indicates individual field trials conducted in Western Canada but are not included within the systematic review.

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