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Direct Fertilizer-Based Emissions

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ABSTRACT

Growing environmental, social, and political pressures has driven the development of policies surrounding emission reductions. Nitrous oxide, a potent greenhouse gas, is emitted predominantly by the agricultural sector, most of which is associated with crop production. Canada's Strengthened Climate Plan, redefined Canadian emission targets under the Paris Agreement, targeting the agricultural sector specifically to reduce fertilizer-based emissions. The methodology to measure N2O emissions varies according to the International Panel on Climate Change (IPCC) varies, depending on the use of a Tier 1, 2 or 3 approach, increasing data inclusion and resolution with Tiers. With the current methodology in place, farmers have limited potential to reduce N2O emissions, as mitigation strategies predominantly hinge on impractical and inaccessible options, such as reducing fertilizer application or changing location. Based on the current measures, Canadian emissions are high relative to other major production regions. A model across IPCC Annex I parties adjusting for average wheat yield as a benchmark and incorporating fertilizer application rate for different countries demonstrated low-efficiency and yield in Canada. Multiple scenarios are tested to determine how an improved Canadian efficiency measure, use of a disaggregated emission factors, and a combination of both, would influence the model and benchmark values. Improving the methodology to measure N2O emissions would improve measurement accuracy and support development of emission reduction policies for farmers to implement within operations

Keywords: *Emission Reduction, IPCC, Fertilizer, Nitrous Oxide, Greenhouse Gas*

Global Agricultural Greenhouse Gas Emissions:

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Canada's Strengthened Climate Plan was introduced in 2020 as an update to the Pan-Canadian Framework, with the goal of exceeding the initial nationally determined contribution (NDC) under the Paris agreement[1] (Environment and Climate Change Canada, 2020). While the Pan-Canadian Framework left the agricultural sector relatively unaffected (Environment and Climate Change Canada, 2016), the Strengthened Climate Plan proposed Canada's first agricultural sector-specific emission reduction target (Environment and Climate Change Canada, 2020, p. 45).

The proposed target sought to reduce fertilizer-based emission levels by 30 percent of 2020 levels by 2030 (Environment and Climate Change Canada, 2020, p. 45). However, at the time, no further information was included. On February 25th, 2022, Agriculture and Agri-food Canada (AAFC) released a discussion document detailing several aspects of the target and a pathway to emission reductions (Agriculture and Agri-Food Canada, 2022). The emission reduction target only applies to synthetic fertilizer and covers direct N_2O emissions and indirect emissions from leaching and volatilization. Emissions from organic fertilizers, such as manure, compost, digestate, or emissions from fertilizer production, are not explicitly covered in the reduction target. AAFC provided a list of potential short-term mitigation options to meet the proposed target. The options primarily focused on different aspects of 4R Nutrient Stewardship[2], including conservation management practices and crop rotation changes.

Increasing adoption of 4R and other best management practices (BMP) poses a challenge to producers and policymakers. This process is further complicated as Canada's methodology for estimating N_2O emissions from agricultural soils does not account for many of the proposed practices (Environment and Climate Change Canada, 2021c, sec. A3.4.5.1). As a result, current adoption of BMPs is not reflected, possibly leading to inaccurate emission estimates. Additionally, the current state of the methodology is a barrier to meeting reduction targets without a significant reduction in fertilizer use. This outcome would be highly unlikely as many emission variables included in the model are based on weather topography and soils characteristics which are outside the control of producers, see Table 1.

[1] Canada's initial NDC was to reduce greenhouse gasses by 30 percent of 2005 levels by 2030. The NDC has since been updated with the enhanced NDC setting a target to reduce greenhouse gasses by 40-45 percent of 2005 levels by 2030 (Environment and Climate Change Canada, 2021)

[2] 4R is a nutrient stewardship program which aims to improve fertilizer use efficiency by applying the right source at the right rate, right time, and right place (Fertilizer Canada, n.d.).

This report will focus on direct emissions from synthetic fertilizer, accounting for 83 percent of the total emissions accounted within the proposed target[3]. It will provide a review of current emission measurements across 42 Annex I parties to the United Nations Framework Convention on Climate Change (UNFCCC) and discuss policy implications derived from the measurements. Additionally, international emission factors and emission intensity measures will be compared using country-specific data from National Inventory Submissions.

DATA

Data for this report was collected from the 2021 National Inventory Submissions (NIS), including the National Inventory Report and the Common Reporting Format (CRF) tables. The submissions were compiled from the UNFCCC NIS repository, followed by manual data extraction. A total of 42 countries were included, comprising of all Annex I parties to the UNFCCC (United Nations Framework Convention on Climate Change, 2022), with the exception of Monaco and the European Union (EU). Monaco was excluded as it does not report any agricultural emissions (Direction de l'Environnement, 2021), and the EU provides a limited summary of member states (European Environment Agency, 2021). The emission factor comparison section of this report uses data from Tables 3.d and 4.1 of each country's CRF tables covering a period of 1990 to 2019. Table 3.d provides data on direct and indirect N_2O emissions from agricultural soils (both cropland and grasslands), while Table 4.1, provides total land area estimates for various land use categories. Table 2 provides a list of all included countries and sources.

MEASUREMENTS

N_2O is the third most emitted greenhouse gas in Canada, after CO_2 and CH_4, and accounts for approximately 5 percent of total emissions, measured in CO_2 equivalent (CO_2e) (Environment and Climate Change Canada, 2021d, pp. 7–12). Unique to agricultural production, roughly 80 percent of N_2O originates from the agricultural sector, of which 73 percent was attributed to crop production in 2019. Crop production N_2O emissions can be divided into direct and indirect emissions from agricultural soils, accounting for 83 and 17 percent of total N_2O emissions, respectively (Environment and Climate Change Canada, 2021d, p. 12). Direct emissions can be further subdivided by nitrogen source, the majority being synthetic fertilizer, accounting for 52 percent of direct emissions and 43 percent of the total(Canada, 2021).

Biochemical reactions within the soil called nitrification and denitrification result in direct N_2O emissions (United States Environmental Protection Agency, 2021b, sec. 3.12). Nitrification occurs within the soil when microorganisms convert

[3] Estimate based on 2019 data presented within the CRF tables and discussion document

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). N_2O is produced as an intermediate step in nitrification and denitrification processes. These naturally occurring biological processes serve an essential role within the nitrogen cycle. However, high fertilization application can result in excess nitrogen in soil, increasing emissions.

In Canada, agricultural soil emissions increased by 30 percent since 2005 to 82 kt N_2O in 2019. This spike in emissions appears to be driven primarily by the increased application of synthetic fertilizers, which has grown by 71 percent since 2005 (Environment and Climate Change Canada, 2021b). This growth is particularly prominent in Western Canada, where Alberta, Saskatchewan, and Manitoba increased emissions by, 26, 47, and 57 percent, respectively (Environment and Climate Change Canada, 2021d).

IPCC TIER 1 APPROACH

The IPCC methodology used in estimating emissions from synthetic fertilizer application can be found in Chapter 11.2 of the 2006 Guidelines and the 2019 Refinement. Additionally, within the 2019 Refinement, a more detailed description of the process used for estimating the emission factor can be found in Annex 11A.2.

Estimating nitrous oxide emissions originating from synthetic fertilizers is straightforward. Following an IPCC Tier 1 approach, the total quantity of fertilizer applied to managed agricultural soils is multiplied by an emission factor converting nitrogen applied to N_2O-N emitted. N_2O-N is multiplied by ${}^{44}/_{28}$ to convert to N_2O (de Klein et al., 2006, p. 11.11). A single emission factor is used in the 2006 guidelines, equal to 0.01 kg N_2O-N kg N^{-1}, with an uncertainty range of 0.003 to 0.03. The 2019 Refinement uses the same emission factor of 1 percent but additionally provides disaggregated emission factors based on seasonal rainfall, irrigation, and fertilizer type (Hergoualc'h et al., 2019, p. 11.12). The emission factors range from 0.001 in non-irrigated dry regions to 0.016 in areas with high rainfall ($\frac{p}{PE} > 1$) and synthetic fertilizer use. While the default factor remained the same, the estimated uncertainty of the estimate decreased to 0.001 to 0.018. A full list of emission factors within the 2019 Guidelines can be found in Table 3. Of the 42 countries included within this review, 36 use a Tier 1 approach, of which two use country-specific factors, see Table 3.

The use of the Tier 1 emissions factor poses challenges in emission reduction strategy development, as the factor is only based on nitrogen application amount. Using disaggregated emission factors may improve estimate accuracy; however, the default values provided have limited policy value as producers are unlikely to move production from wet regions to dry regions or stop irrigating crops to reduce emissions. The remainder of this section covers the emission factors and approaches used by each of the six countries that have developed country-specific factors.

COUNTRY-SPECIFIC TIER 1 APPROACHES

Ireland reports using a Tier 1 approach for estimating emissions from inorganic fertilizers (Duffy et al., 2021, sec. 5.5). The emission factors used are dependent primarily on the fertilizer type. Different emission factors have been estimated for fertilizer types and includes Calcium Ammonium Nitrate (CAN), Urea, and Urea + N-Butyl Thiophosphoric Triamide (NBPT), a commonly used urease inhibitor. Changing fertilizers can reduce emissions while maintaining nitrogen application levels. Switching from CAN to Urea or Urea+ NBPT could result in emission reductions, as the emission factor for CAN is 5.6 times higher than Urea, and 3.5 times higher than Urea + NBPT[4], see Table 3.

Like Ireland, the Netherlands reports using a Tier 1 approach for estimating emissions using country-specific emission factors (Ruyssenaars et al., 2021, sec. 5.4). The factors can be found in Table 3 and are differentiated by land use (grassland and arable) and soil type (mineral and mineral and organic). The limited dimensions of variables included in the Tier 1 approach presents restrictions in emission reduction potential within applied policy. Under these conditions, farmers are severely limited in emission reduction potentials as only reducing fertilizer applications or changing locations would reduce estimated emission.

AUSTRALIA

Australia reports using a Tier 2 methodology, resembling a highly disaggregated Tier 1 approach, where the quantity of fertilizer used in one of seven predefined productions systems is multiplied by its corresponding emission factor (Australian Government Department of Industry Science Energy and Resources et al., 2021, p. 346). The production systems are based on production types (Pasture, Crop, Sugar Cane, Cotton, Horticulture) and irrigation (Irrigated Pasture, Irrigated Crop), and the values range from 0.002 N_2O-N kg N^{-1} (non-irrigated crop production) to 0.019 (sugar cane production). Australia's methodology results in major emission reductions compared to IPCC default factors. However, the methodology has limited value in policy development, as emission reductions are only possible through changes of production systems (e.g., crop to pasture) or reduction in fertilizer use.

CANADA

Canada's methodology is highly developed compared to other Tier 2 countries and uses an emission factor based on climate, soil, topography, and management practices (Environment and Climate Change Canada, 2021c, sec. A3.4.5.1). The estimates reflect a relatively high spatial resolution, estimating separate emission factors for each of the 405 Eco-

[4] While on average urea has a lower emission factor than urea + NBPT this includes application on both arable and grasslands. When comparing across only arable land CAN = 0.0035, Urea =0.0027, and Urea + NBPT = 0.0020 (Duffy et al., 2021, p. 397).

districts where agricultural production occurs[5]. For each Eco-district, a base emission factor (EF_{base}) is estimated using Equation 1 where F_{topo} is the fraction of the Eco-district identified as being likely regularly saturated or poorly drained, EF_{CT} is the emission factor based on the Eco-district's precipitation to potential evaporation ratio ($\frac{P}{PE}$), and 0.017 is the emission factor for saturated soil, i.e. $\frac{P}{PE} = 1$ (Environment and Climate Change Canada, 2021c, p. 101).

$$EF_{Base} = 0.017 * F_{topo} + EF_{CT} * (1 - F_{topo}) \quad (1)$$

The $\frac{P}{PE}$ ratio is based on long-term weather data collected by 958 weather stations across Canada and the United States, measuring average rainfall and evaporation from May to October from 1971 to 2000 (Environment and Climate Change Canada, 2021c, p. 102). The $\frac{P}{PE}$ ratio is used to estimate EF_{CT}, using Equation 2. The EF_{CT} value is further multiplied by 1.4 to adjust for the spring thaw in Eastern Canada (Environment and Climate Change Canada, 2021c, p. 102).

$$EF_{CT} = 0.022 * \frac{P}{PE} - 0.0048 \quad (2)$$

N_2O-N emissions from inorganic fertilizer use can be estimated at the Eco-district level by multiplying total fertilizer usage, base emission, and soil texture factors (Environment and Climate Change Canada, 2021c, p. 101). Three soil texture classes are used in the methodology, fine, medium, and coarse, and are assigned a value of 1.2, 1, and 0.8. The soil texture factor is the weighted average of the soil texture classes. Given the dry conditions, the soil texture factors are not used in western Eco-districts, with the factor assigned a value of 1.

The Canadian methodology further adjusts eco-district emission estimates to account for three specific practices: adoption of no-till and reduced tillage (NT-RT), summer fallow, and irrigation (Environment and Climate Change Canada, 2021c, pp. 110–112). Adjusting N_2O-N emissions to account for NT-RT uses a factor of -0.2 in Western Canada and 0.1 in Eastern Canada[6] (Environment and Climate Change Canada, 2021c, p. 110). As seen in table {}, conservation tillage is viewed as a strategy for reducing emissions, however, the adoption of NT-RT will increase N_2O-N emissions in Easter Canada given Canada's current methodology. The effect of summer fallow varies between regions and years, depending

[5] Eco-districts are defined within Canada's ecological framework and comprise of areas with similar biological and climatic characteristics. Eco-district sizes vary but a minimum size requirement is set at 100,000 ha (1,000 km^2) (Agriculture and Agri-Food Canada, 2013).

[6] The included management practices are considered additional to the EF_{Base} estimate. The equation used to estimate the additional emissions from NT-RT is as follows: $N_2O_{till} = \left(N * \left(EF_{Base} * Frac_{NT-RT} * (F_{till} - 1)\right)\right) * \frac{44}{28}$, where N is the total nitrogen applied, $Frac_{NT-RT}$ is the share of land the Eco-district under NT-RT and F_{till} is the factor (Environment and Climate Change Canada, 2021c, p. 110).

on crop rotation and estimated available nitrogen within the soil (Environment and Climate Change Canada, 2021c, p. 111). An adjustment factor for irrigated land is calculated by taking the difference of 0.017 ($\frac{P}{PE} = 1$) and EF_{CT} and then multiplying it by the fraction of irrigated cropland in the Eco-district (Environment and Climate Change Canada, 2021c, pp. 111–112). The difference between 0.017 and EF_{CT} can be interpreted as the additional emissions resulting from irrigation and implies an emission factor for irrigated land equal to 0.017 kg N_2O-N kg N^{-1}. As observed by David et al. (2018) emissions from irrigated land are likely overestimated within the Canadian Prairies; this finding appears to be supported when comparing emission factors from other dry regions, see Table 3 and 4.

Canada has a well-developed emission methodology for estimating direct N_2O emission factors. While practices like NT-RT and irrigation are considered, policy development remains limited by the methodology. The main variables used for estimating the emission factor$\frac{P}{PE}$ and topography, are outside of producers' control. While specific practices such as NT-RT, summer fallow, and irrigation are accounted for, high-adoption rates for NT-RT, and a single emission factor for irrigation limits their usefulness. The high spatial resolution use of base emission factors and factor modifiers such as irrigation and NT-RT provides opportunities to improve methodology in the future.

JAPAN

The methodology used by Japan closely resembles a Tier 1 approach, where a series of set emission factors are multiplied by their corresponding activity data (Ministry of the Environment & National Institute for Environmental Studies, 2021, sec. 5.5.1.1). Separate emission factors are used for different commodities; Paddy Rice, Tea, Other Crops, and fertilizer type; Nitrogen fertilizer and Nitrogen Fertilizer treated with dicyandiamide (DCD). Nitrogen fertilizer treated with DCD had a reported emission factor of 74 percent non-treated Nitrogen for Other Crops, and 72 percent for Tea. This methodology provides opportunities to develop policy aimed at reducing emissions by promoting DCD adoption.

NEW ZEALAND

New Zealand's methodology for estimating direct emissions from inorganic fertilizer resembles a Tier 1 approach (Ministry for the Environment, 2021, sec. 5.5.2). Emission factors are differentiated by fertilizer types; country-specific factors are used for urea-based fertilizer (0.0059 kg N_2O-N kg N^{-1}), while all other fertilizers use the IPCC default factor. New Zealand further differentiates nitrogen sources in estimating indirect emissions to include urea with urease inhibitor but the Ministry for the Environment does not differentiate in direct emission methodology (Ministry for the Environment, 2021, sec. 5.5.2).

RUSSIA

Russia's methodology resembles the Netherlands' approach with differentiated emission factors based on soil type (Romanovskaya et al., 2021, sec. 5.7). The methodology applies separate emission factors to four soil types: Chernozems, Soddy-Podzolic Soils, Other soil types, and Application Under Rice[7]. Except for reducing production on Soddy-Podzolic Soils, which have a higher reported emission factor, see Table 3, the only option in reducing direct N_2O emissions is to reduce total fertilizer use as no additional management practice is included.

UNITED KINGDOM

The United Kingdom uses a country-specific Tier 2 model which estimates direct N_2O emissions as a function of fertilizer type, nitrogen application rate (N), and in the case of emissions from other nitrogen fertilizers, average annual rainfall (R) (Brown et al., 2021, sec. 5.5.2). Cumulative annual N_2O-N emissions ($CumN_2O$), measured in g N_2O-N ha^{-1} are estimated using Equations 3 and 4. Equation 3 estimates cumulative emissions from urea-based fertilizers, while Equation 4 is used for other fertilizer types (i.e., Ammonium Nitrate).

$$\ln(CumN_2O + 1) = 0.494 + 0.002035 * N \quad (3)$$

$$\ln(CumN_2O + 1) = 0.1616 + 0.00000354 * N + 0.0005187 * \mathrm{Rain} + 0.00000354 * \mathrm{R} * \mathrm{N} \quad (4)$$

To estimate the emission factor, the difference between $CumN_2O$ at application rate N and N=0 is first calculated and divided by the fertilizer application rate; see Equation 5 (Brown et al., 2021, sec. 5.5.2). The difference between the cumulative emissions at N and $N = 0$ can be interpreted as the emissions resulting from fertilizer application. Dividing by application rate allows for a per-unit comparison.

$$EF = \frac{(CumN_2O_N - CumN_2O_{N=0})}{N} \quad (5)$$

Emission factors are estimated at 100 km^2 (10,000 ha) resolution (Brown et al., 2021, sec. 5.5.2), a substantially higher resolution than in Canada, Eco-district level (min 100,000 ha), or other country-specific Tier-2 factors which appear to use country level estimates. Given the granularity of the estimate, the methodology should effectively account for production differences across regions and better explain weather effects compared with other Tier 2 methods. However, the model fails to account for many practices which could significantly reduce emissions.

[7] Categories are a direct translation of the original Russian (Черноземы, Дерново-подзоли-стые почвы, Другие типы почв, Внесение под рис)

UNITED STATES

The United States is currently the only country to use a Tier 3 approach for N_2O emissions from agricultural soils (United States Environmental Protection Agency, 2021b, sec. 3.12). The method uses a DayCent ecosystem model[8] linking three emission sources: N_2O from agricultural soils, CH_4 from rice cultivation, and soil organic carbon. The emission sources are highly interdependent, given the interrelationship of the carbon, hydrological, and nutrient cycles. The model simulates daily carbon, nutrient, and gas exchange between the atmosphere, soil, and plants, based on soil, climate, and management characteristics.

The DayCent model accounts for numerous management practices, such as crop rotation, tillage, drainage, irrigation, and the use of cover crops, and incorporates more detailed weather, soil, and crop data compared with other Annex I countries (United States Environmental Protection Agency, 2021b, sec. 3.12). The model is currently the only dynamic model used to estimate N2O emissions from agricultural soils, quantifying past producers' decisions on current emission levels, resulting in a more accurate emission estimate.

Despite a more comprehensive methodology, the DayCent model and the Canadian approach have similar challenges. First, the model does not account for enhanced efficiency fertilizers, inhibitors, or slow-released N sources, and may not fully account for the other 4R practices or proposals within the discussion paper (United States Environmental Protection Agency, 2021b, sec. 3.12). Second, irrigation is poorly defined, only differentiating between irrigated and non-irrigated land, excluding actual water usage (United States Environmental Protection Agency, 2021b). Third, the discrete emission factors in the Canadian model support development of transparent and straightforward policy and mitigation efforts, whereas the DayCent approach convolutes future mitigation pathways.

COUNTRY COMPARISON

This section compares emissions originating from agricultural soils with a focus on emissions from synthetic fertilizers. Data used in this comparison was collected from Tables 3.d and 4.1 and covered 1990 to 2019. The section also includes land and production-based estimates. Summary statistics can be found in Table 5, which provides the mean value, min, max, and a comparison with Canada across several productions, emission, and land-based dimensions.

[8] The DayCent ecosystem model is a modified version of the Century model.

LAND AND FERTILIZER USE

A total of 42 countries are compared, covering a total of 1.9 billion hectares of agricultural land, comprising both cropland and managed grassland[9]. The production scale varies considerably between countries, with total agricultural land ranging from 6,000 hectares (ha) in Liechtenstein (Liechtenstein, 2021) to 562.3 million in Australia (Australia, 2021). Canada reported the 5th highest total agricultural land in 2019 with 53.7 million hectares (Environment and Climate Change Canada, 2021a), see Figure 1. Cropland as a share of total agricultural land also varies considerably between countries; Malta has the highest percentage of cropland at 100 percent (Malta, 2021), followed by Denmark, 94 percent (Denmark, 2021), Finland, 91 percent (Finland, 2021), and Canada, 88 percent (Canada, 2021). On the opposite end of the scale, Iceland, New Zealand, and Australia report the lowest level of cropland as a share of total agricultural land with values of 2 percent, 3 percent, and 7 percent respectively (Australia, 2021; Iceland, 2021; New Zealand, 2021) , see Figure 2.

Total synthetic fertilizer use has decreased overall since 1990, falling from 35.4 million tonnes to 34.4 million[10]. However, at the country level, values differ greatly. New Zealand has the largest growth in synthetic fertilizer use, increasing by 662 percent since 1990 (New Zealand, 2021). Australia also increased synthetic fertilizer use by 205% (Australia, 2021). Canada, in comparison, increased fertilizer uses by 120 percent over the same period (Canada, 2021). Large decreases were observed in several former Soviet countries, including Kazakhstan, -85 percent, Russia, -59 percent, Estonia, -43 percent, and Slovakia, -42 percent, see Figure 3 (Estonia, 2021; Kazakhstan, 2021; Russian Federation, 2021; Slovakia, 2021).

The lack of disaggregated data between fertilizer applied to grassland and cropland is a challenge when comparing implied fertilizer application rates between countries. For example, Canadian implied application rates, fertilizer divided by land area, are between 49.1 and 55.7 kg N ha^{-1} when using total agricultural land and cropland. Using the same method, the estimated implied application rate for New Zealand is between 30.0 and 949.1 kg N ha^{-1}, See figure 4. As a result, the intensity measures will be reported using total agricultural land instead of total cropland.

EMISSION FACTORS

As discussed in the methodology section, the emission factors are an estimate of the amount of nitrogen emitted as N_2O. In 2019, 32 of 42 countries reported a factor of 0.010 or 1 percent equivalent to the IPCC default value. Australia, Japan, New Zealand, the United Kingdom, Canada, and Kazakhstan reported values below the IPCC default. The

[9] Calculations made from data collected from CRF Table 4.1
[10] Calculations made from data collected from CRF Table 3.d

Netherlands, the United States, Ireland, and Russia reported values above, see Figure 5 and 6. Canada reported a value of 0.0085 in 2019 (Canada, 2021), reflective of the emission factors originating from the Canadian Prairies, see Table 4. The average emission factors for Alberta, Saskatchewan, and Manitoba are 0.0082, 0.0076, and 0.0089, respectively (Environment and Climate Change Canada, 2021c, sec. 6.4.4). Prairie province emission factors are well below Central and Eastern Canadian provinces; in Ontario, the emission factor was estimated to be 0.0146. The reported estimate in Quebec of 0.0165 was over twice as high as Alberta and Saskatchewan. Figure 6 demonstrates provincial-level emission factors range from the some of the lowest to some of the highest across all countries within this review.

Alberta and Saskatchewan have relatively low average emission factors. However, they are noticeably higher than some other country-specific Tier 2 factors. Emissions originating from non-irrigated dry land have a reported emission factor of 0.002 in Australia, almost four times lower than in Saskatchewan (Australian Government Department of Industry Science Energy and Resources et al., 2021, p. 346). Interestingly, if Canada were to use set emission factors, brown and dark brown soil regions in Saskatchewan and Alberta would be comparable to Australia, with an emission factor of 0.0016 kg N_2O-N kg N^{-1}(Environment and Climate Change Canada, 2021c, p. 101).

Irrigation may also play a large role in higher average emission factors in Western Canada. The implied emission factor for irrigated fields is 0.017 kg N_2O-N kg $N^{-1,}$ over ten times higher than emissions from brown and dark brown soil regions and approximately twice as high as the provincial average emission factor in Alberta and Saskatchewan (Environment and Climate Change Canada, 2021c, p. 101). Research conducted by David et al., (2018) suggest that the emission factors for irrigated land are overestimating emissions within the Canadian Prairies. The study conducted was on a small scale (three field) over two years. However, the results were similar to that of the reported by Australia. In year one, dry-land (non-irrigated) and irrigated emission factors were estimated with the values of 0.0054 and 0.0077 kg N_2O-N kg N^{-1}. respectively, in year two the estimated emission factors were 0.0012 and 0.0055 kg N_2O-N kg N^{-1}.

Lack of differentiation between fertilizer types also contributes to Canada's relatively high emission factor. Harty et al. (2016) found that by switching from calcium ammonium nitrate (CAN) to urea-based fertilizer, N_2O emissions observably decrease between 58 to 87 percent. These findings appear to be incorporated into the emission methodologies of Ireland, New Zealand, and the United Kingdom. In Ireland, switching from CAN to Urea or Urea + NBPT would decrease the emission factor by 82 and 71 percent, respectively (Duffy et al., 2021, sec. 5.5). In New Zealand, switching to urea would decrease the emission factor by 41 percent (0.01 to 0.0059) (Ministry for the Environment, 2021, sec. 5.5.2). In the United Kingdom, separate emission factors are estimated for urea and other fertilizer types and are dependent factors such as application rate and weather (Brown et al., 2021, sec. 5.5.2).

LAND-BASED EMISSION INTENSITIES

Average total N_2O emissions per hectare of land decreased from 3.05 kg N_2O in 1990 to 2.61 kg in 2019. Individual values range between 0.07 in Australia to 7.07 in the Netherlands. Canada reported the 11th lowest value in 2019 at 1.53 kg N2O ha^{-1}; this value has increased by 52 percent since 1990, see Figure 8. This spike in emissions can likely be attributed to the 120 percent increase in fertilizer use (Canada, 2021). As seen in Figure 9, land-based intensity measures in Canada are comparable to Latvia and Italy.

Narrowing the scope of emission estimates to include only emissions originating from synthetic fertilizers in 2019, average N_2O emissions per hectare of land was found to decrease from 0.087 kg N_2O to 0.069 kg in 2019. Decreased intensity distribution was also observed, with the range shrinking from 2.6 kg N_2O to 0.95 kg. Under this scenario, average emissions per hectare in Canada increased from 0.370 to 0.66. Compared with other jurisdictions, Canadian emissions inflated from the lowest quartile in 1990, to the second-highest quartile in 2019, slightly above the median value, see Figure 8. Canadian emission intensity estimate is above the median compared to other countries, over all ranked 11th and comparable to the United Kingdom and Slovenia on an intensity basis, see Figure 10.

PRODUCTIVITY COMPARISON

One of the justifications for the federal emission reduction target provided in the AAFC discussion document was Canada's high emission intensity compared to major producing regions. Canada's emission intensity estimate by AAFC was 0.249 kg CO_2e per kg cereal crop (Agriculture and Agri-Food Canada, 2022). This places Canada above the OECD and EU averages, 0.207 kg, and 0.18 kg, respectively, ands countries like France and Russia, 0.121kg and 0.139 kg, respectively. Comparing all cereal crops may not be the most appropriate measure, as emission intensities between cereal types differ. Fouli et al. (2021) highlights these differences when comparing intensities across Canadian commodities. Large emission intensity differences were reported between different wheat varieties, with the reported value of durum wheat much lower than winter wheat, 160 kg compared to 1900 kg.

This report takes a different approach by estimating a benchmark value based on Canada's average wheat yield and emission factors. First, average wheat yield data for 2019 was collected from the FAOSTAT database[11](Food and Agriculture Organization of the United Nations, 2021). Second, the benchmark was first estimated using Canadian (Can)

[11] 2017 data was used for Malta as 2018 and 2019 data was unavailable, Iceland and Liechtenstein were excluded given lack of data.

data by dividing average yield (Y_{Can}) by the product of the emission factor (EF_{Can}) and a substitute nitrogen application rate (assumed 100 kg ha^{-1}, AR_{Can}), see Equation 6.

$$Can = \frac{Y_{Can}}{EF_{Can} * AR_{Can}} \tag{6}$$

Third, the fertilizer application rate for country i that would be needed to equal the Canadian benchmark Can, was estimated using Equation 7, the value of Can, country-specific emission factors, and average yield data.

$$Can = \frac{Y_i}{EF_i * AR_i} \rightarrow AR_i = \frac{1}{\left(Can * \frac{EF_i}{Y_i}\right)} \tag{7}$$

By comparing the percent difference between the fertilizer application rates between Canada and country i resulting in the same benchmark value, wheat production efficiency relative to Canada can be calculated. Given the measure, positive values indicate greater production efficiency, requiring higher fertilizer levels to reach the benchmark value. Referencing Table 6 and Figure 11 it appears that average Canadian production efficiency was low compared to the total group. Although below average, several major producing countries such as the United States, Turkey, Russia, and Kazakhstan had large negative differences, suggesting less efficient production. From Figure 12, Canada is comparable in efficiency to Ukraine, Italy, and Poland, and less efficient than the Netherlands, the United Kingdom, and New Zealand in wheat production. Relatively low efficiency can be partially attributed to low yield, suggesting Canada may have a problem with productivity, rather than emissions. Of the 40 countries where average yield data was available, Canada had the 10th lowest average yield at 3.38t ha^{-1} (Food and Agriculture Organization of the United Nations, 2021). Average yield values had a range of 1.01t in Kazakhstan to 9.38 in Ireland with average Canadian yields comparable to the US (Food and Agriculture Organization of the United Nations, 2021).

Three hypothetical scenarios are also evaluated to observe the effects of increased efficiency and changes in emission factors. The first scenario conducted increased Can by 10 percent, to simulate an improvement of efficiency, either through increased yields or decreased average emission factor. The average percent difference across the 40 countries decreased from 38 to 26 percent, and the number of countries reporting negative values increased from 10 to 14. The second scenario examined changes to the reported emission factor. Countries which reported using the IPCC default factor were reassigned a value of 0.013, the disaggregated factor for temperate wet climates in the 2019 refinement (Hergoualc'h et al., 2019). The average percent difference decreased from 38 to 18 percent, and countries with negative differences increased from 10 to 18 when compared with the benchmark values. The last scenario used both the increased efficiency measure for Can and the disaggregated emission factor instead of the default factor. Compared with the benchmark value, average percent difference decreased from 38 to 7 percent, and countries reporting negative differences increased from 10 to 23. The median value decreased from 28 to -7 percent, suggesting above average production efficiency in Canada under this scenario, see Figure 11 and 12. While hypothetical, these additional scenarios highlight the importance of the emission factor estimate. If Canada were to further develop its emission methodology, such as differentiating by fertilizer type, or modifying to account for 4R practices, average emission factor decreases are likely. Additionally, if European countries were to develop country specific approaches that account for precipitation, like in the US, UK, or Canada, increases in the average emission factor would be expected. The IPCC climate zones map designates most European land as temperate and moist, similar to much of Central and Eastern Canada (Reddy et al., 2019, p. 3.47), where average emission factors range from 0.013 in Prince Edward Island to 0.017 in Quebec and Newfoundland and Labrador (Environment and Climate Change Canada, 2021c).

CONCLUSION

As environmental, social, and political pressures rise to reduce emission reductions, the importance of accurate and reliable greenhouse gas emission measurements becomes prevalent. Canada has a well-developed methodology for estimating direct N2O emissions from agricultural soils. The approach takes critical steps to account for the effects of weather and the environment on greenhouse gas emissions, incorporating some production practices within the methodology.

Canadian methodology is more developed compared to other regions, particularly Europe, which generally used limited Tier 1 approaches. This creates challenges when comparing N2O emissions between countries, as the uncertainty estimates for default values were estimated to be approximately ±100 percent and therefore may not reflect actual emission levels (Hergoualc'h et al., 2019, p. 11.12). This casts doubt on the reliability of emission estimates that do not account for environmental factors, and essentially equate 1 percent of fertilizer use. Compared to Tier 2 and country-specific Tier 1 methodologies, Canada better captures environmental characteristics. A factor missing from the Canadian methodology, but is accounted for in other countries' methodology, is fertilizer type. The DayCent model developed and used by the United States would clearly improve estimates but would require increase in data and continue to face several of the same issues faced currently by the Canadian methodology.

Relative and absolute land-based emission intensity increased in Canada since 1990, as intensity increased by 52 percent, and fertilizer use increased by 120 percent (Canada, 2021). Overall, Canada has the 11th lowest land-based emission intensity on a total N2O emissions per ha basis. Given the 120 percent increase in fertilizer use, Canada's relatively high intensity measure is no surprise when comparing synthetic fertilizer emissions specifically. However, despite sharp increase, intensity was approximately average compared with other jurisdictions. Canada ranked relatively poorly comparing emission intensity on a wheat productivity basis given reported emission factors. However, Canada production was more efficient than some major wheat producing countries like Kazakhstan, Russia and the United States.

The Canadian model lacks accountability of the mitigation efforts promoted as short term BMPs within the AAFC document. Producers in Canada aiming to meet the national emission targets will require updated and comprehensive methodology. To do so, Canadian policy designers and actors need to ensure that current and upcoming programs reduce emissions are accounted for within the national methodology in parallel. The current quantification protocol for agricultural nitrous oxide emission reductions is not effective at reducing provincial emissions at the national level, as the carbon offset measures are not included in the national methodology. Improvement to the current Canadian methodology through transparency and use of discrete emission factors may enhance policy and communication development. Canada has a well-developed methodology for estimating direct N_2O emissions from agricultural soils. The approach takes critical steps to account for the effects of weather and the environment on greenhouse gas emissions, incorporating some production practices within the methodology. The model lacks to account for many of the mitigation efforts promoted as short term BMPs within the AAFC document. If Canadian producers are to meet the national emission targets, updating the methodology is essential. Canadian policy makers need to ensure that programs developed in parallel to reduce emissions are accounted for within the national methodology. Programs like the quantification protocol for agricultural nitrous oxide emission reductions would not be effective at reducing provincial emissions at the national level, as the requirements for the carbon offset are not included in the national methodology.

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TABLES

Table 1

Emission Factor Variable Inclusions

Model	Tier	Nitrogen Source	Application Rate	Soil Type	Weather	Tillage	Irrigation	Rotation	Production Type
2006 Guidelines	1								
2019 Refinement	1				1[a]		1[a]		
Ireland	1	1							
Netherlands	1			1					
Australia	2				1		1		1
Canada	2			1	1	1	1	1[b]	
Japan	2	1							1
New Zealand	2	1							
Russia	2			1					
United Kingdom	2	1	1		1				
United States	3		1	1	1	1	1	1	1

Note. a. Indicates disaggregated emission factors (Hergoualc'h et al., 2019) b. Crop rotation is indirectly accounted for in estimating emissions from summer fallow (Environment and Climate Change Canada, 2021c). Information used was collected from the 2021 National Inventory Submissions.

Table 2

Country List

Country	Abbreviation	National Inventory Report	Common Reporting Format Tables	Translation
Australia	AUS	(Australian Government Department of Industry Science Energy and Resources et al., 2021)	(Australia, 2021)	
Austria	AUT	(Anderl et al., 2021)	(Austria, 2021)	
Belarus	BLR	(Narkevich I.P. et al., 2021)	(Belarus, 2021)	Russian
Belgium	BEL	(Belgian Interregional Environment Agency et al., 2021)	(Belgium, 2021)	
Bulgaria	BGR	(Executive Environment Agency at the Ministry of Environment and Water, 2021)	(Bulgaria, 2020)	
Canada	CAN	(Environment and Climate Change Canada, 2021a)	(Canada, 2021)	
Croatia	HRV	(Marković & Glückselig, 2021)	(Croatia, 2021)	
Cyprus	CYP	(Ministry of Agriculture Rural Development and Environment, 2021)	(Cyprus, 2021)	
Czechia	CZE	(Beranova et al., 2021)	(Czechia, 2021)	
Denmark	DNK	(Nielsen et al., 2021)	(Denmark, 2021)	
Estonia	EST	(Kupri et al., 2021)	(Estonia, 2021)	
Finland	FIN	(Statistics Finland & The Natural Resources Institute Finland, 2021)	(Finland, 2021)	
France	FRA	(Andre et al., 2021)	(France, 2021)	French
Germany	DEU	(Federal Environment Agency, 2021)	(Germany, 2021)	
Greece	GRC	(Ministry of the Environment and Energy, 2021)	(Greece, 2021)	
Hungary	HUN	(Katalin, 2021)	(Hungary, 2021)	

Country	Abbreviation	National Inventory Report	Common Reporting Format Tables	Translation
Iceland	ISL	(Keller et al., 2021)	(Iceland, 2021)	
Ireland	IRL	(Duffy et al., 2021)	(Ireland, 2021)	
Italy	ITA	(di Cristofaro & Cordella, 2021)	(Italy, 2021)	
Japan	JPN	(Ministry of the Environment & National Institute for Environmental Studies, 2021)	(Japan, 2021)	
Kazakhstan	KZA	(Tokpaev, 2021)	(Kazakhstan, 2021)	Russian
Latvia	LVA	(Skrebele et al., 2021)	(Latvia, 2021)	
Liechtenstein	LIE	(Weber, 2021)	(Liechtenstein, 2021)	
Lithuania	LTU	(Juška & Žiukelytė, 2021)	(Lithuania, 2021)	
Luxembourg	LUX	(Bechet et al., 2021)	(Luxembourg, 2021)	
Malta	MLT	(The Malta Resources Authority, 2021)	(Malta, 2021)	
Netherlands	NLD	(Ruyssenaars et al., 2021)	(Netherlands, 2021)	
New Zealand	NZL	(Ministry for the Environment, 2021)	(New Zealand, 2021)	
Norway	NOR	(The Norwegian Environment Agency et al., 2020, 2021)	(Norway, 2021)	
Poland	POL	(Olecka et al., 2021)	(Poland, 2021)	
Portugal	PRT	(Pina & Portuguese Environment Agency, 2021)	(Portugal, 2021)	
Romania	ROU	(Olteanu, 2021)	(Romania, 2021)	
Russian Fed.	RUS	(Romanovskaya et al., 2021)		Russian
Slovakia	SVK	(Slovak Hydrometeorological Institute et al., 2021)	(Slovakia, 2021)	
Slovenia	SVN	(Verbič et al., 2021)	(Slovenia, 2021)	
Spain	ESP	(MITECO, 2021)	(Spain, 2021)	Spanish
Sweden	SWE	(Swedish Environmental Protection Agency & Swedish Environmental Protection Agency, 2021)	(Sweden, 2021)	

Country	Abbreviation	National Inventory Report	Common Reporting Format Tables	Translation
Switzerland	CHE	(Federal Office for the Environment, 2021)	(Switzerland, 2021)	
Turkey	TUR	(Turkish Statistical Institute, 2021)	(Turkey, 2021)	
Ukraine	UKR	(Ministry of Environmental Protection and Natural Resources of Ukraine, 2021)	(Ukraine, 2021)	
United Kingdom	GBR	(Brown et al., 2021)	(United Kingdom, 2021)	
United States	USA	(United States Environmental Protection Agency, 2021a, 2021b)	(United States of America, 2021)	

Note. UNFCCC National Inventory Submission repository can be found at the following link: https://unfccc.int/ghg-inventories-annex-i-parties/2021

Table 3

IPCC and Country Specific Emission Factors

Model	**Subcategory**	**Emission Factor** (kg N_2O-N kg N^{-1})
2006 Guidelines	**Default Value**	**0.010**
2019 Refinement	**Default Value**	**0.010**
	Synthetic fertilizer Wet climates	0.016
	Dry Climate	0.005
Ireland	**Average Value**	**0.0123**
	CAN	0.014
	Urea	0.003
	Urea +NBPT	0.004
Netherlands	**Average Value**	**0.0106**
	Mineral soils grassland	0.008
	Organic soils grassland	0.030
	Mineral soils arable land	0.007
	Organic soils arable land	0.030
Australia	**Average Value**	**0.0035**
	Irrigated Pasture	0.004
	Irrigated Crop	0.009
	Non-Irrigated Pasture	0.002
	Non-Irrigated Crop	0.002
	Sugar Cane	0.020
	Cotton	0.006
	Horticulture	0.009
Canada	**Average Value**	**0.0085**
Japan	**Average Value**	**0.0065**
	Paddy Rice	0.0031
	Tea	0.029
	Other Crop	0.0062
	Tea (N+DCD)	0.021

Model	Subcategory	**Emission Factor** (kg N_2O-N kg N^{-1})
	Other Crop (N+DCD)	0.0046
New Zealand	**Average Value**	**0.0068**
	Urea	0.006
	Other Synthetic N	0.010
Russia	**Average Value**	**0.0137**
	Chernozems	0.013
	Soddy-Podzolic	0.024
	Other soil types	0.010
	Application Under Rice	0.003
United Kingdom	**Average Value**	**0.0072**
United States	**Average Value**	**0.0116**

Note. Canada, United Kingdom, and the United States do not use discrete emission factors. Data used was collected from the 2021 National Inventory Reports and CRF Table 3. d

Table 4

Canadian Emission Factor Comparison with Background Data

Data	Regional Factors	1990	2005	2010	2019
Canada[a]	British Columbia	0.0102	0.0102	0.0102	0.0102
	Alberta	0.0089	0.0083	0.0083	0.0083
	Saskatchewan	0.0076	0.0070	0.0070	0.0076
	Manitoba	0.0089	0.0095	0.0089	0.0089
	Ontario	0.0146	0.0146	0.0146	0.0146
	Quebec	0.0165	0.0165	0.0165	0.0165
	New Brunswick	0.0159	0.0159	0.0159	0.0159
	Nova Scotia	0.0153	0.0153	0.0153	0.0153
	Price Edward Island	0.0134	0.0134	0.0134	0.0134
	Newfoundland & Labrador	0.0165	0.0165	0.0165	0.0165
	Canada[b]	0.0112	0.0096	0.0093	0.0085
IPCC[c]	IPCC Default	0.010			
	IPCC Wet Climate	0.014			
	IPCC Dry Climate	0.005			
	IPCC - Wet Climate - Temperate	0.013			
	IPCC - Dry Climate - Temperate	0.007			
	IPCC - Dry Climate - Irrigated	0.004			
	IPCC - Dry Climate - Non-Irrigated	0.001			
Canada Background Data[d]	Brown/Dark Brown Soil	0.002			
	Black/ Gray Soil	0.008			
	Ontario & Quebec Soil	0.017			
	Irrigation	0.017			
	NT-RT factor (Western Canada)	-0.800			
	NT-RT factor (Eastern Canada)	0.100			

Note. a.(Environment and Climate Change Canada, 2021c, sec. A6.4.4) b. (Canada, 2021)c. (Hergoualc'h et al., 2019, sec. 11A.2) d. (Environment and Climate Change Canada, 2021c, sec. A3.4.5.1)

Table 5

CRF Table Summery Statistics (1990, 2005, 2019)

Variable	Units	Year	Mean	Min		Max		Canada	Rank[b]
Total Synthetic Fertilizer Applied	t	1990	843850	237	LIE	9910000	USA	1200000	8
Emission Factor	kg N2O-N / kg N	1990	0.01000	0.0064	JPN	0.0136	RUS	0.0112	4
Total Emissions: Synthetic Fert	kt N2O	1990	15.01	0.004	LIE	211.688	USA	21.088	6
Total Emissions: Direct	kt N2O	1990	49.69	0.016	LIE	914.533	USA	47.856	8
Total Emissions: Ag Soils	kt N2O	1990	59.48	0.022	LIE	1060.091	USA	57.220	8
Total Reported Crop Land	kHa	1990	15323	2	LIE	174471	USA	50047	3
Total Reported Ag Land[a]	kHa	1990	46270	6	LIE	559278	AUS	57008	5
Ratio of Total Ag Soil Emission to Total Ag Land	kg N2O / Ha	1990	3.057	0.070	AUS	11.560	NLD	1.004	38
Ratio of Fertilizer Emissions to Total Ag Land	kg N2O / Ha	1990	0.873	0.010	AUS	2.620	NLD	0.370	36
Total Synthetic Fertilizer Applied	t	2005	674294	187	LIE	10700000	USA	1540000	4
Emission Factor	kg N2O-N / kg N	2005	0.0098	0.0043	AUS	0.0136	RUS	0.0096	37
Total Emissions: Synthetic Fert	kt N2O	2005	11.41	0.003	LIE	214.801	USA	23.133	4
Total Emissions: Direct	kt N2O	2005	43.40	0.015	LIE	914.668	USA	51.531	6
Total Emissions: Ag Soils	kt N2O	2005	50.98	0.020	LIE	1051.644	USA	62.977	5
Total Reported Crop Land	kHa	2005	13942	2	LIE	165727	USA	49119	3
Total Reported Ag Land[a]	kHa	2005	45614	6	LIE	562349	AUS	55736	5

Variable	Units	Year	Mean	Min		Max		Canada	Rank[b]
Ratio of Total Ag Soil Emission to Total Ag Land	kg N2O / Ha	2005	2.481	0.08	AUS	8.020	NLD	1.130	35
Ratio of Fertilizer Emissions to Total Ag Land	kg N2O / Ha	2005	0.632	0.001	KAZ	1.890	NLD	0.415	29
Total Synthetic Fertilizer Applied	t	2019	812717	184	LIE	13000000	USA	2640000	2
Emission Factor	kg N2O-N / kg N	2019	0.010	0.0035	AUS	0.0137	RUS	0.0085	38
Total Emissions: Synthetic Fert	kt N2O	2019	13.12	0.0029	LIE	236.374	USA	35.449	3
Total Emissions: Direct	kt N2O	2019	46.98	0.0150	LIE	974.547	USA	67.948	6
Total Emissions: Ag Soils	kt N2O	2019	56.22	0.0199	LIE	1156.442	USA	82.031	6
Total Reported Crop Land	kHa	2019	13674	2	LIE	161933	USA	47414	3
Total Reported Ag Land[a]	kHa	2019	45205	6	LIE	559406	AUS	53729	5
Ratio of Total Ag Soil Emission to Total Ag Land	kg N2O / Ha	2019	2.608	0.07	AUS	7.070	NLD	1.527	32
Ratio of Fertilizer Emissions to Total Ag Land	kg N2O / Ha	2019	0.692	0.003	KAZ	1.640	NLD	0.660	20

Note. Data was collected from 2021 CRF Tables 4.1, see Table 2.

Table 6

Summary of Productivity Based Emission Intensity Scenarios

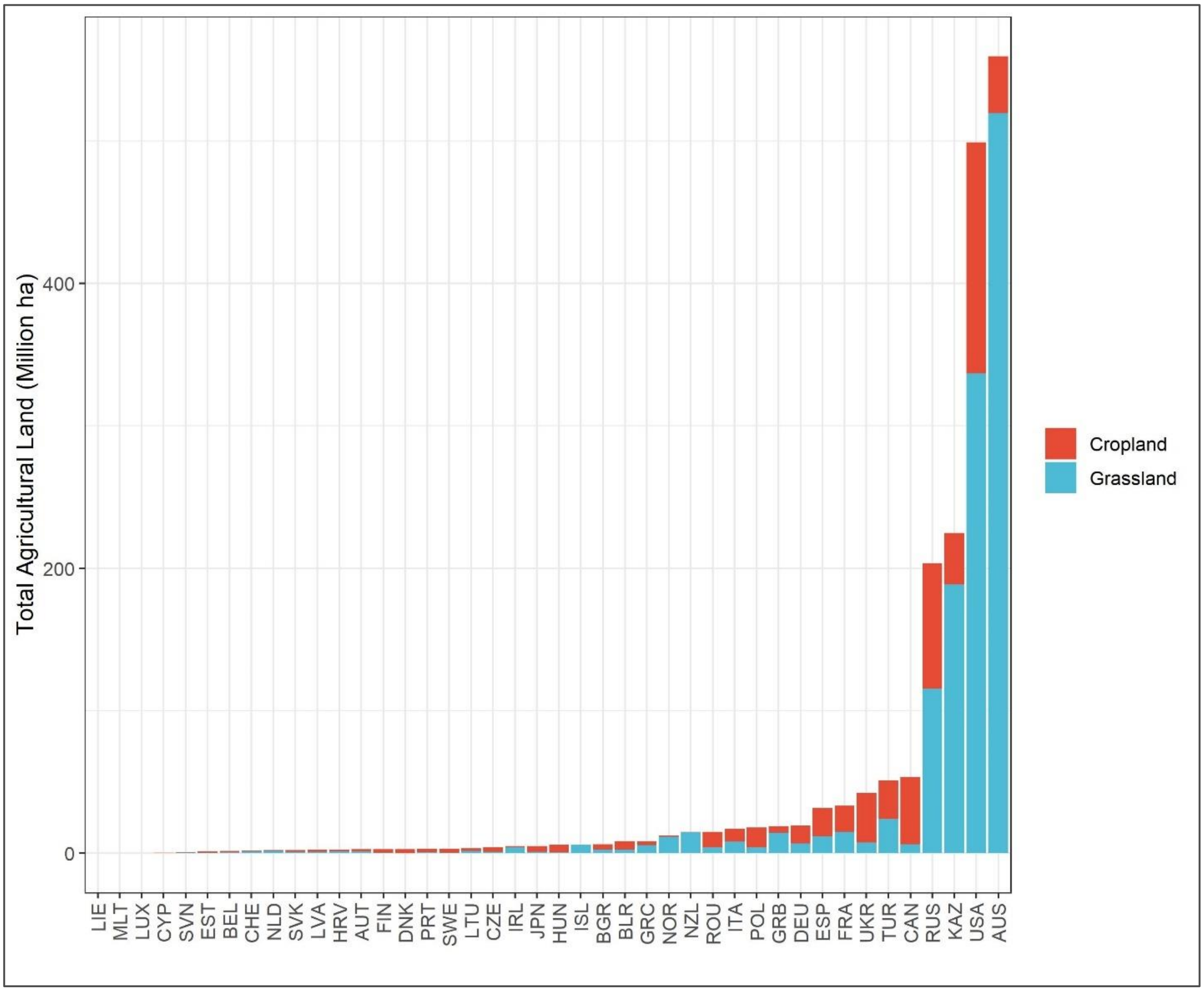
Variable	Measure	Mean	SD	Min Value	25th Percentile	50th Percentile	75th Percentile	Max Value	Canadian Value
Wheat Yield	t / ha	5.19	2.18	1.01	3.43	4.97	5.96	9.38	3.38
Emission Factor	kg N_2O-N / kg N	0.0097	0.0016	0.0035	0.0100	0.0100	0.0100	0.0137	0.00855
Benchmark	%	0.38	0.64	-0.71	-0.01	0.28	0.71	2.31	0
Scenario 1	%	0.26	0.58	-0.73	-0.08	0.16	0.56	2.01	0
Scenario 2	%	0.18	0.63	-0.71	-0.18	0.02	0.44	2.31	0
Scenario 3	%	0.07	0.58	-0.73	-0.26	-0.07	0.31	2.01	0

Note. Data was collected from the FAOSTAT database and 2021 CRF Tables 3.d and 4.1, see Table 2.

FIGURES

Figure 1

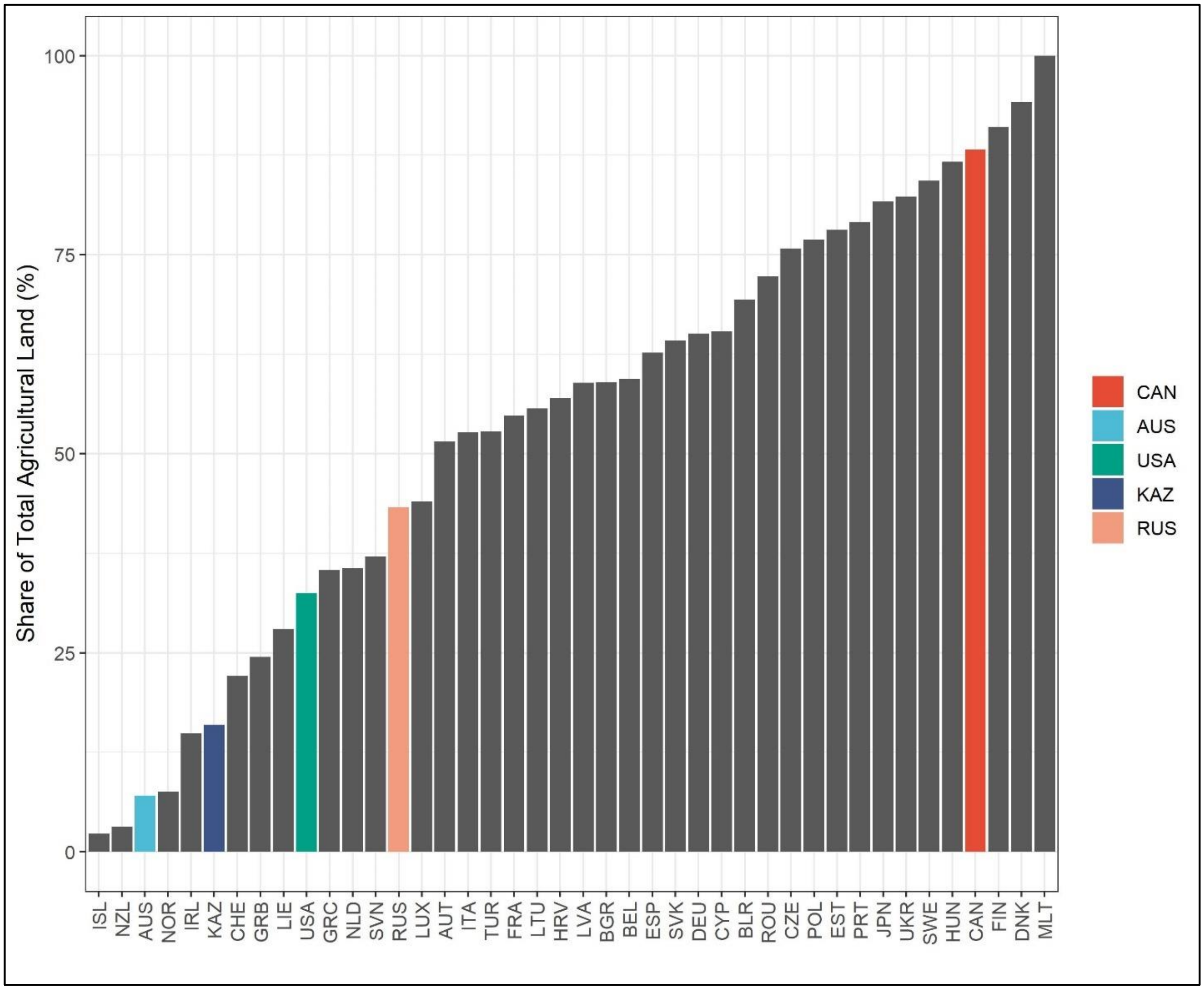
Total Agricultural Land by Country: 2019



Note. Data was collected from 2021 CRF Tables 4.1, see Table 2.

Figure 2

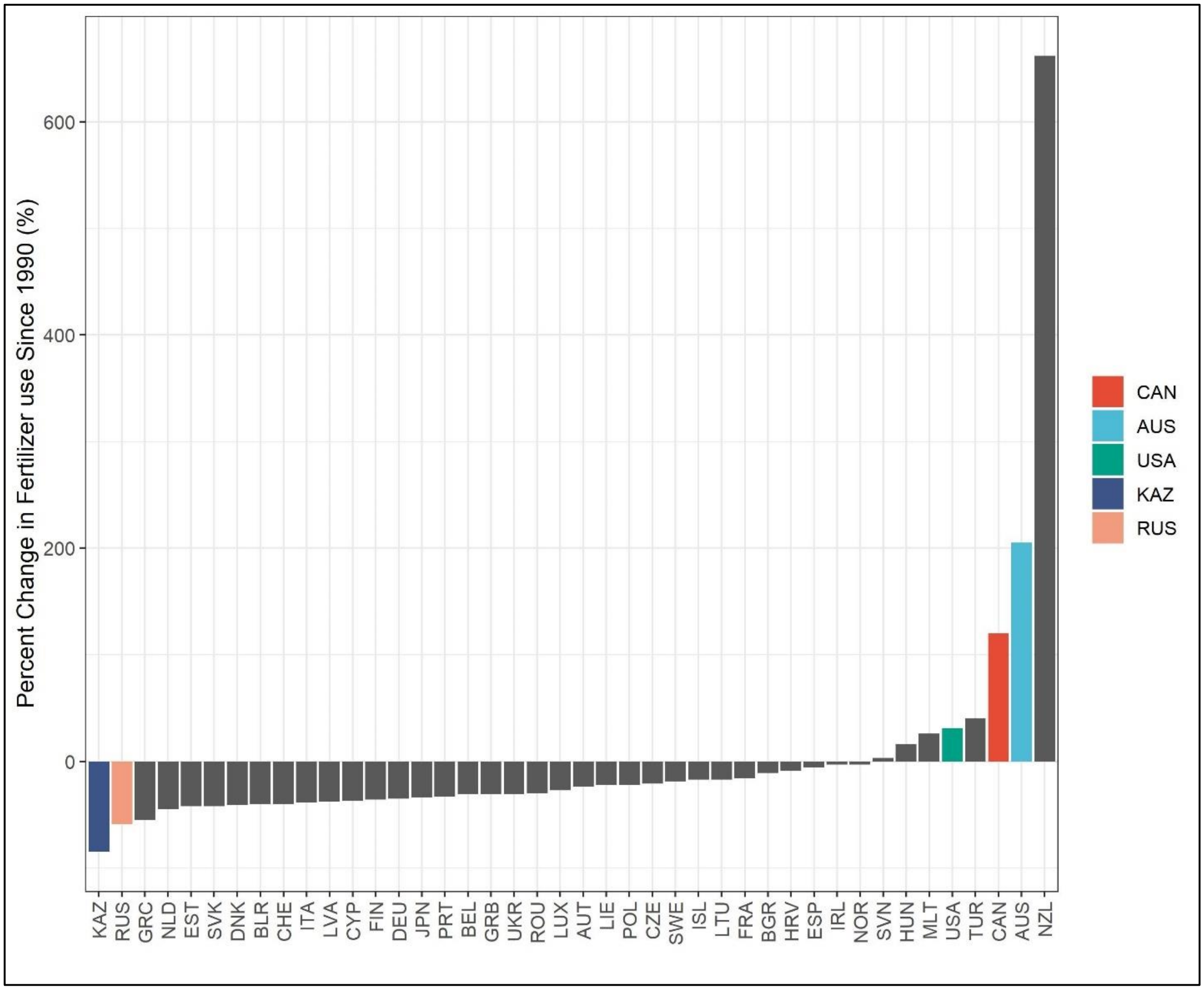
Cropland as a share of total agricultural land area: 2019



Note. Data was collected from 2021 CRF Tables 3.d, see Table 2.

Figure 3

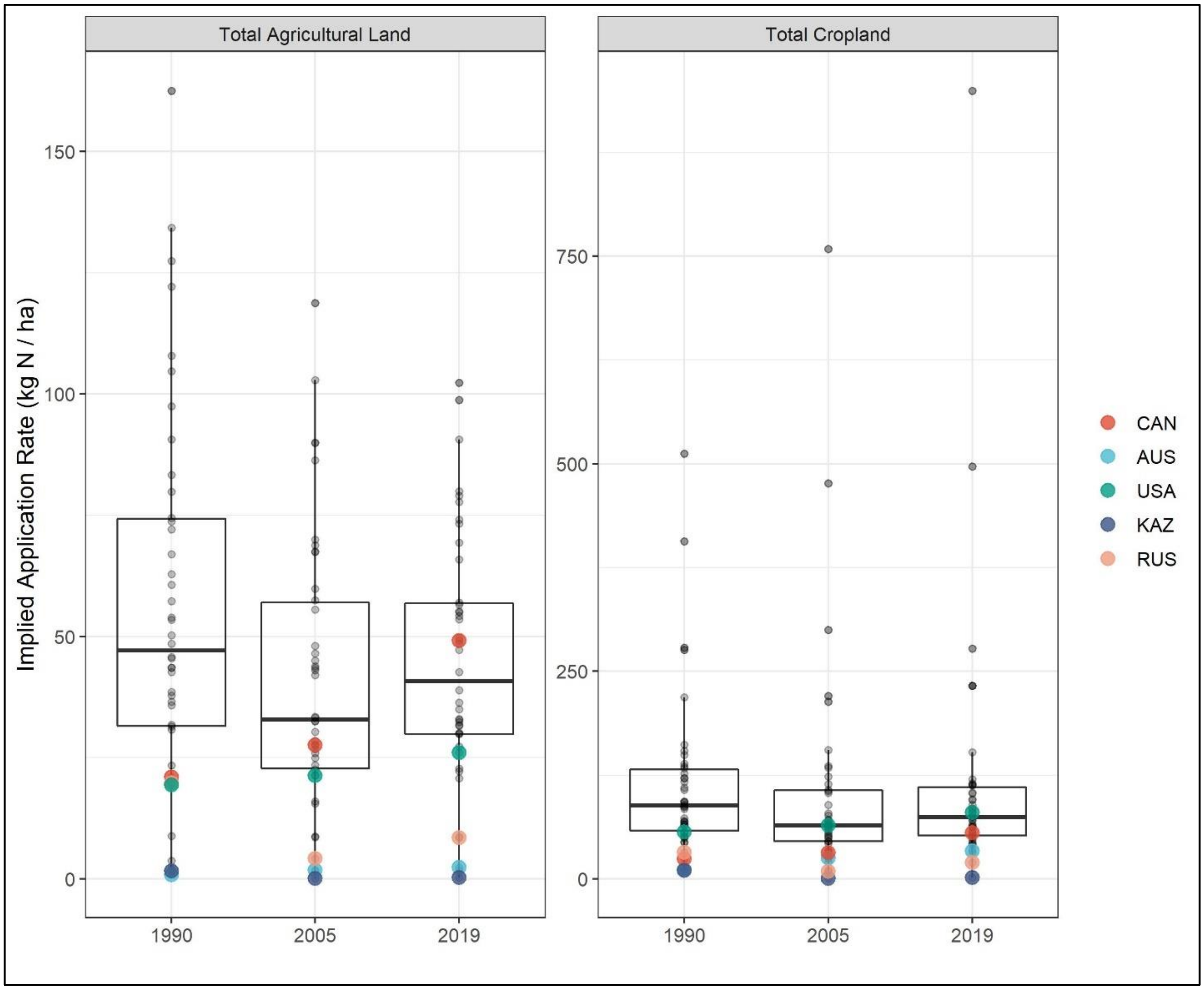
Change in Inorganic Fertilizer Use Since 1990



Note. Data was collected from 2021 CRF Tables 3.d, see Table 2.

Figure 4

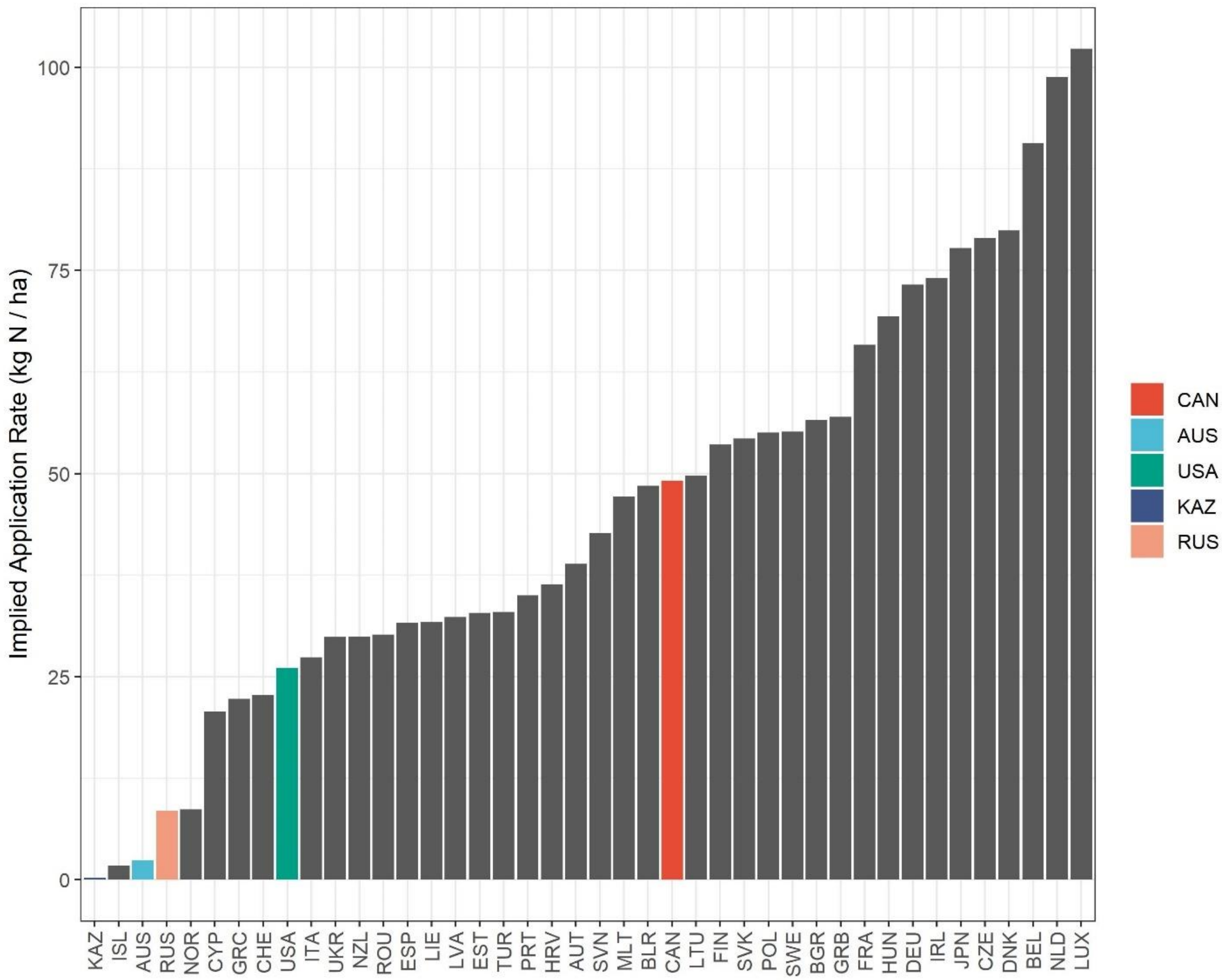
Implied Application Rate Comparison



Note. Data was collected from 2021 CRF Tables 3.d and 4.1, see Table 2.

Figure 5

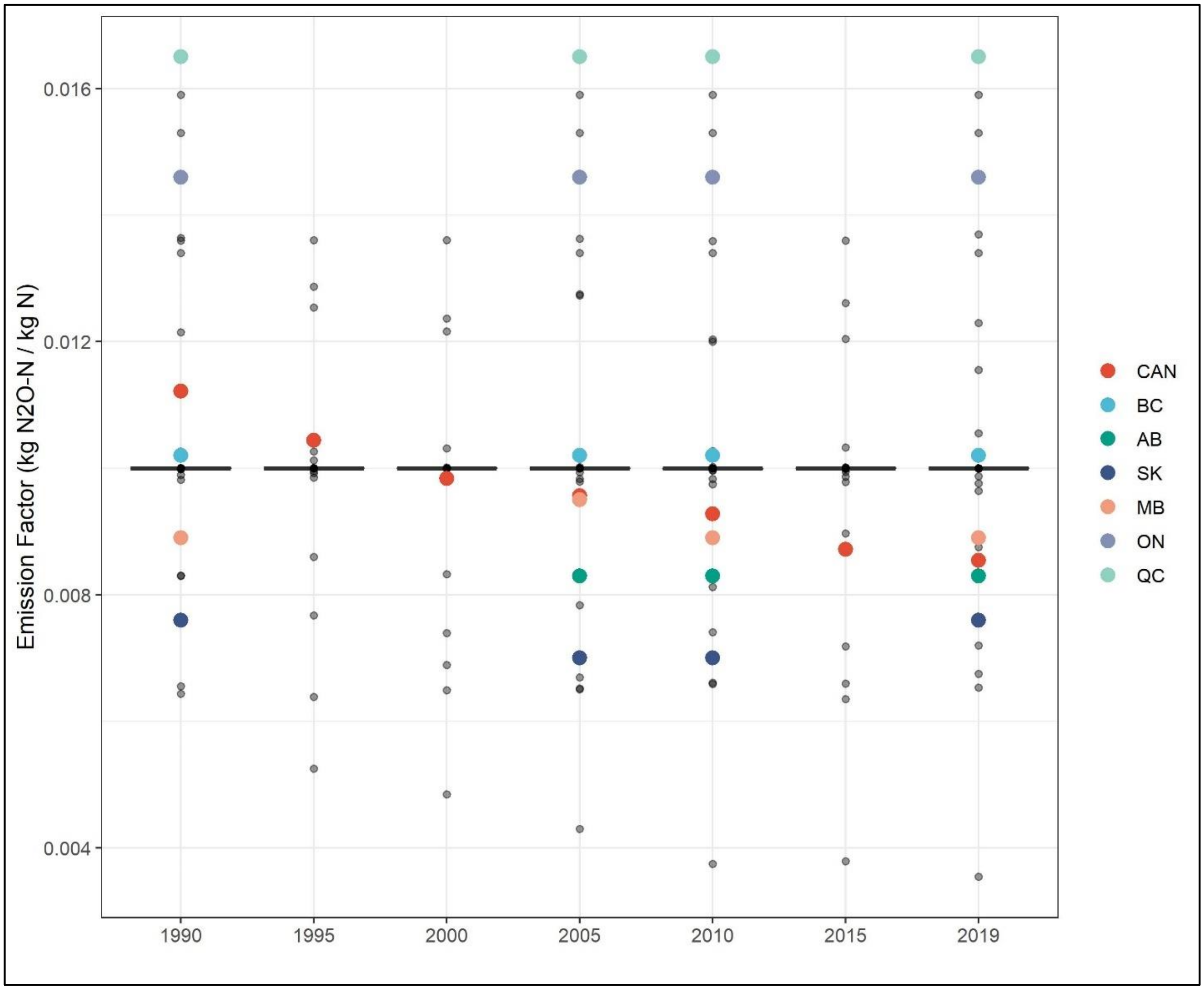
Implied Inorganic Fertilizer Application Rate on Total Agricultural Land: 2019



Note. Data was collected from 2021 CRF Tables 3.d and 4.1, see Table 2.

Figure 6

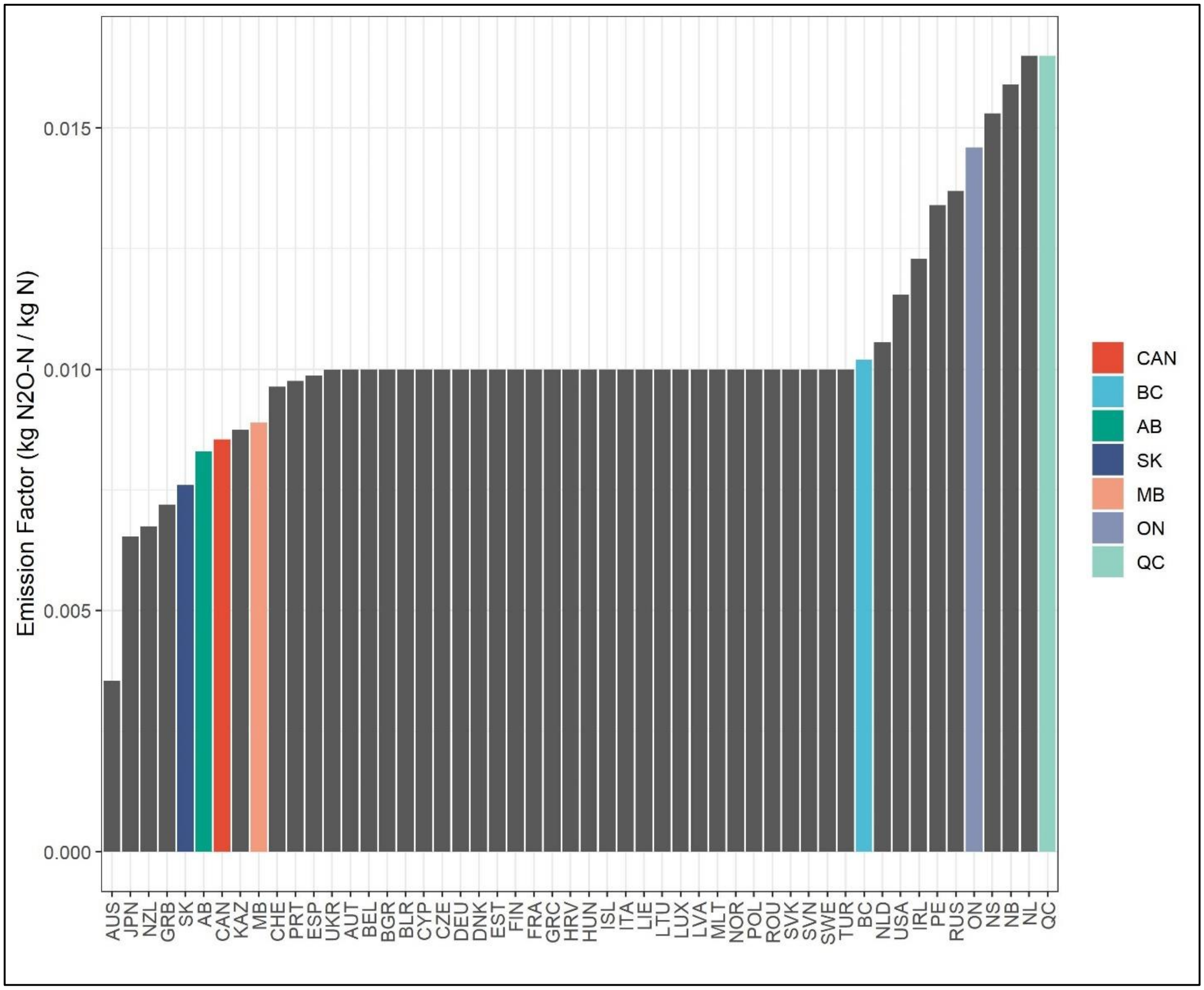
Reported Emission Factors, With International and Provincial Estimates



Note. Data was collected from 2021 CRF Tables 3.d, see Table 2.

Figure 7

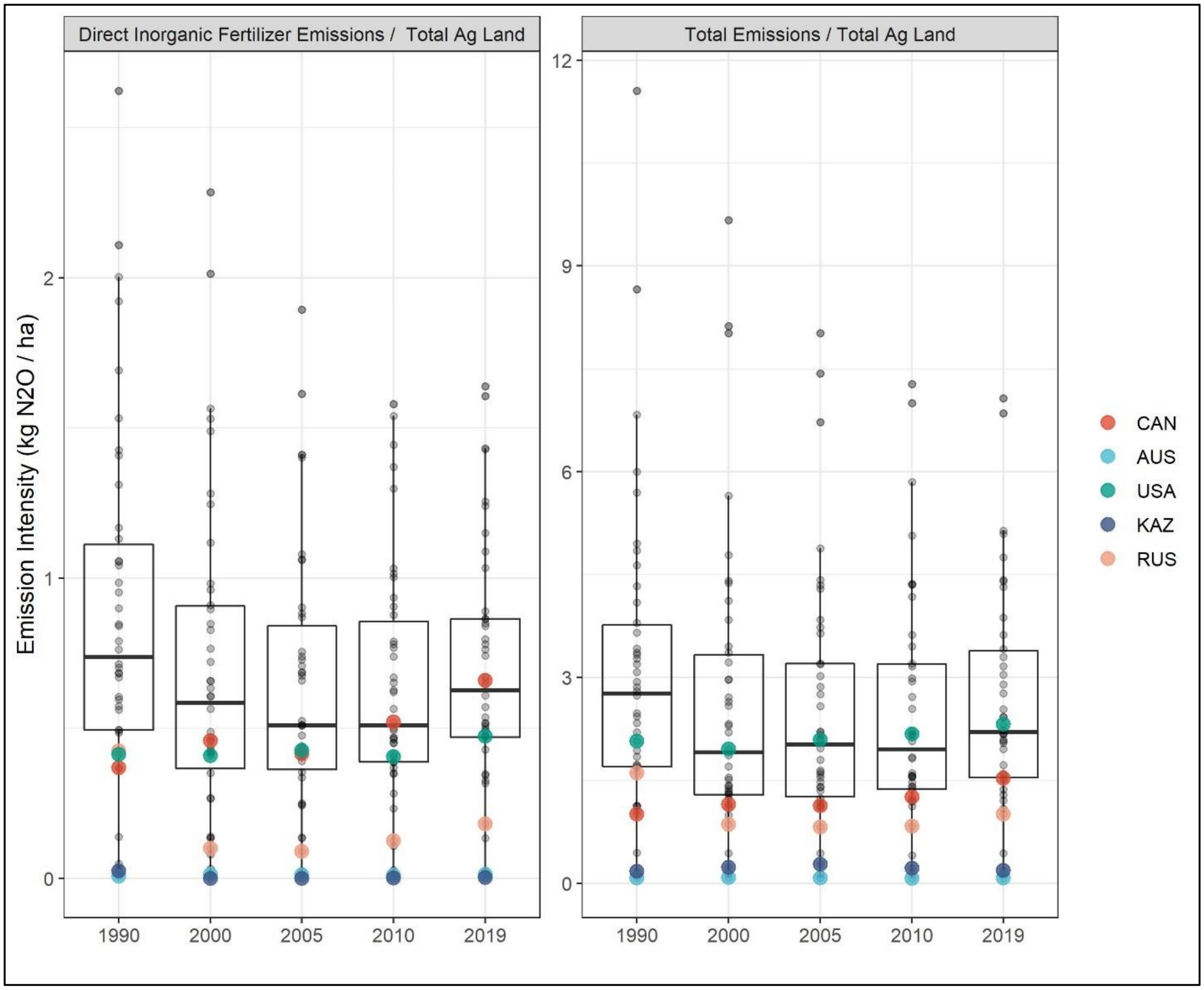
Reported Emission Factor Comparison: 2019



Note. Data was collected from 2021 CRF Tables 3.d, see Table 2.

Figure 8

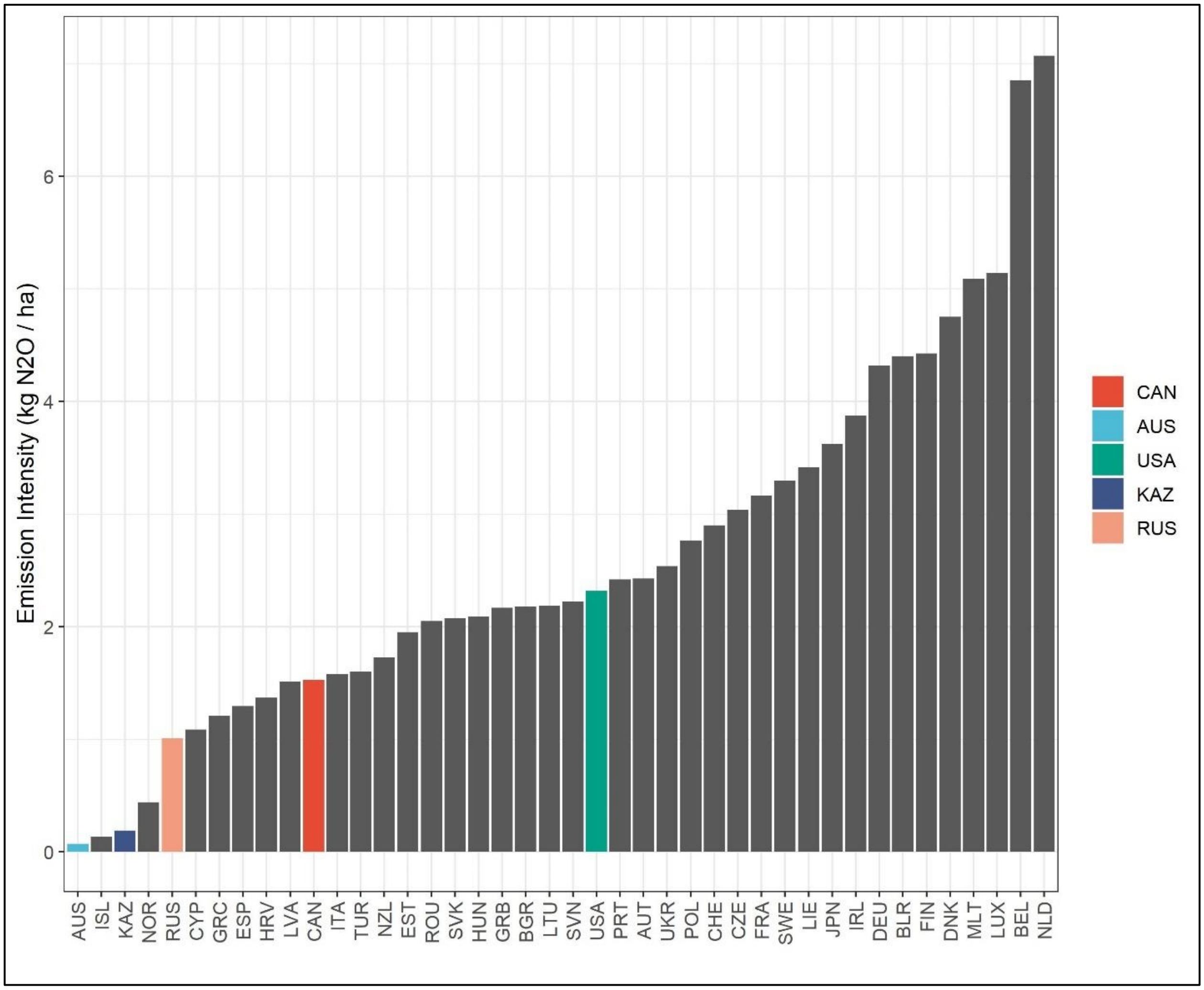
Comparison of Land Based Intensity Measures



Note. Data was collected from 2021 CRF Tables 3.d and 4.1, see Table 2.

Figure 9

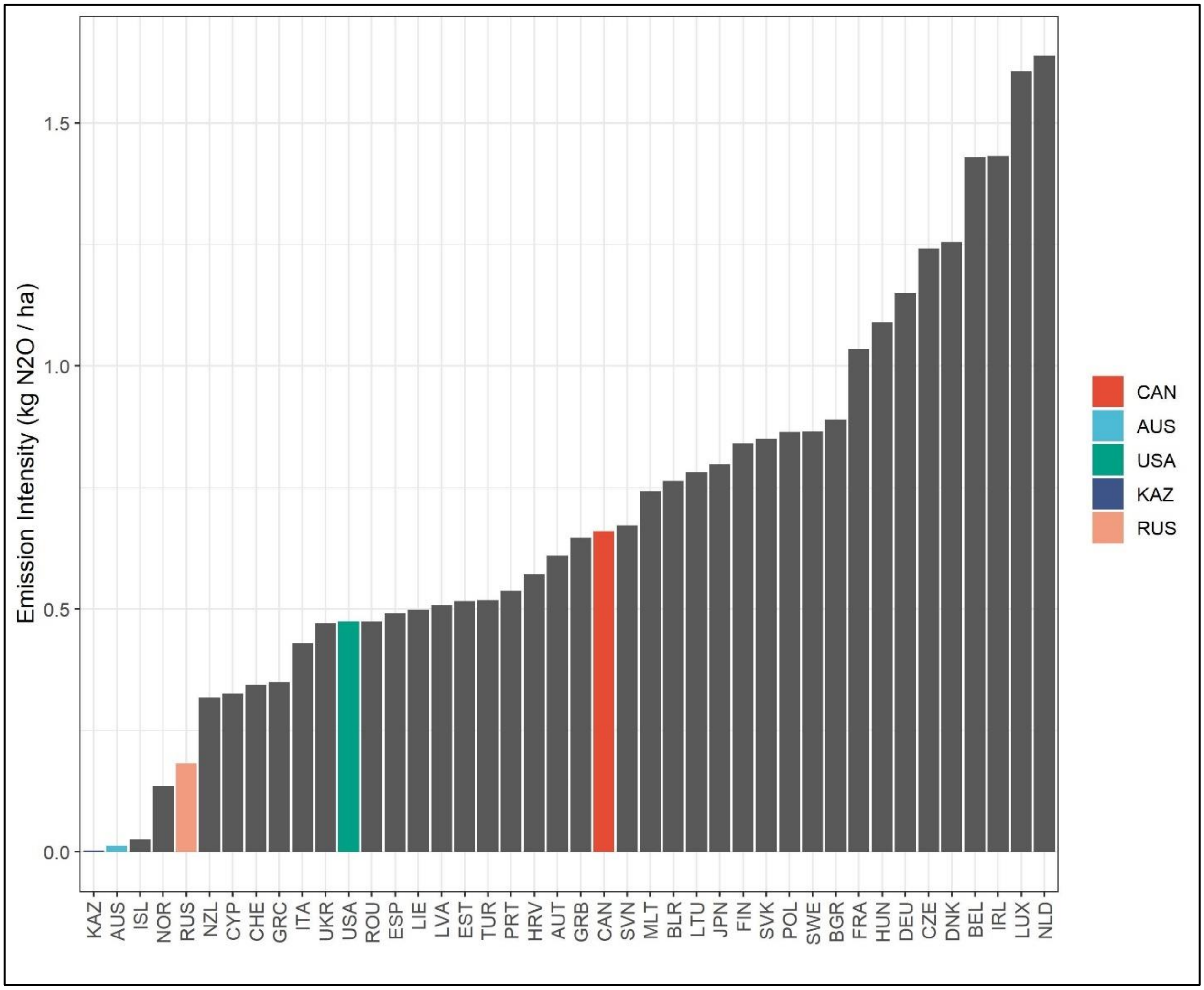
Emission Intensity Total Agricultural Soils Emissions / Total Agricultural Land: 2019



Note. Data was collected from 2021 CRF Tables 3.d and 4.1, see Table 2.

Figure 10

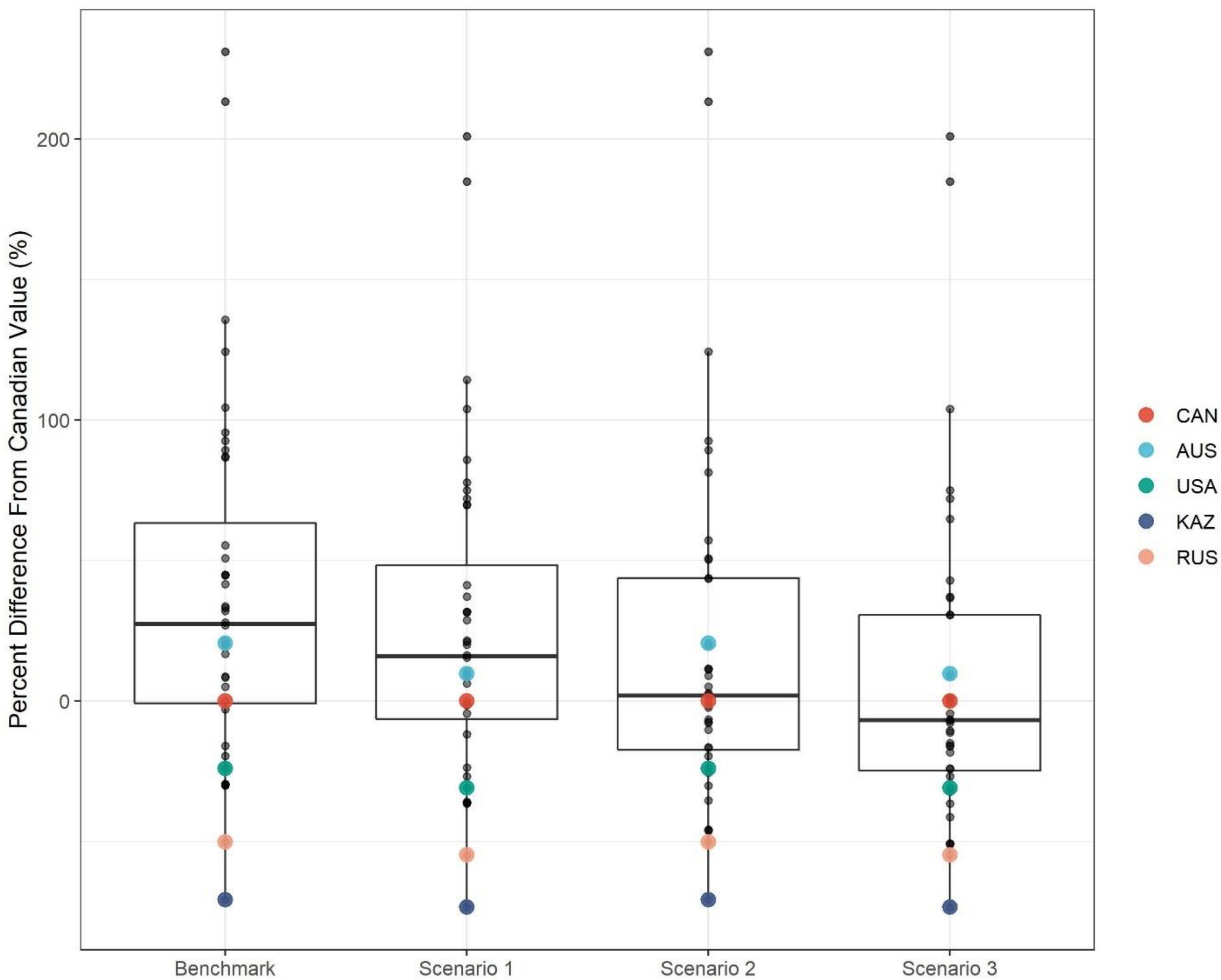
Emission Intensity Direct Inorganic Fertilizer Emissions / Total Agricultural Land: 2019



Note. Data was collected from 2021 CRF Tables 3.d and 4.1, see Table 2.

Figure 11

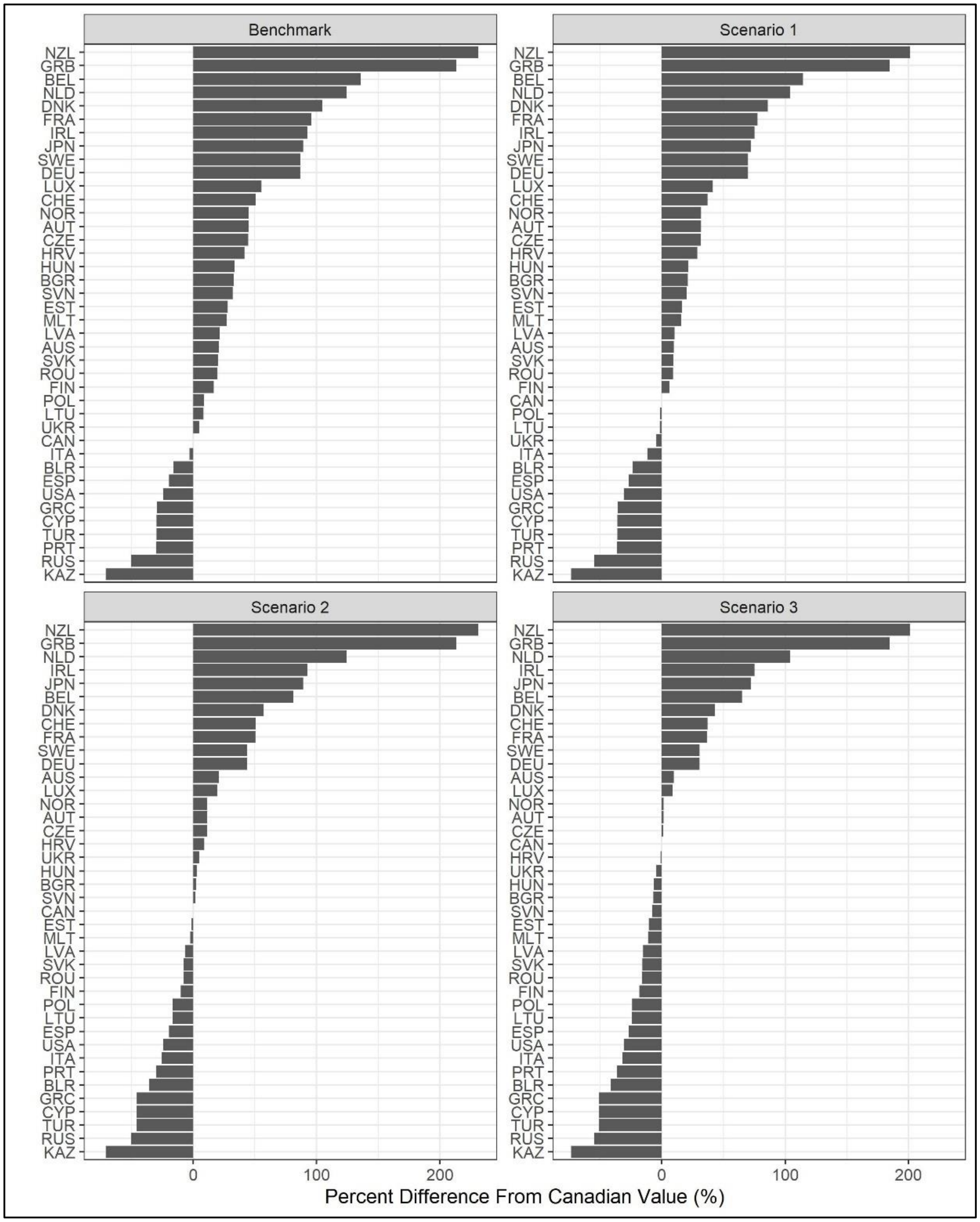
Productivity Based Emission Intensity Comparison Between Groups



Note. Data was collected from the FAOSTAT database and 2021 CRF Tables 3.d and 4.1, see Table 2.

Figure 12

Productivity Based Emission Intensity Comparison Between Countries



Note. Data was collected from the FAOSTAT database and 2021 CRF Tables 3.d and 4.1, see Table 2.

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