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NITROUS OXIDE EMISSION ESTIMATION FROM MANAGED SOILS IN ARGENTINA: DIFFERENCES BETWEEN IPCC 2006 GUIDELINES AND THE IPCC 2019 REFINEMENT

Andrés Said[1], Marcelo Beltrán[2] y Gabriel Vázquez-Amábile[3]

[1] Universidad de Buenos Aires, Facultad de Agronomía - Ministerio de Agricultura, Ganadería y Pesca. Argentina
E-mail: andresdsaid@gmail.com
[2] UNSADA, Instituto Nacional de Tecnología Agropecuaria - Instituto de Suelos. Argentina
E-mail: beltran.marcelo@inta.gob.ar
[3] Universidad de La Plata, Facultad de Ciencias Agrarias y Forestales. Argentina
E-mail: gvazquez@crea.org.ar

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SUMMARY

Based on the IPCC 2006 guidelines, the total GHG emission for 2016, in Argentina, were estimated to reach a total net 364 $MtCO_2eq$. Particularly, N_2O emissions from managed soils sector represented 12% of total emissions. The IPCC 2019 refinement to the 2006 guidelines for GHG inventories provides an up-to-date and robust scientific basis to support the preparation and continuous improvement of estimates. The aims of the present work were to carry out a desk study to estimate nitrous oxide emissions from managed soils, using the IPCC 2019 and to compare this methodology with the one currently used for national GHG inventories (IPCC 2006) in Argentina. The nitrogen sources accounted for GHG emissions were: (i) synthetic fertilizer, (ii) crop residues, (iii) mineralization from soil organic matter, (iv) urine and dung from grazing animals, and (v) organic fertilizer. The adoption of the updated emission factors from the 2019 IPCC refinement would have a significant impact on the estimation of nitrous oxide (N_2O) emissions. Compared to the 2006 IPCC guidelines, the application of these factors in Argentina would lead to decrease emissions from managed soils in 18.95 $MtCO_2eq$, representing a 46% reduction for this category. This reduction would be significant in the greenhouse gases (GHG) inventories of Argentina (by approximately 5%), and for other countries with similar economies. These changes might affect the prioritization of mitigation actions for the analyzed categories, when considering cost and benefits.

Key words: 2019 IPCC refinement, nitrous oxide, National Greenhouse Gas Inventories, IPCC Guidelines.

ESTIMACIÓN DE EMISIONES DE ÓXIDO NITROSO DE LOS SUELOS GESTIONADOS EN ARGENTINA: DIFERENCIAS ENTRE LAS DIRECTRICES DEL IPCC DE 2006 Y EL REFINAMIENTO DE 2019

RESUMEN

Según las directrices del IPCC de 2006, las emisiones totales de gases de efecto invernadero (GEI) en 2016 se estimaron en 364 $MtCO_2eq$ en Argentina, representando el óxido nitroso (N_2O) de los suelos gestionados el 12% de estas emisiones. El refinamiento 2019 de las Directrices del IPCC de 2006 para los inventarios de GEI proporciona una base científica sólida y actualizada para respaldar la preparación y la mejora continua de las estimaciones. El objetivo de este artículo es realizar un estudio teórico para estimar las emisiones de óxido nitroso de suelos gestionados, utilizando el refinamiento del IPCC 2019 y compararlo con la metodología utilizada actualmente para los inventarios nacionales de GEI (IPCC 2006) en Argentina. Las fuentes de nitrógeno contabilizadas que generan emisiones de GEI fueron: (i) fertilizante sintético, (ii) residuos de cultivos, (iii) mineralización de materia orgánica del suelo, (iv) orina y estiércol de animales de pastoreo, (v) fertilizante orgánico. La aplicación de los factores del refinamiento del IPCC 2019 tendría un impacto significativo en la estimación de las emisiones de óxido nitroso (N_2O). En comparación con las directrices del IPCC 2006, la aplicación de estos factores en Argentina llevaría a disminuir las emisiones de suelos manejados en 18,95 $MtCO_2eq$, lo que representa una reducción del 46% para esta categoría. Esta reducción sería significativa en los inventarios de GEI de Argentina (en aproximadamente un 5%), y posiblemente en los inventarios de GEI de otros países con economías similares. Estos cambios podrían afectar la priorización de acciones de mitigación para las categorías analizadas, al considerar costos y beneficios.

Palabras clave: refinamiento 2019 IPCC, óxido de nitroso, inventario nacional de gases de efecto invernadero, Directrices IPCC.

INTRODUCTION

The nitrous oxide (N_2O) is the third larger contributor to radiative forcing among naturally present greenhouse gases (GHG) after carbon dioxide (CO_2) and methane (CH_4) (Rochette *et al*., 2018). Therefore, since it represents one of the most important GHG, the estimations of the N_2O emissions needs to be improved. The global atmospheric concentration has increased 40% since 1750 and continues increasing at a rate of 0.73 ppb year^{-1} (IPCC, 2014). Agriculture is the largest N_2O emitter among anthropogenic emissions sources, accounting for 60% of its total emissions (Aguilera *et al*., 2013).

The emissions of N_2O are produced through different biological processes of the nitrogen (N) cycle, such as nitrification and denitrification, and by abiotic processes such as chemo denitrification (Araujo *et al*., 2020). N_2O emissions resulting from anthropogenic N inputs or N mineralization from soil organic matter occur through a direct pathway (*e.g.* directly from the soils where N is added/released). Additionally, these emissions from managed soils arise due to two indirect pathways: (i) following volatilization and subsequent redeposition of ammonia (NH_3) and nitrogen oxides (NO_x), and their products ammonium (NH_4^+) and nitrate (NO_3^-), to soil and water (from manure management, fossil fuel combustion and biomass burning); and (ii) after leaching and runoff of N, mainly as NO_3^- (IPCC, 2019). The main contributions of N to soils from agricultural practices are produced through manure deposited in pastures, the application of nitrogen fertilizers to the soil and the decomposition of crop residues (Castesana *et al*., 2020). Major proximal drivers of N_2O emissions are soil NO_3^- content, soil NH_4^+ content, oxygen (O_2) availability, soil temperature and soil moisture (Davidson *et al*., 2000; Smith *et al*., 2012).

Measuring soil N_2O emission can be data intensive and expensive especially in countries with a wide range of types of soils and high weather variability. To facilitate countries to report their emissions to the United Nation Framework Convention on Climate Change (UNFCCC), the International Panel on Climate Change (IPCC) developed a global, standard methodology for estimating national GHG inventories (Bastianoni *et al.*, 2014). The most common simple methodological approach consists of combining information on the extent to which a human activity takes place (called activity data) with coefficients which quantify the emissions or removals per unit activity (called emission factors; EF). Therefore, the basic equation to estimate emissions is activity data multiplied by its emission factor (IPCC, 2006). The guidelines provide default factors that are employed for the basic method of estimation (called tier 1). For key categories, the use of local emission factors based on country-specific data (called tier 2 or 3) is recommended, for being more accurate than the use of default factors.

Regarding the continuous research and knowledge progress, IPCC guidelines have been updated to support improvements on the preparation of national Greenhouse Gases (GHG) inventories. Two versions were published in 1996 and 2006. In 2019, a Methodology Report was published by IPCC to provide supplementary methodologies and updated default factors to the current 2006 IPCC guidelines. Even though Non-Annex I Parties of the UNFCCC should use the Revised 1996 intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (UNFCC, 2002), several countries such as Argentina have moved to the IPCC 2006 guidelines (SGAyDS, 2019). For example, when 2006 IPCC guidelines were adopted by Argentina, there were significant changes in the GHG emissions reported for the agriculture, forestry and other land use (AFOLU) sector compared with the inventory compiled using the IPCC 1996 guidelines. Differences were particularly important for N_2O emissions.

The IPCC 2006 guidelines amended the 1996 version by removing the biological nitrogen fixation as a direct source of N_2O, because of the lack of evidence of significant emissions arising from the fixation process (IPCC, 2006). As a result, the N_2O emissions of the Argentine AFOLU sector for the years 2010 and 2012 were 50% lower with 2006 methodology than with the 1996 methodology. Considering all the changes introduced by the 2006 guidelines, total emissions for the AFOLU sector were reduced by 27% with respect to the estimates of the IPCC 1996 guidelines, in both years (AACREA, 2015).

The latest version, "2019 Refinement to the 2006 Guidelines for National Greenhouse Gas inventories" (thereafter, IPCC 2019) does not modify the previous guidelines, but it clarifies, where necessary, and updates the 2006 emission factors and other parameters based on current scientific information (Sperow, 2020). Countries may use on a voluntary basis the IPCC 2019 refinement (UNFCCC, 2021), and its application is expected to be adopted in the near future. Furthermore, a local study carried out in Argentina found that the IPCC 2019 EF values for dung deposited on pasture should be used for GHG inventories since they were more accurate than previous IPCC values (Lombardi *et al.*, 2021).

The IPCC 2019 provides new guidance that affects the N_2O emissions from managed soils. Contrasting with IPCC 2006, the refinement introduces a disaggregated default emission factors related to climate conditions (wet or dry) for estimating N_2O emissions from managed soils. Additionally, reference carbon stock and tier 1 carbon stock change factors have been updated for tillage management, grassland management and land use, which affects the mineralized N (IPCC 2019). Based on the IPCC 2006 guidelines, the total GHG emission for 2016, in Argentina, were estimated to reach a total net 364 $MtCO_2$eq. Particularly, N_2O emissions from managed soils sector represented 12% of total emissions (SGAyDS, 2019).

The aim of the present work was to carry out a desk study to estimate nitrous oxide emissions from managed soils, using the IPCC 2019 refinement and to compare this methodology with the one currently used for GHG inventories in Argentina (*e.g.* IPCC 2006). This comparison is relevant for two reasons. First, the IPCC 2019 refinement does not replace the IPCC 2006 guidelines, being rather an alternative to be used by countries, so both are valid. Second, this comparison shows the importance of adjusting local emission factors to be used in GHG inventories.

MATERIALS AND METHODS

Study area

Argentina, located in South America, has a total surface area of 2.78 million km^2, ranking as the eighth-largest country in the world. Argentina presents a very diverse climate due to its vast territory, with a wide range of rainfall from 2000 mm in the northeast to 200 mm in the south region of the country (Rodríguez y de la Casa, 1990; Bianchi y Cravero, 2010). With almost 40 million ha of grain planted per year and more than 50 million head of cattle, Argentina is a large net exporter of agricultural products such as soybean, wheat, corn, sunflower, sorghum, beef, and milk.

Estimation of greenhouse gas (GHG) emissions

GHG were estimated for the years 2008, 2010, 2012, 2014 and 2016 by using the "2019 refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories methodology (thereafter, IPCC 2019). Values computed by IPCC 2006 guidelines (thereafter, IPCC 2006) were obtained from the Third Biennial Update Report of Argentina (SGAyDS, 2019).

This section briefly explains the differences in the emission factors from both sources (IPCC 2006 and IPCC 2019), as well as the activity data used for comparison (Table 1). Activity data were the same for both estimations, which guarantees that differences in emissions derived specifically from the methodology. Equation 11.1 of the guidelines was employed for calculating direct N_2O emissions from managed soils (IPCC, 2019). To calculate indirect emissions due to volatilization and leachability/runoff, Equation 11.9 and Equation 11.10 were used, respectively. GHG emissions were estimated in $MtCO_2$eq using the global warming potential (GWP) conversion factors of 310 for N_2O (IPCC, 1996). Even though IPCC provided updated GWP values, we considered GWP from the Second Assessment Report (SAR) that was used in the Third Biennial Update Report of Argentina.

The nitrogen sources accounted for GHG emissions were: (i) synthetic fertilizer, (ii) crop residues, (iii) mineralization from soil organic matter, (iv) urine and dung from grazing animals, and (v) organic fertilizer. The GHG emissions from the management of organic soils were not included in the study since they are reduced in Argentina. The selection of the tier methodology for each emission category was also made, maintaining the one applied by Argentina in its Third Biennial Report. Most sources were calculated with tier 1 except for the ones related to dairy cattle and non-dairy cattle (urine and dung from grazing animals and organic N applied as fertilizer).

Synthetic nitrogen fertilizer

The amount of N applied to soils by synthetic fertilizer is presented in Table 2. The Argentine Chamber of Fertilizer and Agrochemical Industry provided historical records of consumption of synthetic fertilizer by product at the national level. Fertilizer application was adjusted by N grade to calculate the N applied. The total aggregated values were then divided into districts (departments), considering the crop area distribution and crop's yields and N requirements, as recommended by the International Plan Nutrition Institute (IPNI, 2016). Furthermore, it has been clustered into a type of product (urea, ammonium-based, nitrate-based, ammonium-nitrate-based).

Nitrogen from crop residues

The methodology required crop harvested area and

Table 1. IPCC 2006 and IPCC 2019 refinement default factors to estimate direct and indirect nitrous oxide (N_2O) emissions from managed soils.

Factor	IPCC 2006 value[a]	Disaggregated	IPCC 2019 value
EF_1 for N additions from synthetic fertilizer, organic amendments and crop residues, and N mineralized from mineral soil as a result of loss of soil carbon [kg N_2O–N (kg N)$^{-1}$]	0.010	Synthetic fertilizer inputs in wet climates	0.016
		Other N inputs in wet climates	0.006
		All N inputs in dry climates	0.005
$EF_{3PRP, CPP}$ for cattle (dairy, non-dairy and buffalo), poultry and pigs [kg N_2O–N (kg N)$^{-1}$]	0.020	Wet climates	0.006
		Dry climates	0.002
$EF_{3PRP, SO}$ for sheep and 'other animals [kg N_2O–N (kg N)$^{-1}$]	0.010		0.003
EF_4 [N volatilization and re-deposition], kg N_2O–N (kg NH_3–N + NO_x–N volatilized)$^{-1}$	0.010	Wet climates	0.014
		Dry climates	0.005
EF_5 [leaching/runoff], kg N_2O–N (kg N leaching/ runoff)$^{-1}$	0.0075	-	0.011
$Frac_{GASF}$ [Volatilization from synthetic fertilizer], (kg NH_3–N + NO_x–N) (kg N applied)$^{-1}$	0.100	Urea	0.150
		Ammonium-based	0.080
		Nitrate-based	0.010
		Ammonium-nitrate-based	0.050
$Frac_{GASM}$ [Volatilization from all organic N fertilizers applied, and dung and urine deposited by grazing animals], (kg NH_3–N + NO_x–N) (kg N applied or deposited)$^{-1}$	0.200	-	0.210
$Frac_{LEACH-(H)}$ [N losses by leaching/runoff], kg N (kg N additions or deposition by grazing animals)$^{-1}$	0.300	Wet climates	0.240
		Dry climates	0.000

[a] Default factors of the IPCC 2006 that have been considered for the Third Biannual Updated Report of Argentina.

Table 2. Total amount of nitrogen (N) from synthetic fertilizers, by source and climate condition per year (1000 t year^{-1}).

Product	Climate condition	2008	2010	2012	2014	2016
Urea	wet	255.4	363.8	317.8	319.3	365.4
	dry	130.2	147.8	152.3	224.6	265.8
Ammonium-based	wet	71.1	97.4	90.5	72.6	85.7
	dry	36.2	39.6	43.4	51.1	62.4
Nitrate-based	wet	1.3	1.0	0.8	1.1	0.9
	dry	0.7	0.4	0.4	0.8	0.7
Ammonium-nitrate-based	Wet	84.2	90.8	84.4	67.9	73.6
	dry	42.9	36.9	40.4	47.7	53.5

yield statistics at a district level. The aggregated values at the national level obtained by year and crop (Table 3) from public information of the MAGyP. The analysis considered 19 cultivated species including maize, wheat, soybeans, sorghum, barley, sunflower, and forages. The estimation of N from crop residues (above and below ground), including N-fixing crops, and from forage/pasture renewal was perform with a tier 1 approach, applying Equation 11.6 and default values from IPCC 2019 (Tables 11.1A and 11.2).

Mineralized nitrogen from soil organic matter

Mineralization emissions were determined from organic carbon (C) stock losses in mineral soils due to land-use change or management practices. Annual soil C stock changes were calculated with Equation 2.25 (IPCC, 2019) using the updated default reference C stocks and stock change factors. Equation 11.8 was applied to estimate the net annual amount of N mineralized in mineral soils (IPCC, 2019).

Urine and dung from grazing animals

The annual amount of N in urine and dung deposited on pasture, paddocks and grazing animals was calculated using Equation 11.5 from the IPCC 2019 (see estimated values aggregated at the national level in Table 4). The annual amount of N was calculated for dairy cattle, non-dairy cattle (beef), and other cattle including buffalo, swine, sheep, poultry, goats, camelids, horses, mules, and asses. The activity data corresponding to the number of heads for each livestock species, were obtained from the Third Biennial Update Report of Argentina (SGAyDS, 2019).

Organic nitrogen applied as fertilizer

The annual amount of organic N fertilizer was calculated based on the amount of N from animal manure applied to soils, excluding urine and dung from grazing animals (Table 4). Applied manure derived from intensive livestock farms with manure management system such as uncovered anaerobic lagoon and solid storage.

Table 3. Crop production (1000 t) per year in Argentina.

Crop	2008	2010	2012	2014	2016
Annual forages	6,151.4	6,559.3	5,071.4	3,696.0	3,187.2
Barley	1,481.6	1,365.4	4,102.2	4,729.9	4,953.2
Birdseed	9.0	9.7	23.2	52.9	29.4
Colza	20.4	17.2	50.6	111.9	67.3
Cotton	489.6	753.5	708.6	1,019.6	673.1
Dry bean	336.7	338.1	361.1	429.8	366.5
Flax plant	9.5	52.0	21.3	20.4	20.0
Maize	22,026.8	22,663.0	21,196.6	33,087.1	39,792.8
Millet	14.8	9.1	17.4	2.6	6.8
Oats	472.4	181.9	414.9	444.8	553.4
Peanut	625.3	611.0	685.7	1,165.9	1,001.1
Perennial forages	60,996.5	64,384.8	57,847.3	62,596.0	59,557.8
Rice	1,255.0	1,243.2	1,567.9	1,581.8	1,404.9
Rye	77.1	25.1	43.1	52.1	60.6
Safflower	33.4	43.8	108.2	3.0	51.5
Sorghum	2,940.7	3,637.4	4,252.3	3,466,4	3,029.3
Soybean	46,238.8	52,676.2	40,100.1	53,397.7	58,799.2
Sugar cane	21,376.8	18,889.8	19,766.3	19,245.0	18,436.0
Sunflower	4,650.3	2,223.9	3,340.5	2,063.4	3,000.3
Wheat	16,492.9	9,123.4	14,683.4	9,315.0	11,571.2

Table 4. Total amount of nitrogen (N) from manure deposited by grazing animals and animal manure N applied as fertilizer per ton per year (t year^{-1}).

	Livestock	2008	2010	2012	2014	2016
Annual amount of urine and dung N deposited on pasture by grazing animals	Buffalo	1,650	1,834	3,825	4,414	5,543
	Camelids	1,874	1,891	2,003	2,306	2,843
	Cattle (D)	243,885	241,702	241,326	246,228	224,969
	Cattle (ND)	1,448,725	1,238,735	1,254,198	1,289,499	1,303,468
	Goats	11,442	12,024	12,667	13,080	14,035
	Horses	76,449	76,484	83,689	92,765	99,347
	Mules and asses	763	764	934	1,204	1,370
	Poultry	0	0	0	0	0
	Sheep	57,890	54,402	53,215	52,624	53,821
	Swine	16,276	16,626	18,481	24,920	27,144
Annual amount of animal manure N applied to soils	Buffalo	0	0	0	0	0
	Camelids	0	0	0	0	0
	Cattle (D)	13,029	12,786	12,763	13,041	12,943
	Cattle (ND)	181,212	152,578	181,212	129,224	120,378
	Goats	0	0	0	0	0
	Horses	0	0	0	0	0
	Mules and asses	0	0	0	0	0
	Poultry	34,137	38,504	41,123	42,514	42,067
	Sheep	0	0	0	0	0
	Swine	12,301	12,565	13,967	18,833	20,514

D: dairy   ND: non dairy

Sewage sludge, compost and other organic amendments are not common practices applied to soils in Argentina. The amount of N from managed manure available for soil application was updated with the total fraction of N managed from manure that is lost in the manure management, according to Equation 10.34 (IPCC, 2019). The same livestock categories were considered as the ones described for source urine and manure from grazing animals. To calculate the amount of N from managed manure available for application to mineral soils, the N from codigestate added to biogas plants was considered null, since it is not a significant activity and no activity data are available.

Climate characterization

Aridity index estimated by Soria *et al*. (2014) has been used to classify each district of Argentina into climate regions. The index consists of annual mean precipitation/evapotranspiration ratio (PP/ETP). When this ratio is > 1 the district is wet, otherwise it is dry. The annual PP/ETP ratio allows to determine the appropriate default factors that depend on the humidity condition (Table 1): EF_1, $EF_{3,PRP,cpp,}$ EF_4 and leaching fraction ($Frac_{LEACH}$). Default $Frac_{LEACH}$ factor only applies to wet climates, being zero for dry climates.

RESULTS AND DISCUSSION

The N_2O emissions from soils in Argentina were obtained using IPCC 2006 and IPCC 2019 methodologies for five years -2008, 2010, 2012, 2014, and 2016- (Figure 1) for different sub-categories: (i) synthetic N fertilizer, (ii) crop residues, (iii) mineralized N from soil organic matter, (iv) urine and dung from grazing animals, and (v) organic N fertilizer. The total national N_2O emissions from managed soils was decreased from 41.07 to 22.12 $MtCO_2eq$ on average when IPCC 2019 methodology was applied, representing a reduction of 46.1%. Furthermore, disaggregating between direct and indirect

N_2O emissions showed that the former represents the greater differences between methodologies, considering that these emissions decreased, on average, from 32.94 to 15.15 $MtCO_2eq$, or 54.0% (Figure 2, Table 5). While indirect emissions related to volatilization and leaching/runoff were in average 14.3% lower for IPCC 2019 than IPCC 2006 (from 8.13 to 6.97 $MtCO_2eq$) (Figure 2).

Synthetic fertilizer is the only source of N_2O emissions from managed soils where the application of the updated methodology increased the emissions compared with the IPCC 2006, from 4.95 to 5.73 $MtCO_2eq$ on average. Total N synthetic fertilizers were also disaggregated into three categories, where the impact of the methodologies was estimated: (i) direct emissions, which raised from 3.74 to 4.48 $MtCO_2eq$, (ii) leaching and runoff, which decreased from 0.84 to 0.63 $MtCO_2eq$, and (iii) an increase of volatilization from 0.37 a 0.61 $MtCO_2$ eq.

The highest difference between approaches corresponded to urine and dung from grazing animals, where estimated emissions decreased from 20.94 to 7.45 $MtCO_2eq$ for IPCC 2006 and IPCC 2019, respectively (64.4% reduction). The estimation of emissions from crop residues N also showed important reductions, from 11.04 to 6.05 $MtCO_2eq$ (45.2% reduction). Emissions related to mineralized N from soil organic matter and applied organic N fertilizer have a lower contribution to the total N_2O emissions. However, values also differed

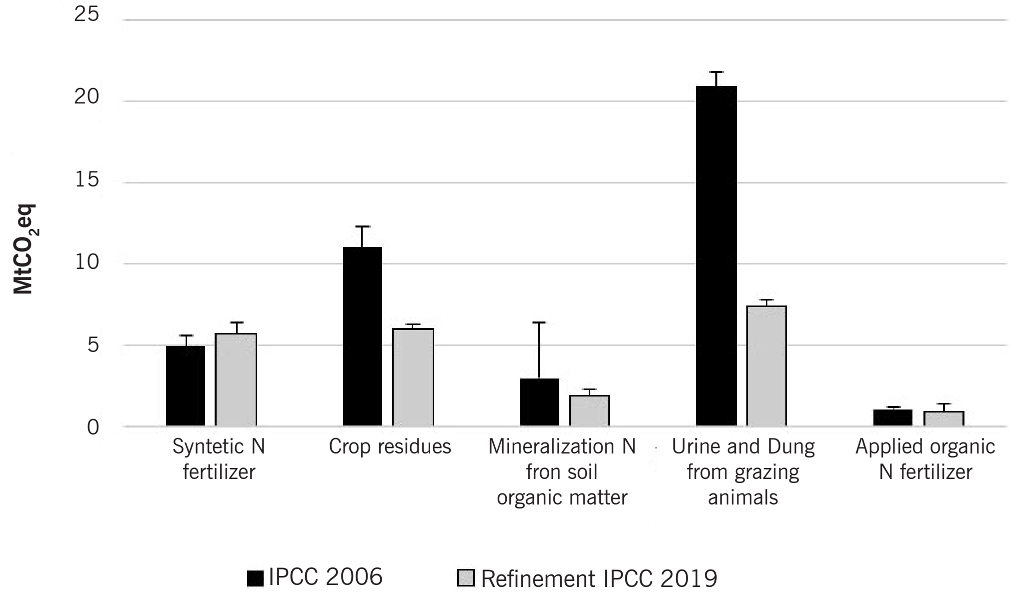

Figure 1. Comparison between IPCC 2006 and IPCC 2019 refinement for nitrous oxide (N_2O) emissions in $MtCO_2eq$ of soils by source. Average value and standard error of the analyzed inventory years: 2008, 2010, 2012, 2014 and 2016.

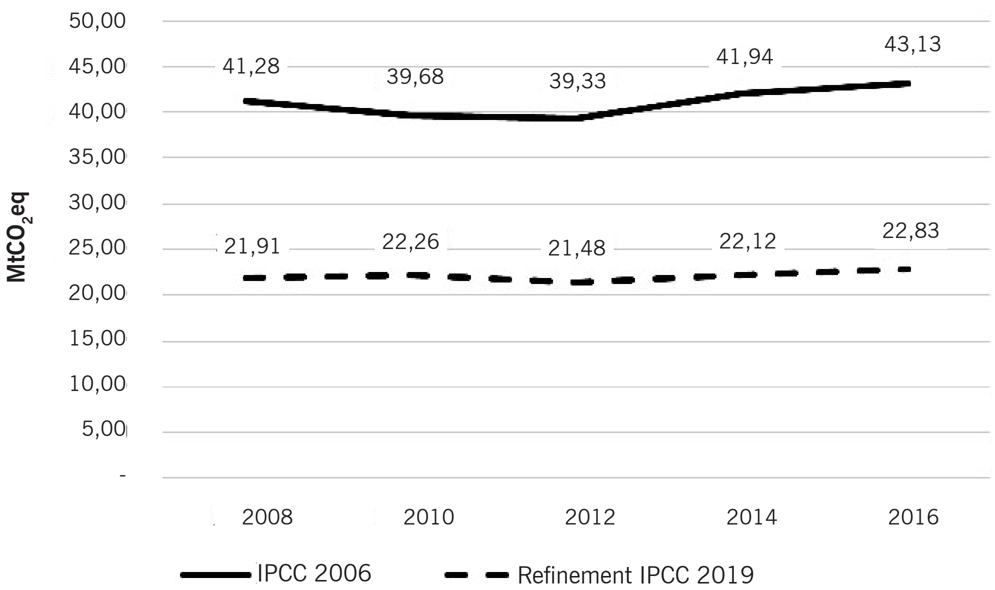

Figure 2. Comparison between IPCC 2006 and IPCC 2019 refinement for nitrous oxide (N_2O) emissions in $MtCO_2eq$ of soils per year.

Table 5. Comparison between the IPCC 2006 guidelines and the IPCC 2019 refinement of direct and indirect nitrous oxide (N_2O) emissions ($MtCO_2eq$) from managed soils. Average of the five analyzed inventory years: 2008, 2010, 2012, 2014 and 2016.

	Direct		Indirect		Total	
	IPCC 2006	IPCC 2019	IPCC 2006	IPCC 2019	IPCC 2006	IPCC 2019
Synthetic N fertilizer	3.74	4.48	1.21	1.24	4.95	5.73
Crop residues	9.02	4.74	2.03	1.31	11.04	6.05
N mineralized from SOM	2.47	1.43	0.56	0.51	3.03	1.93
Urine and dung from GA	16.94	3.95	4.00	3.50	20.94	7.45
Applied N from OF	0.78	0.55	0.33	0.41	1.11	0.96
Total	32.94	15.15	8.13	6.97	41.07	22.07

SOM: soil organic matter   GA: grazing animals   OF: organic fertilizers

between approaches. The estimation of mineralized N from soil organic matter decreased from 3.03 $MtCO_2eq$ to 1.93 $MtCO_2eq$ by applying the methodology proposed by IPCC 2019. Likewise, in the case of applied organic N fertilizer emissions, the updated methodology impacted on a change from 1.11 to 0.96 $MtCO_2eq$.

Most of the differences detected in the estimation of the emissions between methodologies were associated with two sources: (i) urine and dung from grazing animals, and (ii) crop residues. Association (i) could be explained through the updated EF_3 provided in the 2019 IPCC refinement, which has been reduced from 0.02 kg N_2O-N $(kgN)^{-1}$ for cattle, poultry, and pigs to 0.006 and 0.002 kg N_2O-N $(kgN)^{-1}$ in wet and dry climates, respectively. Non-dairy cattle were the category that highly explained these differences because their emissions are considered one of the main GHG emissions in Argentina, accounting for 4% of total emissions (SGAyDS, 2019). Similarly, the variations in emissions from crop residues were explained by the reduction of EF_1 from 0.01 to 0.006 and 0.005 in wet and dry climates, respectively, which strongly influences the direct emissions from N_2O from crop residues.

Progress towards more accurate estimates is expected when using both the updated default values of emission factors (and other parameters) based on the last available scientific information, and the disaggregation of emission factors by climate according to the IPCC 2019 refinement. This improvement is necessary for encompassing the impact of mitigation measures and designing practices to reduce GHG (Liang *et al*., 2020). The magnitude of emissions is also essential information for deciding mitigation options. Therefore, differences in emission's estimate between IPCC 2006 and IPCC 2019 methodologies can influence the prioritization of mitigation alternatives. The latter is relevant for Argentina case, which is committed to the ambitious mitigation goal established in the Paris Agreement of not exceeding the net emission of 359 $MtCO_2eq$ in 2030. This value represents a total decrease in emissions of 19% from the historical peak reached in 2007, and a reduction of 25.7% compared to the previous National Determined Contribution submitted in 2016 (MAyDS, 2020).

When using the IPCC 2006, results indicate that mitigation action should focus on urine and dung from grazing animals specially from cattle, which widely represents the most significant source of nitrous oxide emissions from managed soils in Argentina (on average 51.0% in five years). However, when estimating emissions employing the IPCC 2019 refinement, no source concentrated the majority of emissions. Moreover, almost no differences were observed among there sources: synthetic N Fertilizer (5.73 $MtCO_2eq$), crop residues (6.05 $MtCO_2eq$), and urine and dung from grazing animals (7.45 $MtCO_2eq$). Consequently, these sources result equally important for defining mitigation actions.

The proportion of synthetic fertilizer emissions is the source that showed the highest increases with the IPCC 2019, changing from 12.0 to 26.0 percent of total N_2O emissions from managed soils. The N_20 direct emissions where higher in the wet climates (from 0.010 to 0.016) than in the dry climates, even when EF_1 was higher for dry regions, due to the greater crop production in humid

Table 6. Contribution of Activity data and nitrous oxide (N_2O) soil emissions in percentage (%) by wet and dry climates with IPCC 2019 refinement. Average of the analyzed inventory years: 2008, 2010, 2012, 2014 and 2016.

Emission sources	Livestock category	Activity data		emissions	
		wet	dry	wet	dry
Synthetic N fertilizer		64.0	36.0	84.6	15.4
Crop residues		58.6	41.4	71.0	29.0
Mineralization N from soil OM		74.3	25.7	80.0	20.0
	dairy cattle	63.2	36.8	86.7	13.3
Urine and dung from GA	non-dairy cattle	74.9	25.1	91.8	8.2
	other livestock	38.5	61.5	57.8	43.2
	dairy cattle	62.9	37.1	76.4	23.6
Applied organic N fertilizer	non-dairy cattle	68.0	32.0	80,3	19.7
	other livestock	78.9	21.1	87.5	12.5

OM: organic matter GA: grazing animals

environments (Cruzate and Casas, 2017). Correspondingly, 64.0% of N synthetic fertilizers is applied under wet conditions in Argentina (Table 6). Therefore, efficiency use of N fertilization should be prioritized as a mitigation action in the National Plan of Agriculture and Climate Change.

Unlike the IPCC 2006, the IPCC 2019 refinements provide disaggregated default fractions of N that are lost through volatilization (FracGasf) from different synthetic sources. Therefore, the use of synthetic N sources with lower levels of volatilization should be promoted. This is particularly important in countries such as Argentina, where the urea, which generates the maximum fractions of volatilization from synthetic fertilizer (Pereira *et al*., 2009), is the most widely used fertilizer (by around 70%) (CIAFA, 2016). Furthermore, the use of synthetic fertilizers, and their associated N_2O emissions, are expected to increase not only because of excepted increases in crop yield, but also due to the N fertilizers are below recommended levels to compensate for N extraction in agricultural soils (Cruzate and Casas, 2017).

Regarding the selection of estimation tier, countries are expected to use in their GHG inventories tier two methods for key categories. According to the Third Biennial Update Report of Argentina, tier 2 is used only for grazing dairy and non-dairy cattle. Thus, it is recommended for future studies to move to tier 2 in other relevant inventory categories, according to IPCC 2006 guidelines. The IPCC 2019 provides a similar general advice. However, in this case, soil organic matter mineralization should not probably be considered a key category since the estimation of this source is reduced on average from 2.47 to 1.43 $MtCO_2eq$, having a threshold value of 1.48 $MtCO_2eq$ according to the Third Biennial Update Report for the year 2016 (SGAyDS, 2019).

CONCLUSIONS

The adoption of the updated emission factors from the 2019 IPCC refinement would have a significant impact on the estimation of nitrous oxide (N_2O) emissions. Compared to the 2006 IPCC guidelines, the application of these factors in Argentina would lead to decrease emissions from managed soils in 18.95 $MtCO_2eq$, representing a 46% reduction for this category. This reduction would be significant in the greenhouse gases (GHG) inventories of Argentina (by approximately 5%), and also for other countries with similar economies. These changes might affect the prioritization of mitigation actions for the analyzed categories, when considering cost and benefits.

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