N2O emissions from biomass in the EPA’s RIA

Final Report

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Technical revision and suggestions for improvements – Final Report

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Introduction and objective

The climate crisis requires immediate actions to reduce Greenhouse Gases (GHG) emissions. Shifting from fossil fuels to low carbon emission fuels has an important role in the energy transition. The evaluation of fuels should consider the emissions from their consumption (tailpipe) and also the emissions from the production of the fuel.

EPA was a pioneer institution in including Life-cycle Analysis (LCA) to guide policy decisions. The Renewable Fuel Standard (RFS) was and continues to be a major reference for several other policies adopted worldwide. Despite the excellent work performed by EPA in the RFS rulemaking (in 2009 and 2010), significant improvement in scientific knowledge and availability of databases were observed in the last decade. For sugarcane ethanol (classified as advanced biofuel by EPA), N_2O emissions from biomass cultivation is the most relevant carbon burden and deserves specific attention.

The objective of this report was to review how N_2O emissions were addressed in the sugarcane ethanol LCA modeling and to suggest ways to improve the analysis.

1) N2O emissions from biomass cultivation in the EPA’s RIA

The analysis carried out by EPA in the Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis (RIA)[1] comprised a consequential life cycle assessment, which estimated the potential (direct and indirect) impacts on the international greenhouse gases (GHG) emissions arising from an increase in US demand for biofuels. The entire analysis is linked to the projections on national and international land use changes (LUC), so the results for ethanol life cycle performance was not conditioned to the Brazilian sugarcane cultivation alone. Only emissions related to the industrial phase and transport of ethanol were treated apart from LUC.

The analysis for biofuels was performed using GREET, FASOM and FAPRI models, considering a scenario projected for 2022. In the case of sugarcane ethanol, GREET parameters, along with parameters derived from other sources (FAO, IEA), were combined with FAPRI model results to generate total emissions associated with the increased production from additional US demand.

For the assessment of the international N_2O emissions, EPA considered both direct and indirect emissions from synthetic fertilizer application, crop residues and manure management. Direct and indirect emissions from synthetic fertilizer application and crop residues were calculated based on IPCC guidelines[2] (see Appendix). Crop residues for sugarcane (and some other crops) were not included in the Draft Regulatory Impact Analysis because default crop-specific IPCC factors used in the

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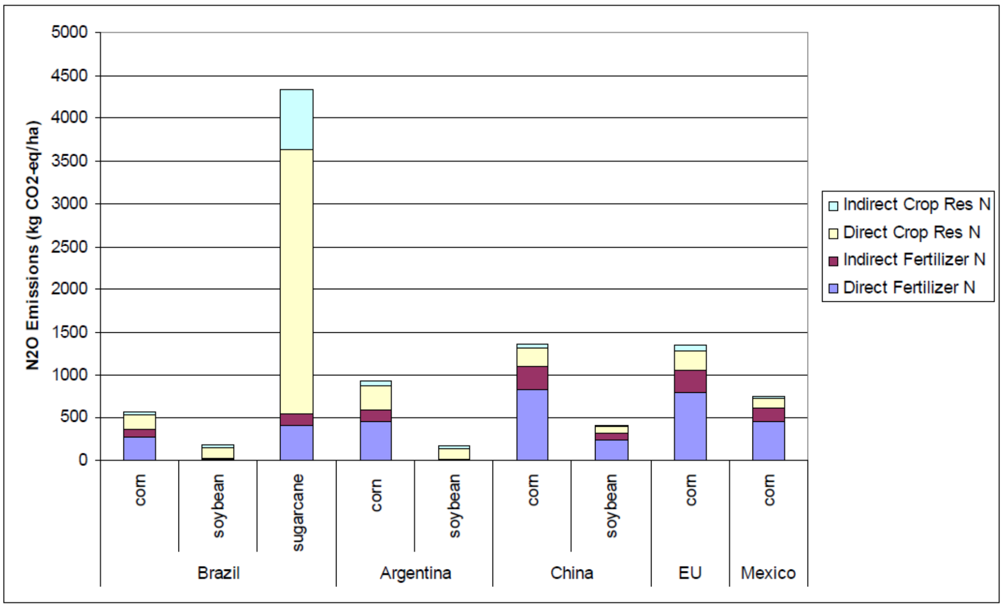
[1] EPA, *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*, (2010).

[2] H. S. Eggleston, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, and Chikyū Kankyō Senryaku Kenkyū Kikan, *2006 IPCC guidelines for national greenhouse gas inventories*, (2006).

calculation were not available. However, in RIA it is mentioned that comments from the peer review process suggested to include proxy emissions from the missing crops based on similar crop types that do have default factors. So, in the final rule analysis EPA included crop residue N_2O emissions from sugarcane production based on perennial grass as a proxy. Based on such assumptions, N_2O emissions from sugarcane cultivation in Brazil were estimated in more than 4000 kg CO_2eq/ha (Figure 1), which are largely dominated by the contributions from direct crop residues N. Using the crop production changes projected by FAPRI-CARD, the total change in N_2O emissions resulted in a specific emission factor of 29.25 kg CO_2eq/mmBTU of ethanol[3].



Source: EPA[4]

Figure 1. Sources of N_2O emissions by crop for select regions, according to EPA's RIA.

2) Assessment of the RIA

Although N_2O emissions from the field do represent important contributions to the life cycle performance of ethanol[5], EPA results remarkably overestimate these contributions. This is mainly due to the differences between sugarcane and perennial grasses parameters used for the estimation of the total amount of the dry mass of the above and below ground biomass, as well as their nitrogen content.

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[3] EPA, *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*.

[4] EPA, *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*.

[5] O. Cavalett, M. F. Chagas, J. E. A. Seabra, and A. Bonomi, 'Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods', *The International Journal of Life Cycle Assessment*, 18/3 (2013), 647–58.

The first difference to be highlighted is the dry matter fraction of harvested product, which is around 0.3 for sugarcane[6], while the default value[7] for perennial grasses is 0.9. In terms of above ground residue dry matter, for perennial grasses it is assumed a ratio of 0.3 with respect to the dry matter fraction of harvested product. For sugarcane, the ratio of straw (tops and leaves) to cane stalks has been estimated as 140 kg (dry) per tonne (fresh weight)[8,9], which is equivalent to 0.47 kg (dry) per kg (dry). More recent studies[10], however, have quantified the straw availability as 120 kg (dry) per tonne (fresh), thus resulting in a 0.4 kg (dry) per kg (dry) ratio. As for the nitrogen content, it is typically within the 0,5-1% range[11] for sugarcane, while perennial grasses have a default value of 1,5%.

In terms of the below ground biomass, the distribution of sugarcane roots is similar to other crops and tropical grasses, with an exponential decline in root biomass and/or length with depth[12] (Figure 2). Typically, 50% of root biomass occurs in the upper 0.2-m soil layer and 85 % in the upper 0.6-m layer[13]. In common with other grasses, root:shoot ratios for sugarcane are highest during early growth and then decline (Figure 3), but values are significant different from perennial grasses. Experimental data from Carvalho et al.[14] show that the below ground biomass (roots and rhizomes) is higher for the plant cane (exceeding 7 tonnes of dry mass per hectare within the 0.6-m soil layer) but feature a significant decline after each ratoon. The root:shoot ratio for plant cane was lower than 0.15 (considering the upper 0.6-m soil layer), but it was already below 0.1 for the 2nd ratoon.

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[6] M. R. L. V. Leal, A. S. Walter, and J. E. A. Seabra, 'Sugarcane as an energy source', *Biomass Conversion and Biorefinery*, 3/1 (2013), 17–26.

[7] Eggleston, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, and Chikyū Kankyō Senryaku Kenkyū Kikan, *2006 IPCC guidelines for national greenhouse gas inventories*.

[8] S. J. Hassuani, M. R. L. V. Leal, and I. de C. Macedo (eds.), *Biomass power generation: sugar cane bagasse and trash*, (CTC ; PNUD, 2005).

[9] M. R. L. V. Leal, M. V. Galdos, F. V. Scarpare, J. E. A. Seabra, A. Walter, and C. O. F. Oliveira, 'Sugarcane straw availability, quality, recovery and energy use: A literature review', *Biomass and Bioenergy*, 53 (2013), 11–19.

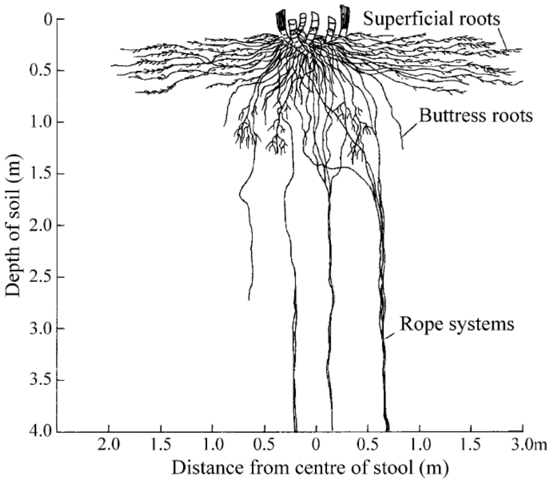
[10] L. M. S. Menandro, H. Cantarella, H. C. J. Franco, O. T. Kölln, M. T. B. Pimenta, G. M. Sanches, S. C. Rabelo, and J. L. N. Carvalho, 'Comprehensive assessment of sugarcane straw: implications for biomass and bioenergy production', *Biofuels, Bioproducts and Biorefining*, 11/3 (2017), 488–504.

[11] Hassuani, Leal, and Macedo, eds, *Biomass power generation*.

[12] D. M. Smith, N. G. Inman-Bamber, and P. J. Thorburn, 'Growth and function of the sugarcane root system', *Field Crops Research*, 92/2–3 (2005), 169–83.

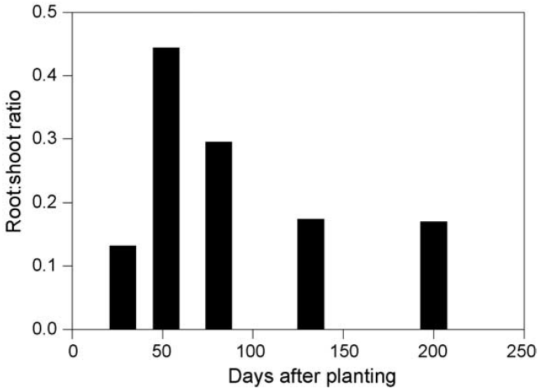
[13] F. Blackburn, *Sugar-cane*, (Longman, 1984).

[14] J. L. N. Carvalho, R. Otto, H. C. J. Franco, and P. C. O. Trivelin, 'Input of sugarcane post-harvest residues into the soil', *Scientia Agricola*, 70/5 (2013), 336–44.



Source: Blackburn[15] *apud* Smith et al.[16]

Figure 2. The root system of an established sugarcane stool.



Source: Smith et al.[17]

Figure 3. Root:shoot ratio (on a dry weight basis) for pot-grown sugarcane (cv. Q96).

For the estimation of N_2O emissions from sugarcane roots, Cavalett et al.[18] assumed a root: shoot ratio of 0.2 combined with a nitrogen content of 0.6% (based on Franco et al.[19]). In the sugarcane inventory of the ecoinvent database[20], N_2O emissions have

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[15] Blackburn, *Sugar-cane*.

[16] Smith, Inman-Bamber, and Thorburn, ‘Growth and function of the sugarcane root system’.

[17] Smith, Inman-Bamber, and Thorburn, ‘Growth and function of the sugarcane root system’.

[18] Cavalett, Chagas, Seabra, and Bonomi, ‘Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods’.

[19] H. C. J. Franco, I. R. Bologna, C. E. Faroni, A. C. Vitti, and P. C. O. Trivelin, ‘Acúmulo de macronutrientes em cana-de-açúcar em função da adubação nitrogenada e dos resíduos culturais incorporados ao solo no plantio’, *Bragantia*, 66/4 (2007), 669–74.

been estimated using a fixed root amount of 8.4 t/ha, and nitrogen content of 0.514%. However, an interesting aspect to consider is that the root system is not completely replaced when ratooning occurs[21]. This issue was acknowledged in the assessment of GHG default emissions from biofuels in EU legislation[22], so the below-ground biomass was not taken into account for the estimation of N_2O emissions.

By replacing perennial grasses with sugarcane parameters for the below ground biomass (holding everything else constant), Khatiwada et al.[23] found that sugarcane ethanol would be able to mitigate from 78% to 111% of gasoline emissions, instead of 59% to 91% as reported in the RIA (Table 1). But further reductions can be expected if more updated information for sugarcane were used (see Table 2 and Figure 4), although this would also affect other aspects of the analysis[24], which have not been explored here.

Table 1. Effect of N_2O emissions from sugarcane residues on the GHG reduction potential.[a]

Scenarios	**International farm inputs and fertilizer N_2O[b] (kg/mmBTU)**	**GHG reduction**
EPA's RIA		
No residue coll., no CBI	37.9	61%
No residue coll., CBI	37.9	59%
Residue coll., no CBI	39.1	91%
Residue coll., CBI	39.1	89%
Khatiwada et al.[c]		
No residue coll., no CBI	19.0	80%
No residue coll., CBI	19.0	78%
Residue coll., no CBI	19.0	111%
Residue coll., CBI	19.0	109%

[a] From Khatiwada et al.[25]

[b] According to the EPA's RIA aggregation; it includes emissions from the production of farm inputs, energy use, trash burning and N_2O emissions from the soil.

[c] The parameters adopted by Khatiwada et al. to estimate the direct and indirect N_2O emissions from below and above ground sugarcane residues (in Brazil only) were the following – cane trash content: 140 kg_{dry}/t cane; root:shoot ratio: 0.2; nitrogen content of the cane trash (dry basis): 0.6%; nitrogen content of the below ground biomass (dry basis): 0.6%. *All remaining parameters were held constant, as given in EPA[26].*

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[20] M. I. S. Folegatti-Matsuura and J. F. Picoli, *Life Cycle Inventories of Agriculture, Forestry and Animal Husbandry - Brazil*, (2018).

[21] Smith, Inman-Bamber, and Thorburn, 'Growth and function of the sugarcane root system'.

[22] R. Edwards, M. Padella, J. Giuntoli, R. Koeble, A. O'Connell, C. Bulgheroni, and L. Marelli, *Definition of input data to assess GHG default emissions from biofuels in EU legislation: version 1c July 2017.*, (2017).

[23] D. Khatiwada, J. Seabra, S. Silveira, and A. Walter, 'Accounting greenhouse gas emissions in the lifecycle of Brazilian sugarcane bioethanol: Methodological references in European and American regulations', *Energy Policy*, 47 (2012), 384–97.

[24] For example, lower amounts of tops and leaves would also affect the total amount of biomass that could be used as supplementary fuel in the sugarcane mill, thereby impacting the amount of electricity exports.

[25] Khatiwada, Seabra, Silveira, and Walter, 'Accounting greenhouse gas emissions in the lifecycle of Brazilian sugarcane bioethanol'.

[26] EPA, *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*.

Table 2. Parameters used to estimate N_2O emissions from crop residues.

Parameter	Units	RIA	Sugarcane parameters
Sugarcane[a]	Mg yr^{-1}	57,910,802	57,910,802
$Frac_{Renew}$	-	1	1
Area[a]	ha yr^{-1}	511,450	511,450
Areaburnt	ha yr^{-1}	0	0
Cf	-	1	1
AG_{DM}	Mg d.m. ha^{-1}	30.6	15.9
N_{AG}	kg N (kg d.m.)$^{-1}$	0.015	0.006
$Frac_{Remove}$	-	0	0
DRY	kg d.m. (kg fresh weight)$^{-1}$	0.9	0.3
Crop	kg d.m. ha^{-1}	101,906	33,969
R_{BG-BIO}	kg d.m. (kg d.m.)$^{-1}$	0.8	0.2
N_{BG}	kg N (kg d.m.)$^{-1}$	0.012	0.006
Slope	Mg d.m. (Mg d.m.)$^{-1}$	0.3	0.47
Intercept	Mg d.m. ha^{-1}	0	0
F_{CR}	kg N yr^{-1}	384,643,548	79,221,977
EF_1	kg N_2O–N (kg N input)$^{-1}$	0.01	0.01
$Frac_{LEACH-(H)}$	-	0.3	0.3
EF_5	kg N_2O–N (kg N leach. and runoff)$^{-1}$	0.0075	0.0075

[a] EPA modeling results[27].

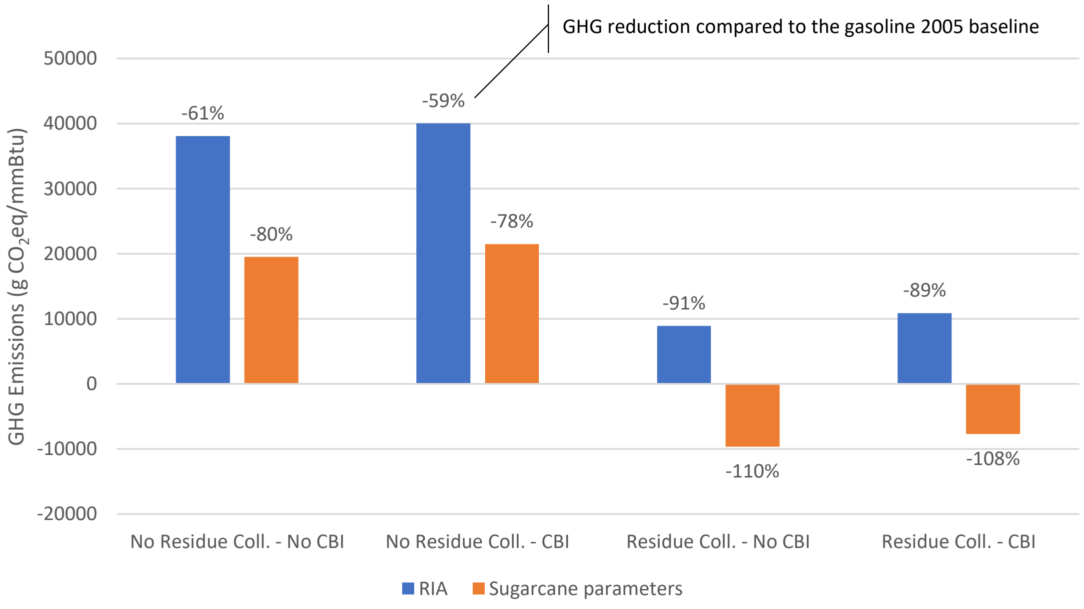

Figure 4. Effect of different sugarcane parameters for N_2O emissions on ethanol life cycle emissions and percent reduction compared to Petroleum Baseline.

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[27] EPA, *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*.

Lastly, it is also important to note that, despite the use of appropriate parameters for the sugarcane biomass, those estimations still rely on N_2O emission factors given by IPCC. These factors are based on global data, most of which from regions of temperate climates that do not represent the prevailing edaphoclimatic conditions of Brazil. Recent independent studies have found that the emission factors for regional-specific conditions (Tier 2) on the direct GHG emissions for sugarcane in Brazil are usually below the IPCC Tier 1 default value[28,29] due to the good drainage properties of the deep Oxisols, where sugarcane is commonly cultivated in Brazil. Carvalho et al. (2021)[28] found N_2O–N EF resulting from N fertilization in the plant-cane stage as 0,71%, and when N is applied in combination with filter cake, EF drops to 0.66% (average of only two studies). As for sugarcane ratoon, which receives most of the N application of the sugarcane areas, the average N_2O–N EF from N fertilizer is 0.60% (ranging from 0.07 to 2.03). If EF_1 were assumed as 0.6% (instead of 1%) the percent mitigation obtained for the “Sugarcane parameters” scenario indicated in Figure 4 would be further reduced to the -80% – -111% range.

3) Final considerations

- There is robust evidence that the N_2O emissions from sugarcane cultivation is overestimated in RIA, so the RFS rulemaking (as well as other (bio)fuels policies) would strongly benefit from an update.
- Regional specific data is available in the literature, particularly in Carvalho et al.[14,28] and Khatiwada et al.[25].
- Sugarcane specific parameters listed in Table 2 are recommended, combined with EF_1 of 0.6%, instead of the IPCC’s Tier 1 emission factor.
- These parameters would lead to an ethanol carbon intensity ranging between -11,200 and 20,000 g CO_2eq/mmBTU (depending on the residue collection and CBI scenario, keeping everything else constant), thereby representing a percent GHG emissions reduction between -80% and -111%.

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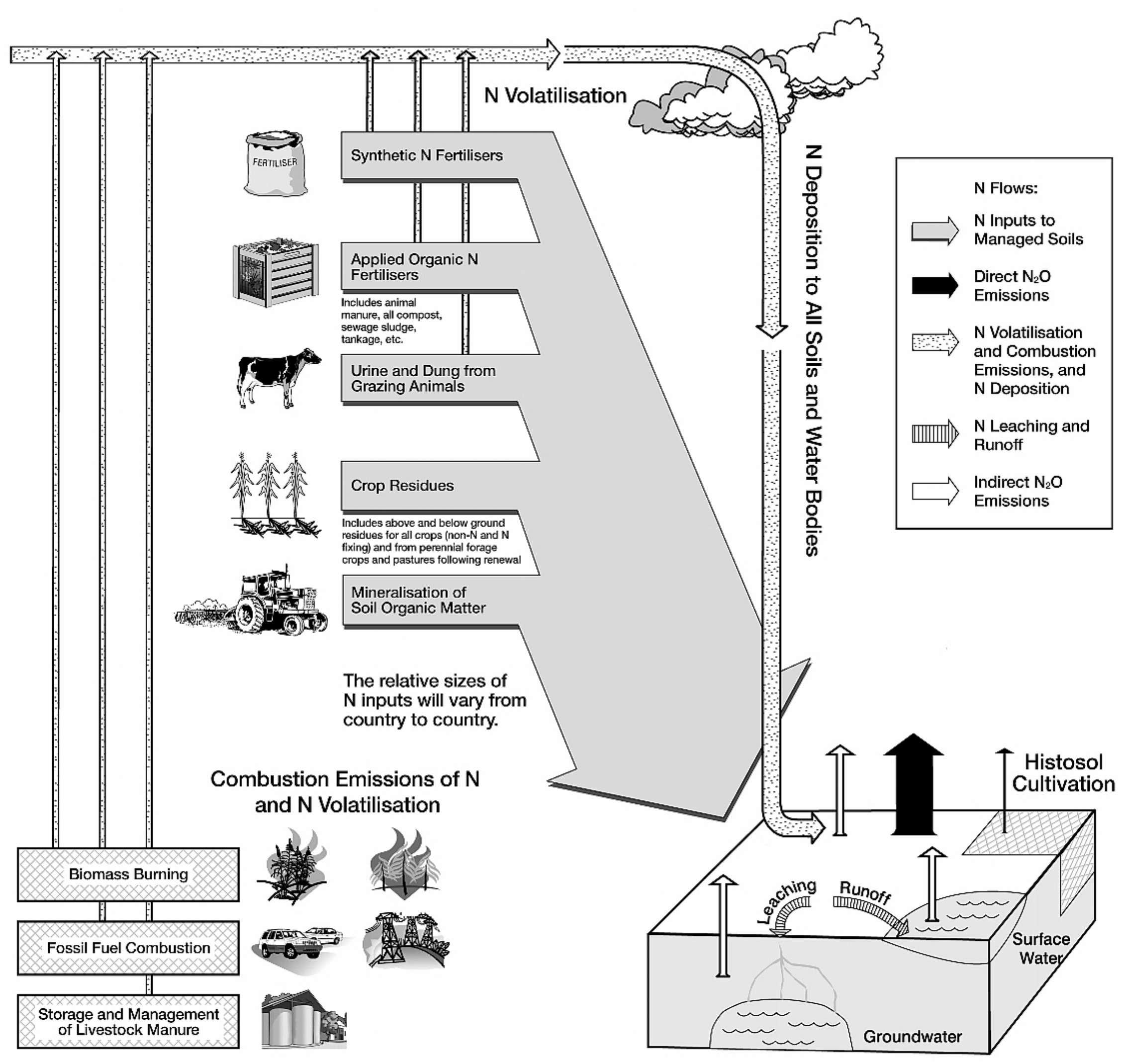
[28] J. L. N. Carvalho, B. G. Oliveira, H. Cantarella, M. F. Chagas, L. C. Gonzaga, K. S. Lourenço, R. O. Bordonal, and A. Bonomi, ‘Implications of regional N2O–N emission factors on sugarcane ethanol emissions and granted decarbonization certificates’, *Renewable and Sustainable Energy Reviews*, 149 (2021), 111423.

[29] The default value for EF_1 has been set at 1% of the N applied to soils or released through activities that result in mineralization of organic matter in mineral soils. But in the 2019 Refinement to the 2006 IPCC Guidelines, alternative emission factors, disaggregated by climatic zone and fertilizer type, are provided. In wet climates, the default value has been set at 0.6% of organic N inputs and 1.6% of synthetic N inputs. For $Frac_{LEACH-(H)}$ and EF_5, the new aggregated default values are 0.24 and 0.011, respectively.

APPENDIX. Calculation of N_2O emissions from crop residues

Nitrous oxide is produced naturally in soils through the processes of nitrification and denitrification, which are controlled by the availability of inorganic N in the soil. IPCC provides a methodology to estimate N_2O emissions using human-induced net N additions to soils (e.g., synthetic or organic fertilizers, deposited manure, crop residues, sewage sludge), or of mineralization of N in soil organic matter following drainage/management of organic soils, or cultivation/land-use change on mineral soils (e.g., Forest Land/Grassland/Settlements converted to Cropland).

The emissions of N_2O that result from anthropogenic N inputs or N mineralization occur through both a direct pathway (i.e., directly from the soils to which the N is added/released), and through two indirect pathways, as illustrated in Figure A1. These emissions can be estimated using equations provided in the IPCC guidelines, using Tier 1 default values when regional specific parameters are not available. As the scope of the present analysis is focused on N inputs from crop residues (F_{CR}), equations 1-3 have been adjusted from IPCC guidelines for the estimation of the direct emissions (N_2O_{Direct}) only from this component:



Source: Eggleston et al.[30]

Figure A1. Sources and pathways of N that result in direct and indirect N2O emissions from soils and waters.

$$N_2O_{Direct} = N_2O - N_{N\ inputs} \times (44/28) \qquad [1]$$

$$N_2O - N_{N\ inputs} = F_{CR} \times EF_1 \qquad [2]$$

Where:

N_2O_{Direct} = annual direct N_2O–N emissions produced from managed soils, kg N_2O–N yr^{-1}

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[30] Eggleston, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, and Chikyū Kankyō Senryaku Kenkyū Kikan, *2006 IPCC guidelines for national greenhouse gas inventories*.

$N_2O - N_{N\ inputs}$ = annual direct N_2O–N emissions from N inputs to managed soils, kg N_2O–N yr^{-1}

F_{CR} = annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils, kg N yr^{-1}

EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input)$^{-1}$; the default value for EF_1 is 0.01 (IPCC Tier 1).

The term F_{CR} can be calculated using Eq. 3, with the default values given in Table A1:

$$F_{CR} = Frac_{Renew} \times \left[\left(Area - Areaburnt \times C_f \right) \times AG_{DM} \times 1000 \times N_{AG} \times \left(1 - Frac_{Remove} \right) + Area \times \left(AG_{DM} \times 1000 + Crop \right) \times R_{BG-BIO} \times N_{BG} \right] \quad [3]$$

Where:

$Area$ = total annual area harvested of sugarcane, ha yr^{-1}

$Areaburnt$ = annual area of sugarcane burnt, ha yr^{-1}

C_f = combustion factor (dimensionless)

$Frac_{Renew}$ = fraction of total area under sugarcane that is renewed annually

AG_{DM} = above-ground residues dry matter, Mg ha^{-1}

N_{AG} = N content of above-ground residues, kg N (kg d.m.)$^{-1}$

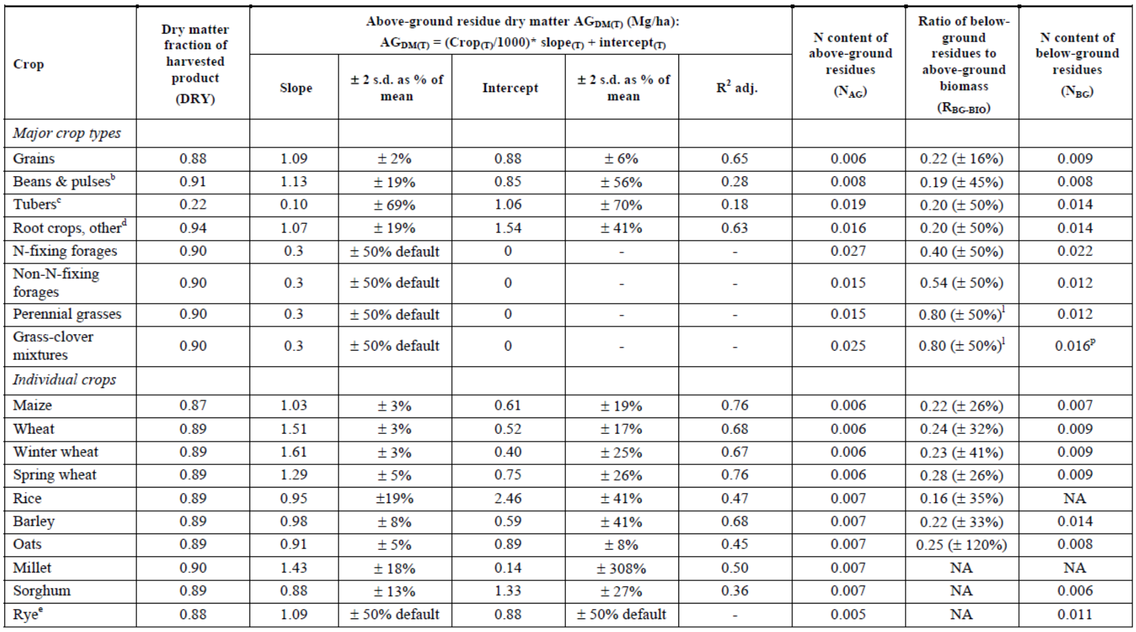
$Crop$ = harvested dry matter yield, kg d.m. ha^{-1}; it can be calculated by multiplying the harvested fresh yield (kg fresh weight ha^{-1}) by the dry matter fraction of the harvested crop (DRY), kg d.m. (kg fresh weight)$^{-1}$

$Frac_{Remove}$ = fraction of above-ground residues of sugarcane removed annually for purposes such as feed, bedding and construction, kg N (kg crop-N)$^{-1}$

R_{BG-BIO} = ratio of belowground residues to above-ground biomass, kg d.m. (kg d.m.)$^{-1}$

N_{BG} = N content of below-ground residues, kg N (kg d.m.)$^{-1}$

Table A1. Default factors for estimation of N added to soils from crop residues.[a]



Crop	Dry matter fraction of harvested product (DRY)	Above-ground residue dry matter $AG_{DM(T)}$ (Mg/ha): $AG_{DM(T)} = (Crop_{(T)}/1000)^* \; slope_{(T)} + intercept_{(T)}$					N content of above-ground residues (N_{AG})	Ratio of below-ground residues to above-ground biomass (R_{BG-BIO})	N content of below-ground residues (N_{BG})
		Slope	± 2 s.d. as % of mean	Intercept	± 2 s.d. as % of mean	R^2 adj.			
Major crop types									
Grains	0.88	1.09	± 2%	0.88	± 6%	0.65	0.006	0.22 (± 16%)	0.009
Beans & pulses[b]	0.91	1.13	± 19%	0.85	± 56%	0.28	0.008	0.19 (± 45%)	0.008
Tubers[c]	0.22	0.10	± 69%	1.06	± 70%	0.18	0.019	0.20 (± 50%)	0.014
Root crops, other[d]	0.94	1.07	± 19%	1.54	± 41%	0.63	0.016	0.20 (± 50%)	0.014
N-fixing forages	0.90	0.3	± 50% default	0	-	-	0.027	0.40 (± 50%)	0.022
Non-N-fixing forages	0.90	0.3	± 50% default	0	-	-	0.015	0.54 (± 50%)	0.012
Perennial grasses	0.90	0.3	± 50% default	0	-	-	0.015	0.80 (± 50%)[l]	0.012
Grass-clover mixtures	0.90	0.3	± 50% default	0	-	-	0.025	0.80 (± 50%)[l]	0.016[p]
Individual crops									
Maize	0.87	1.03	± 3%	0.61	± 19%	0.76	0.006	0.22 (± 26%)	0.007
Wheat	0.89	1.51	± 3%	0.52	± 17%	0.68	0.006	0.24 (± 32%)	0.009
Winter wheat	0.89	1.61	± 3%	0.40	± 25%	0.67	0.006	0.23 (± 41%)	0.009
Spring wheat	0.89	1.29	± 5%	0.75	± 26%	0.76	0.006	0.28 (± 26%)	0.009
Rice	0.89	0.95	±19%	2.46	± 41%	0.47	0.007	0.16 (± 35%)	NA
Barley	0.89	0.98	± 8%	0.59	± 41%	0.68	0.007	0.22 (± 33%)	0.014
Oats	0.89	0.91	± 5%	0.89	± 8%	0.45	0.007	0.25 (± 120%)	0.008
Millet	0.90	1.43	± 18%	0.14	± 308%	0.50	0.007	NA	NA
Sorghum	0.89	0.88	± 13%	1.33	± 27%	0.36	0.007	NA	0.006
Rye[e]	0.88	1.09	± 50% default	0.88	± 50% default	-	0.005	NA	0.011

[a] Source: Eggleston et al.[31]

As for the indirect emissions ($N_2O_{Indirect}$), contributions derive from atmospheric deposition of N volatilized from managed soils and from leaching and runoff. But as indirect N_2O emissions from crop residues are exclusively related to leaching and runoff, this is the only contribution considered in equations 4 and 5:

$$N_2O_{Indirect} = N_2O_{(L)} - N \times (44/28) \qquad [4]$$

$$N_2O_{(L)} - N = F_{CR} \times Frac_{LEACH-(H)} \times EF_5 \qquad [5]$$

Where:

$N_2O_{(L)} - N$ = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O–N yr^{-1}

$Frac_{LEACH-(H)}$ = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$; the default value for $Frac_{LEACH-(H)}$ is 0.30 (IPCC Tier 1).

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[31] Eggleston, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, and Chikyū Kankyō Senryaku Kenkyū Kikan, *2006 IPCC guidelines for national greenhouse gas inventories*.

EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$; the default value for EF_5 is 0.0075 (IPCC Tier 1).