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Discussions

Emissions of greenhouse gases from energy use in agriculture, forestry and fisheries: 1970-2019

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Abstract. Fossil-fuel based energy use in agriculture leads to CO_2 and non-CO_2 emissions. We focus on emissions generated within the farm gate and from fisheries, providing information relative to the period 1970-2019 for both energy use as input activity data and the associated greenhouse gas (GHG) emissions. Country-level information is generated from UNSD and IEA data on energy in agriculture, forestry and fishing, relative to use of: gas/diesel oil, motor gasoline, liquefied petroleum gas (LPG), natural gas, fuel oil and coal. Electricity used within the farm gate is also quantified, while recognizing that the associated emissions are generated elsewhere. We find that in 2019, annual emissions from energy use in agriculture were about 523 million tonnes (Mt CO_{2eq} yr^{-1}), while including electricity they were 1,029 Mt CO_{2eq} yr^{-1}, having increased 7% from 1990. The largest emission increases from on-farm fuel combustion were from LPG (32%), whereas significant decreases were observed for coal (-55%), natural gas (-50%), motor gasoline (-42%) and fuel oil (-37%). Conversely, use of electricity and the associated indirect emissions increased three-fold over the 1990-2019 period, thus becoming the largest emission source from energy use in agriculture since 2005. Overall the global trends were a result of counterbalancing effects: marked decreases in developed countries in 2019 compared to 1990 (-273 Mt CO_2eq yr^{-1}) were masked by slightly larger increases in developing and emerging economies (+ 339 Mt CO_2 eq yr^{-1}). The information used in this work is available as open data at: https://zenodo.org/record/5153241 (Tubiello and Pan, 2021). The relevant FAOSTAT (FAO, 2021) emissions database is maintained and updated annually by FAO.

1. Introduction

Agricultural production more than doubled over the period 1990-2019, with additional increases of more than 50% expected to 2050, to meet projected increases in food demand (FAO, 2018; Calicioglu et al., 2019). Historically, productivity increases were achieved through transitions from traditional, extensive agri-food systems to modern, intensive production systems, characterized by greater energy use within the farm (Smil, 2008). Direct on-farm energy inputs include fuel to power tractors and other agricultural field machinery, irrigation pumps, heat to warm greenhouses and animal shelters. Other uses beyond the farm may include power for forestry machinery and fishing vessels. We consider herein additionally the energy used to generate electricity that may be used on the farm in

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substitution of on-site fossil-fuel combustion, but do not include all other indirect energy use that is typically addressed in life-cycle type analyses (FAO, 2011; Sims et al. 2015; FAO, 2018).

On-farm energy use is a significant component of agricultural production and growth (Utz, 2011), however it often escapes analyses of greenhouse gas (GHG) emissions in agriculture. Indeed, the 'agriculture' sector within national GHG inventories (NGHGI), which countries submit regularly to the UN Framework Convention on Climate Change (UNFCCC), contains only non-CO_2 emissions from crop and livestock bio-physical processes, for instance enteric fermentation in ruminants or nitrous oxide from fertilizers on cropland (IPCC, 2006; Tubiello et al., 2019). The on-farm energy use emissions are reported instead under the 'Energy' sector of the NGHGI, therefore often escaping attention in food-related emissions analysis relevant to National Determined Contributions (Tubiello et al., 2021). Within the UNFCCC context, emissions from agriculture are currently about 5 Gt CO_2eq yr^{-1}, having increased by roughly 50% since 1961 (Tubiello, 2019). They are dominated by livestock processes, and are fairly equally split between CH_4 and N_2O components, respectively in single gases units corresponding to annual emissions in 2018 of 140 Mt CH_4 yr^{-1} and 7.7 Mt N_2O yr^{-1} (FAO, 2020; Tubiello et al., 2021).

Energy use in agriculture, forestry and fisheries nonetheless deserves more attention than paid in current reporting and associated studies, because it is an important food production component deserving analysis in its own right alongside the biophysical crop and livestock processes mentioned above. Additionally, it offers significant opportunities for on-farm mitigation actions directly focussed on CO_2 (Dyer et al., 2014). This paper therefore focuses on quantifying the GHG emissions that arise from the combustion of fossil fuels for energy use in agriculture, forestry and fisheries (capture fishing and aquaculture). As detailed in the methods section, our quantification will focus mostly on the farm and on fishing activities, assuming that emissions associated to energy used in forestry is negligible—i.e., it will focus on energy use for farm operations, for aquaculture and for powering fishing vessels. We include additional estimates of the emissions associated to the off-site generation of electricity used on the farm, tracking results both separately for electricity and on-site fossil fuel use, as well as in the aggregate.

Information on energy consumption in different agricultural operations is available from the literature, albeit there is a lack of consistent global data with country detail provided over relevant time series. Available information indicates that in-farm energy demand in OECD countries is mainly for crop cultivation, harvesting, heating protected crops in greenhouses, crop drying and storage, water pumping and livestock housing (OECD, 2008). Furthermore, on-farm use in high-GDP countries (20 GJ/ha) is almost double the use in low-GDP countries (11 GJ/ha) (FAO, 2011a). Fossil fuel energy inputs have reduced labor inputs, or around 152 MJ for every man-hour of labor inputs in high-GDP countries, and 4 MJ in low-GDP countries (Sims, 2014).

Smil (2008) and FAO (2011) estimated global direct and indirect energy use in agriculture in the early 2000s at 17 EJ, of which 5 EJ to power machinery; 4 EJ for animal husbandry, aquaculture, and fisheries; 2 EJ to produce and maintain agricultural machinery; 5 EJ to extract, synthesize and distribute fertilizers; 0.5 EJ to manufacture pesticides and herbicides; and 0.3 to manufacture irrigation systems. Hence direct energy use in agriculture was a bit more than half this total, about 9 EJ. In addition to these amounts, energy use in agriculture includes electricity from the grid, decentralized renewable sources including bioenergy, conventional technologies, mechanical and thermal energy and biodiesel/biofuels. In many traditional systems, human labour and draught animal power add significant energy inputs.

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2. Materials and methods

Data on energy use in agriculture forestry and fisheries, by fuel type, over the annual time series 1990-2019, were available from UNSD and IEA. These Agencies regularly collect energy data from member countries, including for use in agriculture, forestry and fishing. Biofuels, renewables, and other energy carriers derived from biomass, were analyzed but not considered for calculating GHG emissions, since they were assumed to be carbon neutral (IPCC, 2006). Energy use data from the UNSD Energy Statistics Database (UNSD, 2020) included the following fuels, over the period 1970-2019: Diesel oil; Motor gasoline; Liquefied petroleum gas (LPG); Natural gas, including Liquefied Natural Gas (LNG); Fuel oil; Hard coal. Electricity use data were also taken from the same database.

2.2 Gap filling

The information used in this work is available as open data at: https://zenodo.org/record/5153241 (Tubiello and Pan, 2021). The relevant FAOSTAT (FAO, 2021) emissions database is maintained and updated annually by FAO.

2.3 Gap filling

The energy use data sourced from UNSD were gap filled for both improving the quality of available time series by country and generating data for missing countries. The original set had several missing data points especially for Africa (FAO, 2021). First, a simple linear gap-filling method was applied to estimate data points missing within intervals with data points, over the time period 1970-2019. Conversely, gap-filling of values for carrying backward and forward values without an available interval was performed by applying sub-regional trends. Finally, time series for countries with no data were generated with a multivariate approach, i.e., by computing the sub-regional energy use in agriculture divided by the sub-regional total energy use, and applying the coefficient to the time series of national total energy use, which was available in the UNSD database without major gaps. We validated our gap-filling method by performing random substitutions of existing values and computing the associated error, which was on average below 5%.

2.4 Emissions Estimates

The activity data on energy use described in previous sections served as input for estimates of GHG emissions, made following the Tier 1 method of the Guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2006). In particular, we used default fuel-specific CO_2 emission factors for off-road mobile combustion sources (e.g., tractors, harvesters and other mobile machinery) and stationary combustion sources (i.e., irrigation pumps, space heating), within the following formula:

$$E_i = AD_i * EF_i$$

Where E_i are the emissions (in t CO_2 yr^{-1}) for energy carrier i, computed by multiplying the amount of fossil fuel type AD_i (GJ yr^{-1}) by the relevant emission factor EF_i (t CO_2 GJ^{-1}). The default emission factors applied to relevant fuel categories were those for stationary combustion in the residential and agriculture/forestry/fishing farms

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categories, assumed by IPCC to be used for power generation (heat and/or electricity) (Tab. 2). Fuels reported in metric tons were converted to GJ by assuming a net calorific value of 43.0 GJ/t for diesel, 44.3 GJ/t for gasoline, 47.3 GJ/t for LPG, 44.2 Gg/t for natural gas liquids, 40.4 GJ/t for fuel oil, 25.8 for coal[1] (IPCC, 2016).

Finally, country-specific grid emission factors needed to estimate CO_2 emissions from electricity used were taken from IEA. The associated emissions of CH_4 and N_2O were not considered, as our calculations (not shown) indicated the latter would be five to six orders of magnitude smaller compared to CO_2, on a per ton basis.

Emissions from fisheries were estimated as a separate item (until 2018), using dedicated IEA data, and for information purposes only, i.e., they were assumed to represent additional information, since energy used in agriculture, forestry and fisheries are already included in the UNSD energy statistics. Fisheries statistics from IEA were limited to OECD countries. Only diesel and fuel oil for powering fishing vessels and aquaculture are reported under fisheries, since these two fuels (followed by heat) represent the bulk of energy used in the sector.

Uncertainties were derived by applying ranges for GHG emission factors provided by IPCC 2006 to fuels considered and an error of 5% for emissions associated with electricity consumption (calculated based on the global energy mix for electricity generation in the IEA database).

2.3 Limitations and uncertainty

There are limitations and uncertainties associated with the estimates presented herein. First, we note that the input data on energy refers to use in agriculture, forestry and fisheries, without further breakdown. While we refer often to the associated emissions as generated within the farm gate, they include components of unknown relative magnitude that are in fact generated through forestry and fisheries activities. For the latter, we have provided a partial and incomplete breakdown in the database, using IEA fisheries data. Second, the underlying data on energy use have significant geographical gaps, especially in Africa, as well as temporal gaps, particularly before 1990. For estimates of GHG emissions, we applied default IPCC methods and uncertainty values for EFs to compute the error propagation in equation (1) above, finding an uncertainty range in emissions of -7 to 16% (Figs. 4-5).

2.4 Data availability

The GHG emission data presented herein cover the period 1990-2019, at the country level, with regional and global aggregates. Significant gaps in some countries and regions, especially Africa, imply that specific regional estimates may be systematically underestimated. Additionally, statistics on energy consumption and emissions from fisheries are highly uncertain and likely underestimates, considering that significant amounts of fuel consumed by small vessels, constituting a majority of the global fishing fleet, are not typically reported in official statistics.

Data on energy use in agriculture and associated emissions used in this work are available as open data at: https://zenodo.org/record/5153241 (Tubiello and Pan, 2021). The relevant FAOSTAT (FAO, 2021) database is maintained and updated annually by FAO.

3 Results

Our estimates indicated that world-total GHG emissions from energy use in agriculture including electricity were above 1 billion tonnes in 2019 (1,029 Mt CO_2eq yr^{-1}; 7% greater than in 1990). The average annual increase was

[1] We assumed that coal used in agriculture is mostly 'bituminous coal.'

0.2% over the period 1990-2019 and was consistent with the overall growth in agricultural emissions within the farm gate. Almost half of the estimated emissions (496 Mt CO_2eq yr^{-1}) arose from combustion of fossil fuels for power generation of electricity used on the farm. The most important energy sources after electricity were gas/diesel oil and coal, while motor gasoline, typically associated to field machinery and tractors use in developing countries, contributed a mere 5% of the total (Figs. 2-3). Emissions from electricity grew rapidly over the study period (mean annual growth rates of more than 6%), overtaking gas diesel oil and motor gasoline as the main emission source by roughly the year 2012. This, together with an increase of LPG use, suggests a global transition towards cleaner on-farm energy use, considering grid electricity is typically associated to lower emissions per energy compared to single fossil fuel sources. At the same time, use and hence emissions from natural gas, fuel oil and coal were rather constant over the period 1990-2019, about 38, 123, and 25 Mt CO_2eq yr^{-1} on average. While data for on farm energy use were rich in coverage, trends in emissions from use of diesel oil and fuel oil in fishing vessels were limited by data paucity. Within such limitations, we find a small, decreasing share of emissions from fishing vessels compared to world-total energy use in agriculture, with a total contribution in 2018 (the breakdown of energy used in fisheries is available only until 2018) of about 27 Mt CO_2eq yr^{-1} (3%).

3.2 Regional Distributions and Trends

Our results indicate that on-farm energy use is an important and increasing component of GHG emissions in agriculture (Fig. 1). Emissions declined in Annex I countries over the period 1990-2019, especially energy from coal (-88%) and fuel oil (-77%). Such decline was more than counterbalanced by increases in energy use in non-Annex I parties (NAI), with significant increases in emissions from electricity (three-fold increases since 1990) (Fig. 4). Asia and Europe were the largest emitters among FAO regions, although with starkly different trends over 1990-2019. Indeed, while emissions in Europe decreased over the whole period, from 730 Mt CO_2eq yr^{-1} in 1970 to 410 Mt CO_2eq yr^{-1}in 1990, and further decreased to 145 Mt CO_2eq yr^{-1} in 2019, emissions in Asia nearly doubled over 1990 to 2019, from 380 Mt CO_2eq yr^{-1} to 629 Mt CO_2eq yr^{-1}, while they were 453 Mt CO_2eq yr^{-1} in 1970. Africa was a significant emission source in 2019, having more than doubled since 1990, from 18 MtCO_2-eq to 48 Mt CO_2eq yr^{-1}. Emissions increased more than 55% in Latin America, but only 18% in North America. The smallest contributor to global emissions was Oceania, despite increases by nearly 55% from 1990 (Fig. 7**).** Top emitting countries in 2019 in terms of energy use in agriculture were China (233 Mt CO_2eq yr^{-1}), followed by India (212 Mt CO_2eq yr^{-1}) and the USA (79 Mt CO_2eq yr^{-1}). The top 10 emitting countries were responsible for nearly two-thirds of the world total (Fig. 8).

3.3 Indicators

We developed indicators by cropland area and agricultural production value to help us disentangle effects of country agricultural size, both in terms of area and economy. We defined GHG emission intensity per unit cropland as the total GHG emissions from energy use in agriculture divided by total cropland area of a country. Likewise, energy GHG intensity per production value was computed by dividing total GHG from national energy use in agriculture by total agricultural value added. Data for denominators of both indicators were taken from FAOSTAT (FAO, 2021b, c).

Our results indicate that energy GHG emissions per unit cropland have been fluctuating but have been substantially stable over the last two decades. Nonetheless, significant differences can be noted among regions (Fig. 11). While

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Europe has decreased significantly its energy-related GHG emission intensity in agriculture (-57%) in the period 1990-2018, Africa, Central America and Asia have increased it substantially (+88%, +51% and +44% respectively). This means that more GHG emissions are associated with the cultivation of one unit of cropland in these regions. In absolute terms, the lowest energy intensity per unit of cropland in 2018 was achieved in Africa (0.16 t CO_2eq ha^{-1}), followed by Oceania (0.38 t CO_2eq ha^{-1}), South America (0.42 t CO_2eq ha^{-1}) and Europe (0.48 t CO_2eq ha^{-1}).

In terms of energy-related GHG emissions to agricultural value added, the picture is substantially different, with Europe having significantly improved its energy intensity since 1990 (-68%), followed by Asia (-61%), Latin America and the Caribbean (-54%), Northern America (-53%) and Oceania (-45%), while Africa's intensity remained substantially stable over the last two decades.

In 2019, high levels of GHG emissions per capita (from energy used in agriculture) were estimated for Faro Islands, Greenland and Iceland (Fig 13). In those territories, emissions from gas/diesel oil take more than two-thirds of the total. Fishing is one of the most responsible factors contributing to the high per capita emission from energy use in agriculture in Faroe Island, as fishing vessels take almost one-third of energy use at national level. Fishing is also the primary industry in Iceland. For Greenland, fishing is the second-largest industry by employment. Though Greenland has the highest ratio of using renewable energy (70%), fishing remains a sector depending on traditional fossil fuels.

4 Discussion

Emissions from energy use in agriculture are only about one-fifth of the total in CO_2eq generated from crop and livestock production (Tubiello et al. 2019), however they represent an important contribution in terms of CO_2 gas, the other process emitting CO_2 on the farm being the drainage of organic soils. They are therefore of great importance to GHG mitigation in agriculture. In terms of comparing these results with the existing literature, we note that our approach covers only 7.2 of the 8-10 EJ usually estimated for total fuel consumption within the farm gate (Arizpe et al., 2011; FAO, 2011; Smil, 2008). Additionally, our estimates of energy use in fisheries is admittedly incomplete (0.3 EJ) compared to amounts reported in other studies (Buhaug et al., 2009; FAO, 2011). The reason is that we focused only on electricity and on the most relevant fuels consumed in agriculture, but not all. Specifically for fisheries, the relatively low coverage is also due to the fact that still few countries report disaggregated energy consumption statistics for fisheries alone.

Electricity generation and gas/diesel oil used in agriculture were the two most important emissions sources, responsible for roughly 40% of the total on average during the period 1990 -2019. Electricity is used for different agriculture purposes: irrigation, processes that require heat or mechanical power, such as drying or milling. LPG, natural gas, and heavy fuel oil are typically used for heat generation and, in some rare cases, for motive power. Apart from some sharp variation of their total consumption in agriculture between consecutive years, mainly at the beginning of the '90s, probably due to reporting issues of important consumer countries such as India and the dissolution of the USSR, their emissions remained relatively stable. Compared to other emissions, coal and fuel oil emissions decreased over the last few years, while agricultural production still increased. This can be explained by updated energy use structure - the increased uptake of cleaner energy carriers such as electricity and LPG over fuel oil and coal for heating. China, for example, one of the major emitting countries, decreased emissions from fuel oil use by 48%, while increased emissions due to diesel use by around 59 % and emissions due to electricity

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use by over 170% over the same period 1990-2019. There is anyway still a long way to go to decrease emissions in the agricultural sector in China, due to its still very high reliance on coal as a heat source.

Unlike other regions, Europe's emissions went significantly down, partly because less energy was consumed by primary production in absolute terms. Also, Europe has gradually moved from high GHG emitting energy carriers such as coal and fuel oil towards cleaner ones, such as natural gas and electricity. This is confirmed by the additional analysis done using the energy-related GHG intensity indicators. This analysis shows how Europe has been steadily improving its agricultural GHG intensity (both in terms of unit of cropland and of unit of agricultural production value), thus providing a good example for other regions.

5 Conclusions

This paper provides details of a new dataset added to the existing section of FAOSTAT, which contains information about emissions due to agricultural activities, and which was just opened publicly online (July 2021). It also provides an analysis of energy-related GHG intensity in agriculture, per unit of cropland and per unit of agricultural production value, which has not been published yet. It complements the analysis with selected GHG emission intensity indicators, which are derived directly from FAOSTAT. The calculation makes use of official statistics as reported by countries to the UN, applying IPCC Tier 1 default emission factors for fuels and IEA country-specific emission factors for electricity generation (considering the national energy mix) and relies on official energy consumption in agriculture data reported by countries to the UNSD and the IEA. Further to the above, the share of emissions on fisheries' energy use is estimated and reported separately as a subset. These estimated emission shares provide references to their relevance compared with total emissions but should be used with relevant uncertainties taken into consideration.

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TABLE LEGENDS

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FIGURE LEGEND

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	CO_2			CH_4			N_2O		
	Default (kg/TJ)	**Lower**	**Upper**	**Default (kg/TJ)**	**Lower**	**Upper**	**Default (kg/TJ)**	**Lower**	**Upper**
Gas/Diesel oil	74100	72600	74800	4.15	1.67	10.4	28.6	14.3	85.8
Motor gasoline [2]	69300	67500	73000	80	32	200	2	1	6

Table 1. Fuel-specific emission factors for agriculture off-road mobile combustion sources and machinery applied (IPCC 2006)

	CO_2			CH_4			N_2O		
	Default (kg/TJ[3])	**Lower**	**Upper**	**Default (kg/TJ)**	**Lower**	**Upper**	**Default (kg/TJ)**	**Lower**	**Upper**
Liquefied Petroleum Gases	63100	61600	65600	5	1.5	15	0.1	0.03	0.3
Natural gas	56100	54300	58 300	5	1.5	1.5	0.1	0.03	0.3
Residual fuel oil	77400	75500	78800	10	3	30	0.6	0.2	2
Other bituminous coal	94600	89500	99700	300	100	900	1.5	0.5	5

Table 2. Fuel-specific emission factors for stationary combustion in the residential and agriculture/forestry/fishing/fishing farms categories applied (IPCC 2006)

[2] The default emission factors regard 4-stroke motor gasoline engines.
[3] kg of greenhouse gas per TJ on a Net Calorific Basis

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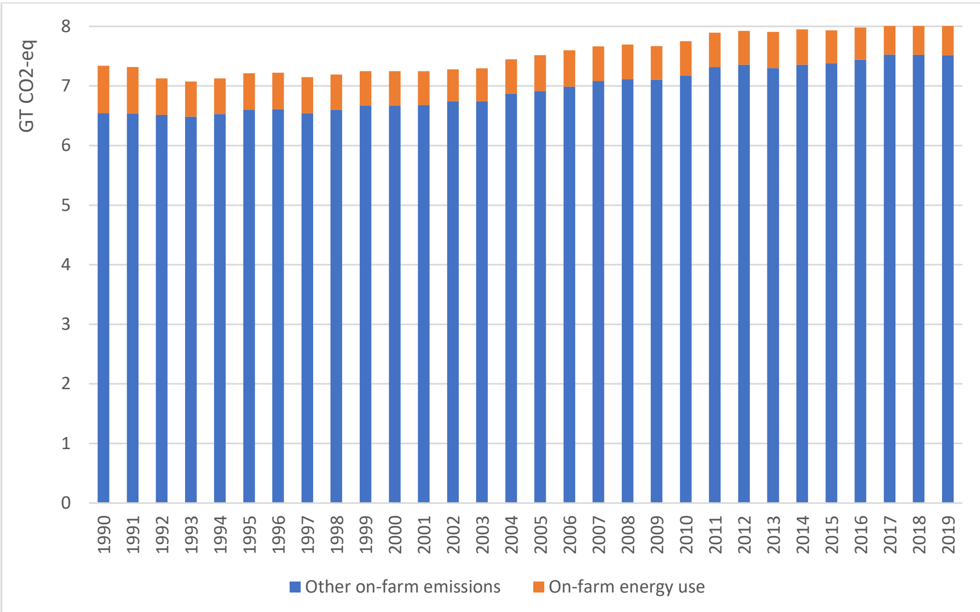

Figure 1. Global emissions from energy use (orange bars) and emission from other on-farm total, excluding energy (blue bars) per year (Gt CO2-eq). Source: FAOSTAT, based on data from IEA and UNSD, 2021

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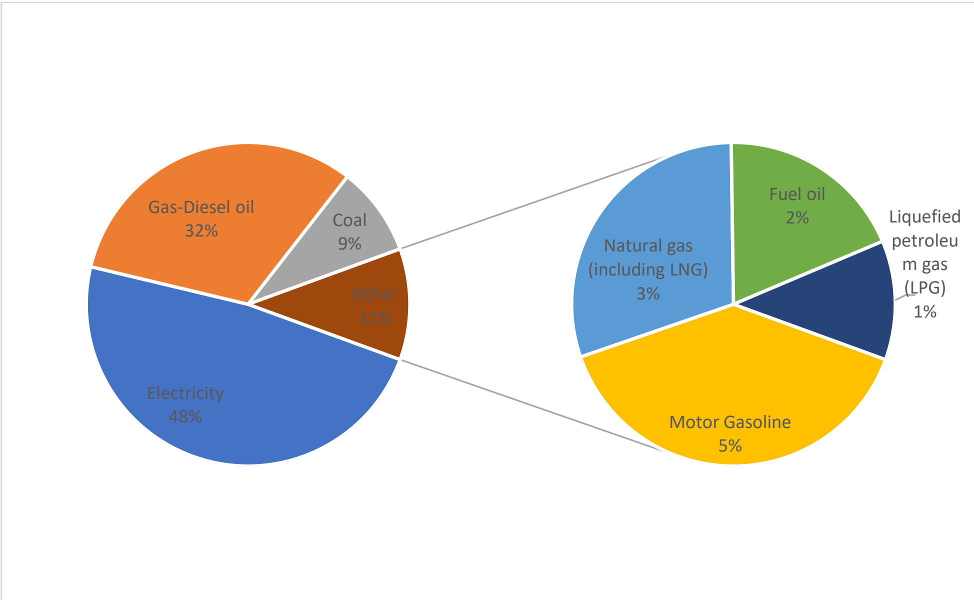

Figure 2. Global shares of emissions due to energy use in agriculture in 2019, by energy carrier (CO2-eq). Source: FAOSTAT based on data from IEA and UNSD, 2021

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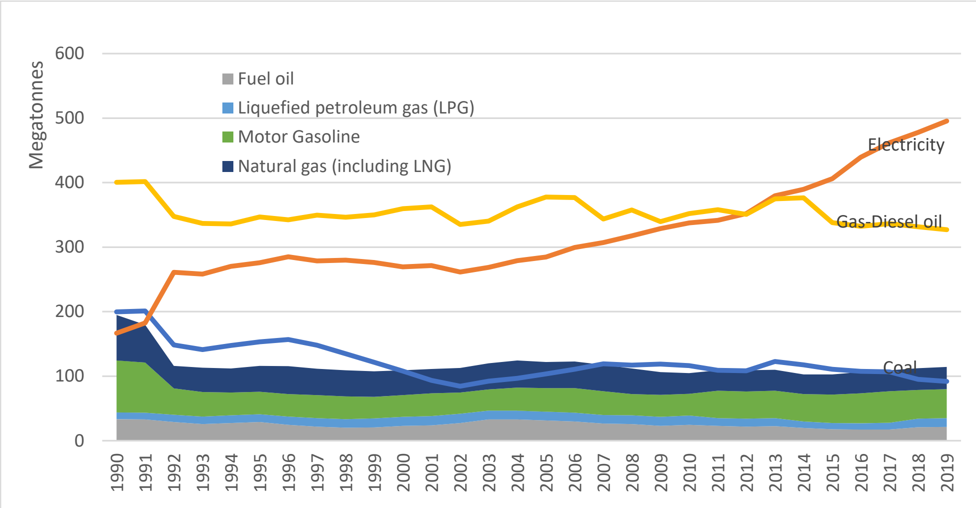

Figure 3. Global GHG emissions from energy use in agriculture from 1990 to 2019, by energy carrier (MtCO2-eq). Source: FAOSTAT, based on data from IEA and UNSD, 2021

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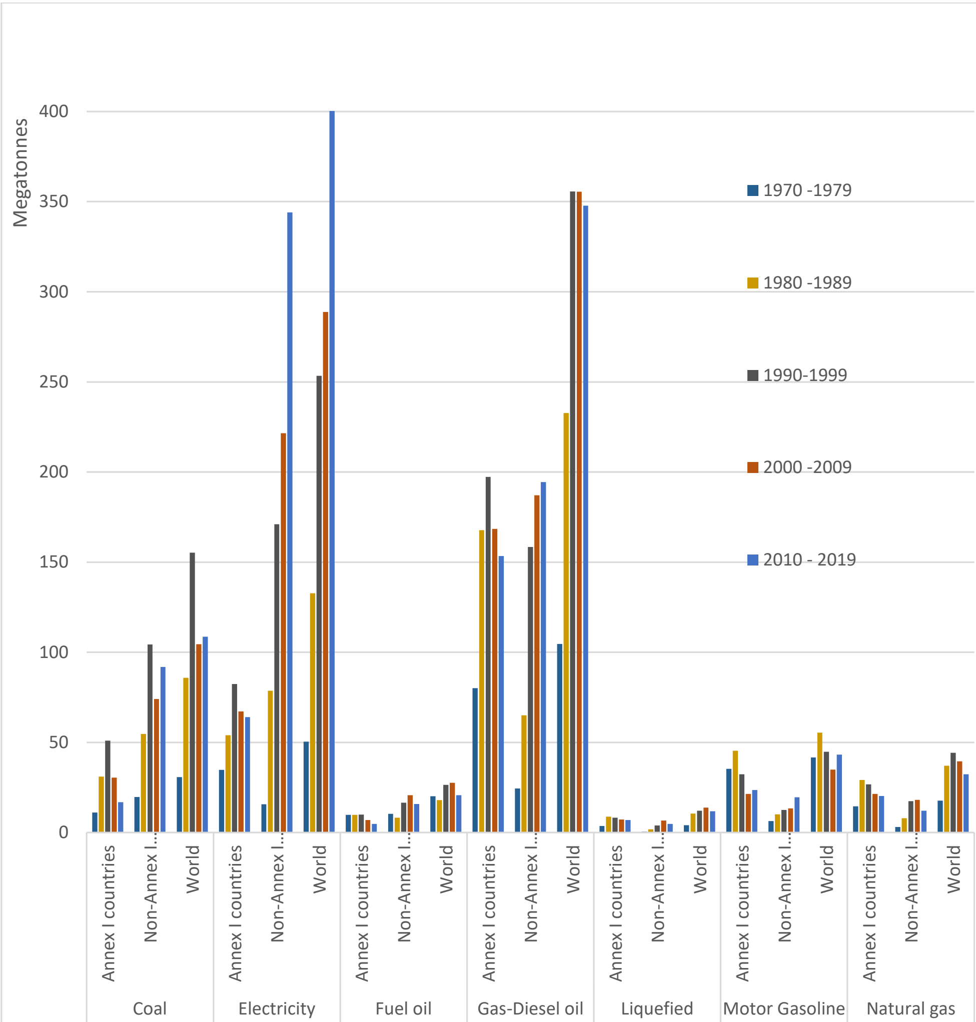

Figure 4. GHG emission trends from 1990 to 2019 for Annex I and NAI, World, by energy carrier (MtCO2-eq). Source: FAOSTAT, based on data from IEA and UNSD, 2021

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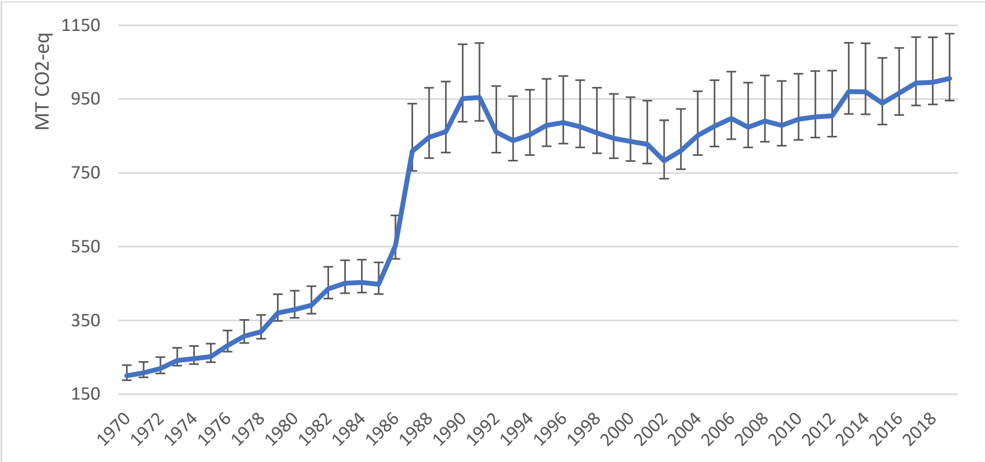

Figure 5. Trend in global GHG emissions from 1990 to 2019, with uncertainty ranges (MtCO2-eq). Source: FAOSTAT, based on data from IEA and UNSD, 2021

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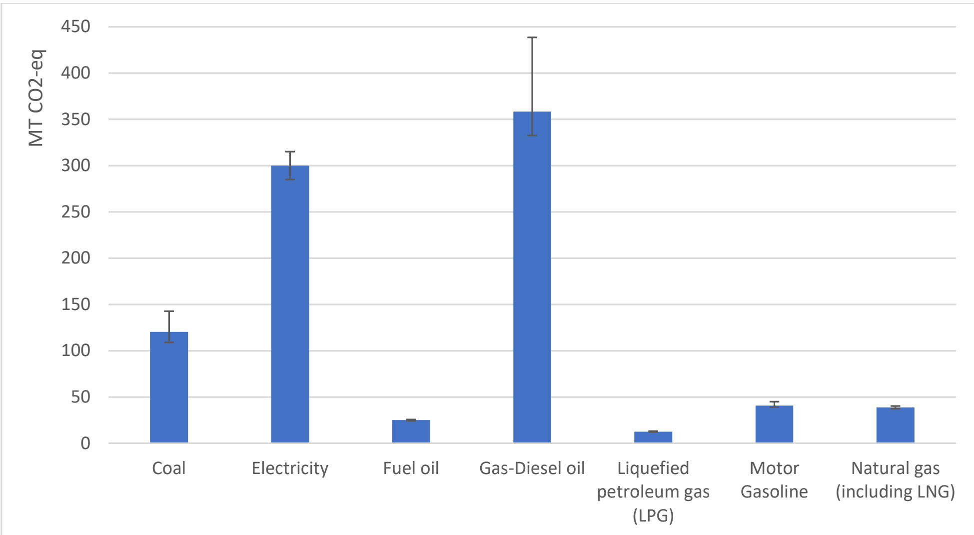

Figure 6. Global GHG emissions from energy use in agriculture (average 1990 – 2019) by energy source with uncertainty ranges (MtCO2-eq). Source: FAOSTAT, based on data from IEA and UNSD, 2021

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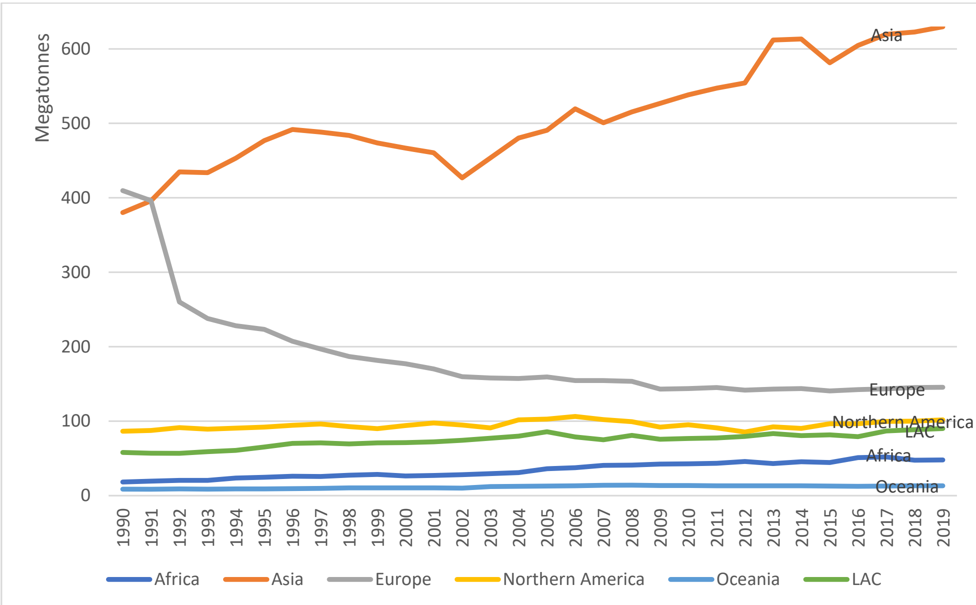

Figure 7. GHG emissions from energy use in agriculture from 1990 to 2019, by region (MtCO2-eq). Source: FAOSTAT, based on data from IEA and UNSD, 2021

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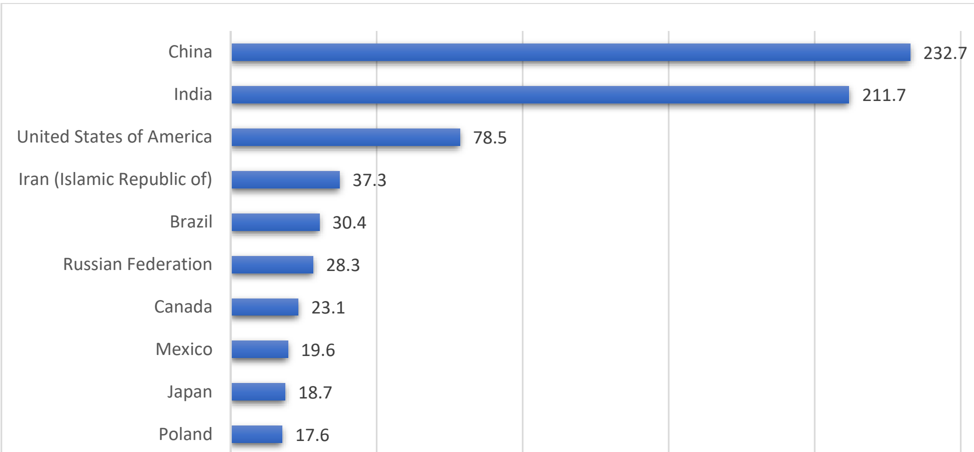

Figure 8. Top 10 countries emitting GHG from energy used in agriculture in 2019 (MtCO2-eq). Source: FAOSTAT, based on data from IEA and UNSD, 2021

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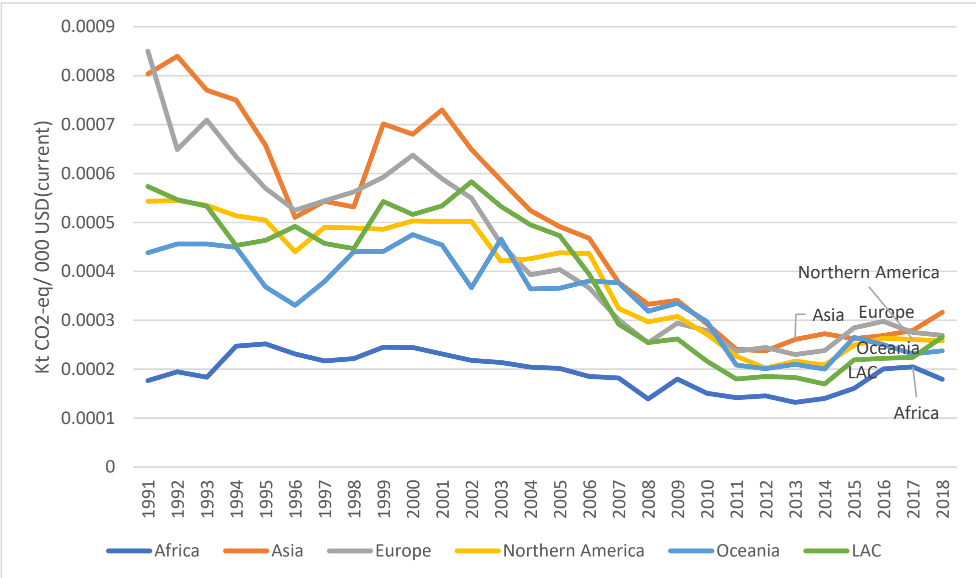

Figure 9. GHG emission from energy use in agriculture per gross agriculture production value 1991-2018 (KtCO2eq/1,000 current USD)

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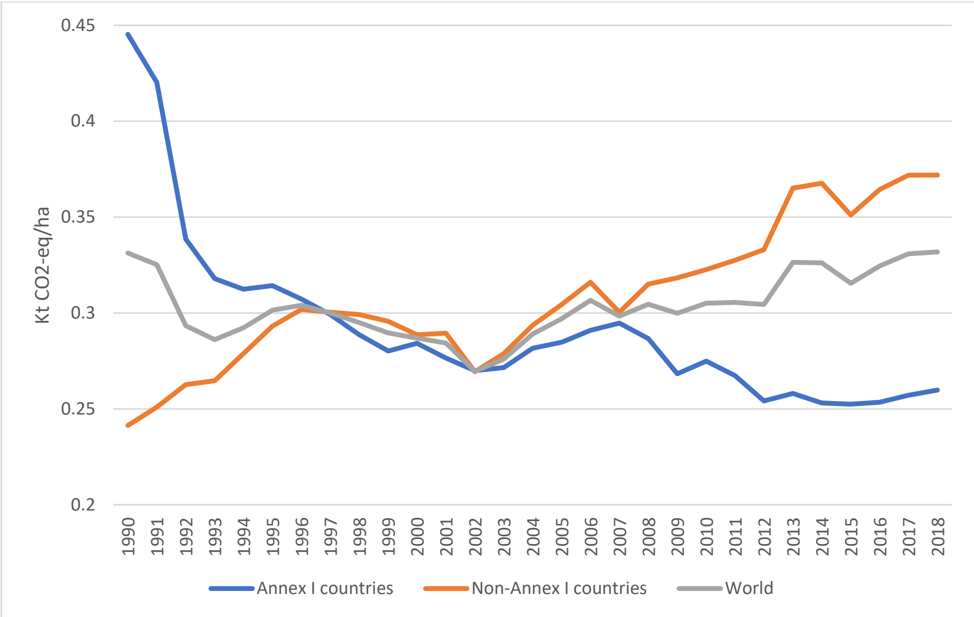

Figure 10. GHG emission from energy use in agriculture per unit of cropland for Annex I and Non-Annex I countries 1990-2018 (Kt CO2-eq/ha). Source: FAOSTAT, based on data from IEA and UNSD, 2021

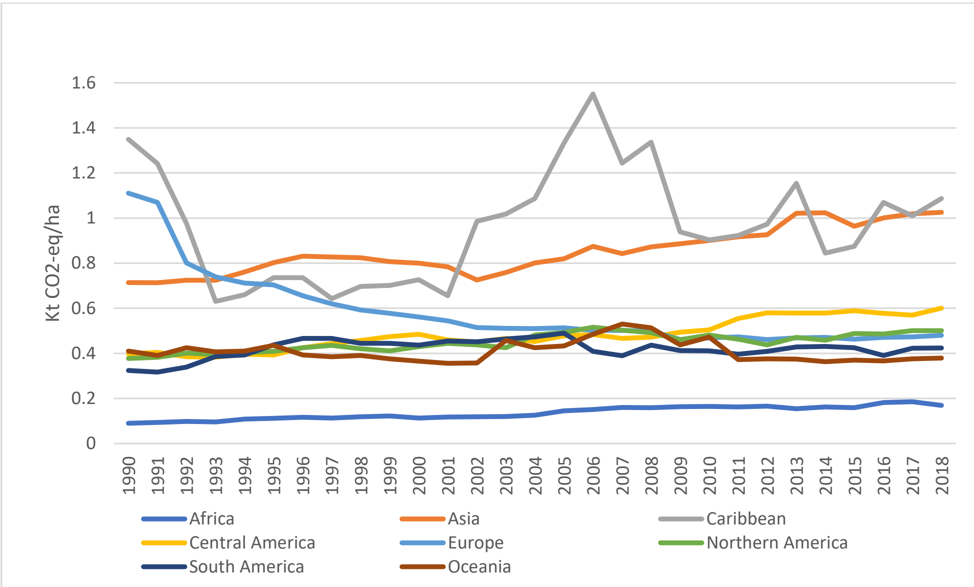

Figure 11. GHG emission intensity trends per unit of cropland by region (Kt CO2-eq /ha). Source: FAOSTAT, based on data from IEA and UNSD, 2021

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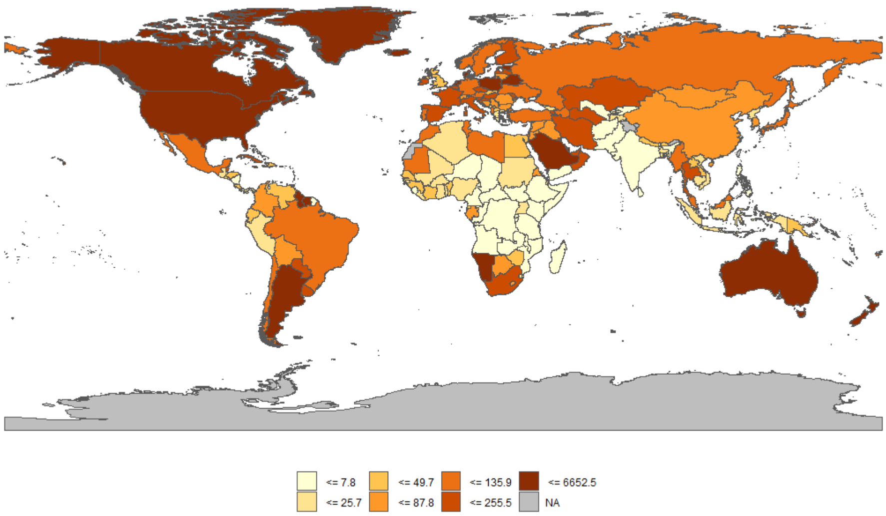

Figure 12. GHG emission from energy used in agriculture per capita in 2019 (Kg CO2-eq /person) [4]

[4] Energy data from FAOSTAT, 2021. Population data from the World Bank (https://data.worldbank.org/indicator/SP.POP.TOTL), with some countries from United Nations, Department of Economic and Social Affairs, Population Division. Falkland Islands (Malvinas), Guadeloupe, French Guyana, Martinique, Niue, Réunion, Romania, Palestine, Democratic Republic of the Congo.

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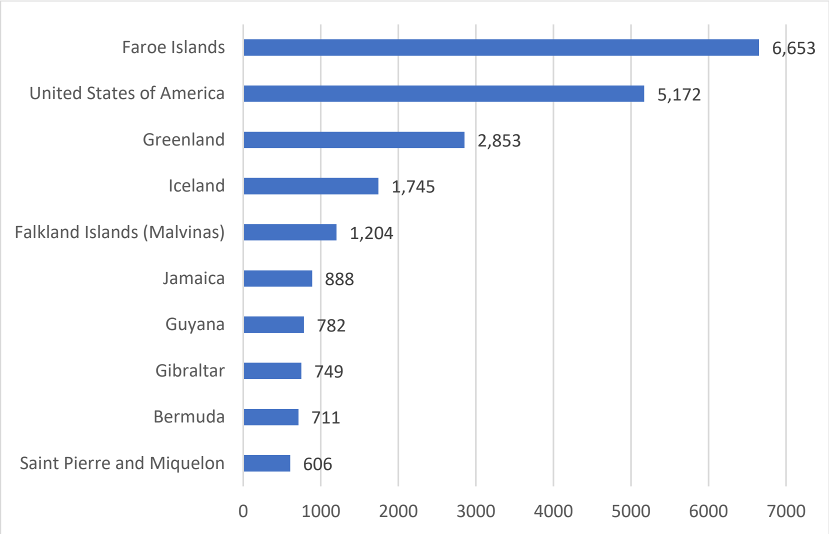

Figure 13. Top 10 GHG emitting countries from energy use in agriculture per capita in 2019 (Kg CO2-eq/person)