The FAOSTAT database of greenhouse gas emissions from agriculture

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Abstract
Greenhouse gas (GHG) emissions from agriculture, including crop and livestock production, forestry
and associated land use changes, are responsible for a significant fraction of anthropogenic emissions,
up to 30% according to the Intergovernmental Panel on Climate Change (IPCC). Yet while emissions
from fossil fuels are updated yearly and by multiple sources—including national-level statistics from
the International Energy Agency (IEA)—no comparable efforts for reporting global statistics for
agriculture, forestry and other land use (AFOLU) emissions exist: the latest complete assessment was
the 2007 IPCC report, based on 2005 emission data. This gap is critical for several reasons. First,
potentially large climate funding could be linked in coming decades to more precise estimates of
emissions and mitigation potentials. For many developing countries, and especially the least developed
ones, this requires improved assessments of AFOLU emissions. Second, growth in global emissions
from fossil fuels has outpaced that from AFOLU during every decade of the period 1961–2010, so the
relative contribution of the latter to total climate forcing has diminished over time, with a need for
regular updates. We present results from a new GHG database developed at FAO, providing a complete
and coherent time series of emission statistics over a reference period 1961–2010, at country level,
based on FAOSTAT activity data and IPCC Tier 1 methodology. We discuss results at global and
regional level, focusing on trends in the agriculture sector and net deforestation. Our results
complement those available from the IPCC, extending trend analysis to a longer historical period and,
critically, beyond 2005 to more recent years. In particular, from 2000 to 2010, we find that agricultural
emissions increased by 1.1% annually, reaching 4.6 Gt CO_2 yr^{-1} in 2010 (up to 5.4–5.8 Gt CO_2 yr^{-1}
with emissions from biomass burning and organic soils included). Over the same decade 2000–2010,
the ratio of agriculture to fossil fuel emissions has decreased, from 17.2% to 13.7%, and the decrease is
even greater for the ratio of net deforestation to fossil fuel emissions: from 19.1% to 10.1%. In fact, in
the year 2000, emissions from agriculture have been consistently larger—about 1.2 Gt CO_2 yr^{-1} in
2010—than those from net deforestation.

Keywords: agriculture, AFOLU, greenhouse gas, emissions, FAOSTAT

1. Introduction

Greenhouse gas emissions from fossil fuels grew 3.3%
in 2010, reaching a record 31.6 GtCO_2 yr^{-1} in 2011,

the highest level in history (IEA 2011). What were, by comparison, the greenhouse gas emissions from agriculture, forestry and other land use (AFOLU) in 2011, or even 2010? We simply do not know. This fundamental gap, including the lack of an international agency reporting official figures for AFOLU emissions alongside those of IEA for fossil fuels, is an obstacle to more precisely characterizing recent total anthropogenic forcing. This in turn creates uncertainty in identifying critical response strategies necessary today and in coming decades for reducing the threat of climate change—from more accurately estimating the course of appropriate mitigation actions, to devising specific interventions in the AFOLU sectors. The latter are of significant interest to many developing countries, including least developed ones, because under post-2012 agreements substantial climate funding in coming decades may become increasingly linked to regular reporting of their GHG emissions and identification of mitigation potentials, often dominated by the AFOLU sector (FAO 2011).

In fact, the latest peer-reviewed document estimating GHG emissions from agriculture and forestry was the IPCC 2007 Report (Smith *et al* 2007), largely based on 2005 data from the Environmental Protection Agency (EPA). According to IPCC, in 2005 emissions from agriculture were 5.1–6.1 GtCO$_2$eq yr^{-1}. Another 7.5–8.5 GtCO$_2$ yr^{-1} were related to the FOLU sectors—and dominated by net deforestation, biomass decay, peat fires and peat degradation. Compared to total estimated anthropogenic emissions of about 50 GtCO$_2$ yr^{-1} in 2005, the AFOLU sector may have accounted for up to a third of total anthropogenic forcing. Ongoing refinement of AFOLU emission estimates, as well as their continuous update, thus matter greatly for both science and policy reasons. Scientifically, improved estimates of anthropogenic forcing and its trend evolution are needed to more reliably predict medium to long-term climatic effects and to determine viable mitigation strategies (e.g., Houghton *et al* 2012, Hansen *et al* 2012). Politically, improving assessment and reporting of AFOLU emissions can help to better support the ongoing dialog on agriculture within the United Nations Convention on Climate Change (UNFCCC) Conference of the Parties/Meeting of the Parties (COP/MOP). This seeks to identify new mechanisms that link climate change response needs with rural development goals of many developing and, especially, least developed countries (LDCs). To this end, the AFOLU sectors may potentially benefit from large international funding—for instance, up to US\$ 100 billion annually under the Green Climate Fund or the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD) (FAO 2011, Karsenty 2012).

The most fundamental problem associated with improving estimates of the AFOLU sector, in order to complement IEA's fossil fuel data, is related to the much higher level of uncertainty characterizing AFOLU emission data compared to the latter. While national CO$_2$ emissions from fossil fuels may carry a 10–15% uncertainty, emissions from agriculture (crops and livestock production) carry much larger

uncertainties, ranging 10–150% (IPCC 2006). Emissions related to the FOLU sector, especially biomass burning and organic soils degradation, may be larger still, albeit somewhat constrainable via atmospheric measurements and inversion modeling (e.g., Friedlingstein *et al* 2011). While the uncertainty consideration is unavoidable, a bottom-up database, global and with country-level detail, can and should nonetheless be constructed in a fashion that is consistent with the IEA approach, in order to begin bridging some of the gaps and meet the science and policy needs highlighted above.

We present results of a new AFOLU emission database developed at FAO, providing a complete and coherent time series of emission statistics over a reference period 1961–2010, at country level, based on FAOSTAT activity data and IPCC Tier 1 methodology.

2. Materials and methods

Anthropogenic emissions of greenhouse gases can be estimated in isolation or via combinations of complementary approaches (Montzka *et al* 2011): (i) inventory-based, bottom-up accounting based on statistical compilation of activity data and regional emission factors; (ii) atmospheric-based, top-down accounting using global mixing ratios and inversion modeling; and (iii) process-based approaches, based on dynamic modeling of underlying processes, with specific rules for scaling-up in space and time.

In order to compile a global GHG emissions database with regional detail, all three methods can and have been used (e.g., IPCC 2006, Crutzen *et al* 2007, Montzka *et al* 2011). However, in order to address sectoral and regional contributions, including in particular with national-level details, methods under (ii) are unsuitable. For national-level reporting of GHG emissions to the UNFCCC, IPCC guidelines (IPCC 1996, 2000, 2003, 2006) indeed endorse a range of methodological approaches specified under (i) and (iii) above, i.e., from simple bottom-up methods (i.e., Tier 1) to more complex procedures, often involving process modeling and rules for scaling-up in time and space (Tier 2 and Tier 3). More specifically, Tier 1 approaches provide for simple estimations, based on generalized emission factors and other parameter values that are specified either globally or regionally. Tier 2 approaches use more specific national values. Tier 3 approaches typically estimate national-level emissions via aggregation of more detailed geo-spatial information.

We developed a global emission database with country-level detail, using activity data from the FAOSTAT database (FAO 2012a) and Tier 1 IPCC methodology. The reason for our choice was as follows. First, it allows the use of activity data (e.g., crop area, yield, livestock heads, etc) that are collected by member countries, typically via National Agriculture Statistical Offices, and reported officially to FAO. This process results in an internationally approved, coherent data platform covering key information on inputs, production, costs and socio-economic indicators, trade and food balances, for a large range of agriculture and forestry products worldwide. The FAOSTAT database is

used widely in peer-reviewed literature, as the basis for many AFOLU-related analyses, from global agriculture perspective studies (e.g., Foley *et al* 2011) to land use change assessments and carbon cycle studies (i.e., Friedlingstein *et al* 2011). Secondly, the use of Tier 1 factors, while generating data with higher uncertainty compared to higher Tiers, allows for the construction of a database where every country is treated equally, so that emission data and their trends can be better compared. This is the same approach followed by the IEA database. By contrast, the UNFCCC GHG database, which provides emissions data communicated by member countries, consists of a range of approaches at various Tiers.

We applied basic, standard IPCC default equations for assessing bottom-up, country-level GHG emissions. Using IPCC guidelines and a Tier 1 approach (IPCC 2006) we computed, for each sector:

$$\text{Emission} = \text{EF} * A \qquad (1)$$

where: emission = greenhouse gas emissions; EF = emission factor; and A = activity data. Specifically, IPCC Tier 1 emission factors, for each emission category, were assigned to countries in the database depending on geographic location or development status, following IPCC (2006) guidelines. The activity data and the range of IPCC EF values used in the database is shown in table 1. Emissions from agriculture were computed for nearly 200 countries for the reference period 1961–2010. Specific methodological choices for each of the sub-categories considered: enteric fermentation; manure; synthetic fertilizers; rice; and deforestation, are described below.

Enteric fermentation. Emissions from enteric fermentation were computed at Tier 1 level, using national-level statistics of animal numbers reported to FAOSTAT.

Manure. Emissions from manure N applied to cropland as organic fertilizer, left on pasture by grazing animals, or processed in manure management systems, were computed at Tier 1 level, using statistics of animal numbers reported to FAOSTAT for estimating both N_2O and CH_4 emission components. For N_2O emissions, a complex set of intermediate datasets was generated as per IPCC guidelines: manure N excretion rates; manure fractions disposed to different manure management systems; manure fractions left on pasture; manure management system losses; and manure N application rates to cropland as organic fertilizer. The values of the intermediate datasets were animal and region specific. Indirect N_2O emissions related to volatilization and leaching processes of manure N management were also computed, following equation (1) and the relevant IPCC emission factors (IPCC 2006). Estimates of CH_4 emissions from specific manure management systems require use of average annual temperature by country, and thus, in an exception to the general Tier 1 approach followed in the database, a higher Tier approach since IPCC guidelines provide no such data as default. As an exception to the database Tier1/FAOSTAT approach, this information was instead obtained from the FAO global agro-ecological zone database (FAO 2012b).

Synthetic fertilizer. Emissions from use of synthetic fertilizers were computed at Tier 1 level, using FAOSTAT fertilizer consumption statistics by country. This was the only category where, following IPCC guidelines, a single emission factor was used for all regions to estimate direct N_2O emissions. Indirect emissions due to volatilization and leaching were also included in our estimates.

Rice. Emissions from rice cultivation were computed at Tier 1 level, using FAOSTAT statistics of harvested rice area and a regional-level distribution of rice management types and emission factors from the 1996 IPCC guidelines.

Deforestation. Country-level emissions from net forest conversion—defined as afforestation minus deforestation—were computed at Tier 1 by using data on net forest area change in FAOSTAT. This area was multiplied by country-level averages of total carbon content in living forest biomass. The latter data is a Tier 2–3 assessment of biomass carbon stocks provided by member countries to FAO via the Forest Resource Assessment (FRA) (FAO 2010). Emissions from net source countries were aggregated globally, to estimate global carbon loss from net deforestation, while those from net sink countries were aggregated separately to estimate a carbon sink from net afforestation. Losses and gains thus computed were considered to be instantaneous at the time of the reported land use changes, as per IPCC guidelines (IPCC 2006). It should be noted that carbon losses from deforestation as well as gains from afforestation are underestimated by using FAOSTAT data for net area changes. Indeed, any afforestation activity in a net source country will imply greater deforestation rates than the net values derived herein; likewise, a net sink country may still have undergone some deforestation, resulting in actual larger afforestation rates than the net values imply. Using data from 2005 (FAO 2010) with a detailed breakdown of deforestation and afforestation activities within most countries, we estimated that actual deforestation rates in 2005 were about 20% larger than those estimated herein as net deforestation. The net global atmospheric signal derived by summing sinks and sources is, however, accurate. Such estimates are used routinely for global carbon balance assessments (e.g., Houghton *et al* 2012).

Uncertainty. Finally, we followed the IPCC 2006 Guidelines (2006) to compute national-level uncertainty figures indicating, for each emitting category, the 95% confidence interval around emission estimates. To this end, we used default IPCC uncertainty values for activity data, parameters and emission factors contributing to a given emission category, as well as applied default IPCC formulas for estimating error propagation of emissions within a country and at the global level.

This letter reports on GHG emission estimates already completed within FAOSTAT for nearly 200 countries, covering over 80–85% of total agriculture emissions and 65% of FOLU emissions, as reported by IPCC 2007 (Smith *et al* 2007). Emissions of non-CO_2 gases (CH_4 and N_2O) from agriculture (1961–2010) refer to enteric fermentation, manure management systems; synthetic fertilizers, manure applied to soils and left on pastures; crop residues; rice cultivation (table 1). Emissions of CO_2 from FOLU refer to

Table 1. AFOLU activity data and emission factors used in the FAOSTAT database.

Emission category	Gas	Activity data[a]	Emission factors (EF)[b]		EF unit	EF source[c]
			Agriculture			
Enteric fermentation	CH_4	Stocks (heads)	Dairy cattle	42–128	kg CH_4/head/yr	Tab.10.10
			Non-dairy cattle	27–60		Tab.10.10
			Buffalo	55		Tab.10.11
			Sheep/goats	5–8		Tab.10.11
			Camels	46		Tab.10.11
			Mules/asses/horses	10–18		Tab.10.11
			Pigs	1–1.5		Tab.10.11
			Llamas	8		Tab.10.11
Rice cultivation	CH_4	Area harvested (ha)	Rice, paddy	10–27.5	g CH_4 m^{-2} yr^{-1}	Tab.4.13 (IPCC 1996)
Manure management	CH_4	Stocks (heads)	Dairy cattle	1–93	kg CH_4/head/yr	Tab.10.14
			Non-dairy cattle	0–13		Tab.10.14
			Buffalo	1–9		Tab.10.14
			Sheep	0.10–0.37		Tab.10.15
			Goats	0.11–0.26		Tab.10.15
			Camels	1.28–3.17		Tab.10.15
			Mules/asses	0.6–1.52		Tab.10.15
			Horses	1.09–3.13		Tab.10.15
			Market swine	0–45		Tab.10.14
			Breeding swine	0–37		Tab.10.14
			Poultry	0.01–0.09		Tab.10.15
	N_2O (direct)	Manure N (t N yr^{-1})	Manure	0–0.02	kg N_2O–N/kg N	Tab.10.21
	N_2O (indirect)		Volatilization	0.01	kg N_2O–N/kg N	Tab.11.3
			Leaching	0.0075	kg N_2O–N/kg N	Tab.11.3
Synthetic fertilizers	N_2O (direct)	N Consumption (t N yr^{-1})	Soil	0.01	kg N_2O–N/kg N	Tab.11.1
	N_2O (indirect)		Volatilization	0.01	kg N_2O–N/kg N	Tab.11.3
			Leaching	0.0075	kg N_2O–N/kg N	Tab.11.3
Manure applied to soils	N_2O (direct)	Manure N (t N yr^{-1})	Soil	0.01	kg N_2O–N/kg N	Tab.11.1
	N_2O (indirect)		Volatilization	0.01	kg N_2O–N/kg N	Tab.11.3
			Leaching	0.0075	kg N_2O–N/kg N	Tab.11.3
Manure left on pasture	N_2O (direct)	Manure N (t N yr^{-1})	Dairy, non-dairy, buffalo, poultry and pigs	0.02	kg N_2O–N/kg N	Tab.11.1
			Sheep and 'other animals'	0.01		
	N_2O (indirect)		Volatilization	0.01	kg N_2O–N/kg N	Tab.11.3
			Leaching	0.0075	kg N_2O–N/kg N	Tab.11.3
Crop residues	N_2O (direct)	Residues N content (t N yr^{-1})	Crops	0.01	kg N_2O–N/kg N	Tab.11.1
	N_2O (indirect)		Leaching	0.0075	kg N_2O–N/kg N	Tab.11.3
Cultivated organic soil						

Table 1. (Continued.)

Emission category	Gas	Activity data[a]	Emission factors (EF)[b]		EF unit	EF source[c]
Burning crop residues						
			Land use			
Forest land	CO_2	Area (1000 ha)	C stock in living forest biomass	3–318	(t C ha^{-1})	FAO (2010)

[a] Derived or calculated from FAOSTAT data.

[b] Ranges of IPCC Tier 1 emission factors applied at country level, with variations due to country regional characteristics, development status, agro-environmental characteristics.

[c] From IPCC Guidelines (2006) unless otherwise specified.

net deforestation (1990–2010). The FAOSTAT database does not include CO_2 emissions or removals from agricultural soil carbon management. These are a far smaller component of total FOLU emissions, are not reported to UNFCCC under current climate agreements, and are typically not included in the regional or global estimates discussed herein.

The FAOSTAT GHG database does not yet include two non-CO_2 emission categories otherwise reported in IPCC (2007)—biomass burning and drained organic soils. For one, they require information currently not available in FAOSTAT, as well as detailed spatial analyses beyond a simple Tier 1 approach. Secondly, the input data for analysis that are available in the literature are sparse and quite uncertain (e.g., Houghton *et al* 2012).

These two emission categories were estimated herein only at global level, in order to allow for a full comparison with IPCC and other available data. Specifically, global non-CO_2 emissions from drained organic soils under cropland were estimated to be in the range 0.2–0.4 GtCO$_2$eq yr^{-1}, based on recent figures for the 2005 area of drained organic soils (FAO 2012a) and the relevant IPCC Tier 1 emission factor (IPCC 2006). Likewise, global non-CO_2 emissions from biomass burning were estimated to be in the range 0.60–0.75 GtCO$_2$eq yr^{-1}, using the 2005 emission range reported by IPCC AR4 (i.e., 12% of total agricultural emissions 5.1–6.1 GtCO$_2$eq yr^{-1}) (Smith *et al* 2007). Both estimates were applied to the period 2005–10.

Finally, the FAOSTAT emissions data for key emission categories were compared to existing databases, with total or partial coverage of AFOLU. The databases available for comparison were those from EPA (2006), EPA (2012) and the JRC/PBL Emissions Database for Global Atmospheric Research (EDGAR) (2012). These databases are likewise built following a Tier 1 methodology. Their structure and coverage were summarized by Winne (2009). Comparisons were also made using national communication data to UNFCCC (2012).

3. Results

The GHG emission data presented herein cover the period 1961–2010, at country level, based on a single, coherent computational platform that links activity data to emissions, based on FAOSTAT analyses and IPCC guidelines. This letter focuses on analyses of temporal emission trends, regional dynamics and comparisons among categories (figure 1). An online version of the FAOSTAT emissions database, allowing for full country-level analysis, is being released near the time of this publication. It is noted that the FAOSTAT emissions database is not a replacement for UNFCCC reporting of its member countries. Rather, the database aims at supporting the international scientific community by providing continuous updates of emission trends from AFOLU sectors, and by providing FAO member countries with a coherent framework for analyses of their emissions baselines and future trends, including the ability to compare across regions and over long time periods, consistently with their internationally reported activity data.

3.1. Global and regional trends in agriculture emissions

Global GHG annual agriculture emissions increased on average by 1.6% yr^{-1} from 1961 to 2010, reaching 4.6 GtCO$_2$ yr^{-1} in 2010 (table 2) for the categories computed herein (and up to 5.4–5.8 GtCO$_2$ yr^{-1} in 2010, if preliminary estimates of emissions from biomass burning and organic soils are included). Over the same period, crop, milk and meat production increased on average 2.2%–6.4% annually (FAO 2012a), implying a significant reduction—up to three times better—in the carbon intensity of agricultural production. At the same time, carbon emissions from fossil fuel and cement manufacture increased at more than three times the rate of those from agriculture, on average 5.2% annually (CDIAC 2012).

In 2010, as during the period 2000–2010, the largest contributor to agriculture emissions was enteric fermentation, responsible for nearly 40% of total emissions, followed respectively by emissions from manure left on pasture, synthetic fertilizer use, biomass burning, rice cultivation and manure management systems. N_2O emissions from organic soils, crop residues and manure applied to soils represented together only 10% of the total (figure 1).

Under the UNFCCC reporting framework, N_2O emissions from agricultural soils, including emissions from synthetic fertilizers, manure and crop residues, are treated as a single reporting category. To this end, our estimates indicate a total contribution of agricultural soils of 37% in 2010,
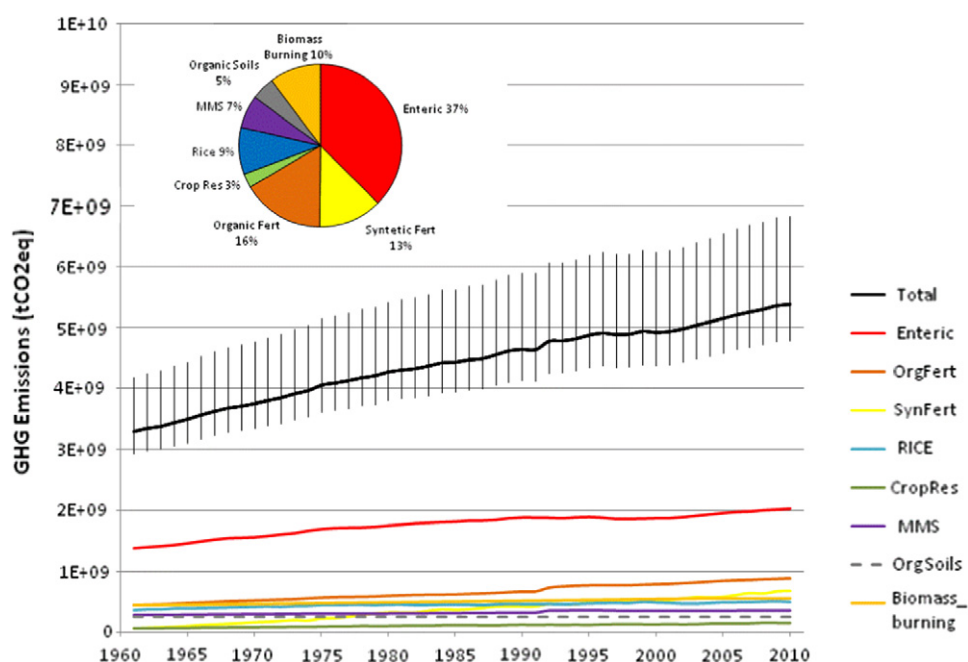
Figure 1. Global emissions for the main agriculture categories, relative to the period 1961–90. Error bars represent 95% confidence intervals, computed using IPCC Guidelines (2006) on uncertainty estimates. The pie chart inset indicates per cent contribution of each category to total emissions from agriculture for the end year 2010.

Table 2. FAOSTAT AFOLU emissions data (MtCO$_2$eq yr^{-1}). Fossil fuel and cement emissions data (CDIAC 2012) are provided for comparison.

Agriculture category	1961	1990	2000	2005	2010
Enteric fermentation	1 375	1 875	1 863	1 947	2 018
Manure left on pasture	386	578	682	731	764
Synthetic fertilizer	67	434	521	582	683
Rice cultivation	366	466	490	493	499
Manure management	284	319	348	348	353
Crop residues	66	124	129	142	151
Manure applied to soils	59	88	103	111	116
Total	2 604	3 883	4 136	4 354	4 586
Net deforestation		4 315	4 296	3 397	3 374
Combined total		8 198	8 432	7 751	7 960
Fossil fuel and cement	9 460	22 554	24 750	29 649	33 509

similar to that of enteric fermentation. A number of alternative aggregations to those indicated by IPCC are possible. For instance, a category 'manure,' defined as the aggregate of emissions from manure left on pastures by grazing animals, manure applied to soils as organic fertilizer, and manure treated in management systems, would represent in our database 23% of total emissions from agriculture. Importantly, a category 'livestock,' defined as the sum of emissions from enteric fermentation and manure emissions, plus emissions from cropland related to feed[4], would represent over 80% of total agriculture emissions, in line with recent estimates (FAO 2008, Leip *et al* 2010), and highlighting the fact that

emissions related to direct human consumption of food crops contribute only 20% of the total. We next offer a more detailed description of the major emission categories for agriculture, with reference to tables 2, 3 and figure 3.

3.1.1. Enteric fermentation. Global emissions in this key category—the largest in agriculture, as discussed—grew from 1.3 to 2.0 GtCO$_2$eq yr^{-1} during the period 1961–2010, with average annual growth rates of 0.95%. During the 1990s emission growth slowed down compared to the long-term average, but picked up again since the year 2000. In 2010, over 1.5 GtCO$_2$eq yr^{-1} were emitted in developing countries, or 75% of the total. Averaged over the period 2000–2010, Asia and the Americas were the largest contributors, followed by Africa and Europe (table 3). Emissions growth rates were

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[4] Computed as the ratio of feed to food for cereal production, or roughly 45% over 2005–10 (FAOSTAT 2012; FAO 2012a).
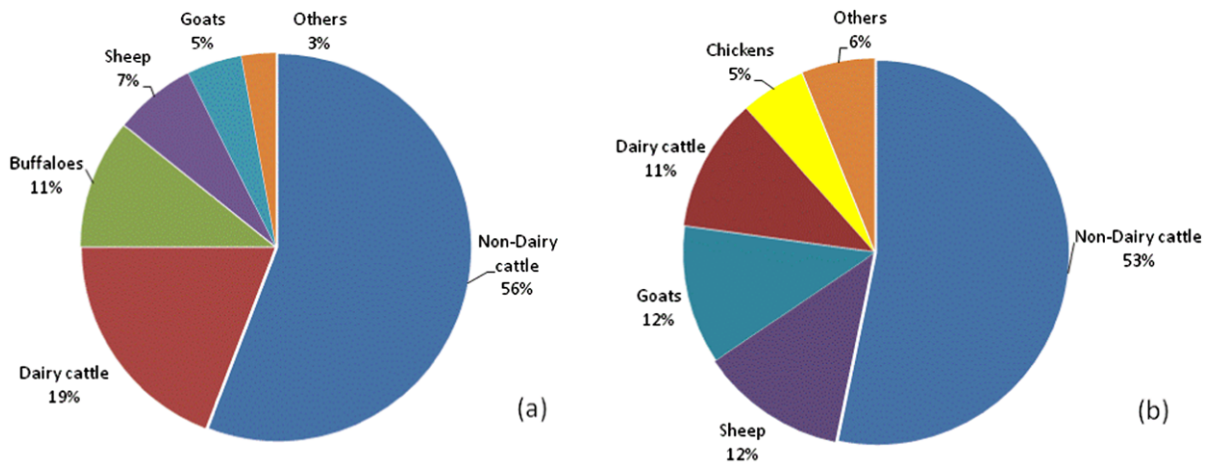
Figure 2. Break down of global emissions by animal type, averaged over the period 2000–2010, for (a) enteric fermentation; and (b) manure left on pasture.
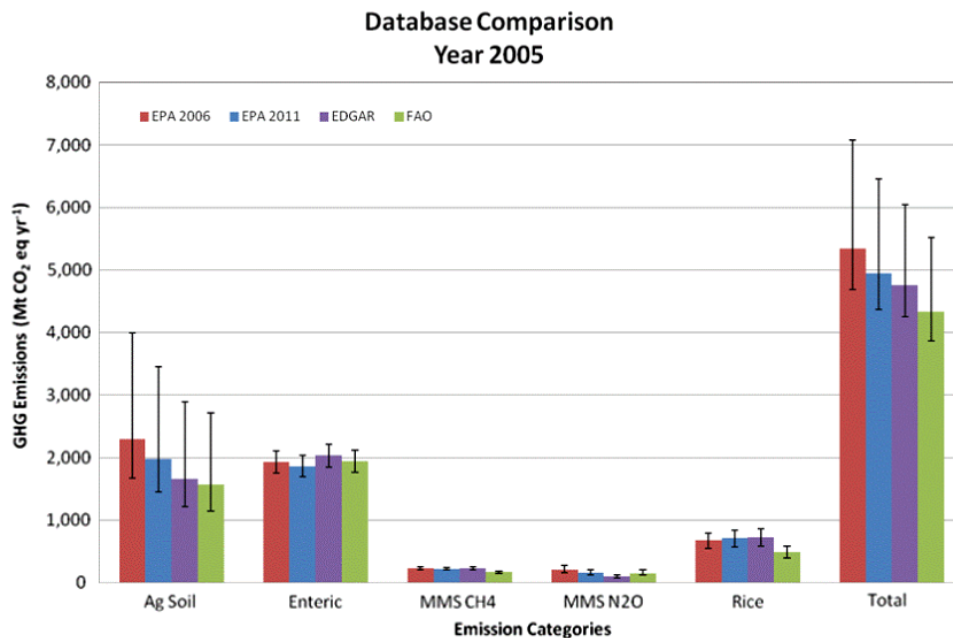

Figure 3. Data comparison between FAOSTAT, EPA and EDGAR databases for key agricultural emission categories, grouped as: agricultural soils, enteric fermentation, manure management and rice cultivation, for 2005. Error bars represent 95% confidence intervals of global aggregated categories, computed using IPCC Guidelines (2006) on uncertainty estimates.

largest in Africa, on average[5] 2.4% yr^{-1}. In both Asia and the Americas emissions grew at a slower pace (1–1.2% yr^{-1}), while they decreased in Europe (-1.7% yr^{-1}). Indeed, in the previous decade 1990–2000, Europe's contribution had been larger than Africa's. Over the period 2000–2010, emissions were dominated by cattle, responsible for three-fourths of the total, followed by buffaloes, sheep and goats (figure 2(a)).

3.1.2. Manure. Global emissions from manure N applied to soils—organic fertilizer on cropland or left on pasture—grew during the period 1961–2010 from 0.44 to 0.88 GtCO$_2$eq yr^{-1}. Average annual growth rates were

2% yr^{-1}, with a slow-down in recent decades. Emissions from manure left on pasture were far larger than those from manure applied to soils as organic fertilizer (figure 1 and table 2), with 80% coming from developing countries. During the period 2000–2010, the Americas, Asia and Africa were the largest contributors (table 3). Growth rates over the same period were largest in Africa, on average 2.4% yr^{-1}. Emissions grew at a slower pace in both Asia and the Americas (about 1.5% yr^{-1}), while they decreased in Europe (-1.4% yr^{-1}). Grazing cattle was responsible for two-thirds of the total, followed by sheep and goats (figure 2(b)). By contrast, over the same period 2000–2010, emissions from manure applied to soils as organic fertilizer were larger in developed compared to developing countries. Largest emitters were Europe, followed by Asia

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[5] Regional values are reported statistically, as least-square growth rates.

Table 3. FAOSTAT emissions database. Per cent average contribution by continent to global emissions (MtCO$_2$eq yr^{-1}), over the period 2000–2010.

Agriculture category	Africa (%)	Americas (%)	Asia (%)	Europe (%)	Oceania (%)	World
Enteric fermentation	14	34	36	12	4	1939
Manure left on pasture	25	33	31	5	6	725
Synthetic fertilizer	3	20	61	14	1	600
Rice cultivation	4	5	89	1	1	490
Manure management	4	27	36	30	3	349
Crop residues	6	28	46	18	2	141
Manure applied to soils	3	28	28	40	1	110
Total agriculture	12	27	45	13	3	4354
Net deforestation	32	60	4	0	4	3500

and Americas (table 2). Africa contributed little to the total, albeit with robust growth rates of 3.4% yr^{-1}. Swine and cattle contributed 95% of the total. Compared to manure applied to soils, emissions from manure management grew more slowly, i.e., from 0.28 to 0.35 GtCO$_2$eq yr^{-1} during the reference period 1961–2010, with average annual growth rates of only 0.5% yr^{-1}. Over the period 2000–2010, emissions were dominated by Asia, Europe and the Americas (table 3).

3.1.3. Synthetic fertilizer. Emissions from synthetic fertilizers had the largest absolute growth rates. They grew on average 19% yr^{-1} during the reference period 1961–2010, specifically more than ten times, i.e., from 0.07 to 0.68 GtCO$_2$eq yr^{-1}. Growth slowed down in recent decades, to about 2% yr^{-1}. At the current pace, emissions from synthetic fertilizers will overtake those from manure left on pasture within a decade—becoming the second largest agriculture emission category after enteric fermentation. In 2010, 70% of emissions from synthetic fertilizer were from developing countries. On average during the period 2000–2010, Asia was by far the largest emitter, followed by the Americas and Europe (table 3). Emissions growth rates over the same period were robust in Asia (5.3% yr^{-1}) and Europe (1.7% yr^{-1}), but negative in Africa (−3.3% yr^{-1}). Emissions and application of synthetic fertilizers had a year-on-year drop in 2008 in some regions, specifically −4.4% (Europe) and −9.8% (Americas).

3.1.4. Rice. During the reference period 1961–2010, global emissions grew slowly, from 0.37 to 0.49 GtCO$_2$eq yr^{-1}, with average annual growth rates of 0.7% yr^{-1}. It should be noted that while our emissions estimates are lower than other existing databases (i.e., see figure 3), they are more consistent with recent assessments (Yan *et al* 2009). Global emission growth slowed down in recent decades, consistently with trends in rice cultivated area, and even decreased on a year-on-year basis in several years during the period 2000–2010. Emissions from rice were dominated by developing countries, which contributed over 94% of emissions during 2000–2010. Asia was responsible for almost 90% of the total (table 3). Emissions growth rates were nonetheless largest in Africa (1.8% yr^{-1}), followed by Europe (1.4%). Growth rates in Asia and the Americas were much smaller over the same period (0.2% yr^{-1}).

3.1.5. Global and regional trends in emissions from net deforestation. Global carbon emissions from net deforestation during the period 1990–2010 decreased to 3.4 GtCO$_2$eq yr^{-1}, in line with findings in recent literature (see, e.g., Friedlingstein *et al* 2011). Average growth rates were −2.3% yr^{-1} over the same period. During the most recent decade, 2000–2010, carbon emissions from net deforestation were largest in the Americas and Africa (table 3). The largest estimated decrease in emissions was in Asia (−18% yr^{-1}), followed by the Americas (−2.9% yr^{-1}) and Africa (−0.2% yr^{-1}). By contrast, emissions from net deforestation grew significantly in Oceania (+45% yr^{-1}), largely due to the contribution of Papua New Guinea.

4. Discussion

The FAOSTAT Emissions database presented herein allows for estimates of GHG emissions from all major agricultural activities, consistently with basic agriculture and land use activity data reported at national level by FAO member countries. A number of limitations apply to the data presented herein. First, we followed IPCC guidelines developed for the period 1990–2010 to also derive emissions for previous decades. A few key emission categories are largely unaffected by this choice, i.e., emissions from synthetic fertilizers and rice cultivation, which depend on physical processes and associated emission factors that do not change in time. By contrast, emission factors linked to specific livestock parameters, of importance to computing emissions from manure and enteric fermentation, were likely different in many regions in earlier decades compared to the period 1990–2010, due to the introduction of new breeds and more efficient production methods. Comparison of IPCC emission factors for developed and developing regions can be used as a proxy for such changes; they indicate that—while production efficiencies improve—GHG emissions per animal tend increase when moving from traditional to market oriented production system. This implies that our GHG estimates for categories linked to animal manure and enteric fermentation are likely overestimates prior to 1990, so that actual long-term average growth rates in these categories may have been larger than reported herein. Second, the database presented here is based on Tier 1 default IPCC methodology. While this approach is at the basis of building a

coherent database, allowing for comparisons across countries and regions—indeed, global and regional emission figures in the IPCC Assessment Report 2007 (Smith *et al* 2007) are also based on Tier 1 approaches—more refined computational methods could be used to reduce uncertainty of our estimates. To this end the IPCC Guidelines (2006) suggest that moving form Tier 1 to higher Tiers may lead to a 10–20% decrease in the uncertainty of national emission factors associated to the physical processes involved. However it should also be highlighted that complex, landscape dynamic models typically used in Tier 2–3 assessments also carry uncertainties, for instance related to spatial and temporal aggregation schemes, applicability ranges, etc. We have performed initial comparisons of the FAOSTAT emissions data (Tier 1) with the corresponding UNFCCC Annex I developed countries GHG data (largely Tier 2–3), and found small, often statistically non-significant differences between the two sets of data. Further investigations will be carried out in future work.

Within the limitations discussed above, the FAOSTAT data we presented are an improvement over existing databases, in that they offer a coherent framework for analyses of both activity data and emission estimates across time and space, at country level, within a unified data platform. The dataset can be updated annually from FAOSTAT data. As a first example of the database applications, we estimated total emissions from agriculture to be 4.6 $GtCO_2eq\ yr^{-1}$ in 2010. Combined with global estimates of biomass burning and degraded organic soils, emissions ranged 5.4–5.8 $GtCO_2eq\ yr^{-1}$ in 2010, from 5.2–5.6 $GtCO_2eq\ yr^{-1}$ in 2005. These estimates are fully consistent with the emission range provided by IPCC (2007). We further compared the sectoral estimates of the FAOSTAT GHG database for 2005 to available global data from EPA (2006, 2012) and EDGAR (2012), noting that the data from EPA (2006) were used for summary graphs in the agriculture chapter of IPCC (2007), while data from EDGAR (2012) are currently being used to produce summary graphs for IPCC AR5 (figure 3). These comparisons indicated that, within the uncertainties discussed, the FAO and EDGAR databases estimate lower GHG emissions compared to EPA for the 'agriculture soils' category. FAO estimates for methane emissions from rice, as already noted, are lower than both EPA and EDGAR.

While it is tempting to also assess the share of emissions from agriculture and deforestation to the total anthropogenic forcing, we note that estimates of total anthropogenic GHG emissions are quite uncertain (see e.g., Montzka *et al* 2011), because they depend on summing a fairly robust set of data—global carbon emissions from fossil fuel use and cement manufacture, plus non-CO_2 gases mostly from industrial production—to a highly uncertain one, related to agriculture, forestry and land use changes. We therefore chose to more simply compare total emissions from agriculture (without contributions from biomass burning and organic soils) and from net deforestation to CO_2 global emissions from fossil fuel use and cement manufacture (Andres *et al* 2012).

We find that over the reference period 1961–2010 considered, agriculture emissions grew at average annual increases of 1.6% yr^{-1}, compared to 5.2% yr^{-1} for fossil fuels

and cement (see table 2). As a result, the ratio of agricultural emissions to fossil fuel emissions has continuously decreased during the period 1961–2010, from 27.5% in 1961 to 13.7% in 2010. For the more recent period 1990–2010, agriculture GHG emissions declined from 17.2% to 13.7%, while emissions from deforestation declined from 19.1% to 10.1% of those from fossil fuels. While emissions from agriculture were smaller than those from net deforestation in 1990, they became the larger source since the year 2000. In the year 2010, emissions from agriculture were about 35% larger than those from net deforestation, i.e., 4.6 $GtCO_2eq\ yr^{-1}$ compared to 3.4 $GtCO_2eq\ yr^{-1}$.

Finally, we note that the aggregated AFOLU emissions estimated in the FAOSTAT database decreased over the period 1990–2010, from 8.2 $GtCO_2eq\ yr^{-1}$ to 8.0 $GtCO_2eq\ yr^{-1}$ (table 2). This was due to the discussed decline in net deforestation emissions after the year 2000. Robust, continuous growth in agriculture emissions has nonetheless led to renewed growth of total AFOLU emissions since 2005.

5. Conclusions

In this letter we provided details of a new and robust database of agriculture emissions, based on common FAOSTAT activity data and IPCC Tier 1 default emission factors. The approach ensures consistency with previous global and regional estimates, as well as comparability across regions and time, for the 1961–2010 reference period. Recognizing that countries report their emission data to UNFCCC with a range of nationally validated approaches, the FAOSTAT emissions database could nonetheless represent a benchmark for data quality control/quality assurance, aimed at helping countries fill data gaps and improve analysis, similar to the role of the AIE database with respect to fossil fuel emissions.

Our analyses indicated that AFOLU emissions are increasing, but not as fast as the rate of emissions from fossil fuels, meaning that the ratio of AFOLU to total anthropogenic GHG emissions is declining. Over the same period, agricultural productivity has increased faster than have emissions, showing an improvement in the GHG intensity of agricultural products—though with different rates of progress in different regions. Agricultural emissions from all contributing sectors were found to be increasing, with some faster than others. For example, emissions from synthetic fertilizer application are growing much faster than those from manure. Deforestation emissions, however, are declining. In terms of difference between regions, agricultural emissions in developing countries are increasing at a faster rate than those in developed countries, with some regions (e.g. Europe), showing declines.

Significant data gaps preclude calculation of emissions on an equivalent basis for comparison to other emission categories. These data gaps concern biomass burning, fires and drained organic soils. In this letter, we have used alternative data sources to fill this gap, but a priority should be to improve collection and analysis of data on extent of biomass burning and the extent of drained organic soils, an activity towards which FAOSTAT could contribute via

dedicated questionnaires to member countries and renewed work on geo-spatial data analysis.

The database and approach outlined in this letter is more than an accounting exercise. The outputs provide important information on the key sources of GHG emissions from the AFOLU sector, the regions in which they occur and the rates of change. Wherever greenhouse gas emissions occur, there is potential to reduce emissions, so the outputs of this study can also be used to identify hotspots (in terms of regions and activities) for potential mitigation action. It is in defining the regionally appropriate mitigation actions that we can turn the problems identified in a spatial emissions database into practical solutions (Smith *et al* 2008).

Acknowledgments

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