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The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990–2012

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Abstract

We refine the information available through the IPCC AR5 with regard to recent trends in global GHG emissions from agriculture, forestry and other land uses (AFOLU), including global emission updates to 2012. Using all three available AFOLU datasets employed for analysis in the IPCC AR5, rather than just one as done in the IPCC AR5 WGIII Summary for Policy Makers, our analyses point to a down-revision of global AFOLU shares of total anthropogenic emissions, while providing important additional information on subsectoral trends. Our findings confirm that the share of AFOLU emissions to the anthropogenic total declined over time. They indicate a decadal average of 28.7 ± 1.5% in the 1990s and 23.6 ± 2.1% in the 2000s and an annual value of 21.2 ± 1.5% in 2010. The IPCC AR5 had indicated a 24% share in 2010. In contrast to previous decades, when emissions from *land use* (land use, land use change and forestry, including deforestation) were significantly larger than those from *agriculture* (crop and livestock production), in 2010 agriculture was the larger component, contributing 11.2 ± 0.4% of total GHG emissions, compared to 10.0 ± 1.2% of the land use sector. Deforestation was responsible for only 8% of total anthropogenic emissions in 2010, compared to 12% in the 1990s. Since 2010, the last year assessed by the IPCC AR5, new FAO estimates indicate that land use emissions have remained stable, at about 4.8 Gt CO_2 eq yr^{-1} in 2012. Emissions minus removals have also remained stable, at 3.2 Gt CO_2 eq yr^{-1} in 2012. By contrast, agriculture emissions have continued to grow, at roughly 1% annually, and remained larger than the land use sector, reaching 5.4 Gt CO_2 eq yr^{-1} in 2012. These results are useful to further inform the current climate policy debate on land use, suggesting that more efforts and resources should be directed to further explore options for mitigation in agriculture, much in line with the large efforts devoted to REDD+ in the past decade.

Keywords: AFOLU, Agriculture, Climate Change, Emissions, GHG, Mitigation

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Introduction

Agriculture, Forestry and Other Land Use (AFOLU) activities generate greenhouse gas emissions by sources as well as removals by sinks, through the oxidation and fixation of organic matter *via* photosynthesis, followed by loss from decomposition and fire, including complex microbial processes associated with human management and disturbance of ecosystems. Agriculture activities emit mainly non-CO_2 gases (CH_4 and N_2O), while land use and land-use change activities emit and remove mainly CO_2 gas.

Assessing historical and current trends of AFOLU emissions, including *agriculture* (crop and livestock production) and *land use* (land use, land use change and forestry) dynamics at global and regional level, is important both for science and climate policy. On the science side, better data help to characterize anthropogenic forcing of the atmosphere, while providing useful

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constraints to carbon cycle assessments. On the climate policy side, better data provide support for concerted global action, allowing for transparent exchange of information between parties, based on more accurate greenhouse gas inventories for reporting under the United Nations Convention on Climate Change (UNFCCC). More reliable data, for instance, provided the operational basis for implementation of the Kyoto Protocol's first commitment period, the adoption of the Bali Action Plan and the Cancun Agreements. Better AFOLU data specifically contributed to raising awareness on the need to reducing emissions from deforestation and forest degradation (REDD+) (FAO, 2011). Indeed, early quantifications of the share of deforestation to total anthropogenic emissions helped to make the case for forests and the land use sector being as an effective, short-term climate change mitigation option, compared to more complex and costly long-term measures in other sectors, including agriculture (Stern, 2007).

Despite the high relevance of this information, quantification of AFOLU emission sources and sinks remains uncertain, even at the global level. The recent IPCC WGIII Summary for Policy Makers (SPM) states that AFOLU contributed 24% of total anthropogenic emissions in 2010 (IPCC, 2014). This estimate, however, was based on only one of three global emission data sources available in the IPCC AR5 WGIII AFOLU chapter. These included the EDGAR database, which was the single data source used in the IPCC AR5 SPM, and additionally the FAOSTAT database and the Houghton dataset (Smith *et al.*, 2014).

We show in this paper that different absolute values and relative shares of emissions from agriculture and land use are obtained by integrating valuable information from the FAO and Houghton's available estimates, in addition to EDGAR.

Materials and methods

Three global AFOLU datasets used in the IPCC WGIII chapter 11 (Smith *et al.*, 2014) are considered herein: EDGAR (2013), FAOSTAT (2014) and the bookkeeping method of Houghton *et al.* (2012). These data sources robustly represent the range of AFOLU data used in the IPCC AR5 WGIII for global and regional emission analyses. Specifically, EDGAR data were used as a reference for estimating total anthropogenic emissions and performing cross-sectoral synthesis, while Houghton's and FAO data were used for more in-depth analyses of the AFOLU sector. Three data combinations were considered herein as follows: (i) EDGAR only (E); (ii) FAOSTAT only (F); and (iii) FAOSTAT for agriculture and peat degradation and fire, plus Houghton for forest and land use change (H). The three combinations correspond to data analyses reported in the IPCC AR5 WGIII SPM (E) and in the IPCC AR5 WGIII Ch. 11, Section 11.2.2 (F) and 11.2.3 (H).

The FAOSTAT Emissions database covers all agriculture, forestry and other land use activities and their associated emissions of CO_2, CH_4 and N_2O, following IPCC, 2006 Guidelines at Tier 1 and land approach 1 (Tubiello *et al.*, 2013; FAO, 2014). Emissions are estimated for nearly 200 countries, for the reference period 1961–2012 (agriculture) and 1990–2012 (FOLU), based on activity data collected by FAO. Emissions and removals are calculated both within and across land categories, including effects of crop and livestock management, land use and land conversion. FAOSTAT includes estimates of emissions from biomass fires, peatland drainage and fires, based on geo-spatial information, as well as forest carbon stock changes based on national-level FAO Forest Resources Assessment data (FAO, 2010). FOLU carbon balances in FAOSTAT should only be intended as first-order estimates of underlying complex dynamics arising from afforestation/reforestation, degradation, regrowth and harvest activities. The FAOSTAT emission estimates are at the basis of regular FAO annual emission updates for AFOLU (FAO, 2014).

The EDGAR database covers all IPCC sectors (energy, transport, industry, buildings, and AFOLU), applying IPCC guidelines for emission estimation (EDGAR, 2013). Several methodological differences with FAOSTAT and Houghton exist, which result in differences in emission estimates. The latter are quantified in the results section below. Methodological differences are as follows: First, for agriculture, EDGAR follows the Revised 1996 IPCC Guidelines rather than the 2006 IPCC Guidelines used by FAOSTAT, with repercussions that will be discussed in the results section. Second, and more importantly, for FOLU, EDGAR does not follow either IPCC Guidelines or standard carbon cycle approaches (Le Quéré *et al.*, 2013), in contrast to the FAOSTAT and Houghton data.

Specifically, EDGAR emission estimates for forest and forest conversion, the largest component of FOLU emissions, are termed collectively *Forest Fires and Decay*. While the associated sub-category *Forest Fires* contains data taken directly from the *Global Fire Emissions Database* (GFED version 2; Van der Werf *et al.*, 2006), the interpretation of the *Forest Decay* emission estimates is more difficult, due to lack of transparent information in the relevant EDGAR literature and associated metadata. Apparently the EDGAR *Forest Decay* category refers to emissions from the decay of dead biomass left over after fire damage. These are used as proxy to subsequently estimate overall land use and land use change emissions from forestland, by applying unpublished scaling factors directly to the relevant GFED forest fire data. Such an approximation is incorrect, because not all carbon losses from deforestation and other forest emissions are necessarily associated with the use of fire.

Another area of inconsistency with both the IPCC guidelines and FAOSTAT, is the fact that EDGAR includes the emissions from energy use in agriculture in AFOLU, while they should be reported in the energy sector.

The Houghton dataset is based on a bookkeeping approach for estimating CO_2 emissions due to land use and land use change, such as deforestation and afforestation, forest degradation, wood harvest and shifting cultivation (Houghton *et al.*, 2012). The method uses parameter values for biomass stock, biomass growth and decay rates, taken from published national inventories and the FAO Forest Resource Assessment (FAO, 2010). In the IPCC AR5, the Houghton dataset provides the basis for the central estimates of FOLU emissions for the carbon budget (Ciais *et al.*, 2013; Smith *et al.*, 2014). Furthermore, this dataset is at the core of the Global Carbon Project's annual carbon emission updates for land use change (Friedlingstein *et al.*, 2011; Le Quéré *et al.*, 2013).

Units

AFOLU activities emit all three major GHGs, as discussed above. The analyses that follow use CO_2 equivalent (CO_2 eq) as a common metric for comparison across emission categories, obtained by using the 100-year global warming potentials specified by the current UNFCCC reporting procedures for national GHG inventories[1] (IPCC, 1997 and 2006).

Uncertainty

While CO_2 emissions related to fossil fuel carry relatively low uncertainties, around ±10%, uncertainties in AFOLU are much larger. Uncertainty for global emission estimates from crop and livestock carry ±30% uncertainty ranges (e.g., Tubiello *et al.*, 2013). Uncertainties in FOLU are even larger, with a ± 50% uncertainty range (Le Quéré *et al.*, 2013; Pongratz *et al.*, 2014). All data presented in this paper are characterized by the above uncertainties. The ranges indicated in the results section below, however, refer to the variability of mean estimates across the three datasets used for analysis, rather than to the above uncertainties.

Results

EDGAR total AFOLU emission estimates were 12.7 Gt CO_2 eq yr^{-1} on average over the period 2000–2009 (2000s hereafter) and 11.9 Gt CO_2 eq yr^{-1} for the year 2010. By contrast, estimates made with FAOSTAT and Houghton data show the same total AFOLU decadal average emissions of 9.9 Gt CO_2 eq yr^{-1} for 2000s and a range of 9.5–10.1 Gt CO_2 eq yr^{-1} in 2010. The two datasets thus exhibit substantial differences with EDGAR, producing estimates that are lower than EDGARs by nearly 3 Gt CO_2 eq yr^{-1} for the 2000s decadal estimates and about 2 Gt CO_2 eq yr^{-1} for 2010.

The aim of this paper is therefore to investigate the reasons for these differences, in an effort to improve the characterization of AFOLU emissions and their contribution to total anthropogenic forcing. We include analysis of recent emission data, published by FAOSTAT and the Global Carbon Project up to the year 2012, to gain further insights into the trends identified by the IPCC AR5 WGIII up to the year 2010.

Differences between EDGAR and FAOSTAT/Houghton

We identified four major differences between EDGAR and FAOSTAT/Houghton, as follows.

First, as discussed in the methodological section above, EDGAR reports excess agriculture emissions, by counting under AFOLU the emissions arising from energy use in agriculture. These represent an excess of 0.6 Gt CO_2 eq yr^{-1} in 2010, which should be subtracted from the 11.9 Gt CO_2 eq yr^{-1}EDGAR estimates published in IPCC AR5 WGIII Section 11.2.2. Reallocation to the energy sector is needed in order to be consistent with existing IPCC guidelines and UNFCCC reporting rules. This results in revised total AFOLU emissions by EDGAR of 11.3 Gt CO_2 eq yr^{-1} in 2010.

Second, additional differences between EDGAR and FAOSTAT agriculture estimates were identified within the IPCC AR5 (Tubiello *et al.*, 2013; Smith *et al.*, 2014). These differences, which are behind the 5.2–5.8 Gt CO_2 eq yr^{-1} emission range identified by the IPCC AR5 WGIII Ch. 11, were further analyzed herein. They arose mainly from rice and savannah burning emission estimates, explaining 0.3 Gt CO_2 eq yr^{-1} and 0.2 Gt CO_2 eq yr^{-1}, respectively, of the 0.6 Gt CO_2 eq yr^{-1} gap between the two databases. Rice differences were explained by the use of different parameters linked to different IPCC Guidelines between EDGAR (IPCC, 1997) and FAOSTAT (IPCC, 2006). Differences in estimates for savannah burning were related instead to different Tier approaches between FAOSTAT and the GFED3 database used by EDGAR (Rossi S, Tubiello FN, Salvatore M, Ferrara A, Rossi S, personal communication).

The third and more significant difference identified between EDGAR, FAOSTAT and the Houghton datasets was in estimated FOLU emissions. These generate a range of emission estimates of 4.2–5.5 Gt CO_2 eq yr^{-1} for the year 2010 (Table 1), with Houghton and EDGAR providing the lower and higher estimates, respectively, and FAOSTAT estimates in the middle of the range. The reason for this large difference across databases, about 1.3 Gt CO_2 eq yr^{-1}, was more difficult to assess compared to those observed for the agriculture sector.

Specifically, while differences between Houghton and FAOSTAT were easily explained by the different Tier approaches between FAOSTAT and the GFED3 database used by Houghton for forest and peat fires (Rossi S, Tubiello FN, Salvatore M, Ferrara A, Rossi S, personal communication), differences between EDGAR and the other two databases could not be resolved. Indeed, IPCC AR5 WGIII Section 11.2.3 had already

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[1] GWP-CO_2 = 1; GWP-CH_4 = 21; GWP-N_2O = 310.

Table 1 Emissions by recent decade and in 2010 (Gt CO_2 eq)

	1990s				2000s				2010			
Database	E	H	F	Mean±SD	E	H	F	Mean ± SD	E	H	F	Mean±SD
Agriculture	5.1	4.6	4.6	4.8 ± 0.3	5.5	5.0	5.0	5.1 ± 0.3	5.8	5.2	5.2	5.4 ± 0.3
FOLU	6.8	6.6	5.7	6.4 ± 0.6	6.5	4.9	4.9	5.5 ± 0.9	5.5	4.2	4.9	4.9 ± 0.6
AFOLU	11.9	11.2	10.3	11.1 ± 0.8	12.0	9.9	9.9	10.6 ± 1.2	11.3	9.5	10.1	10.3 ± 0.9

Data sources: E: EDGAR; H: Houghton; F: FAO.

acknowledged the significant differences between EDGAR and FAOSTAT/Houghton for FOLU, noting that the EDGAR estimates could only be considered approximations of overall land-based CO_2 fluxes. Additional analyses we made over a test period 2001–2010, focusing on comparing the EDGAR sub-category *Forest Decay*, and potentially relevant FAOSTAT and Houghton categories net forest conversion and forest carbon stock change, failed to add insight into the observed differences. As discussed in the methodology section, a lack of needed details from published sources for EDGAR limited our ability to tease out plausible explanations for the substantial differences in estimates. This large unexplained gap and the serious methodological issues raised above with regard to the EDGAR category *Forest Decay* suggest that, at a minimum, the EDGAR database should not be used as a single source for analyzing FOLU emissions, as was done instead in the IPCC AR5 SPM.

Aggregate AFOLU emission estimates

Based on the above results and conclusions, we re-estimated total AFOLU emissions and their share to total anthropogenic emissions, by jointly analyzing the three datasets used in IPCC WGIII AR5 (Fig. 1). The aggregated results confirmed the historical AFOLU trends reported by IPCC, while adding new details, as reported below.

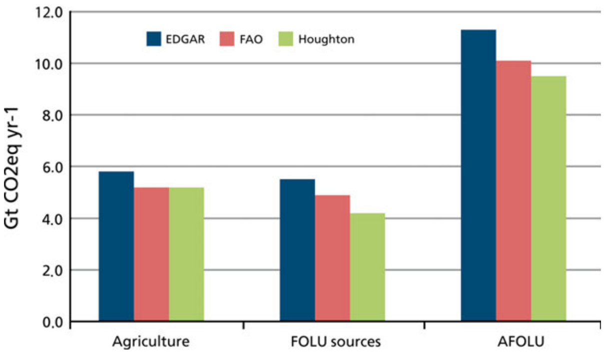

Fig. 1 Total AFOLU emissions, with sub-components, for the year 2010, estimated with the three databases used in IPCC AR5.

Decadal average agriculture emissions grew, from 4.6 to 5.1 (4.8 ± 0.3) Gt CO_2 eq yr^{-1} in the 1990s to 5.0–5.5 (5.1 ± 0.3) Gt CO_2 eq yr^{-1} in the 2000s, reaching 5.4 ± 0.3 Gt CO_2 eq yr^{-1} in 2010 (Table 1). Overall, the results confirmed a growth trend in agriculture emissions of about 1% over the last two decades (FAO, 2014). Recent updates by FAO, to 5.4 Gt CO_2 eq yr1 in 2012, confirm the trends assessed by IPCC until 2010, with emission growth driven primarily by synthetic fertilizer use and livestock (FAOSTAT, 2014).

Decadal average FOLU emissions declined, from a range of 5.7–6.8 (6.4 ± 0.6) Gt CO_2 eq yr^{-1} in the 1990s to a range of 4.9–6.5 (5.5 ± 0.9) Gt CO_2 eq yr^{-1} in the 2000s, reaching 4.9 ± 0.6 Gt CO_2 eq yr^{-1} in 2010 (Table 1). As for agriculture estimates, the three IPCC WGIII sources confirmed a marked decline of FOLU emissions over the last two decades, as already noted in the IPCC AR5, due largely to a slowdown in deforestation rates.

Furthermore, recent FAO updates indicated that total FOLU emissions, as well as emissions from net forest conversion, a proxy for deforestation, remained stable in both 2011 and 2012 at their 2010 levels of 4.8 and 3.8 Gt CO_2 eq yr^{-1}, respectively (FAOSTAT, 2014). The same trend was reflected in recent updates of FOLU emissions minus removals, resulting in a range of 2.9–3.2 Gt CO_2 eq yr^{-1} in 2012 (FAOSTAT, 2014; Le Quere *et al.*, 2014).

As a result of the above opposite trends between agriculture and land use emissions, total AFOLU emissions declined slightly, from 10.3 to 11.9 (11.1 ± 0.8) Gt CO_2 eq yr^{-1} in the 1990s to 9.9–12.0 (10.6 ± 1.2) Gt CO_2 eq yr^{-1} in the 2000s, reaching 10.3 ± 0.9 Gt CO_2 eq yr^{-1} in 2010 (Table 1).

Aggregate AFOLU share of total anthropogenic emissions

Using the above aggregate AFOLU emission results, together with EDGAR's estimates of non-AFOLU sectors, we produced three different estimates of total anthropogenic emissions, corresponding to a range of

Table 2 Share of AFOLU and its sub-components to total anthropogenic emissions, by decade and for 2010

	1990s			2000s			2010		
Sector	E (%)	H (%)	F (%)	E (%)	H (%)	F (%)	E (%)	H (%)	F (%)
Agriculture	12.9	11.8	12.1	11.8	11.3	11.3	11.6	11.0	10.8
FOLU	17.1	17.0	15.1	14.2	11.2	11.2	11.1	8.9	10.1
AFOLU	30.1	28.8	27.1	26.0	22.4	22.4	22.8	19.9	20.9

Table 3 Aggregated share of AFOLU and its sub-components to total anthropogenic emissions, using the three main datasets available in IPCC AR5 WGIII

Sector	1990s (%)	2000s (%)	2010 (%)
Agriculture	12.3 ± 0.6	11.5 ± 0.3	11.2 ± 0.4
FOLU	16.4 ± 1.1	12.2 ± 1.7	10.0 ± 1.2
AFOLU	28.7 ± 1.5	23.6 ± 2.1	21.2 ± 1.5

47.7–49.0 Gt CO_2 eq yr^{-1} in 2010. It was thus possible to assess the shares of AFOLU to total anthropogenic emissions, for each of the three databases considered (Table 2). The resulting aggregate analysis confirmed that the share of AFOLU decreased over time, while the use of the three datasets allowed us to further refine the recently published IPCC AR5 findings.

Results (Table 3) indicated that the decadal average share of AFOLU decreased from 28.7 ± 1.5% in the 1990s to 23.6 ± 2.1% in the 2000s and reached an annual value of 21.2 ± 1.5% in 2010, lower than the 24% reported by the IPCC AR5 WGIII SPM. Similarly, results confirmed that both the share of agriculture and FOLU decreased over time (Table 3).

The agriculture share decreased less than the AFOLU aggregate, from a decadal average of 12.3 ± 0.6% in 1990s to 11.5 ± 0.3% in 2000s, reaching an annual value of 11.2 ± 0.4% in 2010.

By contrast, the FOLU share decreased substantially more than the AFOLU aggregate, from a decadal average of 16.1 ± 1.1% in 1990s to 12.2 ± 1.7% in 2000s, reaching an annual value of 10.0 ± 1.2% in 2010. Figure 2 provides a visual representation of the time dependency of these figures. Finally, using the explicit information provided by the FAOSTAT database on net forest conversion, our results further indicated that the share of deforestation to total anthropogenic emissions was a mere 7.9% in 2010, down from 8.6% in the 2000s and 12.0% in the 1990s.

These new results, while confirming findings of the IPCC AR5, including the observed magnitude and decreasing trend of FOLU emissions since 1990, also represent a significant down-revision of previous notable assessments of FOLU and deforestation emissions. For instance, when first proposing avoided deforestation as a cost-effective global mitigation option, Stern (2007) assessed the share of both FOLU and deforestation for the year 2000 at 18%. The IPCC AR4 (IPCC, 2007), based on EDGAR-only data, had likewise estimated a FOLU share of 17.4% for the year 2004.

Discussion

The findings of this work confirm general known trends in AFOLU emissions over the last two decades, but add additional new estimates that further quantify the continuous increase in agriculture emissions and the substantial decrease in emissions from forest and other land use. These absolute trends,

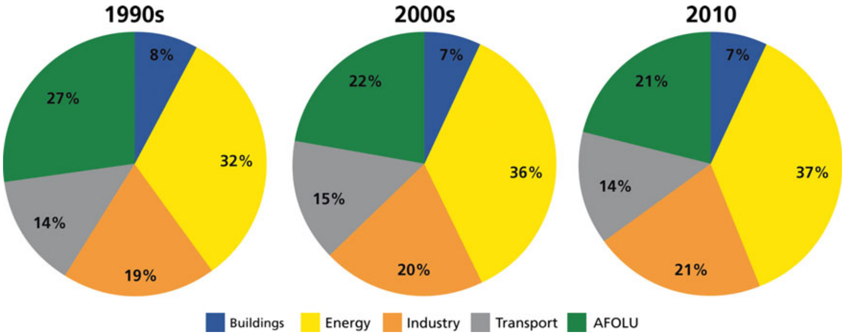

Fig. 2 Historical changes in the share of AFOLU to total anthropogenic emissions, 1990–2010, based on FAOSTAT data for AFOLU and EDGAR data for non-AFOLU sectors.

plus the fact that energy emissions continue to grow faster than those from AFOLU, result in decreasing shares of AFOLU compared to total anthropogenic emissions over time.

By aggregating all three databases available in IPCC AR5 WGIII, this work was able to further refine critical trends in AFOLU. Results indicated that the share of AFOLU emissions to total anthropogenic emissions in 2010 was 21% rather than 24% and that agriculture (11%) has become as large a contributor to global emissions as forest and land use combined (10%). Furthermore, this analysis added new estimates for AFOLU up to the year 2012, confirming trends that the IPCC AR5 had analyzed only until 2010.

Despite the large uncertainties that characterize emission estimates in AFOLU, these findings are important for several reasons.

First, they highlight difficulties in the use of a widely applied database of emission estimates, EDGAR, indicating specific problems in its FOLU emission estimates. As a result, the findings of this work warn against the use of this database as the sole source of FOLU data.

Second, our results show that crop and livestock activities have become the dominant source of AFOLU emissions, indicating the need to increase attention to this sector, in parallel to the ongoing international REDD+ efforts to reduce emissions from deforestation and forest degradation. In fact, a large component of FOLU emissions are in any case driven by agriculture, in particular deforestation and peatland degradation.

In conclusion, the analysis presented herein contributes to the global knowledge base on GHG emissions from AFOLU and points to the importance of developing better integrated and multisource data for an improved understanding of the role that agriculture, forestry and other land use activities can play, under current and future international climate agreements, toward limiting dangerous anthropogenic interference with the climate system.

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