Analysis of global emissions, carbon intensity and efficiency of food production

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. Using data from a new GHG global database developed at FAO, we focus on global indicator trends in the agriculture sectors, in relation to the carbon intensity of key food commodities. In particular, we find that the carbon intensity of meat and milk production decreased significantly over the period from 1961 to 2010, largely due to increases in animal productivity. At the same time, agricultural emissions nonetheless increased by 1.6% annually, reaching 5.4-5.8 Gt CO_2 yr^{-1} in 2010

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Analisi delle emissioni globali di gas serra, intensità di carbonio ed efficienza della produzione alimentare

Le emissioni di gas serra (GHG) dovute a pratiche agricole come, ad esempio, la produzione di raccolti e gli allevamenti di bestiame, la silvicoltura e gli usi del terreno associati, sono responsabili di una importante frazione di emissioni antropogeniche. Utilizzando i dati di un nuovo database globale di emissioni GHG sviluppato alla FAO, riportiamo i risultati di un'analisi globale sulla intensità di carbonio di alcuni prodotti alimentari chiave. In particolare, si è riscontrato che l'intensità di carbonio della produzione di latte e carne è diminuita considerevolmente dal 1961 al 2010, principalmente grazie all'aumento della produttività animale. Durante lo stesso periodo, le emissioni agricole sono comunque cresciute dell'1,6%, raggiungendo 5.4-5.8 Gt CO_2 yr^{-1} nel 2010

Greenhouse gas emissions (GHG) from agriculture, forestry and other land uses (AFOLU) are characterized by large uncertainties, due to several issues. These include, first, gaps in assessing and analyzing critical activity data such as the information related to cropland, grassland and forest management, as well as livestock dynamics and input statistics. Secondly, the biophysical processes responsible for GHG emissions are either poorly understood, requiring too detailed spatial and temporal information and processing, or a combination of both, resulting in large uncertainties

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in the estimated emissions. By contrast, emissions from fossil fuels are well documented and regularly reported by several sources, including, importantly, the International Energy Agency (*IEA, 2011*). This fundamental gap is an obstacle to more precisely characterizing emissions related to food, wood and fiber production, and associated land use and land-use changes. This in turn creates uncertainty in identifying critical performance indicators that can be used in the analysis of trends, informing policy makers on which response strategies are necessary today and in coming decades for reducing the threat of climate change and best suited to specific needs of different regions and production systems. Specific interventions in the AFOLU sector are of significant interest to many developing countries, including the least developed ones, in view of post-2012 agreements and the role for burden sharing between parties to the United Nation Framework Convention on Climate Change, considering that the AFOLU sector is of critical importance to identify development strategies that jointly address resilience, food security and climate change response strategies (*FAO, 2011*).

The latest peer-reviewed document estimating GHG emissions from agriculture and forestry was the IPCC 2007 Report (*Smith et al., 2007*), based mainly on 2004 data from the Environmental Protection Agency (EPA). According to IPCC, in 2005 GHG emissions from agriculture were 5.1-6.1 $GtCO_2eq\ yr^{-1}$, with another 7.5-8.5 $GtCO_2\ yr^{-1}$ related to the FOLU sectors – dominated by gross deforestation, biomass decay, peat fires and peat degradation. Compared to total estimated GHG anthropogenic emissions in 2005 of 50 $GtCO_2\ yr^{-1}$, the AFOLU sector may thus 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 determine viable mitigation strategies (e.g., *Houghton et al., 2012; Hansen et al., 2012*). Politically, improving assessment and reporting of AFOLU emissions is fundamental to support the ongoing negotiations on agriculture within the United Nations Framework Convention on Climate Change (UNFCCC) (*FAO, 2011; Karsenty, 2012*).

Importantly, reliable estimates of GHG AFOLU emissions, by sector and region, allow for the analysis of indicators that are useful to identify mitigation response strategies consistent with the current production systems and their future evolution. Key indicators include efficiency of production with respect to GHG emissions, or more simply, carbon intensity per unit product of a given commodity, related to its productivity within a particular system.

The most fundamental problem associated with improving estimates of the AFOLU sector, in order to complement the IEA's fossil fuel data, is related to the much higher level of uncertainty characterizing the AFOLU data compared to the fossil fuel emission data While CO_2 emissions from fossil fuels may carry a 10-20% uncertainty at the national to global levels, emissions from agriculture (crops and livestock production) carry large uncertainties, ranging 10-150% (*IPCC, 2006*); emissions related to the AFOLU 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 further report on current efforts at FAO to build such database, and provide examples of applications with respect to GHG-related production and productivity indicators.

Materials and methods

We developed a global GHG emission database with country-level detail, using activity data from the FAOSTAT database (FAO, 2012). These data (e.g., crop area, yield, livestock heads, etc.) are those collected by member countries, typically via National Agriculture Statistical Offices, and reported to FAO. This process results in an internationally approved, coherent data platform covering key information on inputs, produc-

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 on Cropland	59	88	103	111	116
Total	**2,604**	**3,883**	**4,136**	**4,354**	**4,586**
Degraded Organic Soils				250-450	250-450
Biomass Burning				550-750	550-750
Agriculture Total (mean)				**5,354**	**5,586**

TABELLA 1 Agriculture GHG emissions ($MtCO_2eq\ yr^{-1}$) from agriculture in the FAOSTAT database by sector. A combined total for 2005-2010 is obtained by adding estimated emissions from biomass burning and degrading organic soils. The year 2005 is included for comparison to IPCC (2007)

tion, costs and socio-economic indicators, trade and food balances, for a large range of agriculture and forestry products worldwide. The database is used widely in peer-reviewed literature as the basis for a range of AFOLU-related analyses, from global agriculture perspective studies (e.g., *Foley et al., 2011*) to land-use change assessments of importance to carbon cycle studies (i.e., *Friedlingstein et al., 2011*).

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 for which the needed AFOLU activity data were available in FAOSTAT:

$$GHG = EF*AD \quad (1)$$

Where: GHG = greenhouse gas emissions; EF = Emission factor; and AD = activity data. Emissions were computed for nearly 200 countries for the reference period 1961-2010, covering emissions of non-CO2 gases (CH_4 and N_2O) arising from enteric fermentation, manure management systems; synthetic fertilizers, manure applied to soils and left on pastures; crop residues; rice cultivation (Table 1). More detailed emission estimates are reported elsewhere (*Tubiello et al., 2012*). This paper reports, instead, on global GHG emission estimates and derived indicators computed with respect to global production data within FAOSTAT (FAO, 2012).

In particular, we analyzed carbon intensity and efficiency of crops, meat and milk supply by combining GHG emissions associated to a given product, based on the underlying FAOSTAT activity data on global primary production across food commodities, together with data on primary supply for direct human consumption in terms of crop and livestock products (e.g., grains, vegetables, meat and milk). To this end we applied simple equations for assessing bottom-up, country-level GHG indicators. Using established IPCC methodological work (e.g., Kaya identities, *IPCC, 2007*), we computed the following indicators, based on the activity data available in FAOSTAT:

$$I_{GHG,P} = GHG_P/P \quad (2)$$

$$\varepsilon_P = P/AD \quad (3)$$

Where: $I_{GHG,P}$ = carbon intensity of product P; GHG_P = greenhouse gas emissions associated to product P (crop, meat, milk); and P = Production. Furthermore, ε_P = Productivity of product P per unit activity data (i.e., milk per cow). Emissions were computed for nearly 200 countries for the reference period 1961-2010. We plotted carbon intensities either as a function of time across the same set of globally aggregated data categories, allowing for an analysis of their time evolution, or alternatively, as a scatter plot against production efficiencies. The analyses with the former method allow for a consolidated analysis of the food system in terms of the dynamics between intensity and efficiency of production.

According to the IPCC (2007) and recent data from FAO (*Tubiello et al., 2012*), the largest contributors to agriculture emissions are enteric fermentation (38%), manure left on pasture (14%), synthetic fertilizer (13%), biomass burning (11%), rice cultivation (9%), manure management systems (7%), N_2O emissions from organic soils (5%), crop residues (3%), and manure applied to cropland (2%). The following GHG aggregations were further considered. We defined a 'livestock' emission category as the sum of emissions from enteric fermentation and manure emissions, plus emissions from cropland related to feed[1]. This represented over 80% of total agriculture emissions, in line with recent estimates (FAO, 2008; Leip *et al.*, 2010). GHG emissions related to direct human consumption of food crops were computed as a difference from the livestock estimates, i.e., they contributed 20% towards total emissions.

It should be kept in mind that the computations performed herein and the data presented are not life-cycle analyses (LCAs) – which typically consider additional GHG emissions related to processes beyond the agriculture sectors activities we analyzed in our database, such as direct and indirect land-use changes related to crop production or pasture; processing and waste at both factory and retail points; and transportation. Thus the carbon intensities we report herein may be lower than in LCA publications. Nonetheless, the novelty of the methodological work presented herein is that, while other databases with total or partial coverage of GHG emissions from AFOLU exist (*UNFCCC, 2012; EPA, 2006; EDGAR, 2012*), the FAOSTAT GHG database allows for a fully consistent elaboration of composite indicators for further analysis, combining in a unified data platform agriculture activity data and associated GHG emissions.

Results

The GHG emission and global agriculture production data presented herein cover the period 1961-2010, at country level, based on a single, coherent computational platform that links activity data to emissions, consistently with FAOSTAT data and IPCC guidelines. This manuscript focuses on analyses of temporal and production system trends. An online version of the FAOSTAT GHG database, allowing for full country-level analysis, is nearing completion and will be released before the end of 2012. It is noted that the FAOSTAT GHG 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 the AFOLU sector, and by providing FAO member countries with a coherent framework for analyses of their emissions baselines and future trends, including the ability to make comparisons across regions and over long time periods, consistently with their internationally reported activity data.

Global and regional trends in agriculture: production and GHG emissions

Global GHG agriculture emissions increased on average by 1.6% per year from 1961 to 2010, reaching up to 5.4-5.8 GtCO2 yr-1 in 2010 (*Tubiello et al., 2012*). Over the reference period, total crop production and primary supply (crop, meat and milk products) grew by almost four times. The efficiency of such production, defined as the ratio of primary supply to total production, has remained fairly constant, at about 55% over the entire 50-year reference period. The efficiency of feed input to food output, defined here as the ratio of livestock products over total food crops supplied to animals, also remained fairly constant, at about 22%. This much lower efficiency, compared to the former, is well-understood, and reflects a series of energy losses through the animal food chain.

Over the reference period, therefore, crop, milk and meat production increased on average 2.2%-6.4% annually, implying a significant improvement – up to four times better – in the carbon intensity of agricultural production. Such production growth rates are significant, as they are comparable to growth in carbon emissions from fossil fuel and cement manufacture over the same reference period (5.2% yr-1). These data can be explained by increases in productivity of milk and meat products, as well as a decrease in the carbon intensity of the same products, given that

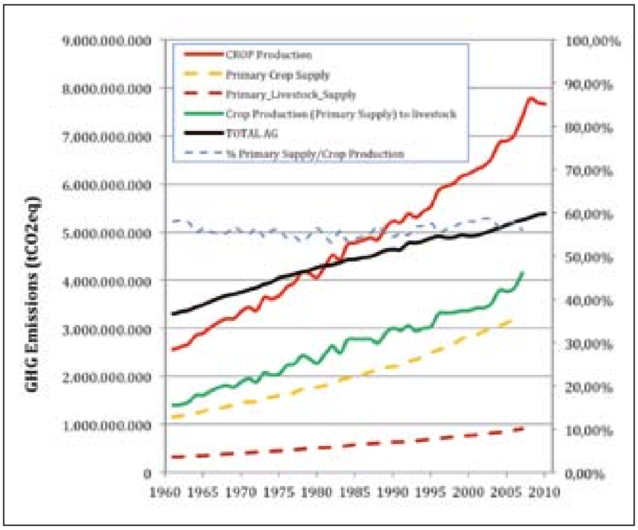

FIGURA 1 Global trends in gross production and primary supply of agriculture food products related to the period 1961-2010

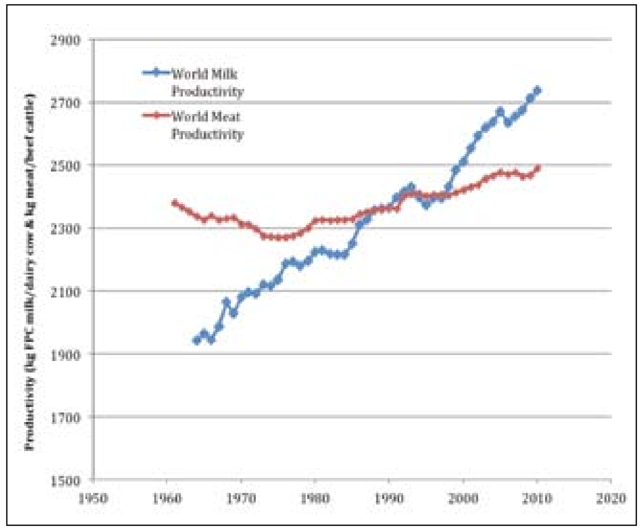

FIGURA 2 Productivity of global milk and meat supply over the period 1961-2010

their associated GHG emissions grew at a significantly lower rate, as discussed below. During the period 1961-2010 in particular, milk productivity increased from about 1900 to over 2700 FPC l/animal (fat protein corrected liters used), with average growth rates of 3% yr-1 (Figure 2). Meat productivity grew a bit more slowly, from about 2300 to 2500 kg/animal, with average growth rates of 2.3% yr^{-1}.

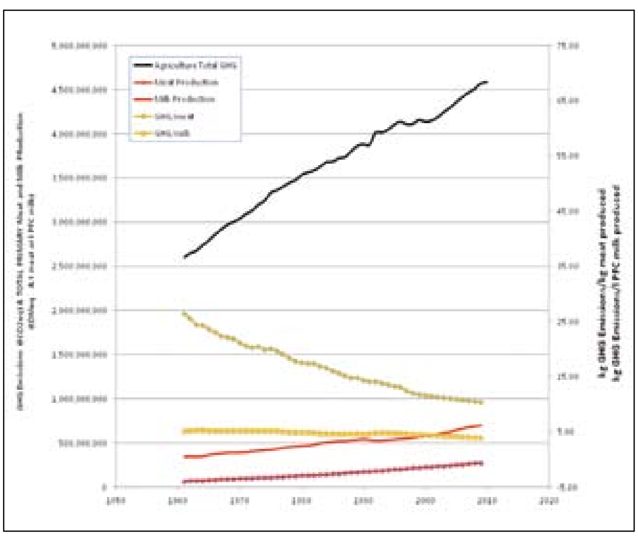

FIGURA 3 Carbon intensity of meat and milk supply and total milk and meat production, over the reference period 1961-2010

Carbon intensity of production and productivity

Changes in carbon intensities of meat and milk over the full period 1961-2010 were computed (Figure 3). Over this reference period, the carbon intensity of meat, $I_{GHG,meat}$, decreased by more than 50%, from about 27 to 15 $kgCO_2eq$/kg meat. At the same time the carbon intensity of milk, $I_{GHG,milk}$, remained fairly constant, going from about 5 to 4 $kgCO_2eq$/l PFC milk.

Recent literature has highlighted the fact that, especially in relation to livestock production, increases in efficiency with respect to GHG emissions can be usefully analyzed in terms of equation (3) above. Indeed, it has been shown that the relationship between the carbon intensity of a given product and its productivity follow an inverse relation (i.e., *Gerber et al., 2011*). As a result of such analyses, improved efficiencies are often seen as a key strategy to achieve a reduction in agriculture GHG emissions in the future. However, the relation characterizing equation (3) is largely due to economies of scale that are achieved in moving from traditional to modern production systems, a transition also likely associated to overall increases in GHG emissions. It is thus of interest to analyze data to help investigate the joint behavior of carbon intensity and GHG emissions as a function of productivity changes. Globally aggregated FAOSTAT GHG and commodity data over the reference period 1961-2010 offer precisely such an opportunity. Results of our analysis indicate that, historically, in conjunction with a 40% improvement in milk productivity, i.e., from 2000 to 2800 kg FPC milk/cow, the carbon intensity of milk also improved (by 27%), but livestock-related GHG emissions increased even more significantly, i.e., by more than 50% (Figure 4).

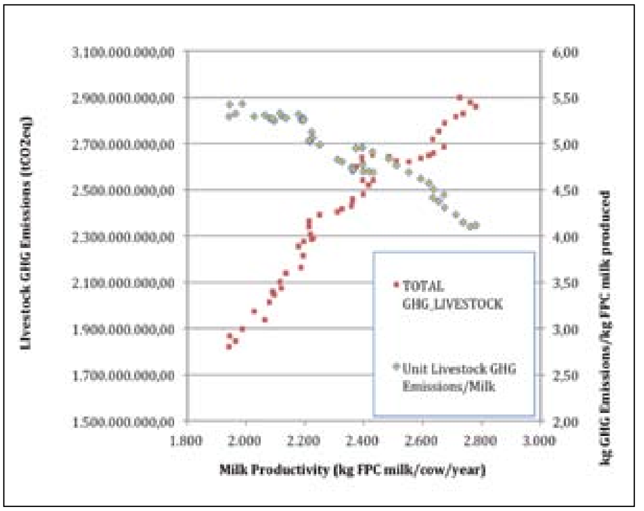

FIGURA 4 Scatter plot of global carbon intensity and GHG emissions of milk, associated to different historical productivity values, computed using country-level FAOSTAT data aggregated globally

Discussion and conclusions

The FAOSTAT 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 the IPCC Guidelines developed for the period 1990-2010 to also derive GHG 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 to 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. Secondly, we have made cursory approximations in order to apportion total GHG emissions to livestock (for milk and meat analysis) and crop production for direct human consumption. This implies that the values we computed need further refinement, although our estimates of carbon intensity for both milk and meat production were fairly consistent with those reported in literature (i.e., *Gerber et al., 2011*).

Within the limitations discussed above, the FAOSTAT GHG data we presented represent nonetheless an improvement over existing databases, in that they offer a unified framework for coherent analysis of both activity data and emission estimates across time and space. As a first example of the database application, we estimated total GHG emissions from agriculture to be 5.4-5.8 $GtCO_2eq\ yr^{-1}$ in 2010, from 5.2-5.6 $GtCO_2eq\ yr^{-1}$ in 2005. The latter estimate is fully consistent with IPCC results (*IPCC, 2007*).

We further analyzed agricultural GHG data in conjunction with the underlying activity data related to food production, quantifying how carbon intensities of milk and meat production decreased overtime in the period 1961-2010, as a function of increased productivity. We further showed that, historically, improved productivities were associated to both decreased carbon intensities and increased overall GHG emissions, indicating that increases in production efficiencies were in fact linked to economies of scale within expanding global agricultural growth – leading to both increased overall supply of goods and, as a consequence, of overall GHG emissions.

Finally, the database and approach outlined in this paper are 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 GHG emissions occur, there is potential to reduce emissions or to improve production efficiencies, 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 emission and production efficiencies database into practical solutions (*Smith et al., 2007*).

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1. Computed as the ratio of feed to food for cereal production, or roughly 45% over 2005-2010 (FOASTAT, 2012).

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