

# Global and regional trends in greenhouse gas emissions from livestock

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**Abstract** Following IPCC guidelines (IPCC 2006), we estimate greenhouse gas emissions related to livestock in 237 countries and 11 livestock categories during the period 1961–2010. We find that in 2010 emissions of methane and nitrous oxide related to livestock worldwide represented approximately 9 % of total greenhouse gas (GHG) emissions. Global GHG emissions from livestock increased by 51 % during the analyzed period, mostly due to strong growth of emissions in developing (Non-Annex I) countries (+117 %). In contrast, developed country (Annex I) emissions decreased (−23 %). Beef and dairy cattle are the largest source of livestock emissions (74 % of global livestock emissions). Since developed countries tend to have lower CO<sub>2</sub>-equivalent GHG emissions per unit GDP and per quantity of product generated in the livestock sector, the amount of wealth generated per unit GHG emitted from the livestock sector can be increased by improving both livestock farming practices in developing countries and the overall state of economic development. Our results reveal important details of how livestock production and associated GHG emissions have occurred in time and space. Discrepancies with higher tiers, demonstrate the value of more detailed analyses, and discourage over interpretation of smaller-scale trends in the Tier 1 results, but do not undermine the value of global Tier 1 analysis.

## 1 Introduction

Greenhouse gas (GHG) emissions from human activities are the primary cause of global warming (IPCC 2007). Although CO<sub>2</sub> emissions from the burning of fossil fuels and changes

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in land use make up the largest share of these GHG emissions, other non-CO<sub>2</sub> greenhouse gases such as methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) also contribute substantially to overall warming. A recent study estimated that global emissions of CH<sub>4</sub> and N<sub>2</sub>O account for approximately 27.7 % of total radiative forcing since the pre-industrial era (EPA 2011). Among sources of non-CO<sub>2</sub> gases, the livestock sector is dominant, emitting roughly 25 % of all non-CO<sub>2</sub> emissions in 2001 (using 100-year time-horizon global warming potentials, GWPs, to compare different gases, which we will do throughout this paper) (Rose and Lee 2008). Thus, direct emissions of CH<sub>4</sub> (primarily from the enteric fermentation of animals) and N<sub>2</sub>O (released from anaerobic decomposition of manure as well as nitrification and denitrification of the organic nitrogen) from livestock worldwide account for about 9 % of total GHG emissions (IPCC 2007). Steinfeld et al. (2006) have estimated that GHG emissions related to livestock production (including fossil fuel emissions occurring elsewhere in the supply chain of livestock products such as transport and feed production) comprise about 18 % of GHG emissions globally. Moreover, according to Tubiello et al. (2013), GHG emissions from livestock make up a very large proportion—70 %—of total emissions from the agriculture, forestry and other land use (AFOLU). However, the long-term trend in GHG emissions from livestock as divided between developed and developing countries has still not been assessed in the scientific literature.

Livestock production systems, especially in developing countries, are changing rapidly in response to population growth, urbanization, and growing demand for livestock products (Herrero and Thornton 2009). For instance, the demand for meat and other animal products (e.g., eggs, milk, and cheese) in developing countries is expected to double by 2050 (Garnett 2009), and satisfying this rising demand will be a substantial challenge for the livestock sector (FAO 2005; Valin et al. 2013). In fact, a number of studies have analyzed the GHG implications of global increasing demand for livestock (e.g., Naylor et al. 2005; Reay et al. 2012; Bustamante et al. 2012), anticipating, for instance, that CH<sub>4</sub> emissions from enteric fermentation could increase by 31 % between 1990 and 2030 and that N<sub>2</sub>O emissions from manure management could increase by 20 % mainly due to developing countries (EPA 2011). Inventories that resolve livestock emissions in time and space are therefore important to efforts to cost-effectively reduce GHG emissions.

The Intergovernmental Panel on Climate Change (IPCC) provides guidelines intended for use by individual countries in estimating livestock emissions, prescribing three different levels of detail (Tiers) that may be used depending on the availability of data (IPCC 2006). For the least detailed IPCC Tier 1 method, default emission factors are recommended for different types of livestock (e.g., beef cattle, dairy cattle, pigs, sheep, buffalo, laying chickens, broiler chickens, etc.). These emissions factors vary significantly among these different types of livestock, and also depend on characteristics such as mean air annual temperature, geographic location, and level of economic development. In particular, the distinction between developed and developing countries is crucial. That is, the same number of livestock raised in developed and developing countries produces different levels of GHG emissions (See, e.g., Garnett 2009). Furthermore, meat consumption varies enormously from developed to developing countries (UNEP 2012). However, the growth of population in developing countries (Godfray et al. 2010) and the consequent increase in meat demand will require a global strategy to ensure sustainable and equitable food as well as several mitigation options for directly reducing emissions due to livestock production. The globally consistent inventory of livestock emissions at the level of individual countries over time that we present here will inform efforts to reduce livestock emissions.

Here, we estimate global GHG emissions from 11 categories of livestock in 237 countries during the period 1961 to 2010 by using a Tier 1 method. We calculate the total impact of

livestock sector, taking into account variation in mean annual air temperature during this time period as well as the level of economic development and geographic location of each country. More specifically, this paper aims to:

1. Assess the total and the per capita GHG emissions from livestock, focusing on trend of developing and developed countries during the period 1961–2010.
2. Assess the total emissions from different livestock categories and sources, focusing on trend of developed and developing countries during the period 1961–2010.
3. Assess the emission intensity of the most important livestock products, focusing on trend of developed and developing countries during the period 1961–2010.
4. Assess the comparison with higher tier calculations developed for single countries in order to understand the real limitations of using tier 1 with respect to more complex procedures.

In discussing the results, we compare the different trends and we show where the livestock production (and associated emissions) increased or decreased over the time.

As used here, developed countries refers to industrialized (Annex I) countries that were members of the Organization for Economic Co-operation and Development (OECD) in 1992, as well as countries with economies in transition (the EIT Parties), such as the Russian Federation, the Baltic States, and several Central and Eastern European States. We also include in this group of developed countries the “observer states” and parties for which there is a “specific COP and/or CMP decision” (UNFCCC 2014a). We refer to the remaining (Non-Annex I countries) as developing countries. We use this grouping of countries throughout the entire period 1961–2010. For a complete listing of countries included in each group, see the [Supplementary data](#).

## 2 Methods

To estimate emissions using the Tier 1 method, data are needed on the average number of animals in each livestock population. The activity data used in this paper for each livestock population were entirely provided by a new FAO statistic database (FAO 2014). The new FAO statistic database, allows the use of activity data such as the average number of animals by livestock class in each country that are collected by member countries, typically via National Agriculture Statistical Offices, and reported officially to FAO. The new platform continues to offer free and easy access to data for countries from 1961 through the most recent year available. Enhanced features include browsing and analysis of data, an advanced interactive data download, and enhanced data exchange through web services.

We take into account eleven different livestock populations: beef cattle, dairy cattle, pigs (market and breeding), sheep, buffalos, goats, mules, asses, horses, camels and chickens. Table 1 provides information about the equations and emission factors used in this paper to estimate livestock emissions in each emission category (Table 1). We follow IPCC guidelines, developed for the period 1990–2010, to derive emissions for the three previous decades. In our analysis we develop a fully Tier 1 (basic method). Although Tier 2 (intermediate) and Tier 3 (complex) methods are generally considered to be more accurate (IPCC 2006), they require a detailed information about livestock in each country that are not yet available for a global analysis.

### 2.1 Enteric fermentation

The process of enteric fermentation produces methane as a by-product, and this methane is expelled by the animal and released to the atmosphere (JRC 2010). We apply the default

**Table 1** Livestock emission category, activity data, equations and source of emission factors used in this paper. Equations and emissions factor sources are from IPCC (2006)

Gas	Emissions category	Activity data	Equations <sup>b</sup>	Emissions factor source <sup>b</sup>	
CH <sub>4</sub> <sup>a</sup>	Enteric fermentation	Stocks (head)	Eq. 10.19	Tab 10.10 Tab 10.11	
	Manure management	Stocks (head)	Eq. 10.22 <sup>c</sup>	Tab. 10.14 Tab. 10.15	
N <sub>2</sub> O <sup>a</sup>	Manure management direct	Manure N <sup>d</sup>	Eq. 10.25	Tab. 10.21	
	Manure management indirect	Manure N <sup>d</sup>	Volatilization	Eq. 10.26 Eq. 10.27	Tab. 11.3
			Leaching	Eq. 10.28 Eq. 10.29	Tab. 11.3
			Manure left on pasture direct	Manure N	Eq. 11.1 Eq. 11.5
	Manure left on pasture indirect	Manure N	Volatilization	Eq. 11.5 Eq. 11.19	Tab. 11.3
			Leaching	Eq. 11.5 Eq. 11.10	Tab. 11.3

<sup>a</sup> We used 21 and 310 as global warming potential of CH<sub>4</sub> and N<sub>2</sub>O respectively (FAO 2014)

<sup>b</sup> Equations and emissions factor sources are specified by the corresponding equations and tables in chapters 10 and 11 of the IPCC guidelines (IPCC 2006)

<sup>c</sup> The temperature values are directly extracted from NOAA Earth System Research Laboratory of the University of Delaware (NOAA 2014). For dairy cattle, beef cattle, market pigs, breeding pigs and buffalo, we used the temperature values for each year during the period 1961–2010. For the other animals we used the average temperature during the period 1961–2010 for each year

<sup>d</sup> We assumed that all sheep and goat manure is left on pasture. Camel, horse, mule and ass manure is considered not to be managed

emission factors presented in the IPCC guidelines for each of the recommended population subgroup (Table 1). The emissions intensity of enteric fermentation applied in this study are specific to the type of livestock, region and level of economic development (Table 1; IPCC 2006).

## 2.2 Manure management

Livestock manure (including both dung and urine) is primarily composed of organic material and water. Methane emissions from manure are mediated by anaerobic and facultative bacteria that decompose the organic material under anaerobic conditions (Bouwman 1996). The methane production potential of manure depends on the specific composition of the manure and it is also influenced by the ambient temperature and the manner in which the manure is managed (EPA 2006). Again following the Tier 1 methodology, our analysis uses population data for each animal category (FAO 2014), mean annual temperature in each nation (NOAA 2014), and default emission factors (Table 1; IPCC 2006).

N<sub>2</sub>O emissions occur via both nitrification and denitrification of nitrogen contained in animal waste (Barton and Atwater 2002). Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to

nitrogen gas (Miller et al. 2009). Therefore, the production of direct N<sub>2</sub>O emissions from managed manure required the presence of other nitrites or nitrates in anaerobic environment preceded by aerobic conditions. According to Tier 1 (IPCC 2006), direct N<sub>2</sub>O emissions depend on total amount of N excretion from all livestock species/categories in each type of manure management system in combination with the IPCC default factor for that type of manure management system (Table 1). N<sub>2</sub>O emissions are not dependent on mean air temperature (Klein et al. 2006). We sum estimated N across all manure management systems and multiply by the appropriate default emission factor (IPCC 2006).

Indirect N<sub>2</sub>O emissions result from volatile nitrogen losses that occur primarily in the forms of ammonia and NO<sub>x</sub>. Nitrogen losses begin at the point of excretion in animal production areas and continue through on-site management in storage and treatment systems (Oenema and Tamminga 2005). The Tier 1 calculation of N volatilization in forms of NH<sub>3</sub> and NO<sub>x</sub> from manure management systems (IPCC 2006) is based on multiplication of the amount of nitrogen excreted (from all livestock categories) and managed in each manure management system by a default value that represent fraction of volatilized nitrogen. N losses is then summed over all manure management systems and multiplied for a default emission factor. Nitrogen is also lost through leaching/runoff into soils that produce indirect N<sub>2</sub>O emissions (Meyer et al. 2002). We use a Tier 2 (IPCC 2006) method to estimate this source of emission.

### 2.3 Manure left on pasture

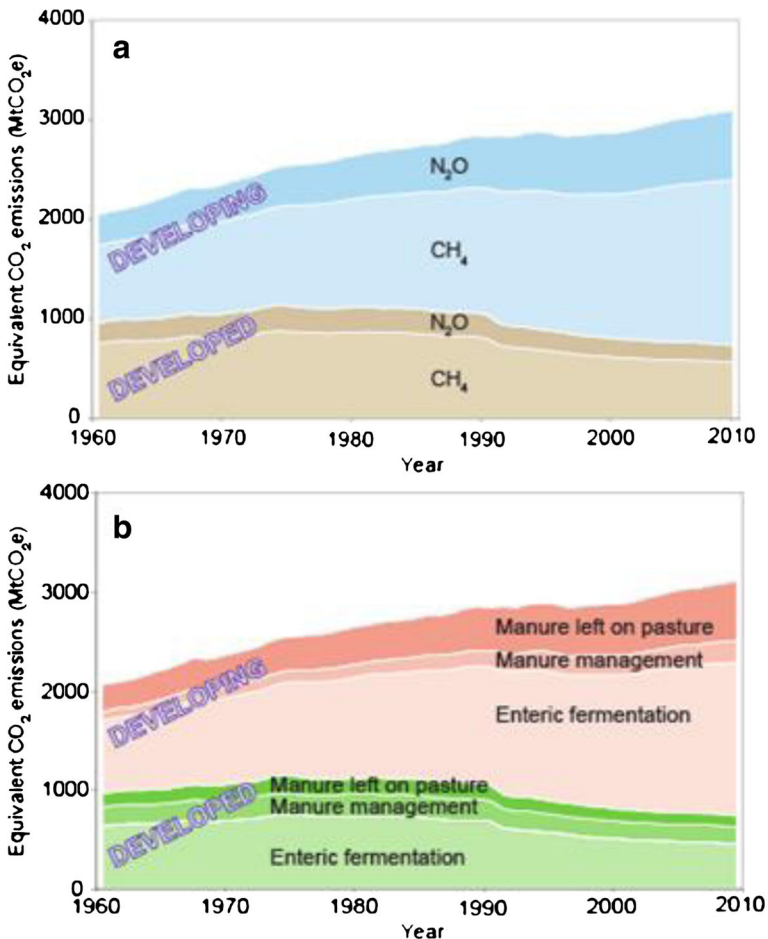
Nitrous oxide is also produced naturally in soils through the processes of nitrification and denitrification (Bateman and Baggs 2005). In this paper we take in account the contribute of N<sub>2</sub>O direct, N<sub>2</sub>O indirect due to volatilization and N<sub>2</sub>O indirect due to leaching/runoff from managed soils refer to annual amount of manure deposited by grazing animals on pasture, range and paddock (Vogeler et al. 2011). The emissions due to manure applied to soils is not included in this paper, because those emissions are attributed to the fertilized crops and not the livestock which produced the manure.

## 3 Results

In this section we present the results of our analysis, focusing on developed and developing countries. Detailed results of calculated emissions related to livestock in each of the 237 countries can be found in the [Supplementary data](#).

### 3.1 Livestock sector emissions

Figure 1 shows the livestock emissions trend for the principal GHGs directly produced by livestock (CH<sub>4</sub> and N<sub>2</sub>O) in different emissions categories (enteric fermentation, manure management, manure left on pasture) for both Developed and developing countries. We find that during the period 1961–2010 global GHG emissions from the livestock sector increased by 51 %. We estimate that global livestock emissions due to enteric fermentation, manure management and manure left on pasture in 2010 were 3.1 Gt CO<sub>2</sub>eq. This represents 22 % (16 % methane and 6 % nitrous oxide) of all non-CO<sub>2</sub> emissions in the same year (10.8 Gt CO<sub>2</sub>eq ; JRC/PBL 2012). In particular, CH<sub>4</sub> emissions due to livestock represented by 28.3 % of global CH<sub>4</sub> emissions whereas N<sub>2</sub>O emissions due to livestock represented by 29.7 % of global N<sub>2</sub>O emissions. The agricultural sector, considering the total GHG emissions, released about 5.4 Gt CO<sub>2</sub>eq in 2010 (JRC/PBL 2012). Thus, we find that, in 2010, the livestock sector



**Fig. 1** Trend of global livestock greenhouse gas (expressed as equivalent CO<sub>2</sub>) emissions during the period 1961–2010 from Developed and Developing countries. **a.** Emissions are subdivided into methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) and expressed in terms of CO<sub>2</sub> equivalents using 100-year GWP measures. **b.** CO<sub>2</sub> equivalent emissions are subdivided into enteric fermentation, manure management, and manure left on pasture. Global greenhouse gas emissions from livestock have been growing over time, primarily due to increased methane emissions from Developing countries

globally contributes about 57 % of total GHG emissions associated to agricultural sector. In 2010, methane was the main greenhouse gas released from livestock sector (72 % of total livestock GHG emissions using 100-year GWPs), and N<sub>2</sub>O was responsible for the remainder (28 %).

Developed countries reached maximum emissions in the 1970s and have since been in decline. In contrast, emissions from developing countries continue to rise. The biggest increase is from methane emissions from developing countries associated with the expansion of beef and dairy cattle production in these countries. Between 1961 and 2010, developing countries livestock emissions increased by 117 % (1.56 % yr<sup>-1</sup>) and the Developed countries emissions decreased by -23 % (-0.52 % yr<sup>-1</sup>). From 1992 to 2010 transition economies<sup>1</sup> livestock

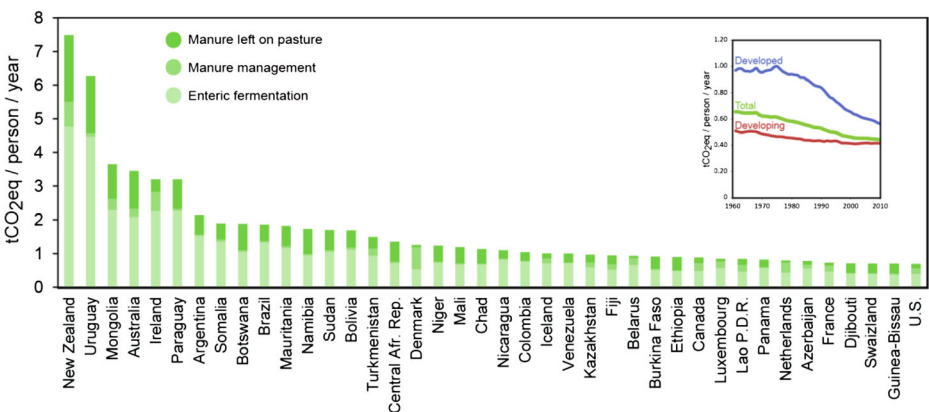
<sup>1</sup> for a complete listing of countries included in this group, see the [Supplementary data](#)

emissions decreased by 46 % ( $-2.2 \text{ \% yr}^{-1}$ ). In 1961, based on the supplemental data, seven countries produced 52 % of the global emissions including (in order) USA (235 Mt CO<sub>2</sub>eq/y, 11.6 %), India (221 Mt CO<sub>2</sub>eq/y, 10.9 %), USSR (198 Mt CO<sub>2</sub>eq/y, 9.8 %), China (139 Mt CO<sub>2</sub>eq/y, 6.9 %), Brazil (100 Mt CO<sub>2</sub>eq/y, 5.0 %), Argentina (86.31 Mt CO<sub>2</sub>eq/y, 4.1 %) and Australia (83 Mt CO<sub>2</sub>eq/y, 4.1 %). In 2010, eight countries produced 52 % of the global emissions including (in order) India (367 Mt CO<sub>2</sub>eq/y, 12.0 %), Brazil (361 Mt CO<sub>2</sub>eq/y, 11.8 %), China (310 Mt CO<sub>2</sub>eq/y, 10.1 %), USA (214 Mt CO<sub>2</sub>eq/y, 10.0 %), Pakistan (92 Mt CO<sub>2</sub>eq/y, 3.0 %), Argentina (86 Mt CO<sub>2</sub>eq/y, 2.8 %), Australia (77 Mt CO<sub>2</sub>eq/y, 2.5 %) and Ethiopia (74 Mt CO<sub>2</sub>eq/y, 2.4 %). Thus, the frequency distribution has changed over time with a longer right-hand tail in 2010. By percentage, livestock emissions over the period of 1961 to 2010 increased the most in Congo (+929 %), the Central African Republic (+894 %) and Oman (+765 %), and decreased most in Bulgaria (−71 %), Hungary (−60 %) and Finland (−57 %).

Figure 2 gives evidence on the livestock emissions per capita, showing both the largest per capita emitter in 2010 and total, developed and developing trend during the period 1961–2010.

Globally, livestock emissions per capita decreased by 32 % from 1961 to 2010 driven by decreases in both developed (−42 %) and developing countries (−19 %). For example, in 1961 U.S. livestock emissions were 1.24 tCO<sub>2</sub>eq per person, but emissions decreased to 0.69 tCO<sub>2</sub>eq per person in 2010 (−45 %). In contrast to the general trend in per capita emissions, livestock emissions per capita in Brazil grew from 1.34 tCO<sub>2</sub>eq per person in 1961 to 1.85 in 2010, a 38 % increase. Figure 2 (smaller figure) shows livestock emissions per capita were relatively stable in developed countries between 1961 and 1979 (−3 %), but then decreased sharply between 1980 and 2010 (−40 %).

Figure 2 highlights that Oceania and South America are the regions with the largest livestock emissions per capita; six of the greatest ten emitters belong to these regions (New Zealand, Australia, Uruguay, Argentina, Paraguay and Brazil). In 2010, New Zealand was the largest emitter of livestock emissions per capita (7.48 tCO<sub>2</sub>eq per person), mostly related to enteric fermentation (4.78 tCO<sub>2</sub>eq per person) and manure left on pasture (1.96 tCO<sub>2</sub>eq per person). In Europe, livestock emissions per capita in 2010 were greatest in Ireland (3.19



**Fig. 2** Livestock emissions per capita. The larger figure shows the forty<sup>a</sup> highest per capita emitter countries (expressed as tons of equivalent CO<sub>2</sub> per person) breaking down by emission category (such as enteric fermentation, manure management and manure left on pasture) in 2010. The smaller figure points out the total, developed and developing countries trend of livestock emissions per capita (expressed as tons of equivalent CO<sub>2</sub> per person) during the period 1961–2010. <sup>a</sup>Countries with less than 300 thousand people are not included



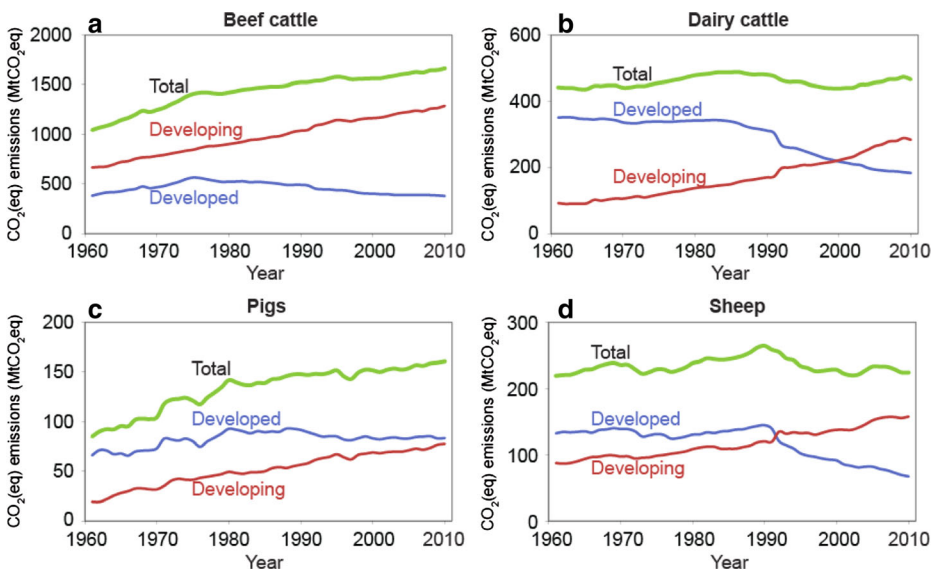
tCO<sub>2</sub>eq per person), again mostly due to enteric fermentation (2.27 tCO<sub>2</sub>eq per person). In Asia, Mongolian livestock emissions per capita are the largest –3.64 tCO<sub>2</sub>eq per person, of which 2.30 tCO<sub>2</sub>eq per person are from enteric fermentation.

### 3.2 Livestock categories emissions

Figure 3 presents the total, developed and developing countries trend of GHG emissions associated with beef cattle, dairy cattle, pigs and sheep production during the period 1961–2010. We find that, on the average, emissions caused by beef cattle contributed 54 % of total livestock emissions, followed by dairy cattle (17 %), sheep (9 %), buffalo (7 %), pigs (5 %), and goats (4 %). Beef and dairy cattle were by far the largest contributors to GHG emissions from enteric fermentation, comprising 74 % of these emissions in 2010.

Emissions released by beef cattle (Fig. 3a) are substantially higher than other livestock categories, and global emissions from these cattle increased by 59 % between 1961 and 2010. However, the increase was almost entirely in developing nations, where beef cattle emissions increased by 94 % between 1961 and 2010. In contrast, beef cattle emissions in developed countries were stable over the period, decreasing by just 1 %. The large difference in growth of emissions from developed and developing countries is also observed in other livestock categories. Because of this rapid growth, developing countries produced more dairy cattle and sheep emissions than developed countries in 2010, which was not the case in 1961 (Fig. 3b and d). Pig emissions (Fig. 3c) in 2010 were about the same in developed and developing countries. Another noteworthy trend is a marked decrease in livestock emissions in transition economies between 1992 and 2010. Over this 18-year period, beef and dairy cattle emissions in transition economies decreased by 47 and 41 %, respectively, sheep emissions dropped by 41 % and pig emissions declined by 83 % (4.4 % per year).

In 2010, beef cattle emissions in Brazil were larger than any other country (311 MtCO<sub>2</sub>eq), representing 18 % of global emissions from beef cattle in that year. Dairy cattle emissions in



**Fig. 3** Trend in global beef cattle, dairy cattle, pigs and sheep greenhouse gas emissions for Developed and Developing countries the period 1961–2010 in units of megatons of CO<sub>2</sub> equivalent



2010 were largest in India (58 MtCO<sub>2</sub>eq), or 12 % of global emissions from dairy cattle in that year. China was the largest overall emitter of both pig and sheep emissions (49 and 25 MtCO<sub>2</sub>eq, respectively), or 30 and 25 % of global emissions from these two livestock categories, respectively.

### 3.3 Livestock production intensity

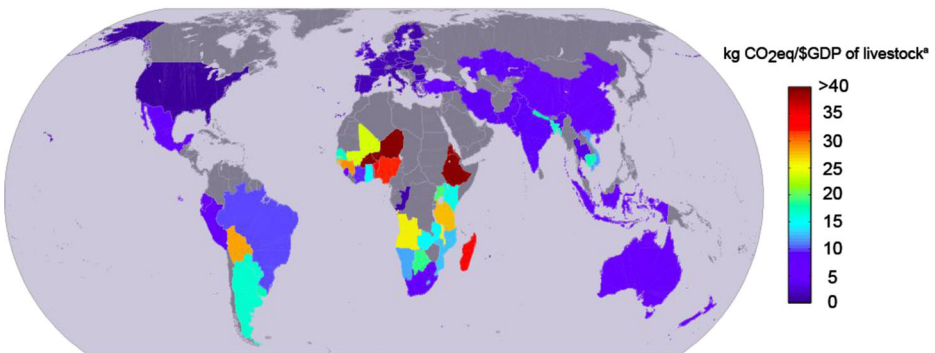
We assess the emissions intensity of livestock production as livestock emissions per dollar of total economic output from the livestock sector in each country.

Figure 4 shows substantial differences in emissions intensities of livestock production among countries, with the highest intensities occurring in developing countries, and particularly Africa. We find that in the twenty countries with the highest livestock emissions intensities, eighteen are in Africa. Eritrea, Niger and Ethiopia have the highest overall emissions intensity of livestock production in the world (75.6, 40.7 and 40.6 kgCO<sub>2</sub>eq/\$ respectively). Livestock production in South America is also quite emissions intensive, especially in Bolivia and Argentina where 28.9 and 16.7 kgCO<sub>2</sub>eq are emitted per dollar of livestock produced, respectively. In Asia, the most emissions intensive countries were Vietnam and India, where 11.9 and 10.7 kgCO<sub>2</sub>eq are emitted per dollar of livestock produced, respectively.

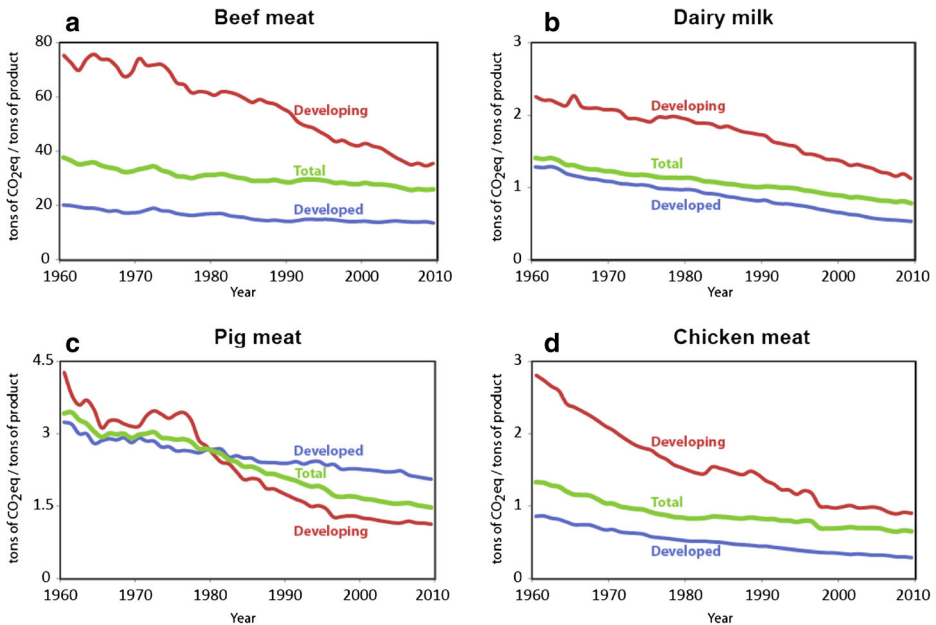
In comparison, the emissions intensity of livestock production in developed countries was much less. Ireland had the highest emissions intensity of any country in Europe: 2.8 kgCO<sub>2</sub>eq/\$ of livestock produced. In the U.S., 0.5 kgCO<sub>2</sub>eq were emitted per dollar of output from the livestock sector.

Figure 5 decomposes the intensity of livestock emissions by primary livestock products, using FAO data on the masses of beef, milk, pork and chicken produced 1961–2010 (FAO 2014).

Global emission intensities generally decrease for all products over the time. Although emissions intensities in developing countries are consistently higher than in developed countries (with the noteworthy exception of pork in the last two decades), the developing country



**Fig. 4** Map showing livestock emissions per \$ GDP (dollar are adjusted for purchasing power parity) in the livestock sector. Livestock emission data is developed as described in the text. The year used for livestock emissions is the same as that used for GDP. However, data on GDP of livestock for developing countries are provided by Agriculture and Consumer Protection Department and are referred to 2002 (FAO 2005) (currency U.S. dollars) whereas data on GDP of livestock for developed countries are provided by Joint Research Centre report and are referred to 2007 (JRC 2010) (currency U.S. dollars). Data on GDP of livestock data for the U.S. is provided by Williams (2011) and is referred to 2007 as well (currency U.S. dollars). For countries in grey, data on GDP of livestock is not available. Livestock emission intensities in developing countries are higher than Developed countries, in particular in African countries



**Fig. 5** Map showing livestock emissions per ton of beef meat, dairy milk, pig and chicken meat produced during the period 1961–2010. Emission intensity in developing countries is higher than developed countries (except for pig meat in the last two decades). Global emission intensity decreases over the time. Beef meat is the product associated to highest intensity. Data on production of livestock products is from the United Nations Food and Agriculture Organization (FAO 2014)

intensities are decreasing over the time while intensities in developed countries have changed very little. Between 1961 and 2010, the emissions intensities of beef, milk, pork and chicken produced in developing countries have decreased by 52, 50, 73 and 67 %, respectively (Fig. 5). Beef production is the most emissions intensive; in 2010, the emissions intensity of beef ranged from 11 tCO<sub>2</sub>eq per ton of beef produced in the U.S. and 101 tCO<sub>2</sub>eq per ton of beef produced in India. The range in intensity of milk production is similar: In 2010, 0.4 tCO<sub>2</sub>eq were emitted per ton of milk produced in Sweden, and 14 tCO<sub>2</sub>eq were emitted per ton of milk produced in Cambodia

### 3.4 Comparison with higher tier calculations

Although a global analysis using higher IPCC Tiers is prevented by lack of reliable data from all countries, we can compare our results with Tier 2 inventories that have been developed for New Zealand (where per capita livestock emissions are the largest of all countries; Ministry of the environment 2014) and Ireland (with the greatest per capita livestock emissions in Europe; UNFCCC 2014b). The compared-to studies use a Tier 2 method and represent the official annual reports of all anthropogenic emissions and removals of greenhouse gases of these countries.

New Zealand's official inventory reported 1,052 Gg of CH<sub>4</sub> emissions from enteric fermentation in 1990, 1,141 Gg CH<sub>4</sub> in 2000 and 1,096 Gg CH<sub>4</sub> in 2010. In comparison, our Tier 1 estimates for these years are 1,034 Gg CH<sub>4</sub>, 982 Gg CH<sub>4</sub>, and 995 Gg CH<sub>4</sub>, 2, 14, and 9 % less than the Tier 2 results, respectively. Similarly, New Zealand's inventory reports 38.7 Gg N<sub>2</sub>O emitted in 1990, 25.4 Gg in 2000, and 33.8 Gg in 2010, whereas our estimates

for these same years are 30.0 Gg, 30.5 Gg, and 31.9 Gg, or 22 % less in 1990, 20 % more in 2000, and 6 % less in 2010.

Differences between the Irish Tier 2 inventory and our Tier 1 estimates are of a similar magnitude. Ireland's official inventory reported 9,570 Gg CO<sub>2</sub>eq of CH<sub>4</sub> emissions from enteric fermentation in 1990, 9,490 Gg in 200 and 8,540 Gg in 2010. In comparison our Tier 1 estimates for these same years are 9,850 Gg CO<sub>2</sub>eq, 10,880 Gg and 10,140 Gg, or 3, 15, and 19 % more than Tier 2 results, respectively. Ireland's inventory reports 2,790 Gg CO<sub>2</sub>eq emitted from manure management in 1990, 2,790 Gg in 2000, and 2,570 Gg in 2010, whereas our estimates for these same years are 2,430 Gg, 2,760 Gg, and 2,600 Gg, or 13 % less in 1990, 1 % less in 2000 and 1 % more in 2010.

The differences between our results and these more detailed inventories are therefore significant, but given the large uncertainties that apply to all estimates of non-CO<sub>2</sub> livestock emissions (IPCC 2006), the results are remarkably similar. However, the comparison does indicate that trends in livestock emissions may not always be recognized by the Tier 1 approach. For instance, the reported 44 Gg increase in New Zealand's CH<sub>4</sub> emissions from enteric fermentation between 1990–2010 was not visible in our results, which instead show a decrease of 39 Gg CH<sub>4</sub> over the same time period. In Ireland, too, the reported 1,030 Gg CO<sub>2</sub>eq increase in CH<sub>4</sub> emissions from enteric fermentation is missed by our analysis which instead shows 280 Gg CO<sub>2</sub>eq decrease. These discrepancies demonstrate the value of more detailed, higher Tier analyses, and discourage over interpretation of smaller-scale trends in the Tier 1 results, but do not undermine the value of global Tier 1 analysis while the data necessary for the higher Tier analyses is being developed.

#### 4 Discussion

We find that the GHG emissions from livestock are increasing globally, mostly due to emissions growth in developing countries and in particular due to increases in enteric fermentation (Fig. 1). In contrast, GHG emissions from livestock in developed countries decrease during the analyzed period. Livestock emissions per capita in developed countries have been relatively stable throughout the period 1961–2010, but have decreased steadily over time in developing countries (Fig. 2).

Beef and dairy cattle, especially in developing countries, represent the largest source of livestock-related emissions (Fig. 3). This is due to both the abundance of these animals and the fact that emissions per animal are substantially higher for cows than for other livestock categories. Dietary preferences are a strong driver of livestock emissions, with beef generally related to substantially more GHG emissions per calorie than pork and poultry, and much more than vegetables (Fig. 3; Engstrom et al. 2007). For this reason, substitution of pork and poultry for beef is an option for mitigating livestock emissions (Fig. 5). This is in contrast to the global trend towards increased reliance on cattle (FAO 2014). However, pigs and poultry are dependent on grain and soy products and they might have a negative impact on GHG emissions.

The decade of most rapid change was from 1991–2000 with substantial increases in emissions from developing countries and decreased emissions in developed countries. Narula and Dunning (2000) stated that the beginning of this decade was characterized by considerable ideological and economic upheaval. In particular they claimed that, since 1989, over 80 developing countries have liberalized their economic policies from inward-looking, import-substituting regimes towards outward-looking, export-oriented policy regimes. These economic processes also affected the livestock sector in developing countries, encouraging an

increase of production and export of livestock products resulting in a contemporaneous growth of livestock emissions from these countries (Moran and Wall 2011). Figure 4 shows that the economic productivity associated with each GHG emission is greater in developed countries than in developing countries as well as the emissions generated per ton of product (Fig. 5). Moreover Fig. 5 points out that in spite of the livestock production is less efficient in developing countries, their emission intensity relative to the main livestock products is decreasing more rapidly than developed countries. Thus, it is possible that international trade that exports livestock products from developing countries and imports these into developed countries may have two effects: first, to increase greenhouse gas emissions and second, to increase global economic productivity (Caro et al. 2014; Bastianoni et al. 2014).

This study presents Tier 1 method calculations of livestock emissions from 237 countries. However higher Tier inventory for livestock emissions are available for few single countries. Comparing two methods we show that different results may occur. For instance, a Tier 2 method calculation of livestock emissions in New Zealand and Ireland reflects that farmed livestock became more efficient over the time. Such changes can be accounted for in a higher Tier inventory but not in a Tier 1. However, the increased demand for livestock sector (and associated GHG emissions) is captured by a Tier 1. Moreover, Tier 1, by using generalized parameter values, allows for the construction of a database where every country is treated equally (Tubiello et al. 2012), so that emission data can be adequately compared whereas higher Tiers use more specific national values (IPCC 2006).

## 5 Conclusions

Equivalent CO<sub>2</sub> emissions from the livestock sector have increased globally by 51 % from 1961 to 2010 because of increased demand for livestock products. Although in developed countries GHG emissions from livestock have decreased by 23 %, however in developing countries they have increased by 117 % over the time. In developing countries, most of this increase is associated with CH<sub>4</sub> emissions from enteric fermentation.

Global per capita emissions from livestock slightly decrease during the period 1961–2010. Whereas per capita emissions decrease in developed countries, they are rather steady in developing countries over the time. The decrease of both total and per capita GHG emissions from livestock sector reveals a decreased livestock production in developed countries during the analyzed period. Oppositely, our analysis shows that an increased livestock production in developing countries occurs, mainly due to increased population and consequent demand for livestock products.

Beef and dairy cattle represent the largest source of livestock-related emissions, especially in developing countries. Moreover, emissions released from beef and dairy cattle substantially increased in developing countries and decreased in developed countries during the period 1961–2010. This is mainly due to both higher emission factors and higher demand for livestock products associated to beef and dairy cattle in developing countries.

Developing countries tend to have higher equivalent CO<sub>2</sub> emissions per unit GDP generated in the livestock sector and higher CO<sub>2</sub> emissions per quantity of good produced. This suggests that improvements in both the overall state of economic development and farming practices can contribute to maximizing economic productivity of emissions that do occur in the livestock sector.

Unlike higher tiers, the tier 1 method calculations presented in this paper do not reveal where livestock production becomes more efficient over the time, however it shows how livestock production (and associated GHG emissions) has occurred in time and space. This

will provide a sound technical basis for developing and implementing policies aimed at reducing emissions from the livestock sector.

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