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Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity

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Abstract

Livestock production systems currently occupy around 28% of the land surface of the European Union (equivalent to 65% of the agricultural land). In conjunction with other human activities, livestock production systems affect water, air and soil quality, global climate and biodiversity, altering the biogeochemical cycles of nitrogen, phosphorus and carbon. Here, we quantify the contribution of European livestock production to these major impacts. For each environmental effect, the contribution of livestock is expressed as shares of the emitted compounds and land used, as compared to the whole agricultural sector. The results show that the livestock sector contributes significantly to agricultural environmental impacts. This contribution is 78% for terrestrial biodiversity loss, 80% for soil acidification and air pollution (ammonia and nitrogen oxides emissions), 81% for global warming, and 73% for water pollution (both N and P). The agriculture sector itself is one of the major contributors to these environmental impacts, ranging between 12% for global warming and 59% for N water quality impact. Significant progress in mitigating these environmental impacts in Europe will only be possible through a combination of technological measures reducing livestock emissions, improved food choices and reduced food waste of European citizens.

Introduction

Nowadays agricultural land occupies about 180 million hectares or 42% of the land area of the European Union[10] from which a great portion is used as grassland and for cultivating feed (FAO 2006). Historically, livestock helped to transform inedible materials (grass and waste) into high quality food. However today livestock production systems affect air quality, global climate, soil quality, biodiversity and water quality (Sutton *et al* 2011b, 2011c), by altering the biogeochemical cycles of nitrogen, phosphorus and carbon. In particular, reactive nitrogen (N_r) plays a key role in several environmental impacts (N_r represents all forms of nitrogen other than N_2, including ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), and N losses to water bodies). Nitrogen cascades or recycles through crop and livestock production systems, in form of feed for livestock and of manure to grow crops, as illustrated in figure 1, leading to several un-intended flows that give rise to environmental concerns (Sutton *et al* 2011a, Leip *et al* 2011a).

[10] Data refer to the situation with 27 Member States, in this article we will use the term 'Europe' also to refer to the EU27.

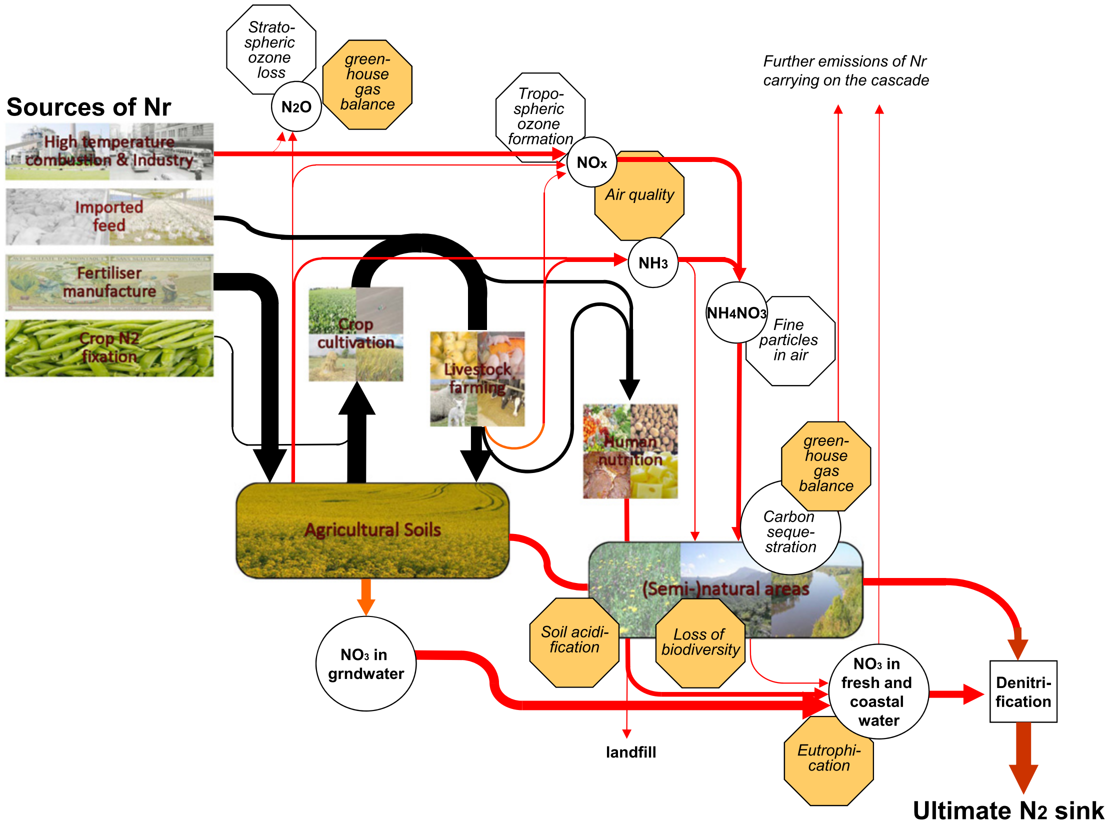

Figure 1. Nitrogen cascade illustrating the central role of agriculture. The figure shows the input of new reactive nitrogen (N_r) production, contrasting the intended flows to and from European agriculture (black arrows), the unintended flows as this pass down the cascade (red arrows), and the resulting environmental concerns (orange boxes). Updated from Sutton *et al* (2011a).

The emissions from the livestock sector contribute to five major environmental impacts:

(i) The emissions of ammonia (NH_3) and nitrogen oxides ($NO_x = NO + NO_2$) contribute to the formation of secondary particulate matter (PM) and tropospheric ozone, both with serious impacts on air quality. Across Europe, ammonium in particles may account for 5–15% of total $PM_{2.5}$ (Putaud *et al* 2010). Loss of statistical life expectancy due to exposure to $PM_{2.5}$ is estimated at 6–12 months for large parts in Europe (Amann *et al* 2011).

(ii) Emissions from the livestock sector affect radiative forcing in many ways; long-lived greenhouse gases (GHGs) occur as methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) from the use of fossil fuels or through land use and land use change. Emissions of NO_x contribute to tropospheric ozone formation—an important greenhouse gas in its own right—which reduces carbon sequestration through damage to vegetation (Ainsworth *et al* 2012, Simpson *et al* 2014). Conversely, aerosols produced by NO_x-driven photochemistry also affect climate, generally having a cooling effect (Simpson *et al* 2014, Shindell *et al* 2009). The interactions between atmospheric chemistry, vegetation and aerosols are complex and only partially understood (Ainsworth *et al* 2012, Simpson *et al* 2014), but overall, it is estimated that the emissions of N_r from Europe lead to a small, but uncertain, cooling (Butterbach-Bahl *et al* 2011). Deposition of N_r contributes also to additional carbon sequestration in forests by stimulating plant growth and altering rates of ecosystem respiration, generally reducing CO_2 concentrations (de Vries *et al* 2011a, Zaehle *et al* 2011). Globally, livestock systems are estimated to contribute about 14.5% to total GHG emissions (Gerber *et al* 2013). Estimates of the share of GHG emissions from land use changes to total livestock emissions range between 9%–35% (FAO 2006, 2010, Lesschen *et al* 2011, Weiss and Leip 2012).

(iii) Terrestrial biodiversity is affected by livestock production through land use (including historic land use changes), ammonia emissions and consequent deposition and climate change. Intensively managed grassland and arable land used to grow livestock feeds have a low biodiversity, while extensive grazing avoids shrub encroachment or reforestation and helps maintain landscapes of high biodiversity. Habitat changes and land fragmentation can lead to truncation of

Table 1. Overview of emissions caused by livestock rearing and feed that were quantified in the study.

	Livestock rearing	Feed	
	Direct and energy[a]	Cultivation excl. energy[b]	Energy incl. feed processing and transport[c]
Air quality	NH_3, NO_x	NH_3, NO_x	NO_x
Climate change	CH_4, N_2O, CO_2 (NH_3, NO_x)	N_2O, CO_2 (NH_3, NO_x)	CO_2
Soil quality	NH_3, NO_x, SO_2	NH_3, NO_x	NO_x, SO_2
Terrestrial biodiversity	CH_4, N_2O, CO_2, NH_3, NO_x	N_2O, CO_2, NH_3, NO_x, land use	NO_x, CO_2
Quality of inland and coastal water	N and P losses	N and P losses	

Note: Direct livestock rearing includes livestock housing and manure management and storage; energy consumption from housing, milking, buildings etc. Cultivation of forages (grass, fodder maize, fodder beet etc) and other feed includes all direct and indirect emissions not linked with the consumption of energy.

[a] Place of emissions is EU27.

[b] Place of emissions is EU27 for forages and both EU27 and rest of the world for other feed.

[c] Place of emissions is both EU27 and rest of the world.

migratory routes or the replacement of native species with invasive ones (Reid *et al* 2010). N_r deposition reduces species richness through eutrophication, acidification, direct foliar impacts, and exacerbation of other stresses (Dise *et al* 2011, Bobbink *et al* 2010).

(iv) Finally, livestock production has a role in the deterioration of the quality of freshwater and coastal water, increasing losses of N and phosphorus (P) to the water system. There is evidence that concentrations of 25 mg L^{-1} nitrate (NO_3^-) in drinking water are related to an increase of incidences of colon cancer by about 3% (van Grinsven *et al* 2010). The stoichiometric excess of nitrogen and phosphorus in coastal water with respect to silica (Si), can enhance water eutrophication (Billen and Garnier 2007, Grizzetti *et al* 2011, Voß *et al* 2011).

In this study we quantified the contribution of livestock production systems to the above mentioned five impacts combining new data based on a cradle-to-gate Life Cycle Assessment (LCA) calculation with results of other studies on emissions at the European scale. The results are discussed with respect to total emissions in the EU27. Although several compounds are included in the analysis, this paper will give particular attention to reactive nitrogen flows in agricultural production systems.

Methods

Overall approach

We estimated emissions of CO_2, CH_4, N_2O, NH_3, NO_x, SO_2, and N and P losses to the hydrosphere related to livestock production in Europe and interpreted the results in the light of the five major environmental threats. This was done by (i) extending the LCA approach in the agro-economic Common Agricultural Policy Regionalised Impact (CAPRI) modelling system (Britz and Witzke 2012)[11], developed for the assessment of GHG emissions and N footprints, to provide cradle-to-farm gate LCA data for reactive nitrogen, in combination with (ii) model results for other compounds (P and SO_2) to provide a comprehensive picture of the environmental impact of EU livestock production. Table 1 gives an overview of emission sources quantified indicating how they are linked to livestock production systems. As the table indicates, emissions caused by livestock rearing were calculated for EU27 only. Emissions from imported livestock products were not included in the analysis, while further emissions associated with cultivation, processing and transport of (non-forage) feed might occur within or outside the EU.

The CAPRI N-LCA approach

The emissions of GHGs (N_2O and CH_4) and reactive nitrogen (N_r) to air (NH_3, NO_x) and water (N leaching and runoff) and other N flows (such as trade of food and feed) were estimated with CAPRI, using the cradle-to-gate LCA approach implemented for the estimation of GHG emissions (Weiss and Leip 2012) and further extended to include the estimation of N footprints per product group (Leip *et al* 2014b). Here we present new data that have been calculated when further extending the model with flows of all N_r. All new data presented here include emissions occurring within Europe and outside the EU territory for imported feed and/or land use change (LUC; LUC emissions were calculated using the land use transition probabilities of scenario II in Weiss and Leip (2012), table A1). Also included are credits for carbon sequestration in managed grassland as well as emissions due to foregone carbon calculation in croplands according to Weiss and Leip (2012). To analyze

[11] http://www.capri-model.org/

international N flows to and from EU27, the detailed trade data matrix of the trade module in the FAOSTAT database (FAOSTAT 2014) was used taking into account the N content to the 504 commodities involved (vegetal, animal and fiber products) (Lassaletta *et al* 2014). Internal flows among EU 27 countries were calculated and subtracted. The net N import to EU27 for each world country was estimated by the difference between total imports and exports.

A general description of the CAPRI model and its relevant modules can be found in Britz *et al* (2010), Jansson and Heckelei (2011), Leip *et al* (2011b, 2011d), Britz and Wizke (2012) and Perez-Dominguez *et al* (2012).

In the CAPRI LCA module (Weiss and Leip 2012, Leip *et al* 2014b, Westhoek *et al* 2015), total agricultural emissions E_{agri} were estimated as the sum of flows caused by agricultural production activities, plus emissions caused in earlier phases of the products life cycle, including energy use or land use change. Supplementary Information S1 gives detailed results of the N-LCA for the main six vegetable and six livestock product groups to which the data were aggregated. Differently from Weiss and Leip (2012) and in accordance to Leip *et al* (2014b) the allocation of flows from primary crop products to secondary products (e.g. soya to soybean oil and soybean cakes) is done by mass. The allocation of emissions from feed production to specific livestock products makes use of the animal budget module in CAPRI where energy and protein requirements are matched with domestic and imported feed supply, and data on farm expenditures for feed (Britz and Witzke 2012, Leip *et al* 2011d). In a first step, emissions from crop activities are converted into emission intensities and allocated to animal activities and in a second step to animal products (Weiss and Leip 2012).

For our purpose, E_{agri} was divided into emissions related to livestock production E_{lvst} and those related to production of crops for other purposes (food, fuel, fibre) E_{crop}. E_{lvst} includes emissions from livestock production systems E_{anim} (e.g. CH_4 emissions from enteric fermentation, emissions from energy use for milking etc) plus the emissions from feed production, transport and processing E_{feed}.

For each crop product, allocation to food or feed is done on the basis of the market balance which is available in CAPRI at the national level (see supplementary information S2). The share of total quantities of flows allocated to food crops was calculated on the basis of total domestic production (gross production) minus the quantity used for feed, while the share of the flow used to feed is allocated to livestock products based on feed intake quantities. Emission sources considered are given in table 2.1 by Westhoek *et al* (2015).While this study is restricted to quantifying emissions from EU27 agriculture, E_{feed} includes both emissions from domestic feed production E_{feedeu} and emissions from imported feed products $E_{feedrow}$:

$$\begin{aligned} E_{agri} &= E_{lvst} + E_{crop} \\ &= E_{feedrow} + E_{feedeu} + E_{anim} + E_{crop} \end{aligned}.$$

Global warming

The contribution to global warming was assessed as the sum of direct GHG emissions (CO_2, N_2O and CH_4), indirect N_2O emissions and C sequestration. Direct N_2O and CH_4 emissions were from CAPRI-LCA, using a global warming potential of 298 kg CO_2eq (kg N_2O)$^{-1}$ and 25 kg CO_2eq (kg CH_4)$^{-1}$ (IPCC 2007). Indirect N_2O emissions were estimated as 1% of the emitted N (IPCC 2006). Indirect C sequestration in forests was calculated using an average carbon uptake (sequestration) factor of 35 kg C per kg N deposited for European boreal and temperate forests (de Vries *et al* 2014, 2009) and a fraction of 0.25 kg N deposited on forest per kg N emitted, based on EU27 total NH_3–N emissions from agriculture and NH_3–N deposition on forests (de Vries *et al* 2011b). Other 'cooling effects'(Butterbach-Bahl *et al* 2011) were not included in the quantification.

Air quality

The contribution to air quality impacts was assessed on the basis of the sum of NH_3 and NO_x emissions, as calculated with CAPRI N-LCA.

Soil acidification

Contribution to soil acidification was assessed on the basis of the sum of SO_2, NH_3 and NO_x emissions. NH_3 and NO_x emissions were calculated with CAPRI N-LCA. Total SO_2 emissions were obtained from the EDGAR data base (European Commission 2011). SO_2 emissions caused by agricultural activities were approximated by the ratio of CO_2 emissions from agriculture related to energy use (Weiss and Leip 2012) and total energy CO_2 emissions in EU27 (EEA 2011). This gives a share of about 6%, which is associated with livestock products (4%) and vegetable products (2%), in accordance with the global estimate of FAO (FAO 2006).

The contribution of agricultural sources to emissions of acidifying substances was estimated on the basis of acidity equivalents (Schöpp and Posch 2003). This method converts emissions of S, NO_x and NH_y to acidity equivalents on the basis of the molecular weight m (64, 46, and 17 for SO_2, NO_x, and NH_4^+ , respectively) and the charge per mole z (−2, −1, and +1 for SO_4^{2-},NO_3^-, and NH_4^+, respectively) to get the conversion factors 0.03125 Geq (Gg SO_2)$^{-1}$, 0.02174 Geq (Gg NO_2)$^{-1}$, and 0.05882 Geq (Gg NH_3)$^{-1}$.

Terrestrial biodiversity

The contribution of agriculture, livestock and feed to loss of relative mean species abundance (MSA) was estimated using shares of land use and emissions of

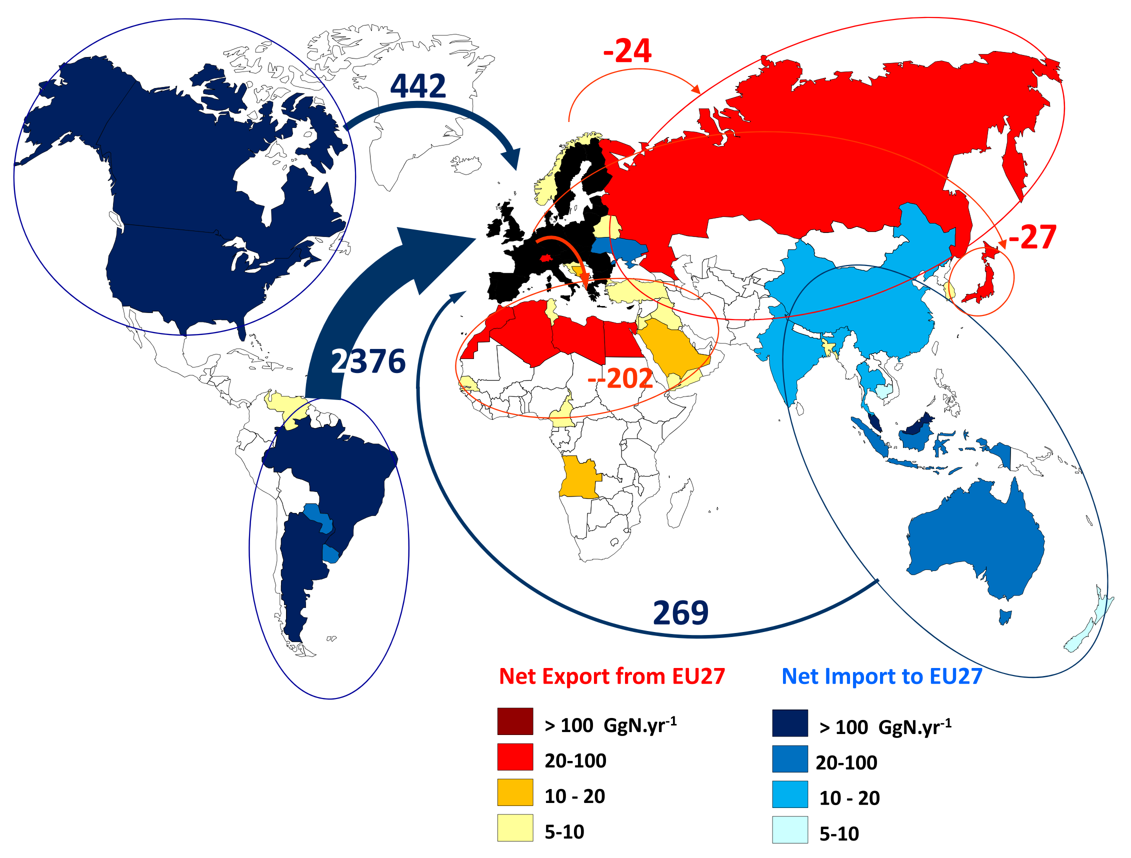

Figure 2. N flows from any EU27 to the other world regions and countries for the year 2004 calculated from FAO database (FAOSTAT 2014, Lassaletta *et al* 2014). EU27 marked in black, blue countries are those which are net exporting N to Europe. Yellow, orange, red countries are those which are net importing N from Europe. Arrows show flows between large regions and EU27. Flows below 20 GgN are not represented.

NH_3, NO_x, and net GHG exchange, accounting for C sequestration, as calculated with the CAPRI-LCA. The data are linked to the estimates of the effect of the main drivers for biodiversity loss as calculated with the GLOBIO-model (Alkemade *et al* 2009, Kram and Stehfest 2012, van Vuuren *et al* 2015). This model gives an absolute loss of 65% MSA caused by land conversion into arable, grazing and forestry (35%, 15% and 14%, respectively), and to pressures such as N deposition (2%), climate change (3%) and land fragmentation (30%) (for details see supplementary information S3).

Water quality

The contribution of agriculture, livestock and feed to N_r losses to the hydrosphere was derived from the results of CAPRI N-LCA. Contribution of livestock and feed to dissolved inorganic phosphorus (DIP) losses has been calculated by applying the share of P in fertilizers (mineral fertilizer and manure) per crop from CAPRI LCA to Global NEWS results on total and agricultural flows of DIP (Mayorga *et al* 2010). We were unable to quantify the role of agriculture in the load of particulate phosphorus (PP).

A quantification of the impact of N and P losses was done by combining an analysis of potential risk of eutrophication, based on the Indicator for Coastal Eutrophication Potential (ICEP, Garnier *et al* 2010, Billen *et al* 2011) with the estimation of livestock contribution to river nutrient loads provided by the model GREEN (Grizzetti *et al* 2012) in the different European coastal areas (see supplementary information S4).

Results

The role of trade in N emissions in EU27 and other world regions

N flows from EU27 to other world regions and vice versa for the year 2004 are illustrated in figure 2. Much of the proteins grown in Europe are used to feed livestock. From a total of 16.4 Tg N produced on agricultural land in the year 2004 only 2.4 Tg N yr^{-1} (about 15%) were supplied for direct human consumption or further processing. Most of it was used as animal feed (8.8 Tg N yr^{-1} or 54%) or returned to the soil as crop residue (5.1 Tg N yr^{-1} or 31%). Furthermore, we estimate that livestock received 4.2 Tg N yr^{-1} from imports or industry (Leip *et al* 2014b, see also details in supplementary information S2).

According to FAO trade statistics, EU27 was in 2004 a net importer of agricultural products with soybean products for animal feed produced in Argentina, Brazil and USA representing 84% of the total net imports of EU27 (see figure 2; for a comparison of EU27 and global agricultural structure and emissions see supplementary information S5) that entails significant trade of embodied cropland surface (MacDonald *et al* 2015). According to calculations based on FAOSTAT (2014) data, in 2004 about 70% of the European livestock production was used for intranational consumption and 18%–27% (respectively for chicken and cattle meat, expressed in N) was traded between EU27 countries with significant associated embodied GHG emissions (Caro *et al* 2014). The EU was thus close to self-sufficiency for meat and dairy products, but the share of pig meat production was much higher than in the rest of the world, while the share of ruminant meat was significantly lower (22% versus 29% globally).

The environmental impact of agriculture and livestock production in EU27

Table 2 shows the results for total agricultural emissions from the EU27 agricultural sector and emissions related to livestock production, feed production and imported feed. Values are provided for NH_3, NO_x, SO_2, the combined effect of the three pollutants converted to acidity equivalents, GHG emissions (CH_4, N_2O, and CO_2), C-sequestration, water pollution by emissions of N and P (as dissolved inorganic P, DIP), the land use and the contribution to the loss of the MSA. Values reported in table 2 refer to the year 2004. Detailed results of the LCA calculation (N_r and GHG emissions) are given in supplementary information S1.

Total agricultural emissions as compared with the total EU27 emissions from all sources (Leip *et al* 2011a) are given in table 3. Both total and agricultural emissions refer to emissions from EU27 territory. Therefore, agricultural emissions in table 3 do not include emissions associated with imported feed (see table 2).

Air quality

Agricultural sources of NH_3 from manure management, and manure and mineral fertilizers on soils totalled 2.8 $Tg\,N\,yr^{-1}$ in 2004. The contribution of livestock production to total agricultural emissions was particularly high for NH_3 (82%) due to the importance of manure management. The share of NH_3 emissions linked to livestock feed was 41% of agricultural emissions, of which about 8% occurred outside Europe.

Total agricultural NO_x emissions at 0.46 $Tg\,N\,yr^{-1}$ were dominated by emissions from fossil fuel used for farm operations and during processing or transport of animal feed. The share of energy related emissions was higher for crop products (88%) than for livestock products (77%) with an overall contribution to emissions of 85% (0.39 $Tg\,N\,yr^{-1}$). As there were only small NO_x emissions from livestock production systems, most of the emissions were related to feed production, processing and transport (0.23 $Tg\,N\,yr^{-1}$) and we estimated that about 51% of those occurred outside the EU territory or were linked to feed transport.

For the sum of NH_3 and NO_x emissions, the share of agricultural emissions from livestock was 80% due to the dominance of NH_3 emissions. 42% of emissions were related to feed production, and 10% were associated with feed imports.

Global warming

The direct emissions of GHGs from the agriculture sector itself in 2003–2005 was 483 $Tg\,CO_{2eq}\,yr^{-1}$, contributing about 10% of total anthropogenic GHG emissions in the European Union (EEA 2011). However, we estimated emissions of more than twice that amount when including associated emissions that agriculture causes in other sectors, such as energy, industry, or land use and land use change (Weiss and Leip 2012). Overall, 81% of total European agricultural emissions (including associated emissions and emissions from outside of the EU27) were caused by livestock production. As much as 39% of agricultural emissions were estimated to occur outside the EU territory or from associated emissions. This includes especially feed imports, feed transport and emissions from land use change. Carbon sequestration induced by N deposition on forests was found to reduce agricultural emissions by about 100 $Tg\,CO_{2eq}\,yr^{-1}$ (i.e., 10%). As agricultural N emissions are closely linked to manure management (see supplementary information S1), the N benefit for carbon sequestration was mainly located within the EU.

Soil quality

Emissions of acidity equivalents were dominated by NH_3 which accounted for about 85% of the acidity equivalent emissions for livestock (including associated emissions).

Terrestrial biodiversity

Expressed in terms of MSA, we estimated that overall agriculture, through arable and grazing and emissions of N and GHG, caused a loss of 34% MSA, i.e., more than half of the overall loss of biodiversity (Alkemade *et al* 2009). Of this agriculture related loss, 76% was estimated to be caused by livestock, with most of this through feed production.

Quality of inland and coastal water

Nitrogen

Diffuse N losses from agricultural systems were estimated at 6.0 $Tg\,N\,yr^{-1}$. This represents percolation of nitrate and organic nitrogen below the rooting zone in agricultural soils, including both cropland and pasture land, and run-off from soils or barn yards.

Table 2. Share of the livestock sector, feed production and feed imports on the emissions of pollutants due to agriculture in EU27 with relevance for air quality, global warming, soil quality, biodiversity and water quality for the year 2004.

	Air and soil quality		Air and soil quality		Air quality		Global warming	
	NH_3		NO_x		NH_3 and NO_x		GHG	
	Emissions [Tg N yr^{-1}]	Share	Emissions [Tg N yr^{-1}]	Share	Emissions [Tg N yr^{-1}]	Share	Emissions [Tg CO_{2eq} yr^{-1}]	Share
Agriculture	2.8	100%	0.46	100%	3.2	100%	1062	100%
Livestock	2.3	82%	0.30	66%	2.6	80%	861	81%
Feed	1.1	41%	0.23	49%	1.4	42%	560	53%
Feed imports	0.2	8%	0.12	25%	0.3	10%	411	39%

	Global warming		Global warming		Soil quality		Soil quality	
	C-sequestration		GHG + sequestration		SO_2		NH_3 and NO_x and SO_2	
	Emissions [Tg CO_{2eq} yr^{-1}]	Share	Emissions [Tg CO_{2eq} yr^{-1}]	Share total	Emissions [Teq yr^{-1}]	Share	Emissions [Teq yr^{-1}]	Share
Agriculture	−104	100%	958	100%	0.021	100%[a,f]	0.19	100%
Livestock	−82	80%	779	81%	0.014	67%	0.15	79%
Feed	−43	42%	516	54%	0.010	50%	0.08	42%
Feed imports	−10	10%	400	42%			0.01	8%[d]

	Biodiversity[b]		Biodiversity[b]		Water quality N		Water quality P[b]	
	Land Use		Loss of biodiversity		N		DIP[c]	
	Area [Mio km^2]	Share	Relative MSA [%]	Share	Emissions [Tg N yr^{-1}]	Share	Emissions [Tg P yr^{-1}]	Share
Agriculture	2.0	100%	−34%	100%[a,e]	6.0	100%	0.025	100%
Livestock	1.4	69%	−25%	76%	4.4	73%	0.018	73%
Feed	1.4	69%	−25%	74%	4.2	71%	0.018	73%
Feed imports	0.2	11%			0.6	10%		

Notes

[a] Own calculation;

[b] Emissions occurring outside Europe not included in these estimates;

[c] DIP emissions represent about 50% of total P export to the coastal zones;

[d] Not considering SO_2;

[e] Alkemade *et al* 2009;

[f] EEA 2011.

73% of these emissions were associated with livestock, which was dominated by feed production. The share of leaching and runoff occurring outside of the EU territory was estimated at 10%.

Phosphorus

Diffuse losses of DIP from agriculture were estimated at 0.025 Tg P yr^{-1}, while weathering in agricultural systems contributes an estimated additional 0.003 Tg P yr^{-1} (Mayorga *et al* 2010). By far the largest share of net P input (P input minus P crop removal) was retained in the soil, which is considered a benefit as long as this leads to increased soil fertility, i.e., with low erosion. We do not have an estimate of agricultural dissolved organic phosphorus (DOP) or PP, as it is very difficult to distinguish sources for DOP and particularly for PP export. However, most likely the contribution of agriculture is much higher for PP than for DIP while PP dominates P export. The data presented in table 2 relate to DIP only and are therefore to be regarded as a conservative estimate for the total contribution of agriculture to P flows to coastal areas in Europe. Phosphorus losses from livestock were entirely attributed to feed production, with livestock DIP representing 73% of total agricultural losses, even though some additional losses from animal housing or manure storage systems might occur.

We estimate that in Europe the livestock sector accounts for 23%–47% of the nitrogen river load to coastal waters, and 17%–26% of the phosphorus river loads, where the lower limit is calculated considering the contribution of manure alone and the upper limit taking into account manure applications plus mineral fertilizer (see supplementary information S4).

Discussion

To our knowledge, this is the first study to estimate the contribution of livestock production systems, feed and

Table 3. Comparison of estimated agricultural emissions in this study (from Table 2) and reported total EU27 emissions.

	Total Agricultural LCA impact within EU27 territory	Total EU27 budget impact	Data source for total EU27 impact
NH_3 emissions [Tg N yr^{-1}]	2.6	2.7	EDGAR data base (European Commission 2011) for non-agricultural emissions
NO_x emissions [Tg N yr^{-1}]	0.3	2.6	EDGAR data base (European Commission 2011)
GHG emissions $CH_4+N_2O+CO_2$ emissions [Tg CO_{2eq} yr^{-1}]	651	4889	EU GHG inventory (EEA 2011)
Carbon sequestration [Tg CO_{2eq} yr^{-1}]	−93	−171	Same method as for agricultural C sequestration
SO_2 [Teq yr^{-1}]	0.021	0.3	EDGAR data base (European Commission 2011)
Land Use Area [Mio km^2]	1.8	4.2	FAOSTAT
Air quality $NO_x + NH_3$ emissions [Tg N yr^{-1}]	2.9	5.3	
Global warming GHG + C sequestration [Tg CO_{2eq} yr^{-1}]	558	4718	
Soil quality $NO_x+NH_3+SO_2$ [Teq yr^{-1}]	0.18	0.56	
Loss of biodiversity [relative MSA]	−25%	−65%	Alkemade *et al* (2009)
Water quality N N [Tg N yr^{-1}]	5.4	9.1	European Nitrogen Assessment (Leip *et al* 2011a) for non-agricultural sources (sewage, forest including background, deposition on water surfaces)
Water quality P DIP [Tg P yr^{-1}]	0.025	0.25	Mayorga *et al* (2010)

feed imports to total agricultural emissions and their related environmental impact at a comparable level of detail. Plausibility of results have been discussed in depth with regard to GHG emissions (Weiss and Leip 2012) and N-footprints (Leip *et al* 2014b). Estimates of the share of N_r emissions however are different from those given in Leip *et al* (2014b), as the authors calculated the shares on the basis of domestic consumption (human consumption or processing) while in this study we calculated the share on the basis of total production. Below, we first discuss uncertainty aspects of our emission estimates and estimates of emission shares, followed by options to reduce the environmental impact.

Uncertainty of emission estimates

For N, combining $NH_3 + NO_x$ emissions, our estimate of 2.6 Tg N yr^{-1} from agricultural sources using the CAPRI model (excluding energy related NO_x) is 19% and 7% smaller than official estimates of the European Union of 3.2 Tg N yr^{-1} (EEA 2014) and the estimate of the MITERRA model of 2.8 Tg N yr^{-1} (Westhoek *et al* 2014), respectively. The estimated total N excretion in CAPRI, at 8.9 Tg N yr^{-1}, is 88% of the official estimate in EEA (2014, EEA 2014). This difference can be explained by the fact that CAPRI calculates N excretion on the basis of a consistent IPCC Tier 2 approach (animal budget, Leip *et al* 2011b, IPCC 2006) across all countries, while national inventories in Europe are constructed with a large variety of methods and data quality (Leip 2010). National estimates would be of higher quality than CAPRI estimates from countries with good data (Leip et al 2014b), but some countries still need to improve their methodology (EEA 2014). Furthermore, CAPRI uses ammonia abatement measures from the GAINS model (Klimont and Winiwarter 2011) which may not have been considered in national inventories (Leip et al 2010).

In comparison with 4.4 Tg N yr^{-1} agricultural NH_3 emissions in the EDGAR data base, our estimate of 2.6 Tg N yr^{-1} for EU27, excluding emissions from imported feed, is lower. The reason for this might be the lower excretion estimates, although the NH_3 emissions are in line with estimates by the MITERRA model.

While 85% of NO_x emissions were related to energy use, only 0.07 Tg N yr^{-1} were from non-energy sources. A quality check of the total agricultural emission estimate for NO_x is difficult as no comparable study exists including both NO_x budget flows and NO_x emissions related to energy consumption in agricultural systems. Energy consumption in agriculture is calculated in CAPRI with a dedicated energy module which is also used for GHG emission estimates (Kempen and Kraenzlein 2008, Weiss and Leip 2012); this is also the basis of the estimated contribution of SO_2 emissions. The share of agricultural NO_x and NH_3 to total emissions is within −6% to +16% of earlier estimates (Leip et al 2011a).

Our estimate for the share of agricultural GHG emissions to total GHG emissions based on table 3 is about 13%. It ranges between the value of the official EU GHG inventory (10%, EEA 2014) and other estimates on the shares of agriculture or even livestock production on total GHG emissions (Gerber et al 2013, FAO 2006, Weiss and Leip 2012). The official GHG inventory considers only emissions reported in the agriculture sector, whereas LCA studies also include emissions from Land Use Change (LUC) and from imported feeds, which amounted to 39% of total agricultural emissions (see table 2).

Our estimate for N_2O emissions from agricultural soils is considerably lower than official estimates; a comparison of N_2O emissions between various models (de Vries et al 2011b) showed overall satisfying agreement. No methodology is able to capture the huge variability of N_2O emissions caused by changing soil and climate conditions. In view of the general lack of experimental observations, even process-based models are not able to achieve a closer match than independent calculations using inverse methods (Leip et al 2011c).

LUC is certainly one of the most difficult sources to quantify, as it requires data (or good assumptions) on *how much* LUC is occurring as a consequence of EU agricultural and livestock production, as well as *what kind* of LUC is triggered. Indeed, the debate on the best method to estimate LUC emissions from agricultural products is still ongoing (European Commission 2013). The method developed in the CAPRI model (Leip et al 2010, Weiss and Leip 2012) was based on the assumptions that the agricultural market is very fluid and no differentiation between direct and indirect LUC is possible. The approach considers only LUC linked to an expansion of harvested area, very similar to the methods proposed by recent guidelines (Food SCP RT 2013, leap 2014). We used unique LUC factors for imports from a country outside the EU as weighted average for all importing countries accounting for globally connected and substitutable trade flows.

We are aware of the debate on the permanency of carbon sequestration in grassland (Smith 2014), however the approach by Weiss and Leip (2012) is based on the observation that enhanced carbon sequestration rates in grassland are observed also after the 20 years equilibrium time usually used by IPCC methodologies (IPCC 2006), which is also consistent with recent simulations with the CENTURY model (Lugato et al 2014).

Carbon sequestration in forests has been estimated earlier at the scale of the EU27 for the year 2000 by multiplying an estimated N deposition caused by agricultural NH_3 emissions of 0.61 Tg N yr^{-1} with a C response of 50 kg C per kg N deposited leading to a C sequestration near 30 Tg C yr^{-1} or 112 Tg CO_2 yr^{-1} (de Vries et al 2011a), being very close to our estimate of 104 Tg CO_2 yr^{-1}. In our study the estimated N deposition was larger (0.82 Tg N yr^{-1}) while the C:N response was estimated at 35 kg C per kg N deposited.

Estimates of agricultural N-leaching range from 2.0 to 5.7 Tg N yr^{-1} (de Vries et al 2011b), the higher value being also found in the EU GHG inventory (EEA 2014). Possible reasons for these differences—in addition to those already discussed—are available calibration data for nitrate concentrations which might neglect flows of organic nitrogen to water, and the split of total N between the highly uncertain N_2 emissions and N leaching/runoff (de Vries et al 2011b). Our estimate of nitrate leaching at 5.4 Tg N yr^{-1} is consistent with the estimate of the European Nitrogen Budget (Leip et al 2011a) which is used in table 3 for total N input to water. Although livestock dominated overall agriculture P flows (73%), agriculture is responsible for only 10% of the total riverine P export (table 3). This is because point sources from human wastewater dominate (accounting for 0.21 Tg P yr^{-1} out of a total riverine DIP export of 0.25 Tg P yr^{-1}). The contribution of agriculture to the total P load (including DIP, dissolved organic P, DOP and particulate P, PP) may however be larger, specifically for PP, which is about 40% of the total P export to waters in Europe (50% is DIP and 10% is DOP). The share of agriculture in PP export is determined by (i) surface runoff of P in particles of fertilizer and manure, (ii) agricultural practices (e.g. tillage) that affect the erosion rate and (iii) elevated P contents of soil material eroded from agricultural fields due to application of P fertilizers and animal manure. The effects of agriculture on PP export are likely to occur much faster than the strongly delayed effect of DIP export through the soil systems but these mixed contributions make it very hard to assess what the agricultural contribution to the PP load is.

Finally, we have used the MSA indicator as a measure for terrestrial biodiversity. MSA represents an index of the naturalness of an ecosystem. Compared with more traditional measures (e.g. monitoring species changes), this measure has two main advantages: it is possible to attribute biodiversity loss to certain sectors (PBL 2014), and the effect of alternative scenarios on biodiversity can be quantified (PBL 2012, 2014). The patterns of change indicated by the MSA are largely similar to those indicated by other measures as the living planet index as developed by WWF or red list indices (SCBD 2014). A limitation of the MSA indicator is that it does not yield comprehensive information on the actual distribution and abundance of species, such as the status of endangered or threatened endemic species.

Uncertainty of the estimated shares

While some uncertainty is associated with the individual emission estimates, other parameters might dominate the uncertainty of the estimated shares. For example, while the estimate of N_2O emission factors might be associated with an uncertainty of up to 50% (at the European scale), the uncertainty around the estimated share of crops that is used as feed determines the uncertainty of livestocks' contribution on total agricultural N_2O emissions. A bias in the total feed translates directly into a bias of the estimated share of emissions from livestock production, as it not only determines the share of crops used as feed, but also the amount of CH_4 emissions from enteric fermentation in ruminants and manure excretion (which is calculated on the basis of animal retention data) and consequent emissions from manure management. This value is obtained from statistical sources (market balances) and is further constrained by energy and nutrient requirement calculations for major livestock types.

No data are available whether farmers prefer domestically produced crops or imported crops for feed; therefore this value is highly uncertain. Because of the lack of information, we considered equal preference. However, this uncertainty concerns only primary crops that are used for both food and feed, which make only 12% of the total feed, while the rest comes from non-marketable crops (82%), such as grass, fodder maize and beet, or secondary crops (6%). Non-marketable crops are all domestically produced; secondary feed stuff is dominated by imported soya bean.

Options for reducing the environmental impact of livestock production

There are two main routes to reduce the environmental impacts of livestock production:

(i) technical measures (reduce emissions intensity/land use intensity and

(ii) lower livestock production in the EU with demand side measures, i.e., a reduction of food losses and wastes and/or dietary shifts.

Our study presents a 'status quo' analysis (attributional LCA) and does not examine emissions without (or with less) livestock production (case ii). What would happen if livestock production is reduced in Europe has been discussed in depth in Westhoek *et al* (2014, 2015). Based on the observation that the intake of protein as well as saturated fats by European inhabitants is far above the maximum recommended level (WHO 2007, Westhoek *et al* 2011), the authors showed that reducing the consumption of meat, dairy and eggs in the EU27 by 50% would lead to a decrease of N_r emissions by 40% and a reduction of GHG emissions by 25%–40% with expected substantial health benefits (Westhoek *et al* 2014, 2015). Those results hold for two contrasting scenarios on the use of the 'freed' land that would not anymore be required for feed production, i.e., a 'greening scenario' with enhanced production of bio-energy and a 'high price' scenario with increasing export of cereals. They can be regarded as conservative scenarios, as beneficial environmental effects outside Europe had not been quantified, such as the subsequent prevention of land conversion outside Europe (Stehfest *et al* 2013), or the reduction of GHG emissions from bio-energy production (or other options such as afforestation).

From the production side many technical, structural or policy mitigation options are being discussed, addressing feed production (e.g., precision agriculture and agronomic nitrogen use efficiencies), livestock production (e.g. grazing and feeding management and feed supplements, improved herd structures), or housing and manure management (Thornton and Herrero 2010, Gerber *et al* 2013, Golub *et al* 2013, USDA 2013, Cohn *et al* 2014, Havlík *et al* 2014, Hou *et al* 2014, Van Middelaar *et al* 2014, Winiwarter *et al* 2014, Van Doorslaer *et al* 2015). The benefits of sustainable extensification practices have also recently been explored for Europe (van Grinsven *et al* 2015). Bouraoui *et al* (2014) have shown that high reductions of nitrogen losses to water could be achieved in Europe by an optimized use of organic manure. Additional emission reductions could be achieved by decreasing the wastage of the supplied proteins (Westhoek *et al* 2011, Bellarby *et al* 2013, Grizzetti *et al* 2013).

Conclusions

This analysis shows that, while agricultural activities are a major source of pollutants and land use change, livestock production systems dominate the environmental consequences. For the five threats considered here, livestock production contributed between 73% (water quality) to about 80% (biodiversity, air quality, soil acidification and global warming) of the overall agricultural impact.

The results point to the fact that in Europe serious efforts in mitigating the major environmental problems for Europe from agriculture need to address the livestock sector. While technical measures can clearly contribute significantly to emission reductions, they cannot alone be sufficient (Bellarby *et al* 2013, Bajželj *et al* 2014, Eshel *et al* 2014, Leip *et al* 2014a, Witzke *et al* 2014, Pierrehumbert and Eshel 2015, Vanham *et al* 2015). The issues of what European citizens eat and their food waste also need to be addressed. For example, recent scenarios showed that all these actions would be necessary to achieve a stabilization in global N_2O emissions (UNEP 2013).

Moreover, while a shift of production from Europe to other world regions might make Europe 'cleaner', this would possibly come at the cost of higher emission intensities in other regions of the world where production systems might be less optimised (FAO 2010, Cederberg *et al* 2011, Gerber *et al* 2013); this could increase the environmental footprint of products consumed in Europe, unless additional actions were taken to address this.

Our study shows that there are intimate links between key environmental threats, emissions of N_r to the environment, the production of animal products and our diet choices.

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