Animal production and Nitrogen: Global trends in growth and efficiency

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Abstract
This paper briefly reviews the changes in global animal production during the last 50 years, when total production has roughly tripled. Animal production systems are highly diverse and are responding to changes in markets. Systems have become more specialized, productive and larger, especially in developed and rapidly developing countries. Cattle still dominate the world in terms of animal biomass but pigs and poultry have increased faster in number and production. Animal production systems provide nutritious food to humans, income and survivability to numerous smallholder farms, and they may transform residues to valuable products. However, animal production is also implicated in environmental burdens through the emissions of ammonia and greenhouse gases to the atmosphere and nutrients (mainly nitrogen and phosphorus) to water bodies. Further, there are diseases that can be transmitted from animals to people (zoonosis). Nutrient losses greatly depend on the corresponding system, management and regulations. The total amounts of nitrogen and phosphorus in manure produced annually are similar to the amounts in synthetic fertilizer used annually, but manure nutrients are often not used efficiently. Nitrogen use efficiency (NUE) at animal level ranges from 5 to 45%, depending on animal category, feeding and management. NUE of mixed crop-animal systems may range from 5 to 65% depending on NUE at animal level, and the utilization of manure nitrogen and new nitrogen inputs. Solutions for improving N use efficiency in animal production are based on a coherent set of activities in the whole chain of "feed production – animal production – manure management". A high NUE at system is achieved through a combination of a high NUE at animal level and an effective recycling and utilization of manure N in crop production. Various governmental regulations may contribute to a high NUE at system level

Key Words
Animal production, Feed production, Feed conversion, Manure, Livestock density, Nitrogen Use Efficiency (NUE), Nitrogen balances, Nutrients

Introduction
For growth, maintenance of body functions and reproduction, animals and fish (and humans) require some 22 nutrient elements (N, P, K, Mg, Ca, S, Fe, Mn, Zn, Cu, Mo, Cl, Co, Na, Se, I, Cr, Ni, V, Sn, As, F) in specific amounts, in addition to water, carbohydrates, amino acids (protein) and vitamins (McDonald et al 2010; Suttle 2010; Thomson and Almaroso 2011). All nutrient elements are taken up via feed and water ingested. The amounts taken up depend on the nutrient element, animal type, body mass, productivity and management, and range from 1 to 50 mg per kg feed (dry mass) for micronutrients (Fe, Mn, Zn, Cu, Mo, Cl, Co, Se, I, Cr, Ni, V, Sn, As, F) and from 0.1 to 50 g per kg feed for macronutrients (N, P, K, Mg, Ca, S, Na, Cl) (McDonald et al 2010). The health, growth, production and/or reproduction of animals are distorted when the supply of one or more of the elements is suboptimal. Over-optimal supply of elements may lead to toxic effects and imbalances in nutrient supply, and thereby also to malfunctioning. A large percentage of the nutrient elements consumed in the feed are excreted again via dung and urine—typically anywhere from 60% to over 90% of the mineral nutrients present in the feed, depending on animal species, feed composition, productivity and management (Suttle 2010).

The supply of nutrient elements to animals through un-amended feed may limit animal performance and health, and that is why mineral supplements (e.g., amino acid N and S, mineral P, Cu, Zn, Se, Ca, Mg) are sometimes offered to animals, to boost productivity and improve health. This supplementation of animal feeds also enhances the element contents of the animal manures, and hence the fertilization value of the animal manure. However, excessive supplementation with for example copper (Cu) and zinc (Zn) in pig and poultry feed may increase the Cu and Zn contents of pig and poultry manure to high levels, and make these manures pollutants. Antibiotics may also be added to the feed of pigs, poultry and fish in low concentrations to improve animal health and feed conversion efficiency, and residues of these may also end-up in manure.

Animal manures are large sources of organic C and nutrients, and important for improving soil quality and the fertilization of crops. However, inappropriate collection, storage, and subsequent application to cropland contribute to high losses of manure nutrients to air and water bodies. Animal manures currently contribute 40 to 65% of global anthropogenic ammonia (NH_3) emissions, and 40 to 60% of the anthropogenic nitrous oxide (N_2O) emissions, and 30-40% of methane (CH_4) emissions (Steinfeld et al., 2006, 2011). Nitrogen losses to air and water bodies create a cascade of threats, and affect biodiversity, climate and human health negatively (Sutton et al 2013). Excess P in surface waters is associated with water pollution, eutrophication and biodiversity loss. Copper and zinc are toxic to many organisms living in surface waters.

This paper briefly summarizes the changes in animal production and its N use. The emphasis on N (and P) is because the availability of N and P limit global food production most of all nutrient elements, and losses of N and P to the wider environment have significant human health and ecological impacts (e.g., Sutton et al 2013).

Changes in animal number

The changes in the number of the main animals are larger for pigs and poultry than for cattle, and larger in Asia, Latin America and Africa, than in Europe, Northern America and Russian Federation (Figure 1). The increase in the former group of countries is related to the increasing demand of animal-derived food, especially in the economically rapidly developing countries (Herrero and Thornton, 2013).

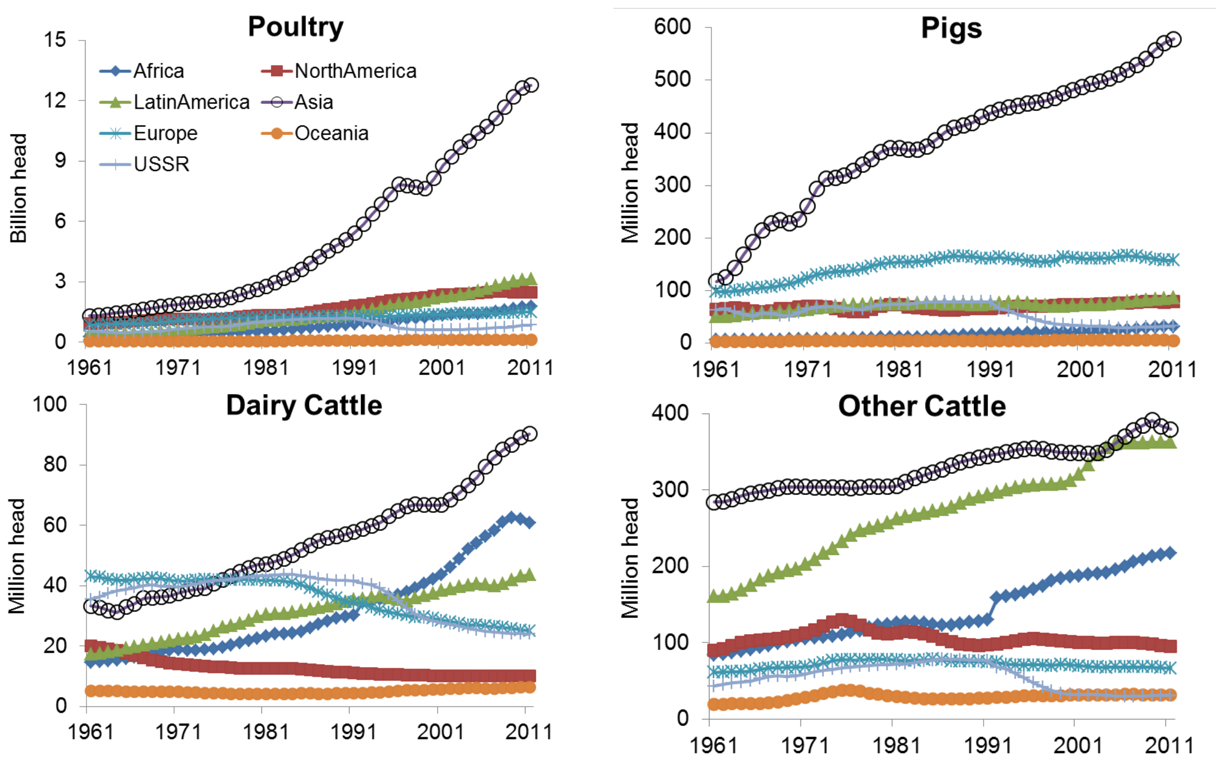

Figure 1. Total number of poultry, pigs, dairy cattle and other cattle per continent in the world between 1961-2012. Number of poultry is expressed in billion head, other animals in millions. Source: FAOSTAT.

The ratio of monogastric animals to total livestock numbers (expressed in livestock units (LSU); a mature dairy cow is set at 1 LSU, beef cattle at 0.5, sheep and goats at 0.1, pigs at 0.35, laying hens at 0.012, other poultry at 0.018 LSU) increased steadily from 0.28 in 1960 to 0.38 in 2010. Hence, the relative importance of poultry and pig production has increased over time, although cattle still dominate the world in terms of animal biomass.

There are large differences between countries in mean livestock unit (LSU) density (range 0 to more than 10 LSU per ha of agricultural land). The changes in the shape of the LSU density distribution over time (e.g., Figure 2) indicate an increase in LSU density combined with a trend of agglomeration in some countries with relatively high LSU densities (distributions become more skewed to the right-hand side over time). The kernel distribution is less peaked and less skewed for ruminants than for monogastric animals; ruminants are present in a greater number of countries at a relatively high and even density compared to monogastric animals Median LSU of ruminants increased over time from 0.45 in 1970 to 0.61 in 2000, and then decreased slightly to 0.59 in 2010. Median LSU of monogastric animals steadily increased during last 50 years, from 0.18 in 1970 to 0.30 in 2010. The median LSU density of all animals increased from 0.72 in 1970 to 0.95 in 2010 (not shown). The changes in mean LSU density is mostly the result of 'natural growth' (i.e., balance between birth rate, slaughter rate and mortality), but rapid changes in mean LSU density has happened in few countries also through cross-border trade of live animals.

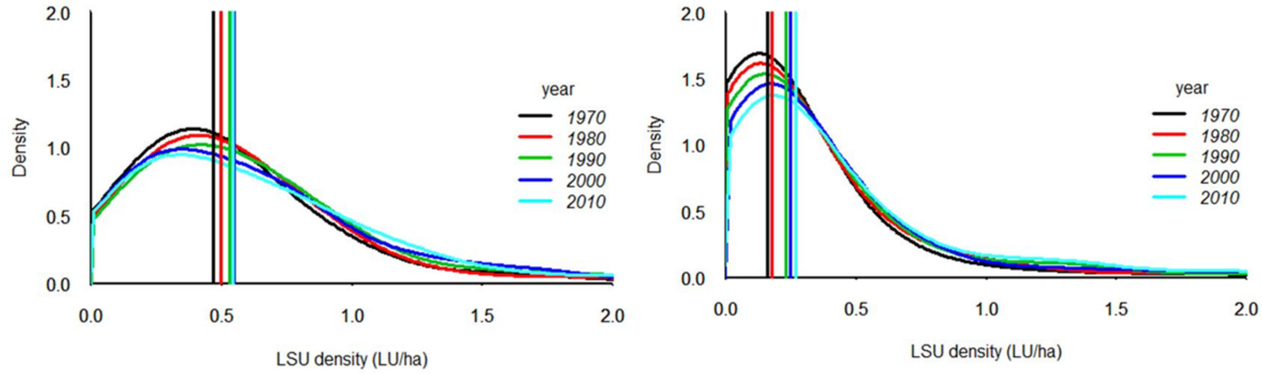

Figure 2. Kernel density distributions of LSU density of the main 151 countries of the world in 1970, 1980, 1990, 2000 and 2010. Vertical lines indicate median values of five years around decades. Left figure shows distributions for ruminants, right-hand figure for monogastric animals (binwidth=0.2; LSU density on x-axis truncated at 2 LSU per ha of agricultural land) (Liu et al., in prep).

The kernel density distribution of mean LSU per country do not reflect the often large variation in LSU within countries. Spatial variations can be large even within small countries (Figure 3), with mean density often larger than median density (indicating skewed distributions). There are indications that regions with LSU >~6 suffer from pressure from citizens and governments, and that livestock farms near big cities are forced to move further away from the city (Wei et al., 2016). Total livestock production in The Netherlands is capped through tradeable production rights, and livestock producers in high livestock density areas may not purchase pig and poultry production rights from areas with lower livestock density (e.g. Willems et al., 2016).

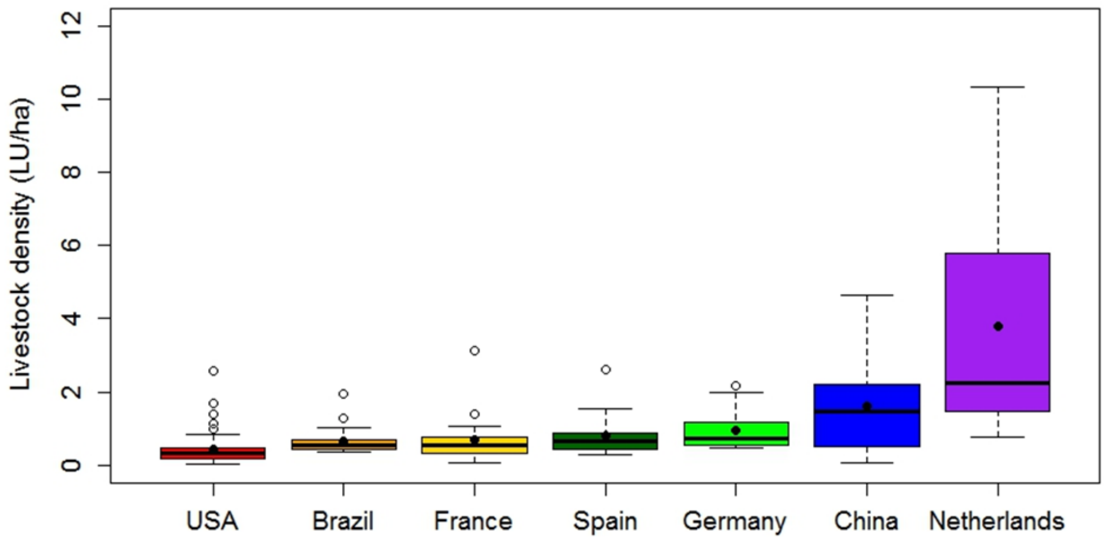

Figure 3. Spatial variation in livestock density within some countries. Data for USA show variations of 52 states in 2012, for France 22 regions in 2007, for Spain 16 regions in 2007, for Germany 14 Bundesländer in 2007, for China 31 provinces in 2010, and for Netherlands 12 provinces in 2007. Lines in boxes indicate medians, black dots means, lower and upper levels of boxes the 25 and 75 percentiles, and the lower and upper bars the 5 and 95 percentiles. Open circles show extreme values. Note that the size of the countries and the regions within countries greatly differs (Wang et al., in prep).

Changes in the areas of agricultural land used for animal production

Currently, about two-third of the total agricultural area (~61 Mha) in the world is used for the production of animal feed. This includes 34 million km^2 of pastures, used for the production of dairy, beef, sheep and goat

production (Table 1). The areas of grassland and arable land have not increased much (<10% in 50 years), but their productivities have increased greatly, through improved crop varieties, pest control and management, and increased use of irrigation an fertilizer N. Global milk and beef production have both increased by ~5% per year during the last 50 years, in part due to intensification of grassland-based systems (e.g., Stott and Gourley, 2016). In addition, an increasing fraction of the arable land is used for the production of maize and soybean, which is used for ~60% as animal feed.
The other one-third of the total agricultural area in the world is used for the production of plant-derived food (i.e., cereals, vegetables, fruits, roots, oil, nuts) and energy (Table 1). The areas of wheat and rice have only slightly increased during the last 5 decades, the areas of maize, vegetables and fruits have doubled, while the areas of oil crops (soybean, oil palm, rapeseed, sunflower) have increased by a factor of about 4. The use of crops for bio-energy has also increased during last decade in some regions; about 40% of the maize grown in North America was used for bio-energy during 2007-2011 (Wang et al., in prep).

Changes in animal production

Traditionally, animals were raised in mixed crop-animal production systems, managed by a family. These family managed mixed systems still dominate the world, in farm number, but the increase in animal production originates increasingly from specialized animal farms that import most or all feed from elsewhere. This relates especially to pig and poultry farms, which have become more 'integrated' in the production –processing-retail chain, and at the same time greatly dependent on the suppliers of animal genes (animal breeds), animal feed, housing and operation techniques, and on the meat processing companies and food retailers. These farms are also termed confined animal feeding operations, feedlots, or factory farms, because of the industrial character. The change from small family-owned and managed mixed systems to large, industry-owned specialized animal production systems has occurred quickly in some countries, for example in China, in part because of food safety and quality reasons (e.g., Sharma and Rou, 2014). The specialization and industrialization of animal production have major implications for animal productivity and nutrient cycling (Thornton, 2010).

Table 1. Areas of forest and agricultural land per continent in 2013, in million km^2. Antarctica is excluded in the total land area (Source: FAOSTAT).

Land use types, million km^2	World	Africa	Americas	Asia	Europe	Oceania
Total land area	130.1	29.7	38.8	31.0	22.1	8.5
Forest area	40.1	6.3	16.0	5.9	10.2	1.7
Permanent grassland	33.5	9.0	8.3	10.8	1.8	3.6
Crop land	15.8	2.7	4.0	5.7	2.9	0.5
Cereal crops	7.2	1.1	1.3	3.4	1.2	0.2
Oil crops	2.9	0.4	1.1	1.1	0.4	0.1
Tuber crops	0.6	0.3	0.1	0.2	0.1	0.0
Vegetables crops	0.6	0.1	0.0	0.4	0.0	0.0
Fruit crops	0.6	0.1	0.1	0.3	0.1	0.0

Specialization and agglomerations of animal production became increasingly rapid since the 2nd half of the 20th century. At the same time, more people started to live in urban areas. As a result, food and feed products needed to be transported over longer distances, facilitated also by Transnational Corporations (TNCs), which increasingly influence the food production – consumption chain. These TNCs contribute also to the diversification of food products in supermarkets, increase the length of the food chain and add value to the products. They become increasingly powerful; the value of the ten largest retailers was roughly similar to the total value of all agricultural produce from farmers in the world in 2005 (Von Braun and Díaz-Bonilla 2008).

Animal productivity has increased greatly during last decades, but productivity differs substantially between countries and continents; e.g., mean milk yield per cow was <1000 litre per year in Africa and >3000 litre per year in America, Australia and Europe during the period 2005-2010 (Table 2), and >7000 litre per cow in northern America and Western Europe (not shown). The steady increase in animal productivity has been made possible through animal breeding and improvements in animal feeding and herd and disease management. Similarly, crop yields per unit surface area have increased by a factor of 3 to 4 in most affluent countries during the last 5 decades. The increase in crop productivity has been made possible through improvements in breeding, irrigation, fertilization, and in crop husbandry practices and pest and disease management.

The increased productivity has been facilitated by scientific and technological developments, education, extension services, and the availability of relatively cheap energy, irrigation water, fertilizers, herbicides and pesticides, and antibiotics. Food processing industries and the retail sector have at the same time diversified and have added value to the products, facilitated through technological advances in processing, cooling, storage and transportation as well as marketing. However, farmers have not benefitted much from the increased productivity and added value generation in the food chain. For example, the real price of milk received by dairy farmers in the Netherlands has decreased by a factor of 5 since 1950, while the price of milk in supermarkets has decreased only by a factor of 2 (Schelhaas 2009). To remain profitable, dairy farmers (as well as other farmers) have to increase the efficiency of production and labour productivity; in the Netherlands, milk production per labourer increased from <5 kg milk per hour in 1960 to >150 kg/hr in 2010. The increased labour productivity has been accompanied by an exodus of farmers and labourers; while total milk production doubled, the number of dairy farms decreased by a factor of 6 between 1960 and 2010. These are common trends in a globalizing world, where the price of food products is determined by the farms with the lowest cost of production (e.g., Mazoyer and Roudart (2006).

Governmental policies have supported agricultural production in many countries, through facilitation of the build-up of good knowledge and physical infrastructure, through market and product support, and through subsidies on inputs (including fertilizers). In general, governmental support measures have been larger for crop production than animal production. Increased awareness of the environmental damages caused by the intensification of agricultural production has also evoked a range of governmental regulations related to the handling and use of N fertilizers, animal manure and pesticides, especially in European Union. Indeed, livestock density in the European Union is largely limited by regulations that force farmers to collect and store all manure from housed animals in leak tight storages, and to limit the manure N application to 170 kg/ha/yr (including the manure from grazing animals) (e.g., Oenema et al., 2011; Willems et al., 2016).

Liberalization and internationalization of markets and the resulting increased competition between farmers has contributed to specialization and increased productivity. Specialization and the resulting decrease in the cost of production has stimulated global trade of food and feed, and has contributed indirectly to the concentration of animal production and the spatial decoupling of crop and animal production. The amount of N traded between countries has increased eightfold (from 3 to 24 Tg N) during 1961–2010, and a large part is related to animal feed (Lassaletta, et al., 2014a; 2014b). Only a few countries have specialized in the production of main feed crops (e.g., soybean and maize in USA, Argentina and Brazil, and oil palms in southeast Asia). The spatial decoupling of crop and animal production has major implications for the utilization of N in animal manures.

Table 2. Annual animal productivity per continent; means for the period 2005-2010 (Source: FAOSTAT)

Crop and animal productivity	America	Africa	Asia	Australia	Europe	World
Milk yield, kg/dairy cow	3238	497	1589	4125	5100	2301
Beef, kg/head other cattle	258	161	147	223	240	207
Pork, kg/head	87	50	74	63	87	79
Egg, kg/layer	12	5	9	11	13	10
Poultry, kg/head broilers	2	1	1	2	2	2

Changes in the amounts of N and P in animal products and manures

Animals retain only a fraction of the carbon and nutrient elements in the animal feed in live-weight gain, milk and egg (Figure 4). For N and P, these fractions range from about 10% in live-weight gain of ruminants used for beef and mutton production, to 20-30% for dairy production, to 30 up to 45% for pork and poultry production. The remainder is excreted in faeces and urine. Total animal protein-N production increased by a factor of 3 between 1960 and 2010 (Figure 4). Most of the increase occurred in Asia, and to a lesser extent in America and Africa. In Asia, most animals were in China (~500 million LSU) and India (~400 LSU) in 2010. Production in Europe remained more or less constant. The total amounts of N and P in manure roughly doubled between 1960 and 2010. The larger increase in protein N production (factor 3) than in manure N production (factor 2) reflects a steady increase in N use efficiency (see below), which is in part related to the increase of monogastric animals relative to ruminants (Figure 1). Cattle (dairy and other cattle) contributed approximately half to the total amounts of N and P in animal manures. Pigs and poultry contributed approximately one-third, while sheep and goat, buffaloes, horses, camels, donkeys and various other small animal make up the rest.

The total amounts of N and P in animal excrements in 2011were about 120 and 23 Tg, respectively. These quantities are similar to or larger than the synthetic fertilizer N and P use in the world. However, the manure N and P are not effectively utilized in crop production, due to (i) the very uneven distribution of faeces and urine by grazing animals, (ii) the often incomplete collection and inappropriate storage of faeces and urine from housed animals, with large volatilization and leaching losses, (iii) the poor timing and methods of manure application, and (iv) the slow release of the organically bound nutrients in the manures. Animal manures have a relatively large share in the total emissions of ammonia (NH_3) and nitrous oxide (N_2O) to air, and of N and P leaching losses to water bodies (Sutton et al., 2013; Strokal et al., 2016).

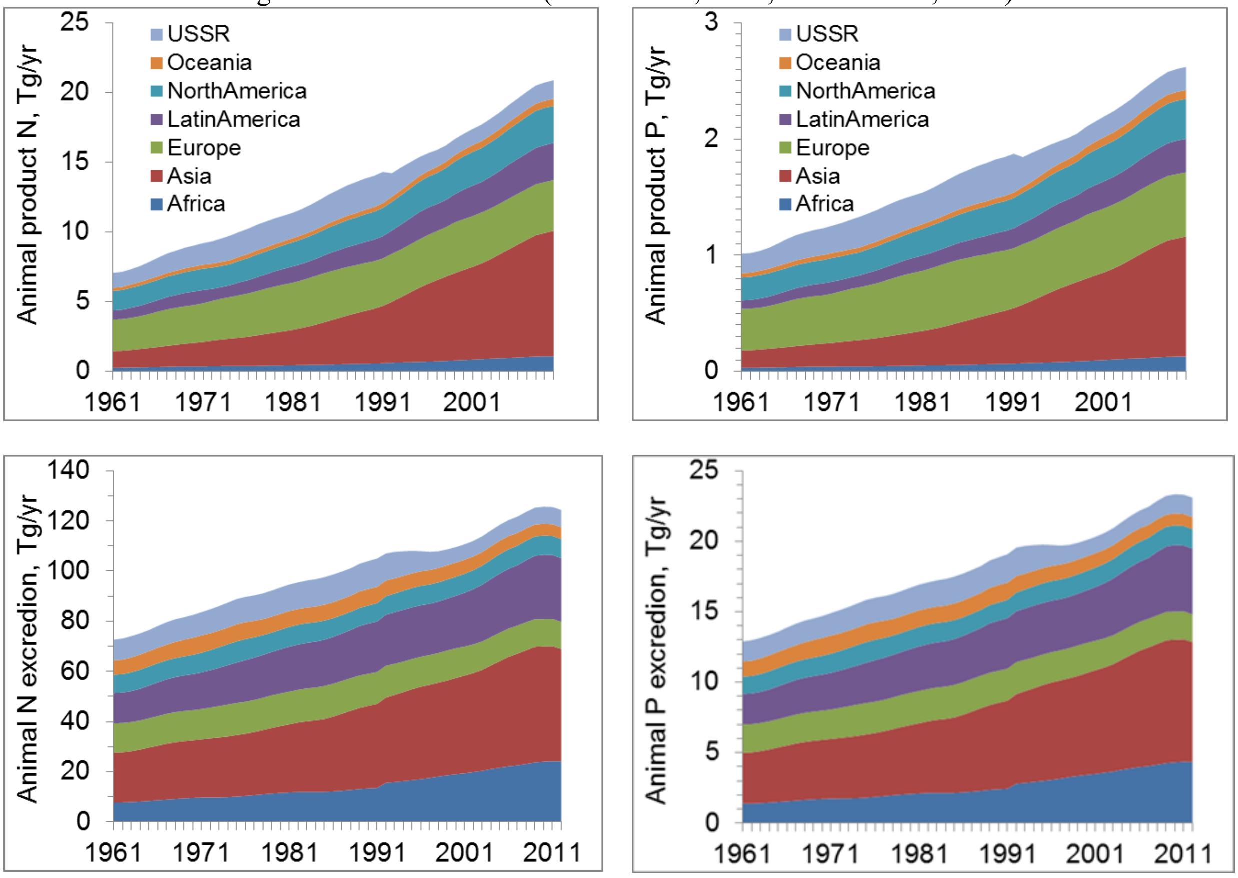

Figure 4. Total amounts of nitrogen (N) and phosphorus (P) in animal live-weight gain, milk, and eggs produced (upper two panels), and the total amounts of N and P excreted in faeces and urine (lower two panels) by all animals per continent between 1961-2011. Data source: FAOSTAT and own calculations, using IPCC 2006 N excretion coefficients. USSR is the former federation of Russia.

Protein N in aquaculture (not shown) was about 1.2 Tg N in 2010 and total N excretion by fish was about 4.6 Tg (Bouwman et al 2011, 2013). Hence, total fish protein N production was about 5% of animal protein N production. Most of the fish (>90%) is produced in Asia. Aquaculture is projected to increase relatively fast in future (Fry et al, 2016).

Animal production and nitrogen balances

There is a distinct relationship between mean livestock density and the N input-output balance of the whole food production-consumption system of a country, i.e., the N surplus increases with an increase in livestock density beyond a livestock density of about 2 LSU/ha. This suggests that beyond that density, farms have increasing difficulty to utilize manure N effectively, and/or have increasing difficulties to mitigate N losses from manure N in animal houses and storages effectively. Hence, the wide variation between countries in mean livestock density shown in Figures 2 and 3 do have implications also for N (and P) balances. Countries with very high livestock density are often water-limited and/or have a limited area of productive agricultural land, while the human population is relatively large and rich. These countries (e.g. some Arab countries and some countries in Europe) import most animal feed from other countries. There is often also a clear relationship between livestock density and N and P balances at farm level. In France, Nesme et al (2015) observed that P surpluses at farm level increased when livestock density exceeded 1.1 LSU/ha. The relationship between livestock density and N (and P) surpluses may change through governmental regulations; for example, farms with a surplus of animal manure in The Netherlands have to export all surplus manure to other farms (Willems et al., 2016). Slurries with a dry matter content of about 10% are transported to other farms up to 200 km away, while dried manures may be transported up to 500 km. The cost of manure processing and transport have to be paid by the livestock producers, which increase the cost of production by up to 5%.

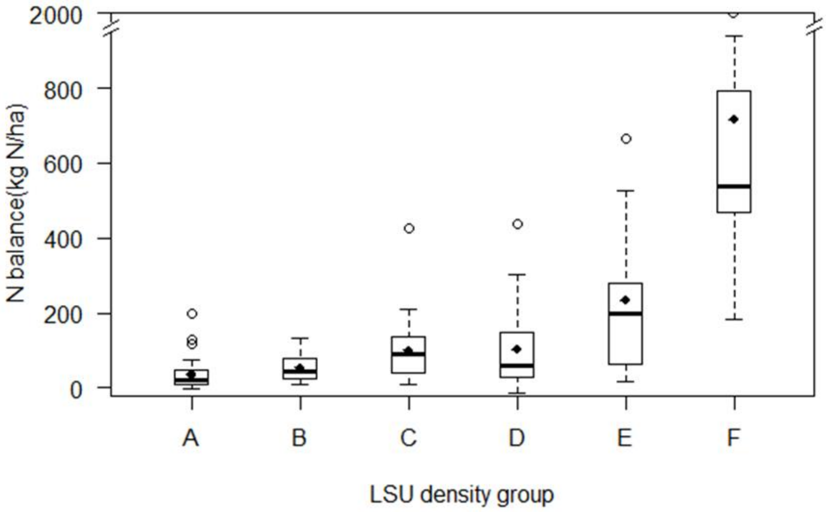

Figure 5. Box plots of mean N balances at country levels for the whole food production-consumption system. In total 6 clusters of countries were distinguished, with increasing livestock unit density (LSU; 10-years averages for the period 2001-2010). Boxes show 25th and 75th percentiles. Lines in the boxes show the median values, dots indicate mean values. A: LSU density <0.5 ha^{-1} (n =34); B: 0.5-1.0 (n=51); C: 1.0-1.5 (n=29); D: 1.5-2.0 (n=18); E: 2.0-3.0 (n=9); F: >3 LSU ha-1 (n=9). Note: n is the number of countries in each cluster (Liu et al in prep).

Changes in nitrogen use efficiency

Nitrogen use efficiency (NUE) is defined here as the ratio between N in animal produce (mainly milk, meat and egg) and N input; it can be defined at animal level (NUE_{animal}) and at system (NUE_{system}) level (Powell and Rotz, 2015). At animal level, NUE_{animal} is the ratio of N in animal produce and N in feed intake. At system level, NUE_{system} is the ratio of N in animal produce and the amounts of 'new' N needed for the feed consumed, where 'new' N is defined as the N inputs via fertilizer, biological N_2 fixation and atmospheric deposition (from sources other than manure NH_3).

Bouwman et al (2015) estimated NUE_{animal} at continental level for the period 1900-2050. These estimates suggest that NUE_{animal} slightly decreased on average between 1900 and 1950, and thereafter increased. Differences between continents are large; in 2000 NUE_{animal} was on average 11% at the global level, 21% in Europe, 18% in northern America, 10% in southeast Asia and 6% in Africa. By 2050, authors expect that NUE_{animal} will have increased by on average 3-5% (absolute values); at the global level NUE_{animal} will be almost 15%. Lassaletta et al (2016) made a distinction between ruminant and monograstric animals. They estimated that global $NUE_{ruminant}$ remained more or less constant at 6.5% between 1960 and 2010, while $NUE_{monogastric}$ increased from about 14% in 1960 to 19% in 2010. In North America $NUE_{monogastric}$ was higher (0.05% absolute values) than in Europe, while $NUE_{ruminant}$ was lower (0.04% absolute values) in North America than in Europe. The latter difference may reflect a greater focus on dairy production in Europe and a greater focus on beef production in North America.

The N use efficiency at the whole feed-animal system level ($NUE_{systems}$) depends on NUE_{animal}, manure N losses from animal houses, storage systems and in pastures, the recovery of manure N in harvested plant biomass and the recovery of 'new' N inputs (from fertilizer, biological N_2 fixation and atmospheric deposition) in harvested plant biomass (Figure 6). At a low NUE_{animal} of 5%, NUE_{system} will only range between 3 and 12%. At a high NUE_{animal} of 45%, NUE_{system} will range roughly between 25 and 70%, depending on the losses of N from manure in storages and the effectiveness of applied manure N (including

N in faeces and urine deposited by grazing animals in pastures) and new N in producing harvested plant protein. Measures aimed at decreasing N losses from manure in animal houses and storages are effective when the manure N is subsequently recovered in harvested plant biomass protein. Further, NUE_{system} greatly depends on the recovery of new N input in harvested plant biomass; in practice this recovery may vary from 50% for wheat and maize production to 70% for forage production and up to 100% for alfalfa, soybean, and pulses. The variation shown in Figure 5 is the full range of values that may be observed in practice. For example, De Klein et al (this issue) list NUE_{system} values for dairy systems that range from 8 to 64%, for NUE_{animal} values ranging from 13 to 36%.

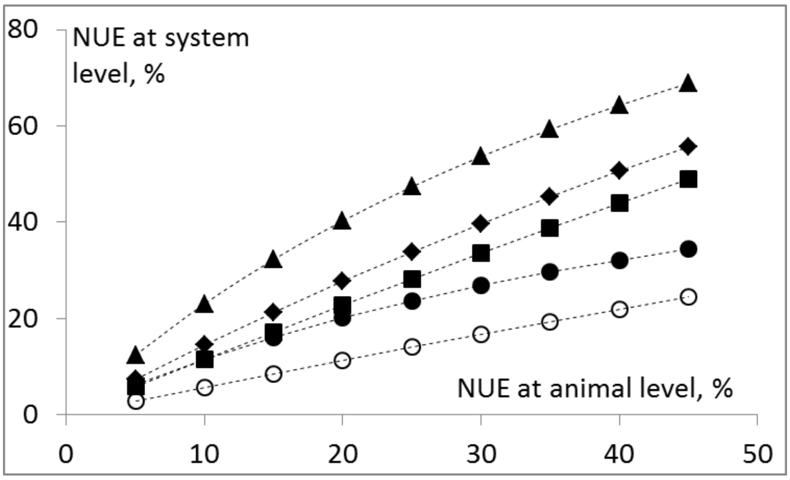

Figure 6. Calculated relationship between NUE_{animal} and NUE_{system}, using the following assumptions related to internal N recycling and recovery of applied N in feed production:

Open circles:	manure N loss 50%;	manure N recovery 30%;	'new' N input recovery 50%
Filled circles:	manure N loss 10%;	manure N recovery 70%;	'new' N input recovery 50%
Squares:	manure N loss 50%;	manure N recovery 30%;	'new' N input recovery 100%
Diamonds:	manure N loss 50%;	manure N recovery 70%;	'new' N input recovery 100%
Triangles:	manure N loss 10%;	manure N recovery 70%;	'new' N input recovery 100%

In practice, estimation of NUE_{system} is complicated because of (i) the spatial separation of specialized crop and specialized animal production systems, (ii) the utilization of residues and wasted in animal production that would not be used otherwise , and (iii) the export of manure to crops not used for feed production. Manure export from specialized animal production systems to specialized crop production systems is common in countries with agglomerations of intensive animal production and strict governmental regulations. In the Netherlands, about 25% of the manure produced has to be exported to surrounding countries, because of insufficient 'room for application' on own agricultural land within the set application limits for N and P. This export has a profound effect on NUE_{system}. During 2010-2015, mean NUE_{animal} was 30%, mean NUE_{crop} was 62%, and mean NUE_{system} was 55% when manure export is considered as an animal output (CBS, 2016). In the case where the manure export is neglected, NUE_{system} would decrease to 42%, while NUE_{system} would be about 50% when manure export is considered a negative N input. Hence, manure export and the handling of manure export in the definition of NUE_{system} have a large effect on the actual value of NUE_{system}.

Concluding remarks

Animal production systems are highly diverse, play key roles in human nutrition and the global food economy, and have a relatively large impact on the environment. Nitrogen plays a key role in animal production, as it is an essential component of protein (meat consist for up to 16% out of N), but also in its environmental impacts, as gaseous N compounds (NH_3, N_2O, N_2) easily escape from the system, especially from the animal manure management chain. In grazing systems, most of the dung and urine are dropped in pastures and nutrients are thus recycled, but the utilization of N is often low due to the spatially uneven distribution of dung and urine. In mixed crop-animal farms, the recycling and utilization of manure nutrients greatly depends on the management of the manures, which is a function of governmental regulations, the availability and affordability of fertilizers, and technology. Recycling and utilization of manure nutrients is challenging in large footloose animal production systems, as the land-base for manure application is largely lacking. As a result, manure N, P, K and micro-nutrients are not used efficiently here.

Nitrogen use efficiencies (NUE) and manure recycling efficiencies differ greatly between systems and animal categories. In pig and poultry production, NUE_{animal} ranges between 30 and 45%, and NUE_{system} between 25 and 65%, depending on manure recycling and recovery of applied in N in the crop. In grassland-based dairy production, NUE_{animal} ranges between 20 and 30%, and NUE_{system} roughly between 10 and 50%. In grassland- based beef production, NUE_{animal} ranges between 5 and 15%, and NUE_{system} roughly between 5 and 30%.

There is considerable potential to reduce N losses from the manure management chain, and to increase the amount of manure applied to crop land and replace fertilizer NPK through adopting integrated options (e.g., Bittman et al., 2014). This requires investments in farm infrastructure and management, i.e. animal housing, manure storage, and facilities for manure transportation and application. Integrated manure and fertilizer nutrient recommendation systems are needed that take account of the total nutrient and available nutrient content of manures, the fertility of the soils and the nutrient requirements of the crops. This requires also training of farmers, in part through farmers' discussion groups. Transferring and implementing improved knowledge and technology in practice requires concerted actions of a broad group of stakeholders, facilitated through targeted incentives from governments and society.

Solutions for improving N use efficiency in animal production will have to be based on a coherent set of activities in the whole chain of "feed production – animal production – manure management" (Figure 6; Hou, 2016). A high NUE at system will be achieved only through a combination of a high NUE at animal level and an effective recycling and utilization of manure N in crop production. Various governmental regulations may contribute to a high NUE_{system} (Willems et a., 2016).

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