The Role of Livestock Production in Carbon and Nitrogen Cycles

Henning Steinfeld[1] and Tom Wassenaar[2]

[1]Animal Production and Health Division, Food and Agriculture Organization of the United Nations, 00100 Rome, Italy; email: henning.steinfeld@fao.org

[2]Joint Research Center of the European Commission, Institute for the Protection and Security of the Citizen, AgriFish Unit, 21020 Ispra (Varese), Italy; email: tom.wassenaar@jrc.it

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Abstract

This review looks at the role of the livestock sector in carbon (C) and nitrogen (N) cycles from a global perspective and considers impacts at the various stages of the commodity chain. With regard to livestock, N and C cycles are closely connected to livestock's role in land use and land-use change. Livestock's land use includes grazing land and cropland dedicated to the production of feed crops and fodder. Considering emissions along the entire commodity chain, livestock currently contribute about 18% to the global warming effect. Livestock contribute about 9% of total carbon dioxide (CO_2) emissions, but 37% of methane (CH_4), and 65% of nitrous oxide (N_2O). The latter will substantially increase over the coming decades, as the pasture land is currently at maximum expanse in most regions; future expansion of the livestock sector will increasingly be crop based. The chapter also reviews mitigation options to reduce C and N emissions from livestock's land use, production, and animal waste.

Contents

1. INTRODUCTION

Livestock are present in most ecosystems of the planet, and they also shape crop agriculture to a large extent through their demand for feed. Therefore, livestock activities have important impacts on virtually all aspects of the environment, including air and climate change, land and soil, water and biodiversity. The impact may be direct, through grazing for example, or indirect, such as the expansion of soybean production for feed replacing forests in South America.

Livestock production is technically extremely diverse. In countries or areas where there is no strong demand for food products of animal origin, low-input production prevails, mainly for subsistence rather than for commercial purposes. This contrasts with commercial, high-input production in areas serving a growing or established high demand. Such diverse production systems make extremely diverse claims on resources. Although intensive livestock production is booming in many developing countries, there are still vast areas where extensive livestock production and its associated livelihoods maintain their traditional forms. For the purpose of this review, a distinction is made between extensive forms of livestock production, with limited use of external inputs, and intensive production. Because feed represents by far the largest cost item in livestock production, extensive systems are defined as depending on low-cost and locally available feed inputs, whereas intensive systems are based on marketable high-cost feed items, such as grains, oil cakes, and cultivated fodder. This review covers livestock's role in carbon (C) and nitrogen (N) cycles from a global perspective and considers impacts at the various stages of the commodity chain.

2. GLOBAL TRENDS IN LIVESTOCK PRODUCTION

The livestock sector is growing and changing rapidly. Until about 1980, most developing countries, with the exception of Latin America and some Near East countries, had annual per capita meat consumption of substantially less than 20 kg. For most people in Africa and Asia, meat, milk, and eggs were an unaffordable luxury, consumed only on rare occasions. A high proportion of the larger livestock in developing countries was not primarily kept for food, but for other important functions, such as providing draught power and manure as well as serving as an insurance policy and a capital asset, usually disposed of only in times of communal feasting or emergency.

Today, the livestock sector is currently growing faster than the rest of agriculture in almost all countries. Typically, its share in agricultural gross domestic product rises with income and the level of development and is above 50% for most Organisation for Economic Co-operation and Development countries. The nature of livestock production is also changing rapidly in many emerging economies, as well as in developed countries. Most of this change can be summarized under the term "industrialization." Through industrialization, livestock escape most of the environmental constraints that have shaped livestock production diversely in the wide range of environments in which it occurs (1).

Growing populations and other demographic factors, such as age structure and urbanization, determine food demand and have driven the intensification of agriculture for centuries. Growing economies and individual incomes have also contributed to growing demand and a shift in diets. These trends have accelerated over the past two decades in large parts of Asia, Latin America, and the Near East, spurring a rapid increase in demand for animal products and other high-value foodstuffs such as fish, vegetables, and oils.

Driven by population growth and rising income in many developing countries, the global livestock sector has seen a dramatic expansion over the past decades, although with considerable differences between developing and developed countries. In the developing countries (**Table 1**), annual per capita consumption of meat has doubled since 1980, from 14 kg to 28 kg in 2002 (2, 3). Total meat supply tripled from 45 million tonnes to 134 million tonnes over the same period. Developments have been most dynamic in countries that have seen rapid economic growth, notably East Asia, led by China. China alone accounted for 57% of the increase in total meat production in developing countries. For milk, developments are less spectacular but still remarkable: Total milk production in developing countries expanded by 118% between 1980 and 2002; and 23% of that increase came from one country, India.

There is a great deal of variation in the extent and character of livestock sector growth. China and East Asia have experienced the most impressive growth in consumption and production, first in meat and more recently also in dairy. In contrast, India's livestock sector continues to be dairy oriented, using traditional feed resources and crop residues. Brazil, Argentina, and other Latin American countries have successfully expanded their domestic feed base, taking advantage of low production costs and abundance of land. They have moved to adding value to feed, rather than exporting it. They are poised to become the major meat-exporting region supplying developed and East Asian countries. Trade in animal products as well as feed is strongly increasing worldwide, partly driven by the variable

Table 1 Past and projected trends in consumption and production of livestock products

	Developing countries					Developed countries				
	1980	1990	2002	2015	2030	1980	1990	2002	2015	2030
Consumption										
Annual per capita meat consumption (kg)	14	18	28	33	38	73	80	78	83	88
Annual per capita milk consumption (kg)	34	38	46	57	67	195	200	202	204	211
Total meat consumption (million tonnes)	47	73	137	191	257	86	100	102	113	122
Total milk consumption (million tonnes)	114	152	222	330	449	228	251	265	278	292
Production										
Annual per capita meat production (kg)	14	18	28	33	38	75	82	80	85	91
Annual per capita milk production (kg)	35	40	50	62	73	300	301	266	270	280
Total meat production (million tonnes)	45	43	134	190	255	88	103	105	116	126
Total milk production (million tonnes)	112	159	244	359	491	352	378	349	369	387

availability of natural resources. With trade in these products, natural resources and environmental impact are transferred, referred to as virtual trade in water and nutrients (4).

In the developing countries, livestock production is rapidly shifting toward monogastrics, notably poultry and pigs. In fact, poultry and pigs account for 77% of the expansion in production. Although total meat production in developing countries more than tripled between 1980 and 2004, the growth in ruminant production (cattle, sheep, and goats) was 111%, whereas that of monogastrics expanded more than fourfold over the same period.

These dramatic developments in rapidly growing developing countries are in stark contrast with trends in developed countries, where consumption of livestock products is growing only slowly or stagnating. With low or no population growth, markets are saturated in most developed countries. Here, total meat production increased by only 22% between 1980 and 2004. Ruminant meat production actually declined by 7%, and that of poultry and pigs increased by 42%. As a result, the share of production of poultry and pigs has gone up from 59% to 69% of total meat production. Among the monogastrics, poultry is the commodity with the highest growth rate across all regions. One reason for this, apart from very favorable feed conversion, is that poultry is a meat type acceptable to most religious and cultural groups.

Today, the livestock sector is a major land user, spanning more than 3.9 billion hectares, equivalent to about 30% of the world's surface land area. The intensity with which the sector uses land is, however, extremely variable. Of the 3.9 billion hectares, 0.5 are used for feed crops, generally intensively managed. Another 1.4 billion hectares are highly productive pasture, and the remaining 2 billion hectares are extensive pastures with relatively low productivity. This puts the livestock sector as the largest user of agricultural land, accounting for about 78% of agricultural land, including as much as 33% of the cropland.

3. THE ROLE OF EXTENSIVE LIVESTOCK PRODUCTION

Extensive livestock production affects natural resources through its land use and associated land-use change, which lead to land degradation, affecting natural resource cycles in a variety of ways. Extensive livestock production systems and their corresponding land use are strongly associated with ruminant livestock species. The digestive system of ruminants also directly contributes to modifications of the C and N cycles, whereas modifications of the latter affect the water cycle.

3.1. Carbon

Livestock's role in global C cycles is mainly determined by the extensive current land use through pastures, their expansion at the expense of forests, and their degradation. Furthermore, livestock release important amounts of methane (CH_4).

Savannah burning. Savannah burning is often associated with extensive livestock farming and has important effects on the global biological C cycle. Burning is common worldwide in establishing and managing pastures. Fire removes ungrazed grass, straw, and litter; stimulates fresh growth; and can control the density of woody plants (trees and shrubs). As many grass species are more fire tolerant than tree species (especially seedlings and saplings), burning can determine the balance between grass cover and ligneous vegetation. Fire stimulates the growth of perennial grasses in savannahs and provides nutritious regrowth for livestock. Controlled burning prevents uncontrolled and possibly more destructive fires and consumes the combustible lower layer at an appropriate humidity stage.

The environmental consequences of rangeland and grassland fires depend on the environmental context and conditions of burning. In tropical savannah areas, burning has significant environmental impact because of the large area affected and the relatively low level of control. In 2000, burning affected some 4 million km^2. More than two thirds of this occurred in the tropics and subtropics (5). Globally about three quarters of this burning took place outside forests. Savannah burning represented some 85% of the area burned in Latin American fires, 60% in Africa, and nearly 80% in Australia (5).

Usually, savannah burning is not considered to result in net CO_2 emissions, because emitted amounts of carbon dioxide (CO_2) released in burning are recaptured in grass regrowth. Apart from CO_2, biomass burning releases important amounts of other globally relevant trace gases (NO_x, CO, and CH_4) and aerosols (6, 7). Many of the emitted elements lead to the production of tropospheric ozone (8, 9), which is another important greenhouse gas influencing the atmosphere's oxidizing capacity, and bromine, also released in significant amounts from savannah fires, decreases stratospheric ozone (8).

Smoke plumes may be redistributed locally, transported throughout the lower troposphere, or entrained in large-scale circulation patterns in the mid and upper troposphere. Often, fires in convection areas take the elements high into the atmosphere, creating increased potential for climate change. Satellite observations have found large areas with high O_3 and CO levels over Africa, South America, and the tropical Atlantic and Indian Oceans (10). Aerosols produced by the burning of pasture biomass dominate the atmospheric concentration of aerosols over the Amazon Basin and tropical Africa (7, 11). Concentrations of aerosol particles are highly seasonal. An obvious peak occurs in the dry (burning) season, which contributes to cooling both through increasing atmospheric scattering of incoming light and the supply of cloud condensation nuclei. High concentrations of cloud condensation nuclei from the burning of biomass stimulate rainfall production and affect large-scale climate dynamics (12).

Desertification of pastures. In contrast to pasture burning, desertification of grazing land causes a net loss of C to the atmosphere. Desertification reduces productivity and vegetation cover and also changes C and nutrient cycles and stocks. Although changes in aboveground biomass and C stocks are often small, total soil C usually declines. Asner et al. (13) found in Argentina that desertification resulted in little change in woody cover, but soil organic C declined by 25% to 80% in areas with long-term grazing. Soil erosion accounts for part of this loss, but the majority stems from the nonrenewal of decaying organic matter stocks, leading to a significant net emission of CO_2.

Lal (14) estimated the C loss resulting from desertification. Assuming a loss of 8–12 tonnes of soil C per hectare (15) on a desertified land area of 1 billion hectares (16), the total historic loss would amount to 8–12 billion tonnes of soil C. Similarly, degradation of aboveground vegetation has led to an estimated C loss of 10–16 tonnes per hectare—a historic total of 10–16 billion tonnes. Thus, the total C loss as a consequence of desertification may be 18–28 billion tonnes of C (17).

Livestock occupy about two thirds of the global dry land area, and the rate of desertification has been estimated to be higher for grazing land than for other land uses [3.2 million hectares per year against 2.5 million hectares per year for cropland (16)]. Considering only soil C loss (i.e., about 10 tonnes of C per hectare), CO_2 emissions from the desertification of pastures amount to 100 million tonnes of CO_2 per year.

Another, largely unknown, influence on the fate of soil C is the feedback effect of climate change. In higher-latitude cropland zones, global warming is expected to increase yields by virtue of longer growing seasons and CO_2 fertilization. At the same time, however, global warming may also accelerate decomposition of C already stored in soils (18, 19). Although there are large uncertainties, van Ginkel et al. (20) estimate the magnitude of this effect, at current rates of increase of CO_2 in the atmosphere, at a net absorption of 0.036 tonnes of C per hectare per year in temperate grassland, after deducting the effect of rising temperature on decomposition. Recent research indicates that the magnitude of the temperature rise on the acceleration of decay may be stronger, with already very significant net losses over the past decades in temperate regions (21, 22).

Pasture expansion into forest. Livestock's role in the deforestation process is of particular importance in Latin America where the the largest net loss of forests and resulting C fluxes occur. Latin America is the world region where expansion of pasture and arable land for feedcrops is strongest, mostly at the expense of forest area. Wassenaar et al. (23) showed that most of the cleared area ends up as pasture and identified large areas where livestock ranching is probably a primary motive for clearing. The conversion of forest into pasture releases considerable amounts of C into the atmosphere, particularly when the area is not logged but simply burned. Cleared patches may go through several changes of land use. Over the 2000–2010 period, the pasture areas in Latin America are projected to expand into forest by an annual average of 2.4 million hectares—equivalent to some 65% of expected deforestation.

Forest clearing produces a complex pattern of net fluxes that change direction over time; the calculation of related C fluxes is the most complex of the emissions inventory components. Responses of biological systems vary over time. The Intergovernmental Panel on Climate Change (IPCC) (24) estimated the average annual flux owing to tropical deforestation for the decade 1980 to 1989 at 1.6 ± 1.0 billion tonnes C as CO_2. Only about 50% to 60% of the C released from forest conversion in any one year was a result of the conversion and subsequent biomass burning in that year. The remainder were delayed emissions resulting from oxidation of biomass harvested in previous years (25).

On the basis of the assumption that forests are completely converted into climatically equivalent grasslands and croplands (24, p. 192) and combining changes in C density of both vegetation and soil in the year of change, emissions from conversion of forests to pastures can be estimated at approximately 1.7 billion tonnes of CO_2 per year. Although it takes more than a year to reach this new status because of inherited or delayed emissions, the resulting emission estimate would not change much as the transformation process is continuous.

In addition to producing CO_2 emissions, land conversion also results in emissions of other gases. For example, Mosier et al. (26) noted that upon conversion of forest to grazing land, CH_4 oxidation by soil microorganisms is typically greatly reduced, and grazing lands may even become net sources in situations where soil compaction from cattle traffic limits gas diffusion.

Enteric fermentation. On the basis of animal numbers and liveweights, the total livestock biomass amounts to some 0.7 billion tonnes (2). According to the function established by Muller & Schneider (27; cited by 28), applied to standing stocks per country and species (with country-specific liveweight), the CO_2 from the respiratory process of livestock amounts to some 3 billion tonnes of CO_2. Emissions from livestock respiration are part of a rapidly cycling biological system, where the plant matter consumed was itself created through the conversion of atmospheric CO_2 into organic compounds. Livestock respiration is therefore not considered to be a net source.

However, the specific characteristics of ruminant physiology lead to net gaseous emissions of C as CH_4. Livestock are globally the most important source of anthropogenic CH_4 emissions. However, there are significant spatial variations in CH_4 emissions from enteric fermentation. In Brazil, CH_4 emissions from enteric fermentation totaled 9.4 million tonnes in 1994–93% of agricultural emissions and 72% of the country's total emissions of CH_4. Over 80% of this originated from beef cattle (29), and the Brazilian cattle population has increased with some 25% since (2). In the United States, CH_4 from enteric fermentation totaled 5.5 million tonnes in 2002, again overwhelmingly originating from beef and dairy cattle. This was 71% of all agricultural emissions and 19% of the country's total emissions (30).

Levels of CH_4 emissions are affected by energy intake and several other animal and diet factors including quantity and quality of feed, animal body weight, age and amount of exercise. Therefore, assessing CH_4 emission from enteric fermentation in any particular country requires a detailed description of the livestock population (species, age, and productivity categories), combined with information on the daily feed intake and the feed's CH_4 conversion rate. As many countries do not possess such detailed information, an approach that is based on standard emission factors is generally used in emission reporting.

CH_4 emissions from enteric fermentation change as production systems intensify and move toward higher feed use and increased productivity. We have attempted a global estimate of total CH_4 emissions from enteric fermentation in the livestock sector using regional and production system-specific emission factors [as outlined by Steinfeld et al. (31)]. Total global emissions of CH_4 from enteric fermentation are estimated at 86 million tonnes CH_4 annually, which is roughly in line with the global estimate by the United States Environmental Protection Agency (32) of about 80 million tonnes of CH_4 annually. The distribution across regions, species, and production systems of such CH_4 emission is given in **Table 2** (31). The relative global importance of mixed systems compared to grazing systems reflects the fact that about two thirds of all ruminants are held in mixed systems.

3.2. Nitrogen

Diatomic nitrogen (N_2) in the atmosphere is a large and stable pool of N. In contrast, the modest capability of natural ecosystems to drive the N cycle constituted a major

Table 2 Global methane emissions from enteric fermentation in 2004

Region/country	Emissions (million tonnes CH_4 per year by source)					
	Dairy cattle	Other cattle	Buffalo	Sheep and goats	Pigs	Total
Sub-Saharan Africa	2.30	7.47	0.00	1.82	0.02	11.61
Asia[a]	0.84	3.83	2.40	0.88	0.07	8.02
India	1.70	3.94	5.25	0.91	0.01	11.82
China	0.49	5.12	1.25	1.51	0.48	8.85
Central and South America	3.36	17.09	0.06	0.58	0.08	21.17
West Asia and North Africa	0.98	1.16	0.24	1.20	0.00	3.58
North America	1.02	3.85	0.00	0.06	0.11	5.05
Western Europe	2.19	2.31	0.01	0.98	0.20	5.70
Oceania and Japan	0.71	1.80	0.00	0.73	0.02	3.26
Eastern Europe and the Commonwealth of Independent States	1.99	2.96	0.02	0.59	0.10	5.66
Other developed countries	0.11	0.62	0.00	0.18	0.00	0.91
Total	15.69	50.16	9.23	9.44	1.11	85.63
Livestock production system						
Grazing	4.73	21.89	0.00	2.95	0.00	29.58
Mixed	10.96	27.53	9.23	6.50	0.80	55.02
Industrial	0.00	0.73	0.00	0.00	0.30	1.04

[a]Excludes China and India.

hurdle in satisfying the food needs of growing populations (33). Extensive livestock, and particularly ruminant, production has traditionally contributed to alleviating this problem by making reactive N fixed in grass and other fodder available to humans through animal products. But in doing so, it often impoverishes natural ecosystems, particularly because livestock use the scarce resource with a low efficiency. In fact, the majority of N they ingest enters the so-called N cascade (34) by which N is transported downstream or downwind in different forms to a series of temporary reservoirs.

N assimilation efficiency varies considerably among different animal species and products. According to estimates by van der Hoek (35), average N assimilation efficiency is around 20% for pigs and 34% for poultry. For the United States, Smil (36) calculated the protein conversion efficiency of intensively produced dairy products at 40%, whereas that of beef cattle is only 5%. The low N assimilation efficiency of extensively held ruminants, in particular cattle, is partly inherent to large animals with long gestation periods and a high basal metabolic rate. But the global cattle herd also comprises a large draught animal population whose task is to provide energy, not protein. For example, in 1995, cattle and horses still accounted for 25% of China's agricultural energy supply (37). In addition, in many areas of the world, grazing animals are fed at bare maintenance level, consuming without producing much.

As a result, a huge amount of N is returned to the environment through animal excretions. When directly deposited on pasture or crop fields, some of the reactive N reenters the plant production cycle. A large share leaves the system through gaseous emission, and volatilization, and, to a lesser extent, leaching and erosion. We focus here on the two dominant reactive forms in which N is lost, nitrous oxide (N_2O) and ammonia, both associated with an important negative environmental impact, contributing to global warming and air pollution, respectively.

N lost to the atmosphere following deposition of manure. Excreta directly deposited on land have high N loss rates through substantial ammonia volatilization. Wide variations in the quality of forages consumed by ruminants and in environmental conditions make N emissions from manure directly deposited on land difficult to quantify. The Food and Agriculture Organization of the United Nations (FAO) & International Fertilizer Industry Association (IFA) (38) estimate the N loss via NH_3 volatilization from animal manure, after application, to be 23% worldwide. Smil (39) estimates this loss to be at least 15% to 20%.

The IPCC proposes a standard N loss fraction from ammonia volatilization of 20%, without differentiating between applied and directly deposited manure. Considering the substantial N loss from volatilization during storage (see the section on intensive production), total ammonia volatilization following excretion can be estimated at ~40%. This rate can be applied to directly deposited manure, assuming that the lower share of N in urine in tropical land-based systems is compensated by higher temperature. We estimate that in the mid-1990s ~30 million tonnes of N were directly deposited on land by animals in the more extensive systems, producing an NH_3 volatilization loss of some 12 million tonnes N. In addition, the postapplication loss of managed animal manure is about 8 million tonnes N (38), resulting in a total ammonia volatilization N loss from animal manure on land of ~20 million tonnes N. These figures continue to grow. Even taking the very conservative IPCC ammonia volatilization loss fraction of 20% and subtracting manure used for fuel results in an estimated NH_3 volatilization loss following manure application/deposition of some 25 million tonnes N in 2004.

With regard to N_2O, the soil emissions originating from the remaining external N input, which is after subtraction of ammonia volatilization, depend on a variety of factors, particularly soil water-filled pore space, organic C availability, pH, soil temperature, plant/crop uptake rate, and rainfall characteristics (26). However, because of the complex interaction and the highly uncertain resulting N_2O flux, the revised IPCC guidelines are based on N inputs only and do not consider soil characteristics. Despite this uncertainty, manure-induced soil emissions are clearly the largest livestock source of N_2O worldwide. Emission fluxes from animal grazing (unmanaged waste, direct emission) and from the use of animal waste as crop fertilizer are of a comparable magnitude. The grazing-derived N_2O emissions are in the range of 0.002–0.098 kg N_2O-N/kg N excreted, whereas the default emission factor used for fertilizer use is set at 0.0125 kg N_2O-N/kg N. Nearly all data pertain to temperate areas and to intensively managed grasslands. Here, the N content of dung, and especially urine, is higher than from less intensively managed grasslands in the tropics or subtropics. It is not known to what extent this compensates for the enhanced emissions in the more phosphorus-limited tropical ecosystems.

Emissions from applied manure need to be calculated separately. The FAO/IFA study (38) estimates the N_2O loss rate from applied manure at 0.6%, i.e., lower than most mineral N fertilizers, resulting in an animal manure soil N_2O loss in the mid-1990s of 0.2 million tonnes N. Following the IPCC methodology would increase this to 0.3 million tonnes N.

In the mid-1990s, animal excreta directly deposited on pastures loaded approximately 30 million tonnes N on land in the more extensive systems. Applying the IPCC "overall reasonable average emission factor" (0.02 kg N_2O-N/kg of N excreted) to this total results in an animal manure soil N_2O loss of 0.6 million tonnes of N. This gives a total N_2O emission of about 0.9 million tonnes N in the mid-1990s.

Applying the IPCC methodology to the current estimates of the livestock production system and animal numbers (31) results in an overall loss of 1.7 million tonnes N per year in the form of direct animal manure soil N_2O. Of this, 0.6 million tonnes derive from extensive grazing systems, 1.0 million tonnes from mixed systems (of which roughly 0.9 million tonnes originate from the more extensive mixed systems), and 0.1 million tonnes from industrial production systems.

4. THE ROLE OF INTENSIVE LIVESTOCK PRODUCTION

The use of marketable and higher quality feed items in the fast-growing intensive livestock sector reduces land requirement per unit of output because the feed items themselves are intensively produced too. But in order to sustain a high quality, intensive animal production, this smaller land area needs to be supplied with large amounts of external inputs like nutrients, water, and energy. The mobilization of these resources and the losses associated with their intensive use affect the respective natural cycles. Because of the inherent inefficiency of animals in transforming even the resulting high-grade products, subsequent losses occur, which are not only important in absolute terms but also because of their spatially concentrated nature.

4.1. Carbon

Intensive livestock production systems have higher requirements for fossil fuel at all stages of the production process. However, compared to extensive modes of production, they have less impact on land-use changes, except through the expansion of crop land for feed production.

Fossil fuel. Significant additions of CO_2 to the atmosphere result from fossil fuel use at the different stages of intensive animal production.

Use of fossil fuel to manufacture fertilizer. A large share of the world's crop production is fed to animals. This includes about 670 million tons of cereals and large amounts of agro-industrial by-products such as brans

Table 3 Chemical fertilizer nitrogen used for feed and pastures in selected countries

Country	Share of total N consumption (%)	Absolute amount (1000 tonnes/year)
United States	51	4697
China	16	2998
France[a]	52	1317
Germany[a]	62	1247
Canada	55	897
United Kingdom[a]	70	887
Brazil	40	678
Spain	42	491
Mexico	20	263
Turkey	17	262
Argentina	29	126

[a]Countries with a considerable amount of N fertilized grassland.

and oil cakes (2). Mineral N fertilizer is applied to much of the corresponding cropland, and about 97% of N fertilizers are derived from synthetically produced ammonia via the energy-intensive Haber-Bosch process.

Combining fertilizer use by crop for the year 1997 (40) with the fraction of these crops used for feed in major N fertilizer consuming countries (41) shows that animal production accounts for a very substantial share of fertilizer consumption. **Table 3** (40, 41) gives examples for selected countries. Except for the Western European countries, production and consumption of mineral fertilizer are increasing in these countries. This high proportion of N fertilizer for feed crops is largely owing to maize, which not only covers large areas in temperate and tropical climates but also demands high doses of N fertilizer. More than half of total maize production is used as feed. Use of N fertilizer for maize and other animal feed crops is especially high in N-deficit areas such as North America, Southeast Asia, and Western Europe. In fact in 18 of the 66 maize producing countries analyzed, maize is the crop with the highest N fertilizer consumption (40). In 41 of these 66 countries, maize is among the first three crops in terms of N fertilizer consumption. The projected production of maize in these countries shows that its area generally expands at a rate inferior to that of production, suggesting an enhanced yield, partially owing to an increase in fertilizer consumption (41).

Other feed crops such as barley and sorghum are also important consumers of chemical N fertilizer. Despite the fact that some oil crops are associated with N-fixing organisms themselves, their intensive production also often makes use of N fertilizer. Such crops predominantly used as animal feed, including rapeseed, soybean and sunflower, garner considerable amounts of N fertilizer: 20% of Argentina's total N fertilizer consumption is applied to production of such crops, 110,000 tonnes of N fertilizer (for soybean alone) in Brazil, and over 1.3 million tonnes in China. In addition, pastures receive a considerable amount of N fertilizer in a number of countries.

The countries of **Table 3** together represent the vast majority of the world's N fertilizer use for feed production and spread about 14 million tonnes of N fertilizer per year for the animal food chain. Adding Commonwealth of Independent States and Oceania, the total amounts to ~20% of the annual 80 million tonnes of N fertilizer consumed worldwide. Furthermore, considering fertilizer use that can be attributed to by-products other than oil cakes, in particular brans, may well take the total up to some 25%.

On the basis of these figures, the corresponding emission of CO_2 can be estimated. Energy requirement in modern natural gas–based systems varies between 33 and 44 gigajoules (GJ) per tonne of ammonia. Taking into consideration additional energy use in packaging, transport, and application of fertilizer [estimated to represent an additional cost of at least 10% (42)], an upper limit of 40 GJ per tonne has been applied here. Energy use in the case of China is considered to be some 25% higher, i.e., 50 GJ per tonne of ammonia, because not only its N fertilizer production is based on coal, but it is mostly produced in small- and medium-sized, relatively energy-inefficient, plants (43). Taking the IPCC emission factors for coal in China [26 tonnes of C per terajoule (TJ)] and for natural gas elsewhere (17 tonnes C/TJ), and estimating C 100% oxidized, results in an estimated annual emission of CO_2 of more than 40 million tonnes at this initial stage of the animal food chain.

On-farm fossil fuel use. In intensive production systems, the bulk of the energy is spent on production of feed, either forage for ruminants or concentrated feed for poultry or pigs. Like the energy used for fertilizer, important amounts of energy are spent on seeds, herbicides and pesticides, diesel for machinery, and electricity. On the basis of data presented by Ryan & Tiffany (44) on Minnesota, a major U.S. state in terms of agricultural production with a focus on intensive livestock production, the bulk of Minnesota's on-farm CO_2 emissions from energy use is related to feed production and exceeds the emissions associated with N fertilizer use. Using the average maize fertilizer application (150 kg N per hectare for maize in the United States) results in emissions for Minnesota maize of about one million tonnes of CO_2, compared with 1.26 million tonnes of CO_2 from on-farm energy use for corn production. These estimates are obtained from combining data by Ryan & Tiffany (44) with efficiency and emission factors from the United States' Common Reporting Format report submitted to the United Nations Framework Climate Change Convention (UNFCCC) in 2005. At least half the CO_2 emissions of the two dominant commodities and CO_2 sources in Minnesota (maize and soybean) can be attributed to the (intensive) livestock sector. Taken together, feed production and pig and dairy operations make the livestock sector by far the largest source of agricultural CO_2 emissions in Minnesota.

In the absence of similar estimates representative of other world regions, it is not possible to provide a reliable quantification of the global CO_2 emissions that can be attributed to on-farm fossil fuel use by the intensive livestock sector. The energy intensity of production as well as the source of this energy vary widely. A rough indication of the fossil fuel use–related emissions from intensive systems can, nevertheless, be obtained by considering that the expected lower energy need for feed production at lower latitudes (lower energy need for corn drying, for example) and the often lower level of mechanization, which are compensated overall by a lower energy use efficiency and a lower share of relatively low CO_2-emitting sources (natural gas and electricity). Minnesota figures can then be combined with global feed production and livestock populations in intensive systems. As a conservative estimate, CO_2 emissions induced by on-farm fossil fuel use for feed production may be 50% higher than that from feed-dedicated N fertilizer production, i.e., some 60 million tonnes CO_2 globally. To this, farm emissions related directly to livestock rearing need to be added, which can be estimated at roughly 30 million tonnes of CO_2.

Fossil fuel for processing and transport. A number of studies assess the energy expenditure for processing animals for meat and other products (45). The wide variation among enterprises makes generalizations difficult. Estimating related emissions is still more hazardous as it is highly uncertain what the source of this energy is and how this varies throughout the world. Among livestock products, large amounts of energy are used to pasteurize milk and transform it into cheese and dried milk. In the above cited case of Minnesota, this makes the dairy sector responsible for the second highest CO_2 emissions from food processing. The largest emissions result from soybean processing, caused by energy-intensive physical and chemical oil extraction. Considering the value fractions (46) of these two commodities two thirds of these soy-processing emissions can be attributed to the livestock sector. Extrapolating to country level results in a total animal product and feed processing-related emission of the United States in the order of a few million tonnes CO_2. Therefore, the probable order of magnitude for the emission level related to global animal-product processing would be several tens of million tonnes of CO_2.

Although rough indications, these figures show that emissions from energy use by processing are much higher than that from transport in the animal food chain. Transport occurs mainly at two key stages: that of feed to animal production sites and that of animal products to consumer markets. Large amounts of bulky raw ingredients for concentrate feed are shipped around the world. One of the most notable long-distance feed trade flows is for soybean, which is also the largest traded volume among feed ingredients, as well as the one showing the strongest increase. Among soybean trade flows, the one from Brazil to Europe is of a particularly important volume. Cederberg & Flysjö (47) studied the energy cost of shipping soybean cake from the Mato Grosso to Swedish dairy farms. Applying the resulting energy need to the annual soybean cake shipped from Brazil to Europe, combined with the IPCC emission factor for ocean vessels, results in an annual emission of approximately 32 thousand tonnes of CO_2. Similarly, we combined traded volumes of pig, poultry, and bovine meat (2, accessed December 2005) with respective distances, vessel capacities and speeds, fuel use of main engine and auxiliary power generators for refrigeration, and their respective emission factors (48). The selected flows represent some 60% of international meat trade. Annually, they produce some 500 thousand tonnes of CO_2. This represents more than 60% of total CO_2 emissions induced by meat-related sea transport, because the trade flow selection is biased toward the long-distance exchange. By contrast, surface transport to and from the harbor has not been considered. Assuming, for simplicity, that the latter two effects compensate each other, the total annual meat transport-induced CO_2 emission would be in the order of 800–850 thousand tonnes of CO_2.

Cropland expansion into forest. Driven by the rising demand for animal products, the fast-growing intensive livestock sector drives, in turn, important increases in feed production. This rise in the demand for feed is not only met by intensification, but also by expansion of the corresponding cropland. Large losses of C to the atmosphere occur where this expansion occurs at the expense of forest. Wassenaar et al. (23) showed that, although less than pasture, large areas of cropland too will replace forest in the Neotropics. Much of this land will produce soybean primarily destined to feed use (49, 50). If we conservatively assume that half of the projected cropland expansion into tropical forests in Bolivia and Brazil can be attributed to providing feed for the livestock sector; this results in an additional annual deforestation for feed of over 0.5 million hectares per year. Similar changes in temperate forest in Argentina are not considered. Applying the same procedure as for pasture expansion into forest (see Section 3, above) results in an estimated corresponding emission of 0.7 billion tonnes of CO_2 per year.

Carbon loss from soils cultivated to produce feed. Most of the organic C loss from soil occurs at the original conversion of natural cover into managed land. However, soils are the largest reservoir of the terrestrial C cycle and continue to release significant amounts of C for a very long time after conversion. It is impossible to evaluate the shares attributable to inherited emissions and to management practices at a broad scale because land use and management change much faster. Under appropriate management practices (such as zero tillage), agricultural soils can conserve a large part of the original C content. Losses beyond this level can be considered to be a result of management practices. Excluding emissions originating from crop residues, Sauvé et al. (51) found annual loss rates of about 100 kg CO_2 per hectare on permanently cultivated temperate brown soils under conventional cultivation practices. The large area in temperate regions that produces coarse grains and oil crops for feed is under large-scale intensive management, which is still dominated by conventional tillage practices. Using the above figure as an approximation of the average loss rate for temperate climate soils with moderate organic matter content, the approximately 1.8 million km^2 of arable land cultivated with maize, wheat, and soybean for feed adds an annual CO_2 flux in the order of 18 million tonnes to the livestock balance.

Tropical soils have lower average C content (24, p. 192), and therefore lower emissions. By contrast, the considerable expansion of large-scale cropping of feeds, not only into uncultivated areas, but also into previous pastureland or subsistence cropping, may increase CO_2 emission. These, however, are impossible to gauge.

In addition, practices such as soil liming contribute to net emissions. Soil liming is a common practice in more intensively cultivated tropical areas because of soil acidity. Brazil, for example, estimated its CO_2 emissions owing to soil liming at 8.99 million tonnes in 1994 (52), and these have most probably increased since then. To the extent that these emissions concern cropland for feed production, they can be attributed to the livestock sector. Comparing reported emissions from liming from national communications of various tropical countries to the UNFCCC with the importance of feed production in those countries adds another 10 million tonnes CO_2.

Methane released from animal manure. As discussed above, the contribution of intensive production systems to CH_4 emissions from enteric fermentation is comparatively low. For CH_4 released from animal manure, the situation is the opposite; manure directly deposited on land, or otherwise handled in a dry form, does not produce significant amounts of CH_4. But substantial amounts are released from the anaerobic decomposition of organic material in livestock manure. This occurs mostly when manure is managed in liquid form, such as in lagoons or holding tanks. Lagoon systems are typical for most large-scale pig operations over most of the world (except in Europe). These systems are also used in large dairy operations in North America and in some developing countries, for example, Brazil.

CH_4 emissions from livestock manure are influenced by a number of factors that affect the growth of the bacteria responsible for CH_4 formation, including ambient temperature, moisture, and storage time. The amount of CH_4 produced also depends on the energy content of manure, which is determined to a large extent by livestock diet. Higher energy feed produces larger amounts of manure with more volatile solids, increasing the substrate from which CH_4 is produced. However, to a certain extent this is offset by higher digestibility of feed, and thus less wasted energy.

The default emission factors currently used in country reporting to the UNFCCC do not reflect the strong changes in the global livestock sector. For example, Brazil's country report to the UNFCCC (52) mentions a CH_4 emission from manure of 0.38 million tonnes in 1994, mainly from dairy and beef cattle. However, Brazil also has a very strong industrial pig production sector, where an estimated 95% of manure is held in open tanks for several months before application (EMBRAPA, personal communication). Hence, Steinfeld et al. (31) reassessed and applied emission factors to the animal population figures specific to each production system. The total annual global emission of CH_4 from manure decomposition is estimated at 17.5 million tonnes of CH_4; this is substantially higher than previous estimates.

China has the largest country-level CH_4 emission from manure in the world, mainly from pigs. At a global level, emissions from pig manure represent almost half of total livestock manure emissions. Just over a quarter of the total CH_4 emission from managed manure originates from industrial systems, nearly exclusively from pigs (85%). About 70% originates from mixed systems, mainly from intensive large ruminant operations in Europe and North America and from small- and middle-scale pig farms in China.

4.2. Nitrogen

Although livestock-induced atmospheric N emissions in extensive systems lead to a reduction of an essential nutrient in often already fragile ecosystems, the situation is again quite the opposite on the intensive side. Large additions of N, disrupting ecosystem equilibrium, result from chemical N fertilizer use and animal concentrations. As a result not only the air is loaded with often polluting forms of N, but also soil and water resources.

N emissions from feed-related fertilizer. It has been estimated that humans have already doubled the natural rate of N entering the land-based N cycle, and this rate is continuing to grow (53). Synthetic fertilizers now provide about 40% of all the N taken up by crops (54). Although less so than animals, crop production too uses the additional resource at a rather low efficiency of about 50%. The fate of the remainder in the N cascade (34) is often hard to predict. Chemical processes involving nitrous oxides are particularly complex (26). Soil N_2O emissions are, among others, determined by temperature and soil moisture. They also depend on the chemical balance of the soil; whereas terrestrial ecosystems in the Northern Hemisphere are limited by N, tropical ecosystems, currently an important source of N_2O and NO, are often limited by phosphorus. N fertilizer inputs into these phosphorus-limited ecosystems generate NO and N_2O fluxes that are 10 to 100 times greater than the same fertilizer addition to N-limited ecosystems (55). Chemical form, mode, and timing of application are also important variables.

Average N losses as ammonia from synthetic fertilizer use are more than twice as high (18%) in developing countries than in developed and transition countries (7%). Most of this difference in loss rates is caused by higher temperatures and the dominant use of urea and ammonium bicarbonate in the developing world. In developing countries, about 50% of the N fertilizer used is in the form of urea (38). Bouwman et al. (56) estimate that NH_3 emission losses from urea may be 25% in tropical regions and 15% in temperate climates. In China, 40% to 50% of the N fertilizer used is in the form of ammonium bicarbonate, which is highly volatile. The NH_3 loss from ammonium bicarbonate may be 30% on average in the tropics and 20% in temperate zones. By contrast, the NH_3 loss from injected anhydrous ammonia, widely used in the United States, is only 4% (56).

In Section 4.1, we estimated that 20% to 25% of mineral fertilizer use (about 20 million tonnes N) can be ascribed to feed production for the intensive livestock sector. Assuming an average mineral fertilizer NH_3 volatilization loss rate of 14% (38), livestock production causes a global NH_3 volatilization from mineral fertilizer of 3.1 million tonnes NH_3-N per year.

N_2O emissions for major world regions can be estimated using the FAO/IFA (38) model. N_2O emissions amount to 1.25% $\pm$ 1% of the N applied. This estimate is the average for all fertilizer types, as proposed by Bouwman (57) and adopted by IPCC (48). Under the same assumptions as for NH_3 above, livestock production can be considered responsible for a global N_2O emission from mineral fertilizer of 0.2 million tonne N_2O-N per year.

There is also N_2O emission from leguminous feedcrops, even though they do not generally receive N fertilizer because the rhizobia in their root nodules fix N that can be used by the plant. Studies have demonstrated that such crops show N_2O emissions of the same level as those of fertilized non-leguminous crops. On the basis of the total area of soybean and pulses, and the share of production used for feed, a total of about

75 million hectares in 2002 (2) released another 0.2 million tonnes of N_2O-N. Adding alfalfa and clovers would probably double this figure, although there are no global estimates of their cultivated areas. Russelle & Birr (58), for example, show that soybean and alfalfa together harvest some 2.9 million tonnes of fixed N in the Mississippi River Basin, with the N_2 fixation rate of alfalfa being nearly twice as high as that of soybean (see also the review in Reference 39). It is therefore plausible that intensive forms of livestock production are linked to more than 0.5 million tonnes per year of total N_2O-N emission from soils under leguminous crops.

Mineral fertilizer N loss to aquatic sources and subsequent emissions. N uptake rate in global crop production is estimated at about 50% on average (35, 39). Smil (39) attempted to derive a global estimate of N losses from fertilized cropland. He estimates that globally, in the mid-1990s, about 37 million tonnes N were exported from cropland through nitrate leaching (17 million tonnes N) and soil erosion (20 tonnes N). In addition, a fraction of the volatilized ammonia from mineral fertilizer N (11 million tonnes N per year) finally also reaches surface waters after deposition (3 million tonnes N per year). This N is gradually denitrified in subsequent reservoirs of the N cascade (34). The resulting enrichment of aquatic ecosystems with reactive N causes emissions not only of N_2, but also of N_2O. Galloway et al. (33) estimate the total anthropogenic N_2O emission from aquatic reservoirs at about 1.5 million tonnes N, originating from a total of some 59 million tonnes N transported to inland waters and coastal areas. Feed and forage production induces a loss of N to aquatic sources of some 8 to 10 million tonnes per year, assuming that such losses are in line with N fertilization shares of feed and forage production (some 20% to 25% of the world total, see the carbon section). Applying the overall rate of anthropogenic aquatic N_2O emissions (1.5/59) to the livestock, induced mineral fertilizer N loss to aquatic reservoirs results in livestock-induced emissions from aquatic sources of around 0.2 million tonnes N N_2O.

N lost to the atmosphere from stored manure. Because of the low N assimilation efficiency of livestock, large amounts of N are lost in the intensive production units. The N harvested in feed over a wide area is used and largely lost in a spatially highly concentrated manner by highly intensive or industrial production units with very large animal numbers. This concentration is often aggravated by excessively N-rich diets. The environmental effect of these enormous concentrations of N depends on the fate of the manure, which is highly variable: lost from stored manure, applied in excess to nearby land or in a more balanced manner over a wider area, sold as fertilizer, or simply discharged into surface waters.

Although of variable duration and mode, storage of manure occurs in all industrial production units. For the most part, excreted N compounds mineralize rapidly during this first phase of manure management. In urine, typically over 70% of the N is present as urea (48). Uric acid is the dominant N compound in poultry excretions. The hydrolysis of both urea and uric acid to NH_3/NH_4^+ is very rapid in urine patches. The magnitude of N_2O emissions depends on environmental conditions. N_2O emissions occur when waste is first handled aerobically, allowing ammonia or organic N to be converted to nitrates and nitrites (nitrification). If an anaerobic stage follows, nitrates and nitrites are reduced to N_2, with intermediate production of N_2O and nitric oxide (NO) (denitrification). These emissions are most likely to occur in dry waste-handling systems, which have aerobic conditions but contain pockets of anaerobic conditions owing to saturation. The amount of N_2O released during storage and treatment of animal wastes also depends on temperature. Unfortunately, there is not enough quantitative data to establish a relationship between the degree of aeration and N_2O emission from slurry during storage and treatment. When expressed in N_2O-N/kg N in the waste (i.e., the share of N in waste emitted to the atmosphere as N_2O), losses from animal waste during storage range from less than 0.0001 kg N_2O-N/kg N for slurries to more than 0.15 kg N_2O-N/kg N in the pig waste of deep-litter stables. Any estimation of global manure emission needs to consider these uncertainties. Expert judgement, on the basis of existing manure management in different systems and world regions, combined with default IPCC emission factors (31), suggests N_2O emissions from stored manure equivalent to 0.7 million tonnes N per year.

With regard to ammonia, rapid degradation of urea and uric acid to ammonium leads to very significant N losses through volatilization during storage and treatment of manure. Although actual emissions are subject to many factors, particularly the manure management system and ambient temperature, most of the NH_3 N volatilizes during storage, before application or discharge. On the basis of the animal population in industrial systems (31), and their estimated manure production (48), the current amount of N in the corresponding animal waste can be estimated at 10 million tonnes and the corresponding NH_3 volatilization from stored manure at 2 million tonnes N. Estimated volatilization losses from stored manure in mixed systems are much higher, though lower on a per animal basis: We estimate that currently over 16 million tonnes N of ammonia volatilizes annually from mixed systems; approximately 5 of these originate from more intensive production systems such as western dairy operations and medium-size pig holdings in China. On the one hand, this N loss reduces emissions from manure once applied to fields; on the other, it gives rise to N_2O emissions further down the N cascade.

Aquatic N_2O emissions after manure N loss. N loss to the atmosphere after application on soil was discussed in conjunction with those following direct deposition in Section 3.2, the former being clearly much lower than the latter. Contrary to the situation in extensive systems, a very large amount of N leaves the local system through surface water flows, either resulting from leaching of excess amounts applied to land or from direct discharge.

In the mid-1990s, about 25 million tonnes of N from animal manure remained available per year for plant uptake in the world's croplands and in intensively used grasslands after losses to the atmosphere during storage and following application and direct deposition. Uptake depends on the ground cover: Legume/grass mixtures can take up large amount of added N, whereas loss from row crops is generally substantial, and losses from bare soil are much higher still. We suppose that N losses from grazing land, through leaching and erosion, are negligible. Applying the crop N-use efficiency of 40% to the remainder of animal manure N applied to cropland, about 9 or 10 million tonnes N entered the N cascade mostly through water in the mid-1990s. Applying the N_2O loss rate for subsequent N_2O emission (see the above section on subsequent emissions from mineral fertilizer N loss), an additional 0.2 million tonnes N N_2O are emitted through this channel. N_2O emissions of similar size can be expected to have resulted from the redeposited fraction of the volatilized NH_3 from manure that reached the aquatic reservoirs in the mid-1990s. Total N_2O emissions following N losses would, therefore, have been in the order of 0.4 million tonnes N N_2O per year in that period.

We have updated these figures for the current livestock production system estimates, using the IPCC methodology for indirect emissions. The current overall "indirect" animal manure N_2O emission following volatilization and leaching then totals around 1.3 million tonnes N per year. However, this methodology is beset with high uncertainties. The majority of N_2O emissions, or about 0.9 million tonnes N, originates from mixed systems.

Table 4 Summary of current impacts on the carbon cycle

Process	Impact on C cycle	Contribution from extensive systems[a]	Contribution from intensive systems[a]
N fertilizer production	Addition of atmospheric CO_2	—	0.04
On-farm fuel use	Addition of atmospheric CO_2	—	~0.09
Savannah burning	Changing carbon distribution in vegetation Contribution to climate change	Majority of burned area worldwide	—
Pasture desertification	Soil carbon loss Addition of atmospheric CO_2	~0.1	—
Deforestation	Soil and vegetation carbon loss Addition of atmospheric CO_2 Changing local carbon cycle	~1.7	~0.7
Soil tillage	Soil carbon loss Addition of atmospheric CO_2	—	~0.02
Soil liming	Addition of atmospheric CO_2	—	~0.01
Enteric fermentation	Addition of atmospheric CH_4	1.6	0.20
Methane from manure	Addition of atmospheric CH_4	0.17	0.20
Processing	Addition of atmospheric CO_2	—	0.01–0.05
Transport	Addition of atmospheric CO_2	—	~0.001

[a]Quantified contributions concern additions to and removals from the atmospheric pool and all are expressed in billion tonnes CO_2 equivalent.

5. SUMMARY OF LIVESTOCK'S ROLE IN CARBON AND NITROGEN CYCLES

Tables 4 and **5** summarize the range of afore-described impacts of the livestock sector on the C and N cycles. Not all impacts are quantifiable, either because of their complex nature, as in the case of Savannah burning, or because of a lack of information, as in the case of eutrophication of surface water from manure ammonia. Figures corresponding to processes leading to N_2O emissions comprise direct as well as indirect emissions. The figures should be considered as indicative values, particularly because the role of mixed

Table 5 Summary of current impacts on the nitrogen cycle

Process	Impact on N cycle	Estimated contribution from extensive systems[a]	Estimated contribution from intensive systems[a]
Mineral fertilizer application	Eutrophication of aquatic systems	—	8–10
	Addition of atmospheric N_2O	—	0.4 (0.2)
	Volatilization/deposition of NH_3	—	3.1
Leguminous feed cropping	Addition of atmospheric N_2O	—	0.5 (0.2)
Extensive grazing	N loss from local terrestrial pools	18	—
	Addition of atmospheric N_2O	1.8 (0.8)	—
	Volatilization/deposition of NH_3	6	—
Manure management	Addition of atmospheric N_2O	1.3 (0.6)	0.5 (0.2)
	Volatilization/deposition of NH_3	11	7
	Eutrophication of aquatic systems	More than 10[b]	

[a]Quantified contributions are expressed in million tonnes N per year, except for additions of atmospheric N_2O, also expressed in billion tonnes CO_2 equivalent (between parentheses).

[b]Overall estimate based on mid-1990s figures but lacks information on the importance of direct discharge of manure to water.

crop-livestock systems is often large. Despite the importance of this category of production systems, little information is available on its characteristics in different parts of the world. In addition, and as a consequence, estimates for the parts of mixed systems to be considered as respectively extensive and intensive production remain largely based on expert knowledge.

Livestock-related emissions of CO_2 are a huge component of the global C budget when deforestation for pasture and feed crop land as well as pasture degradation are taken into account. Although small by comparison, the livestock food chain is becoming more fossil fuel intensive, as the shift from traditional local feed resource-based ruminant production to intensive monogastrics fundamentally entails a concomitant shift away from solar energy to fossil fuel.

The leading role of livestock in CH_4 emissions has long been a well-established fact. With the decline of ruminant livestock in relative terms, and the overall trends toward higher productivities also in ruminant production, the importance of enteric fermentation will likely not grow much more. While much lower in absolute terms, CH_4 emissions from animal manure are considerable and rapidly growing. Together they represent some 80% of agricultural emissions and about 35% to 40% of the total anthropogenic CH_4 emissions.

Livestock activities contribute in a principal way to the emission of nitrous oxides, the most aggressive greenhouse gas. Their contribution to the global budget is as high as 65%, and 75% to 80% to agricultural emissions; current trends suggest that these levels will substantially increase over the coming decades.

Global anthropogenic atmospheric emission of ammonia has recently been estimated at some 47 million tonnes N (33), with 94% produced by the agricultural sector. The livestock sector contributes about 68% to this share, mainly from deposited and applied manure. The resulting air and environmental pollution is a local or regional more than a global environmental problem. Similar levels of N depositions can indeed have substantially different environmental effects according to the type of ecosystem they affect.

It is evident from the above that, although it is certain that the livestock sector plays a major role in C and N cycles worldwide, major knowledge gaps exist. In particular, these relate to feedback mechanisms, such as the effect of climate change and its impact on terrestrial C pools. Furthermore, impacts of the N cycle depend to a large extent on soil conditions, but knowledge is still insufficient to allow for precise and reliable estimates of the related, important fluxes. Equally important, the limited information available on varying forms of waste management in different world regions constitutes another important obstacle toward more accurate estimates. However, currently available information would already warrant a revision of the IPCC default emission factors. Finally, there is a need to translate information on environmental impacts into more accessible material for use by consumers and decision makers, such as comparative life cycle analyses among production systems, locations, and food sectors.

6. TECHNICAL OPTIONS TO MITIGATE CARBON AND NITROGEN LOSSES

Even though there are important knowledge gaps in assessing livestock's role in C and N cycles, sufficient evidence points to a large and growing contribution. Just as the livestock sector has large and multiple impacts on both cycles, so there are multiple and effective options for mitigation. Much can be done, but to get beyond a "business-as-usual" scenario requires a strong involvement of public policy. Most of the options are not cost neutral, and simply enhancing awareness will not lead to widespread adoption. While the policy and institutional aspects are criticial, we do not examine these here but only present the main technical options.

6.1. Sequestering Carbon and Mitigating Carbon Dioxide Emissions

Compared to the amounts of C released from changes in land use and land degradation, emissions from the food chain are small. For C, the environmental focus needs therefore to be on addressing issues of land-use change and land degradation. Here, the livestock sector offers significant potential for C sequestration, particularly in the form of improved pastures.

In addressing land-use change, the challenge lies in slowing and eventually halting and reversing deforestation. Vlek et al. (59) consider that the only available option to free up the land necessary for C sequestration would be intensification of agricultural production on some of the better lands, for example, by increased fertilizer inputs. They demonstrate that the increased CO_2 emissions related to the extra fertilizer production would be far outweighed by the sequestered or avoided emissions of organic C related to deforestation. Apart from improved fertilizer use, other options for intensification include the use of higher-yielding, better-adapted varieties and improved land and water management. Although rationally attractive, the "sequestration through intensification" paradigm may not be effective in all sociopolitical contexts and requires a functioning regulatory framework.

A huge potential exists for net sequestration of C in cultivated soils. The C sink capacity of the world's agricultural and degraded soils is 50% to 66% of the historic C loss from soils of 42 to 78 gigatonnes of C (60). There are proven new practices that can improve soil quality and raise soil organic C levels (e.g., conservation tillage and organic farming), which achieve yields comparable to conventional intensive systems. The full potential for terrestrial soil C sequestration is uncertain, because of insufficient data and understanding of soil organic C dynamics at all levels, including molecular, landscape, regional, and global scales (61). According to the IPCC (62), improved practices typically allow soil C to increase at a rate of about 0.3 tonnes of C per hectare per year. It is unclear if this rate is sustainable: Research shows a relatively rapid increase in C sequestration for a period of about 25 years and a gradual leveling thereafter (63).

Improved grassland management is another major area where soil C losses can be reversed, leading to net sequestration, by the use of trees, improved pasture species, fertilization, and other measures. Because pasture is the largest anthropogenic land use, improved pasture management could potentially sequester more C than any other terrestrial sink (62, **Table 4**). There would also be additional benefits, particularly preserving or restoring biodiversity in many ecosystems.

In the humid tropics, silvo-pastoral systems are one approach to C sequestration and pasture improvement. In dryland pastures, some aspects of dryland soils may help in C sequestration. Dry soils are less likely to lose C than wet soils, as lack of water limits soil mineralization and therefore the flux of C to the atmosphere. Consequently, the residence time of C in dryland soils is sometimes even longer than in forest soils. Although the rate at which C can be sequestered in these regions is low, it may be cost-effective, particularly taking into account all the side benefits for soil improvement and restoration (17).

6.2. Reducing Methane Emissions from Enteric Fermentation Through Improved Efficiency and Diets

The most promising approach for reducing CH_4 emissions from livestock is by improving the productivity and efficiency of livestock production, through better nutrition, genetics, animal health, and general husbandry practices. Greater efficiency means that a larger portion of the energy in the animals' feed is directed toward the creation of useful products, so that CH_4 emissions per unit product are reduced. The trends toward high-performing animals and toward monogastrics and poultry, in particular, are valuable in this context because they reduce CH_4 per unit of product.

A number of technologies exist to reduce CH_4 release from enteric fermentation. The basic principle is to increase the digestibility of feedstuff, either by modifying feed or by manipulating the digestive process. Examples of improvements in fibrous diets are the use of feed additives or supplements and the increased level of starch or rapidly fermentable carbohydrates in the diet (so as to reduce excess hydrogen and subsequent CH_4 formation). In many instances, such improvements may not be profitable at farm level. However, national planning strategies in large countries could potentially bring about such changes. For example, Eckard et al. (64) suggest that concentrating dairy production in the temperate zones of Australia could potentially decrease CH_4 emissions because temperate pastures are likely to be higher in soluble carbohydrates and easily digestible cell wall components.

More advanced technologies are also being studied but are not yet widely applied. These include reduction of hydrogen production by stimulating acetogenic bacteria, defaunation (eliminating certain protozoa from the rumen), and vaccination (to reduce methanogens). These options have the advantage of being applicable to free-ranging ruminants as well, although the latter option may encounter resistance from consumers (65). Defaunation has been proven to result in a 20% reduction in CH_4 emissions on average (66), but regular dosing with the defaunating agent remains a challenge.

6.3. Mitigating Methane Emissions Through Improved Manure Management and Biogas

CH_4 emissions from anaerobic manure management can be readily reduced with existing technologies. Such emissions originate from intensive mixed and industrial systems; these commercially oriented holdings usually have the capacity to invest in such technologies. The potential for emission abatement from manure management is considerable, and multiple options exist. A first obvious option to consider is balanced feeding (increased C to N ratios) because it also influences other emissions. Additional measures include anaerobic digestion (producing biogas as an extra benefit), flaring/burning (chemical oxidation, burning), special biofilters (biological oxidation) (65, 67), composting, and aerobic treatment. It is assumed that biogas can achieve a 50% reduction in emissions in cool climates, and higher in warmer climates, for manures that otherwise would be stored as liquid slurry. Various systems exist to exploit this huge potential, such as covered lagoons, pits, tanks, and other liquid storage structures. These are suitable for large- or small-scale biogas systems, with a wide range of technological options and different degrees of sophistication. Additionally, covered lagoons and biogas systems produce a slurry that can be applied to rice fields instead of untreated dung, leading to reduced CH_4 emissions (68).

6.4. Mitigating Nitrogen Loss

An important mitigation pathway lies in raising low animal N assimilation efficiency through more balanced feeding by optimizing proteins or amino acids to match the exact requirements. Improved feeding practices also include grouping animals by gender and phase of production and by improving the feed conversion ratio through tailoring feed to physiological requirements.

But even with these measures, manure still contains large quantities of N. The use of an enclosed tank can nearly eliminate N loss during storage and offers an important synergy with respect to mitigating CH_4 emissions and production of biogas; N_2O emissions from the subsequent spread of (digested) slurry can also be reduced.

The key to reducing N loss resulting from the application/deposition of manure is the fine-tuning of waste application to land with regard to environmental conditions, including timing as well as amounts and form of application in response to crop physiology and climate. Another technological option is the use of nitrification inhibitors (NIs) that can be added to urea or ammonium compounds. Monteny et al. (65) cite examples of substantially reduced emissions. Some of these substances can potentially be used on pastures where they act upon urinary N, an approach being adopted in New Zealand (69). Costs of NIs may be offset by increased crop/pasture N uptake efficiency. The degree of adoption of NIs may depend on public perception of introducing yet another chemical into the environment (65).

Livestock play an important role in both the global C and N cycle. The contribution to the C cycle mainly stems from livestock's land use and role in land-use change, in particular deforestation and pasture degradation. Livestock's role in the N cycle is mainly determined by their demand for concentrate feed and by livestock waste storage and disposal. As the scope for pasture expansion and intensification is limited, extensive livestock is stagnating, but industrial livestock is growing rapidly. Subsequently, there is an ongoing shift toward a growing role of livestock in the N cycle and a stagnating or declining role in the C cycle, albeit from a very high level.

FUTURE ISSUES

There is a major uncertainty in the quantification of N_2O emissions, in particular with regard to different livestock production systems as well as their feeding and waste management practices, which need to be underpinned by more accurate modeling of soil N_2O fluxes. Furthermore, a major knowledge gap is the feedback mechanisms resulting from climate change. On the biophysical side, quantifications of C loss from agricultural soils and from land degradation (LU) are still unreliable, and better quantification is also needed of the effects on above- and belowground C pools when there are changes in land use. Such quantifications are extremely difficult, which is why they are often neglected.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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