Chapter 4

Reducing N_2O Emissions from Agricultural Sources

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4.1. Introduction

Chapter 3 reviewed the many sources of anthropogenic N_2O in the atmosphere and highlighted the fact that agriculture is its largest source. In this chapter, we briefly review the sources of N_2O emissions in agriculture and possible strategies for reducing these emissions. For the purpose of this chapter, "agriculture" includes (1) producing crops for food, feed and biofuel, and (2) raising animals for meat, egg and dairy products. Aquaculture is not covered here, but in Chapter 7.

4.2. Sources of N_2O emissions from agriculture

Nitrogen is essential for producing food and feed; it is a constituent of protein, amino acids, vitamins, and nucleic acids, which have critical functions in plants, animals and humans. Application of nitrogen generally boosts the growth and development of crops, and hence the production of food. Similarly, animals grow and develop well when there are sufficient proteins and essential amino acids in their feeds. However, nitrogen also causes N_2O emissions. On average 1% of the nitrogen applied to crop land is directly emitted as N_2O into the atmosphere, depending on nitrogen source and environmental conditions (IPCC, 2001, 2006). In addition, there are N_2O emissions related to the storage and management of animal manures, the recycling of residues and wastes, the production of synthetic fertilizers, and some additional nitrogen losses.

Current total N_2O emissions from global agriculture are estimated at approximately 4.1 Tg N_2O-N/yr (range: 3.8 - 6.8)[28]. Nine main sources of N_2O emissions are distinguished (Table 4.1) and these can be classified as either direct or indirect[29]. Each of these sources has a specific emission factor[30]. Fertilizer and animal manure (including droppings from grazing animals) are the largest sources of emissions. Table 4.1 indicates that indirect emissions accounted for approximately 22% of total emissions in 2010. Nitrogen-fixing crops including soybean, clover, alfalfa and other leguminous crops have not been distinguished as separate N_2O sources because emissions during their growth are considered to be negligible (Rochette and Janzen, 2005). However, the total nitrogen stored in these plants is relatively large and they contribute significantly to N_2O emissions as crop residues (Marinho et al. 2004, Mosier et al., 2006, Herridge et al., 2008).

28 Estimated range taken from Table 3.1 in Chapter 3 of this report.

29 Emissions associated with the microbial nitrification and denitrification of fertilizer and manure nitrogen that remains in agricultural soils or animal waste management systems are referred to as direct emissions, while those associated with the volatilization, leaching or runoff of nitrogen from agricultural soils and animal waste management systems are referred to as indirect emissions.

30 Though source-specific, there is a considerable uncertainty in N_2O emission factors (Rypdal and Winiwarter, 2001), especially at field and farm scales, but less at the global scale (e.g., Kros et al., 2012, Leip et al., 2011, Butterbach-Bahl et al., 2013). The large uncertainty at lower scales is related to the diversity of agriculture and environmental conditions, the complexity of the N_2O producing processes and their controls (Robertson and Tiedje, 1987; Davidson et al., 2000), but also to the uneven spread of studies, with few field measurements in Africa (Baggs et al., 2006; Chapuis-Lardy et al., 2009). According to a default inventory methodology (IPCC, 2006), it is assumed that N_2O emissions are linearly related to the amounts of N input, representing 1% of nitrogen applied, with an uncertainty range of 0.03 to 3%. However, some authors have challenged this linearity (McSwiney and Robertson, 2005; Stehfest and Bowman, 2006; Cardenas et al., 2010; Hoben et al., 2011), and argue that emissions increase more than proportionally with nitrogen applied. Furthermore, emission factors have been differentiated according to nitrogen-input sources and environmental conditions. For example, Lesschen et al. (2011a) and Leip et al. (2011) derived fertilizer type, crop residue type, land-use, soil type and rainfall specific emission factors for Europe. For Mediterranean agriculture, Aguilera et al. (2013) differentiated emission factors according to fertilizer type and irrigation scheme. However, lack of activity data (e.g. N fertilizer type and application, N excretion) hamper the reduction of uncertainties (Philibert et al., 2012; Rosenstock et al., 2013).

Table 4.1. Emissions of N_2O from agriculture per continent in 2010, estimated here using the Tier 1 IPCC (2006) approach with source-specific emission factors and national-level activity data from FAOSTAT.

General characteristics & Sources of N_2O	Asia	Africa	Europe	North America	Latin America	Oceania	Global Total
Human population, billion	4.26	1.02	0.74	0.34	0.59	0.04	7
Agricultural utilized area, Mha	1633	1170	469	474	737	412	4895
Synthetic fertilizer N use, Tg	67	3	14	14	7	2	107
Manure N excretion, Tg	39	22	12	7	22	5	107
Grain production, Tg	9455	1669	1818	2170	2101	213	17426
Direct Emissions, Gg N_2O-N							
Applied fertilizer	670	30	135	135	74	15	1059
Nitrogen fertilizer production*	-	-	-	-	-	-	-
Manure management	109	12	45	29	20	4	219
Applied manure	50	5	63	25	22	1	166
Grazing animals	387	331	55	73	342	63	1251
Applied crop residues	119	17	40	45	32	4	257
Burning crop residues**	6	2	1	2	2	0	13
Drainage of peatlands***	90	11	62	24	3	10	200
Indirect Emissions, Gg N_2O-N							
Emission from loss of nitrates (NO_3) to surface and ground water and volatilization of ammonia (NH_3)	420	106	127	97	128	26	904
Total emissions, Gg N_2O-N	***1852***	***514***	***528***	***429***	***623***	***123***	***4069***
Emissions, kg N_2O-N per capita	0.4	0.5	0.7	1.3	1.1	3.1	0.6
Emissions, kg N_2O-N per ha	1.1	0.4	1.1	0.9	0.8	0.3	0.8

* N_2O emissions from industrial processes for fertilizer production are discussed in Chapter 5.
** Emission reduction options for agricultural burning are discussed in Chapter 6
*** Peatlands are organic matter rich soils. Because of their high organic matter content, they may serve as sources of greenhouse gases including carbon dioxide, methane and N_2O. Human activities (land-use change and drainage of the soil for agriculture, forestry and peat extraction) result in the emission of especially carbon dioxide and N_2O into the atmosphere.

Asia is the continent with the largest N_2O emissions (Table 4.1), reflecting the fact that it also has the largest agricultural area and population. On a per capita basis, Asia has the lowest estimated N_2O emissions, followed by Africa and Europe. Expressed per surface area of agricultural land, emissions are highest in Asia and Europe and lowest in Oceania and Africa. The largest source of N_2O emissions in Asia, Europe and North America is the use of fertilizers for food, feed and biofuel production, while in Africa, Latin America and Oceania, the largest source is nitrogen excreted from grazing animals.

4.3. Options for emission reductions

Though intrinsically related to the cycling of nitrogen and the production of food, not all N_2O emitted from agriculture should be considered 'inevitable'. There are possibilities for reducing N_2O emissions, which can be grouped into the following broad strategies:

- Changing diet and reducing food loss/waste.
- Improving nitrogen use efficiency in crop and animal production.
- Adopting technologies and management practices that decrease the fraction of input nitrogen that is released as N_2O (i.e., the emission factor).

These strategies, which may be combined, depending on local situations, to reduce N_2O emission in the food production, processing and consumption chain (Figure 4.1) are further discussed below.

4.3.1. Changing diet and reducing food loss/wastes

Changing diet

Food choices have major impacts on nitrogen use and N_2O emissions per capita. For example, emissions associated with the production of animal-derived protein are about a factor of ten larger than those associated with the production of plant-derived protein (Galloway and Cowling, 2002; Figure 4.2). Within animal-derived food types, the production of ruminants (cattle, sheep and goat) releases more N_2O per kg of product than pork and poultry. Hence, reducing the intake of animal-derived protein, especially by consumers in affluent countries, would reduce demand and consequently production of these food types, thereby decreasing associated N_2O emissions. Reay et al. (2011) showed that the average European consumes 70% more protein than needed to meet dietary requirements (WHO, 2007) indicating a potential to reduce N_2O emissions without compromising good nutrition.

Apart from reduced N_2O emissions, dietary change has the additional benefits of improving human health and reducing ecological impacts associated with animal food production (Steinfeld et al., 2006; Erisman et al., 2008; Sutton et al., 2011a,b). However, it is also obvious that reducing the consumption of

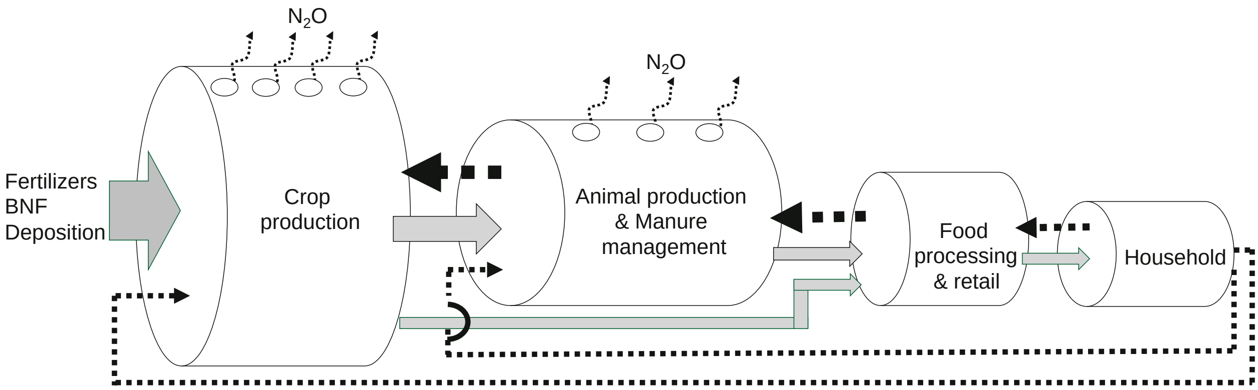

Figure 4.1: A food system approach for reducing N_2O emissions in the production, processing and consumption of food. The cylinders represent 'N_2O-leaky' compartments of the food system. The large grey arrow at the left indicates 'new' nitrogen inputs via fertilizers, biological nitrogen fixation (BNF) and atmospheric deposition. Smaller grey arrows indicate the flow of nitrogen in food and feed from production to consumption in households. Dashed black arrows indicate recycled nitrogen in manure, residues and wastes (based on Ma et al., 2010a, 2012).

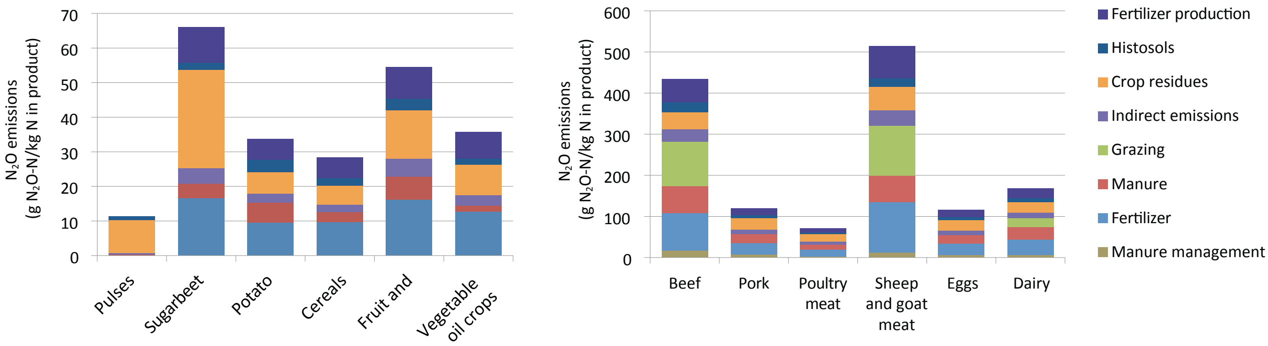

Figure 4.2: Mean N_2O emissions associated with the production of plant-derived food products (left panel) and animal-derived food products (right panel) in the European Union in 2004, expressed in g N_2O-N per unit of protein-N in the products (based on Lesschen et al., 2011b). **Note scale difference.** Note also that emissions derived from fertilizer production are based on the relatively large share of ammonium nitrate-based nitrogen fertilizers in the EU, while mitigation measures in fertilizer plants were not in place everywhere by 2004 (see Chapter 5).

animal-derived protein is not relevant or an option for millions of people in South Asia, Africa, and elsewhere who are currently consuming very low levels of this protein.

Reducing food loss/waste

Globally, an estimated 20 to 40% of food produced is either lost or wasted at various stages in the food production-consumption chain (Parfitt et al., 2010; Gustavsson et al., 2011). For example, the annual amount of wasted food in China is now equivalent to the food needed by 200 million people (Ren, 2013). According to UNEP (2012), American consumers throw away around 25% and British consumers about 33% of food purchased. Furthermore, food is lost in developing countries due to lack of infrastructure for the processing, transportation and storage of produced food. Reducing food loss/waste may proportionally decrease global food requirements, thus, reducing N_2O emissions associated with production. Assuming a wastage reduction of 50%, i.e. from the current 20 to 40% loss to 10 to 20%, (Gustavsson et al., 2011; Kummu et al., 2012), total agricultural N_2O emissions could also decrease by 10 to 20%.[31]

Options for minimizing food wastage include increased public awareness about the importance of not wasting food, improved food labelling, relaxation of quality standards that do not affect taste or quality of food, developing markets for sub-standard products or consumable products deemed as waste, and change in business behaviour aimed at waste reduction. Food loss in developing countries can be substantially lowered by providing necessary infrastructure to small-holders (UNEP, 2012).

It must be noted however, that some level of wastage is inevitable in the food production-consumption chain. Recycling of these wastes as manure for agriculture could potentially reduce the quantity of synthetic fertilizers used in agriculture, thereby decreasing the total N_2O emissions in the food system.

The two strategies discussed above fall under the overall concept of sustainable food systems[32] as described in UNEP (2012).

4.3.2. Increasing nitrogen use efficiency in crop and animal production

Crop production

Although defined in various ways, nitrogen use efficiency (NUE) generally provides an indication on how well nitrogen applied to crops is taken up and converted to crop yield (e.g., Dobermann, 2007). NUE is high when the amount of produce per unit of nitrogen applied is high. If NUE is high, the risks of

31 This is based on the assumption that total N_2O emissions from agriculture are linearly related to the amount of food produced. Hence, a 10-20% reduction in food production will result in similar reduction in N_2O emissions.

32 Sustainable food systems apply sustainability practices in the production, processing, distribution, storage, marketing and consumption of food so as to increase human well-being and minimize impact on the environment. It enables the production of sufficient, nutritious food, while conserving the resources that the food system depends on (UNEP, 2012).

nitrogen losses and N_2O emissions are relatively low. Hence, efforts aimed at improving NUE can yield dual benefits: an increase in crop yield and reduced nitrogen losses, including N_2O emissions (Burney et al., 2010; Thomson et al., 2012).

Emissions of N_2O from crop production rise with increased nitrogen input from fertilizers, manures, composts, wastes, and crop residues (Bouwman et al., 2002; Snyder et al., 2009). However, emissions per unit of crop produce tend to decrease with increased nitrogen input until an optimum input level is reached. Beyond this level, N_2O emissions per unit of crop produce increase sharply because an increasing fraction of applied nitrogen is not utilized by the crops (van Groenigen et al., 2010; Venterea et al., 2011). Hence, a straightforward strategy for increasing NUE and consequently reducing N_2O emissions is to apply only the amount of nitrogen needed for crop growth. This falls under the overall idea of nutrient management[33].

A notable nutrient management strategy is the "4R nutrient stewardship" also referred to as the "4Rs". This strategy encourages the application of the right nutrient sources, in the right amount, at the right time and in the right place[34] (IPNI, 2012). For it to be successful, the 4Rs requires site, soil and crop type-specific knowledge and information, accompanied by appropriate technologies[35] and best management practices. Snyder and Fixen (2012) reported that nitrogen uptake of more than 70% could be achieved for many cereal crops when site-specific nutrient management practices based on the 4Rs are implemented. This is a significant increase over current levels since, for example, nitrogen recovery by corn (*Zea mays*) typically ranges between 40 to 50% (Dobermann 2007).

For global food security, large efforts have to be made to further increase crop yields through plant breeding (increasing the genetic potential of the crop), improved crop husbandry (appropriate seeding time and planting density, appropriate weeding), improved irrigation and drainage management[36], and improved pest and disease management. When properly combined, these efforts have the potential to increase crop yield and nitrogen use efficiency simultaneously (Chen et al., 2011; Hirel et al., 2011). Other options for enhancing NUE include cover cropping[37], multiple cropping[38], buffer strips[39], and conservation tillage[40].

Studies so far indicate that, depending on the local situation, N_2O emissions per surface area and per unit crop produced may decrease by 10 to 60% through the implementation of the above options (Table 4.3). It must be noted however, that significant investments in education, training, demonstration and development of site-specific technologies are needed in order to be able to implement NUE improvement measures. This is because these measures would have to be implemented by the millions of small-holder farmers in the world in site-specific ways. Also, different areas may require different priorities and strategies. For example, crop yields have been stagnant in Africa during the last four decades (Lobell et al., 2009), in part because breeding efforts have not focused on crops predominantly grown in Africa. Meanwhile poor functioning markets have largely prohibited the use of technologies and management practices to increase yields and NUE.

Animal production

Although animals do not directly release N_2O into the atmosphere (or only in trivial amounts), animal wastes are a large source of nitrogen and hence, N_2O production (Steinfeld et al., 2006). Animals convert between 10 to 45% of the nitrogen in their feed into protein nitrogen in meat, milk, eggs, wool and hides, depending on animal species, feed quality and management. The remaining 55 to 90% of the nitrogen in feed is excreted in dung and urine.

Increasing nitrogen use efficiency (NUE) in animal production is increasing the percentage of feed nitrogen that is converted into animal products (Powell et al., 2010). By doing so, less animal feed and less nitrogen are needed to produce a unit of meat, milk, egg, wool and hides, and hence, N_2O emissions associated with animal production will decline. Increasing NUE in animal production requires targeted combinations of animal breeding[41], improvements in feed quality and feed management[42], and improvements in herd management[43] (Steinfeld et al., 2010, Herrero et al., 2010, Bai et al., 2013). We estimate that a site-specific implementation of these management measures could greatly increase animal productivity and decrease the

33 Nutrient management involves putting in place practices aimed at using nutrients, either as fertilizer or manure, in an effective manner such that crop nutrient needs are met, agricultural yield and profitability are enhanced, and environmental protection and sustainability goals are achieved.

34 Right nutrient source implies matching the fertilizer source and product to crop need and soil properties taking into consideration interactions and balance between nitrogen, phosphorus, potassium and other plant nutrients. Right amount means matching the amount of fertilizer applied to the crop needs in order to avoid adding excess which could lead to loss to the environment. Right time implies making nutrients available only when needed by crops. Right place means placing and keeping nutrients where crops can make use of them (Roberts, 2007).

35 Examples of applicable techniques include the use of soil and plant tissue testing to determine crop nutrient needs, precision agriculture technologies such as canopy sensor-based nitrogen applications and variable rate fertilization for accurate application of crop nutrients and the use of enhanced efficiency fertilizers (EEFs) (technological options for N_2O emission reductions are discussed further in section 4.3.3).

36 Improved irrigation and water saving techniques may increase crop yields and NUE, while reducing N_2O emissions by up to 50% (Scheer et al., 2008; Sanchez-Martin et al., 2010; Kennedy et al., 2013).

37 The use of cover crops following the harvest of the main crop may mop up residual nitrogen from the soil, thereby reducing indirect N_2O emissions as well as improving soil quality (e.g., Bergström and Jokela, 2001; Sperow et al., 2003). However, ploughing cover crops into the soil may increase direct N_2O emissions (Garland et al., 2011).

38 Multiple cropping, including perennial cropping, intercropping and agroforestry systems have the potential to increase biomass yield, reduce leaching and erosion, thereby increasing NUE (Li et al., 2003; Zhang et al., 2003) while decreasing indirect N_2O emissions.

39 Buffer strips slow down runoff thereby enhancing infiltration of nutrients and increasing NUE, which may consequently decrease direct and indirect N_2O emissions (Snyder and Bruulsema, 2007).

40 Conservation tillage reduces erosion and runoff from soil thus reducing indirect N_2O emissions (Snyder and Bruulsema, 2007).

41 Breeding can increase the potential of animals to produce more milk and eggs, and to grow faster, and thereby use the ingested feed and nitrogen more efficiently and reduce the percentage released in dung and urine.

42 Improvements in feed quality and feed management involve (i) using feeds that are easily digested and have a proper energy protein ratio, and (ii) adhering to established nutritional requirements dependent on animal species and growth stage, e.g., implementing phase feeding or rotational grazing.

43 Herd management involves, for example, combinations of appropriate housing and ventilation, disease control and management, fertility control and animal welfare management.

Table 4.3. Estimated relative decrease in N_2O emissions through the implementation of NUE enhancement management practices, in percent (Modified, from Good and Beatty, 2011).

Crop	Decrease in N_2O emissions, %	Reference.
America		
Maize	25-40	Mosier et al., 2004; Cassman et al., 2002; Schmidt et al., 2002; McSwiney and Robertson, 2005; Hoben et al., 2011; Ma et al., 2010b
Wheat	28	Matson et al., 1998
Barely	37	Barraclough et al., 2010
Europe		
Wheat	13-20	Sylvester-Bradley and Kindred, 2009; Millar et al., 2010
Asia		
Rice	4-33	Cassman et al., 2003; Wang et al., 2001; Ju et al., 2009; Roy and Misra, 2002
Wheat	61	Ju et al., 2009
Maize	40	Ju et al., 2009

amount of nitrogen excreted per unit animal product by 10 to 30%. However, as in crop production, significant investments in education, training, demonstration and development of site-specific management measures are needed to realize these improvements.

Manure management

The estimated total amount of nitrogen excreted by animals in the world ranges from about 85 to 143 Tg (Oenema and Tamminga, 2005, Davidson, 2009). About half of the urine and faeces (those from grazing animals) are dropped in the field and left unmanaged. The other half is dropped in animal confinement (housing) systems, but less than half of that amount (i.e., 15 to 25% of total nitrogen excreted) is currently collected, properly stored and recycled to agricultural land. However, the ratio of housed animals to grazing animals is increasing because the current expansion of animal production is largely in 'slurry-based, confined animal feeding operations'[44] (Steinfeld et al., 2010).

Ideally, with proper technology, management and incentives, all manure dropped in animal confinements could be recycled to agricultural land, with only a small fraction of the available nitrogen lost during housing, storage and processing. We estimate that adoption of improved manure management measures, such as improved animal housing[45] and improved manure storage techniques[46] (e.g., Rotz, 2004; UNECE, 2013), could increase the fraction of manure nitrogen that is recycled to agricultural land over the next 20 to 40 years from 15-25% to 30-40% of total nitrogen excreted. Additionally, the effectiveness of manure as a fertilizer can be enhanced through the application of the "4R nutrient stewardship" practices discussed earlier. This can double the effectiveness of the manure nitrogen (relative to fertilizer nitrogen) from the estimated current value of 20-30% to 40-60%[47] (Schröder, 2005). As a result, the fertilizer nitrogen value of applied manure could be increased from the current 3-8% of total nitrogen excreted (Oenema and Tamminga, 2005) to as high as 12-24% within the next 20 to 40 years. This could lead to a proportional decrease in the amount of synthetic fertilizer needed for crop production thereby decreasing direct and indirect N_2O emissions associated with fertilizers. Increased recycling of manure nitrogen also has the added advantage of reducing ammonia and methane emissions. However, installing a proper manure collection, processing, storage and application system can be costly (e.g., UNECE, 2013) and may therefore require financial incentives for farmers. For hygienic reasons, manure in some countries has to be pasteurized or composted before application to land, which is also costly.

4.3.3. Technological approaches for reducing N_2O emissions from crop and animal production

Emissions of N_2O from agricultural land are dependent on the site and the type of fertilizer applied (Bouwman and Boumans, 2002; Lesschen et al., 2011a). Under well-drained conditions, emissions tend to be lower from nitrate-based fertilizers than from ammonium- and urea-based fertilizers, while the opposite seems true under moist conditions (Tenuta and Beauchamp, 2003; Smith et al., 2013). Some studies have shown greater N_2O emissions with anhydrous ammonia (used in North America) compared with urea (Venterea et al., 2010; Fujinuma et al., 2011). Hence, N_2O emissions can be reduced by choosing a particular fertilizer for a specific location.

44 Animal excrements are collected either as slurries or solid manures (mixed with bedding material). Solid manure in storages is in general a much larger source of N_2O (factor 10 or more) than slurries stored anaerobically (Mosier et al., 1998a). Stable management practices that accumulate a deep layer of litter and that include composting of manure can be large sources of N_2O. Hence, the design of the animal confinement and the manure stores have a large influence on N_2O emissions from manure management.

45 Animal manures and especially slurries contain a relatively large fraction of nitrogen in the form of ammonium, which is rapidly lost to the atmosphere via ammonia volatilization. Decreasing ammonia losses from manures in animal houses requires improved animal housing systems and also low-protein animal feeding (Rotz, 2004; UNECE, 2013).

46 Decreasing ammonia volatilization losses during manure storage requires roofs on top of the storages or decreasing the surface area where losses can take place, and lowering the pH of stored manure (Rotz, 2004; UNECE, 2013).

47 That is, the fertilization effect of 1 kg of nitrogen manure can be increased from its current value of 0.2-0.3 to 0.4-0.6 kg fertilizer nitrogen. Here, we assume also that the expected growth in livestock production between now and 2050 occurs predominantly in slurry-based, improved animal housing systems, where slurries are stored in leak-tight and covered storages, and applied via low-ammonia-emission-application techniques to land.

Another technological option is the use of 'enhanced efficiency fertilizers' instead of conventional fertilizers.[48] Enhanced efficiency fertilizers have been developed to improve fertilizer efficiency by increasing the availability of nitrogen to crops while reducing nitrogen loss to the environment (Snyder et al., 2009; Zhang et al., 2013) including N_2O emissions (Shoji et al., 2001; Akiyama et al., 2010; Ju et al., 2011). Experiments have shown that these types of fertilizer can decrease N_2O emissions by 35-38%, relative to conventional nitrogen fertilizer (Akiyama et al., 2010). N_2O emission reductions can be further enhanced if site-specific recommendations become available. However, the use of enhanced efficiency fertilizers may increase the cost of fertilizer use by 10% to more than 100%.

N_2O emissions from grazed pastures can be reduced by avoiding animal urine and faeces deposition onto wet soils, taking advantage of the fact that emissions are substantially lower on dry soils than wet soils. Hence, emissions can be reduced by diverting animals onto the drier areas of a field or farm. De Klein et al. (2012) estimated that N_2O emissions may be reduced by 4 to 7 % for every 10% reduction in urine nitrogen deposition onto wet soils.

Emissions of N_2O from grazed pastures can also be reduced by using nitrification inhibitors. Results from 46 studies in New Zealand indicate an average of 57% lower N_2O emissions when the nitrification inhibitor dicyandiamide was applied directly with, or shortly after, urine deposition (de Klein et al., 2011). Studies in Chile indicated an emissions decrease of up to 35% when nitrogen fertilizer and urine were amended with the same chemical (Vistoso et al., 2012; Lanuza et al., 2012). Although nitrogen inhibitors have been shown to be effective in reducing emissions from grazed pastures, they have some practical drawbacks that need to be overcome. First, it is not easy to apply nitrification inhibitors to urine-affected areas in a timely fashion. Second, use of dicyandiamide increases the cost of animal feed production with little or no yield benefit to the farmer. Third, the impacts of inhibitor residues in soil, waters and food have not been sufficiently evaluated. While synthetic chemicals are commonly used as nitrification inhibitors, biological variants are also being studied. [49]

As a final word, scientists are also investigating the possibility of manipulating soil bacteria genetically such that they produce less N_2O (Richardson et al. 2009).

4.4. Co-benefits, success stories and challenges

Apart from reducing N_2O emissions, the four emission reduction strategies discussed above all have potential co-benefits and trade-offs. For example, increasing nitrogen use efficiency reduces requirements for nitrogen inputs (fertilizer, animal manure, etc.) per unit of product produced, and thereby (other factors remaining the same) lowers ammonia emissions from cropland and its contribution to nitrogen deposition, and decreases the total amount of nitrogen that runs off or is leached from fields. Lower nitrogen runoff and leaching means less frequent eutrophication of lakes and rivers and its impacts (Sutton et al., 2011a, 2013).

Some policies targeted at other environmental problems associated with agriculture have ended up contributing to N_2O emissions reduction. An example is the Nitrates Directive of the European Union, which aims "to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters" (EC, 2013), but has also decreased N_2O emissions from agriculture by up to 10% (Velthof et al., 2013). In the Netherlands, emissions of N_2O from agriculture have decreased by more than 30% between 1990 and 2010, mainly due to the implementation of governmental policies and economic incentives to reduce ammonia emissions and nitrate leaching. These actions have increased nitrogen use efficiency without decreasing productivity (Coenen et al., 2012). Similar experiences have been reported for Denmark (Mikkelsen et al., 2010). However, the economic costs of implementing the various measures are considerable. It must also be noted that some measures aimed at reducing ammonia emissions and nitrate leaching may increase the risk of N_2O emissions (e.g., Smith, 2010; Venterea et al., 2012). This points to the need to make strategies site-specific, and to consider the full nitrogen cycle.

Implementing these emission reduction strategies is not without challenges and barriers. These include: balancing the costs of implementation with returns; the need for guidance and training of farmers; and the need for research to make strategies more site- and farm-specific (Johnson et al., 2007, Smith et al., 2008). In addition, some technical options may not be relevant to small-holder farms that continue to produce the bulk of food in developing countries (UNEP, 2012).

In general, measures specifically to reduce N_2O have not been widely implemented in agriculture. An important factor is probably that N_2O emissions are important globally rather than locally, and therefore farmers are not particularly motivated to address the problem. Also, the lack of a single easy technical fix is a barrier to adopting emission reduction measures. On the other hand, local actions against N_2O emissions in agriculture are critical to lowering global N_2O emissions and protecting the climate system and ozone layer, and these can be supported by national and international policies as discussed elsewhere in this report.

4.5. Estimating emission reduction potential

The business-as-usual scenarios presented in Chapter 3 anticipate that N_2O emissions from global agriculture will increase over the next decades. This is mainly because of increasing demand for food, animal feed and the associated increase in fertilizer nitrogen use and production of manure nitrogen. Here we provide an estimate of possible future N_2O emissions from agriculture under different mitigation scenarios, based on estimated fertilizer nitrogen use and

48 Slow-release fertilizer products release their nutrients at a slower rate than conventional fertilizers due to the incorporation of additives that reduce their release. Controlled-release fertilizer products use coatings to delay or extend nutrient release. Stabilized fertilizer products interrupt chemical reactions of nitrogen in the soil in order to prevent losses or emissions to the environment. Nitrification inhibitors are chemicals that inhibit the transformation of ammonium nitrogen into nitrate-nitrogen. All these so-called enhanced efficiency fertilizers have the potential to increase nitrogen use efficiency and have been shown to lower N_2O emissions (Weiske, 2006).

49 Recently, *Brachiaria Humidicola*, a tropical forage grass, was reported to exhibit strong nitrification inhibiting properties in its root-exudates (Subbarao et al., 2009). This finding may provide an option for reducing N_2O emissions and nitrate leaching from pastures through biological nitrogen inhibitors (Subbarao et al., 2013).

manure nitrogen production and estimated N_2O emission factors, using the concept of Davidson (2009).

Business-as-usual scenario (BAU)

To estimate the baseline emissions for 2030 and 2050, separate assumptions were made about fertilizer nitrogen use and manure nitrogen production. These projections were derived from Alexandratos and Bruinsma (2012). Multiplying fertilizer nitrogen use and manure nitrogen production by their associated emission factors yields estimates of 6.4 Tg N_2O-N/yr for 2030 and 7.5 Tg N_2O-N/yr for 2050[50] from the agricultural sector[51] (Table 4.4). Emissions for 2020[52] are estimated by extrapolation to be 6.0 Tg N_2O-N/yr.

Reduction option 1: Improved efficiency of crop and animal production

Here, the same projections of crop production and animal production from BAU were assumed. For crop production, it is assumed that improved nitrogen use efficiency reduces fertilizer requirements per hectare. Also, the use of enhanced efficiency fertilizers leads to lower N_2O emission factors. For animal production, it is assumed that improved nitrogen use efficiency leads to less manure production per unit of milk, meat and egg produced. These assumptions lead to emissions of 5.2 Tg N_2O-N/yr for 2030 and 4.9 Tg N_2O-N/yr for 2050 from the agricultural sector (Table 4.4).[53] Emissions in 2020 are estimated by extrapolation to be 5.3 Tg N_2O-N/yr.

Emissions reduction option 2: Option 1 plus improved efficiency of manure use

Here, the same assumptions from Option 1 were used, plus it was assumed that the increased recycling of manure from animal production reduces the total fertilizer nitrogen use for crop production [54]. This leads to emissions of 5.0 Tg N_2O-N/yr for 2030 and 4.4 Tg N_2O-N/yr for 2050 (Table 4.4). Emissions in 2020 are estimated by extrapolation to be 5.3 Tg N_2O-N/yr.

Emissions reduction option 3: Option 2 plus reducing food loss and waste

Here, the same assumptions from Option 2 were used, plus it was assumed that food waste is cut by half relative to current estimates and that this leads to a reduction in the fertilizer requirements and manure production. This leads to emissions of 4.6 Tg N_2O-N/yr for 2030 and 3.7 Tg N_2O-N/yr

50 Uncertainty ranges are not provided in the estimation of emission reduction potential because the starting data from Alexandratos and Bruinsma (2012) do not include ranges.

51 In crop production, total projected fertilizer usage in 2030 and 2050 is estimated at 231 and 263 Tg per year respectively (Alexandratos and Bruinsma, 2012). This translates into 132 and 150 Tg per year of fertilizer nitrogen respectively, assuming that fertilizer nitrogen use is 57% of total fertilizer use.

Projections of manure nitrogen production were derived from projections of animal number and animal production reported in Alexandratos and Bruinsma, 2012. Using the projections and considering that cattle produce roughly 60% of total manure nitrogen, we estimate that manure nitrogen production will increase by a total of 35% and 61% between 2005 and 2030 and 2005 and 2050 respectively (that is 1.2% growth per annum between 2005 and 2030 and 0.9% growth per annum between 2030 and 2050). Using 143 Tg N as a base value for total manure nitrogen production for 2005 (Davidson, 2009), we estimate total manure nitrogen production at 193 Tg in 2030 and at 230 Tg in 2050.

Emission factors for fertilizer nitrogen and manure nitrogen were derived from Davidson (2009), but revised (see Chapters 8) because that study used somewhat lower estimates of non-agricultural emissions. The new emission factors are 2.37% and 1.71% for fertilizer and manure nitrogen, respectively. Multiplying fertilizer nitrogen use and manure nitrogen production by the emission factors results in emissions of 6.4 and 7.5 Tg N_2O-N/yr for 2030 and 2050, respectively.

52 All 2020 emissions in the estimation of emission reduction potential were derived by extrapolating the values of 2030 and 2050 assuming a linear relationship.

53 For this scenario, it is assumed that nitrogen use efficiency of crop production increases through a massive implementation in practice of combinations of higher yielding and more efficient crop varieties, improved crop husbandry, use of enhanced efficiency fertilizers and improved nutrient management. In their fertilizer use projections for 2050, Alexandratos and Bruinsma (2012) considered a modest improvement in nitrogen use efficiency of 4% between 2005 and 2030. However, nitrogen use efficiency can be improved by a higher percentage; for example, Cassman et al. (2002, 2003), Doberman and Cassman (2005) and Chen et al. (2011) indicated that nitrogen use efficiency in cereal production could increase by 20 to 50% through a combination of plant breeding, proper technology and incentives (see section 4.3.2). Here, we assumed that the mean nitrogen use efficiency for all crops would increase by 10% in 2030 and by 15% in 2050 relative to the BAU scenario. This will decrease fertilizer use by the same percentage in these years, that is by 14 Tg in 2030 and by 22 Tg in 2050, relative to the BAU scenarios.

For animal production, it is assumed that a combination of animal breeding, use of high quality feed, phase feeding, and improved herd and feed management will increase nitrogen use efficiency in animal production, thereby decreasing nitrogen excretion per unit animal product by 10% in 2030 and by 30% in 2050, relative to the BAU scenario (see section 4.3.2, Bai et al., 2013). This will decrease manure nitrogen excretion from 193 Tg to 174 Tg in 2030 and from 230 to 161 Tg in 2050.

Furthermore, it is assumed that the N_2O emission factor for fertilizer nitrogen would decrease by 15% in 2030 and by 20% in 2050, relative to the values used in the BAU scenario, through the use of enhanced efficiency fertilizers, and that the N_2O emission factor for manure nitrogen will have decreased by 5% in 2030 and by 10% in 2050, relative to the values used in the BAU scenario through the use of nitrification inhibitors (see section 4.3.3). The 'new' emission factors are 2.02% and 1.90% for fertilizer nitrogen in 2030 and 2050, respectively, and 1.62% and 1.54% for manure nitrogen in 2030 and 2050, respectively. Multiplying fertilizer nitrogen use and manure nitrogen production by the emission factors results in 5.2 and 4.9 Tg N_2O-N/yr for 2030 and 2050, respectively.

54 Currently, only 15 to 25% of the total amount of manure nitrogen excreted is effectively collected and returned to crop land, with an estimated fertilizer nitrogen effectiveness value of 20 to 30% (see section 4.3.2). In some countries, animal manures are simply discharged into rivers or stockpiled in lagoons and landfill where the liquids evaporate (Ma et al., 2012). As a result, the estimated fertilizer nitrogen effectiveness value of the total amount of manure excreted ranges between 4 and 11 Tg, with an overall mean of 8 Tg (equivalent to 6% of manure nitrogen excreted). For 2030, we assumed that 30% of manure nitrogen excreted is collected and applied to crop land with an efficiency of 40%, and for 2050 we assumed that 40% of manure nitrogen excreted is collected and applied to crop land with an efficiency of 60%, through a massive implementation in practice of improved animal housing systems, leak-tight manure storage systems, and improved nutrient management (4R-strategy). As a result the fertilizer nitrogen effectiveness value of the manure excreted increases to 12% (30% collected and used with an efficiency of 40%) in 2030 and to 24% (40% collected and used with an efficiency of 60%) in 2050. Hence, the fertilizer nitrogen effectiveness value of the total amount of manure excreted will have increased by 6% in 2030 and by 18% in 2050, relative to the BAU scenario. This would result in a fertilizer nitrogen replacement of 10 Tg in 2030 (6% * 174Tg) and of 29 Tg in 2050 (18% * 161 Tg).

Emission factors for fertilizer nitrogen and manure nitrogen are the same as those in Option 1. Multiplying fertilizer nitrogen use and manure nitrogen production by the emission factors results in 5.0 and 4.4 Tg N_2O-N/yr for 2030 and 2050, respectively.

Table 4.4. Fertilizer nitrogen use and manure nitrogen excretions in 2030 and 2050, and the mean N_2O emission factors (EF), using the concept of Davidson, (2009). Effects of the emission reduction strategies on fertilizer nitrogen use and manure nitrogen excretion were assumed to be additive. See text.

		2030			2050		
Emission reduction strategy	Nitrogen source	N input, Tg	Revised EF	N_2O Emissions Tg N_2O-N	N input, Tg	Revised EF	N_2O Emissions Tg N_2O-N
Business-as-usual (BAU)	Fertilizer	132	2.37	3.1	150	2.37	3.6
	Manure	193	1.71	3.3	230	1.71	3.9
Total				***6.4***			***7.5***
Option 1: Improving efficiency of crop & animal production	Fertilizer	118	2.02	2.4	128	1.90	2.4
	Manure	174	1.62	2.8	161	1.54	2.5
Total				***5.2***			***4.9***
Option 2: Option 1 plus improved efficiency of manure use	Fertilizer	108	2.02	2.2	99	1.90	1.9
	Manure	174	1.62	2.8	161	1.54	2.5
Total				***5.0***			***4.4***
Option 3: Option 2 plus reducing food loss and waste	Fertilizer	103	2.02	2.1	89	1.90	1.7
	Manure	156	1.62	2.5	129	1.54	2.0
Total				***4.6***			***3.7***
Option 4: Option 3 plus changing diets	Fertilizer	98	2.02	2.0	80	1.90	1.5
	Manure	133	1.62	2.2	97	1.54	1.5
Total				***4.1***			***3.0***

for 2050 (Table 4.4).[55] Emissions in 2020 are estimated by extrapolation to be 5.1 Tg N_2O-N/yr.

Emissions reduction option 4: Option 3 plus changing diets

Here, the same assumptions from Option 3 were used, plus it was assumed that animal production decreases due to a shift away from meat consumption in affluent countries. This leads to emissions of 4.1 Tg N_2O-N/yr for 2030 and 3.0 Tg N_2O-N/yr for 2050 (Table 4.4)[56]. Emissions in 2020 are estimated by extrapolation to be 4.7 Tg N_2O-N/yr.

The measures described above and summarized in Table 4.4 show that fertilizer nitrogen use may decrease by 25% in 2030 and by 47% in 2050, relative to BAU levels (Table 4.4). Similarly, manure nitrogen excretion may decrease by 31% in 2030 and by as much as 58% in 2050, relative to the BAU scenario. Because of the projected decrease in N_2O emission factors, total N_2O emission decrease more than the projected

55 Reducing food waste by half from the current estimates of 20 to 40% (see section 4.3.1), would decrease the amount of food required to be produced by the same percentage. This will result in a 5-10% decrease in fertilizer needed for crop production, assuming that half of the food produced is derived from fertilizer nitrogen (Smil, 2000; Erisman et al. 2008). Similarly, the manure nitrogen production would decrease by 10 to 20%, when assuming that the relative waste of plant-derived food and animal derived food is similar. Hence, we assume that fertilizer nitrogen use and manure production would have decreased by 5% and 10% in 2030, and by 10% and 20% in 2050, respectively. As a result, fertilizer nitrogen use would decrease further by 5 Tg to 103 Tg in 2030, and by 10 Tg to 89 Tg in 2050, while manure nitrogen excretion would decrease by 18 Tg to 156 Tg in 2030, and by 32 Tg to 129 Tg in 2050.

Emission factors for fertilizer nitrogen and manure nitrogen are the same as those in Option 1. Multiplying fertilizer nitrogen use and manure nitrogen production by emission factors results in 4.6 Tg and 3.7 Tg N_2O-N/yr for 2030 and 2050, respectively.

56 The World Health Organization recommends a daily protein intake of 0.05 kg per capita per day, which translates to about 18 kg per capita per year. WHO also recommends that not more than 50% of the recommended protein intake is animal-derived protein (WHO, 2007). Currently, about 3.5 billion people consume more than 9 kg animal-derived protein per capita per year (range 12-27 kg/capita/yr). In 2030, some 5 billion will consume more than 9 kg animal-derived protein per capita per year (Westhoek et al., 2011). Here, we assume that the affluent half of the world population now consuming an excess amount of proteins in their diet will have reduced their intake of animal-derived protein by 30% in 2030 and by 50% in 2050. As a result, manure nitrogen production would have decreased by roughly 15% in 2030 and by 25% in 2050. This equates to a decrease in manure nitrogen excretion to 133 Tg in 2030 and to 97 Tg in 2050.

Furthermore, currently, 60 to 70% of the utilized agricultural area in the world is used for feed production, including one-third of the cereal area (Steinfeld et al., 2010). If animal production decreases by 15 to 25%, the demand for animal feed also decreases by roughly 15 to 25%. Here, we assume that total fertilizer nitrogen use will have decreased by 5% in 2030 and by 10% in 2050 as a consequence of lower feed needs. As a result, fertilizer nitrogen use will have decreased further by 5 Tg to 98 Tg in 2030, and by 9 Tg to 80 Tg in 2050.

Emission factors for fertilizer nitrogen and manure nitrogen are the same as those in Option 1. Multiplying fertilizer nitrogen use and manure nitrogen production by specific emission factors results in 4.1 and 3.0 Tg N_2O-N/yr for 2030 and 2050, respectively.

decreases in fertilizer nitrogen and manure nitrogen excreted. Total N_2O emissions may decrease by approximately 22% in 2020, 36% in 2030 and 60% in 2050 (Table 4.4). Evidently, these significant reductions can only be achieved with adequate incentives, the help of hundreds of millions of farmers and billions of consumers, and the support of governments and research (see Chapter 8).

4.6. Conclusions

- Agriculture is the main anthropogenic source of atmospheric N_2O. It is in part an inevitable side product of food production due to inefficiencies in the nitrogen cycle.
- N_2O emissions associated with agriculture can be minimized through:
    a) Increasing nitrogen use efficiency in crop and animal production, including manure nitrogen use efficiency.
    b) Implementing technology and management practices that decrease the fraction of input nitrogen that is released as N_2O. These include the use of enhanced efficiency fertilizers and nitrification inhibitors in crop production.
    c) Changing diet and reducing food loss/wastes.
- Total N_2O emissions from the food system can be reduced by up to 60% by 2050 relative to business-as-usual for that year through combinations of these measures.
- Apart from environmental benefits, reducing N_2O emissions from agriculture also yields several health and economic co-benefits.
- Significant investments in education, training, demonstration and development of site-specific technologies are needed to achieve the projected N_2O emission reductions because measures will have to be implemented by billions of consumers and millions of small-holder farmers in the world in site-specific ways.