Options to decrease N losses from our global food system

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Abstract

Food production causes losses of reactive nitrogen (N) to the detriment of the environment but the current level of losses per unit food leaves room for improvement. Due to feedback mechanisms a comprehensive analysis is needed and we developed a quantitative model of the whole food system to assess the effects of improvement measures on the required amount of N fertilizer and resulting N losses as function of food demand. For 2010 we calculate a total N loss from agricultural soils and ammonia volatilization of 172 Mt N y^{-1} and an amount of 32 Mt N y^{-1} entering households in food items. This implies a N loss ratio of 5.4 kg N lost per kg N purchased by households. Due to higher food demand and changed diet as projected for 2050, the N loss ratio increases to almost 6.0 if equal N use efficiencies are used as in 2010 and the total N loss amounts to 293 Mt N y^{-1}. The effects of a number of improvement measures are explored, such as less animal-based products in the human diet and reduced N loss from agricultural soils. Single measures can reduce this ratio to as low as 3.8 but when all measures are combined, the ratio drops to 2.0 with a total N loss of 84 Mt N y^{-1} without affecting the projected food demand for 2050. Our results clearly illustrate that the effectiveness of measures cannot be realistically estimated without taking the whole system into account and that the N loss ratio is a better indicator to estimate environmental impacts of N use than N use efficiency.

Key Words

N balance, N loss ratio, N use efficiency, food production, fertilizer, manure

Introduction

Human activities, including food production, are the major cause of reactive nitrogen (N) losses to the environment (Bouwman et al., 2013). These losses are a threat for the global climate, human health, ecosystem services and biodiversity (Rockström *et al*., 2009; De Vries *et al*., 2013; Steffen *et al*., 2015). Food production is inevitably associated with N losses requiring replenishment, but the current level of losses per unit food leaves room for improvement (Schröder, 2014). Alexandratos & Bruinsma (2012) estimate an increase of 60% in global food demand over the period 2006 – 2050 due to an increase in population and diet changes. Without improvements of the N use efficiency (NUE), this increase in food demand will further aggravate the adverse environmental impact of N losses (Zhang *et al*. 2015). Measures directed at a better NUE do not only refer to improved agricultural land management but also to other domains in the food system, e.g. livestock production and waste management. Domains are connected by feedback loops, e.g. a lower share of animal-based products in the human diet will reduce the N losses from livestock but it will simultaneously reduce the availability of manure as a source of fertilizer N and increase the demand for plant-based food items. Consequently, the effect of an individual measure can only be assessed by taking the whole system into account. We have therefore developed a quantitative model that connects the N flows within and among the domains of the food system. By using this model we investigate the effectiveness of measures in reducing the N losses under future food demand levels.

Methods

The N balance of our food system

The present model comprises five domains: *Population* (households), *Food balance* (i.e. food processing chains), *Livestock*, *Organic fertilizer* and *Agricultural land*, including cropland and grassland (Figure 1). Statistical data from FAOSTAT at the global level in 2010 combined with additional information from other sources, are used to derive quantitative input–output relations of each domain. These relations are used to quantify the N flows among the five domains and across the boundary of the total food system (inputs, wastes and losses). Several feedback loops are included, such as the use of residues for animal feed and manure as organic fertilizer. Ultimately, the required N fertilizer and the N losses are calculated as function of food demand.

Scenarios

The model is used to calculate the global N flows of the world in 2010 and the projected situation in 2050 (+ 60% food demand and diet changes according to Alexandratos & Bruinsma, 2012). In the basic scenario for 2050 the input–output relations derived for 2010 are used. Subsequently, a number of measures are applied in the model through adjustment of the parameters for 2050, either as single measure or in one combination of all measures (see Table 1). Single measures comprise: a reduction in food wastes affecting the demand and supply levels, less animal-based product, improvement of livestock feed conversion efficiency, higher yields of crops and grassland, a reduction of NH_3 volatilization from manure and synthetic fertilizers and a decrease in N losses from agricultural land.

Table 1. The codes and descriptions of the scenarios. All scenarios starting with "+" were applied to the basic scenario for 2050 and relative changes were imposed on the flows calculated for 2050.

Code	Description
2010	The current situation in 2010.
2050	Higher food demand (+60%) and changed human diet as basic scenario for 2050.
+W	50% reduction in the fractions of wastes in households and food balance chains of all food items.
+D	50% reduction in supply shares of animal-based products in the human diet with a higher consumption of plant-based products to compensate the decreased energy supply from animal-based products.
+F	25% improvement of the feed conversion efficiencies for all animal products.
+Y	50% increase in biomass yields for all crops and grassland
+V	50% reduction in NH_3 volatilization from fertilizer application and manure storage/application
+R	50% reduction in the loss fractions of available N in the soil
+All	All above measures (+W+D+F+Y+V+R) combined.

Selected N flows

For this paper we focus on *Food N*, i.e. the supply of N from the *Food balance* to the *Population* and the total *N loss* from agricultural land and through NH_3 volatilization from manures and applied fertilizers (Figure 1). Additionally, the ratio between *N loss* and *Food N* is calculated to illustrate their relation in different scenarios.

Results

Global N flows

The global N flows calculated with our model for 2010 (Figure 1) comprise a total input of 210 Mt N y^{-1} (left-hand side), a total waste/other use of 42 Mt N y^{-1} (right-hand side) and a total loss of 172 Mt N y^{-1} to the atmosphere and ground- and surface water (bottom side). Within the food system only 32 Mt N y^{-1} enters the households by the purchase of food and 26 Mt N y^{-1} is actually consumed by the human population. This implies that the effectiveness of conversion of the 210 Mt N into consumed N is as low as circa 12%. Crop residues (14.3 Mt N y^{-1}) and process residues (19.6 Mt N y^{-1}) are important animal feed N flows. Organic fertilizer (102 Mt N y^{-1}), mainly consisting of animal manure, is a valuable input of N for agricultural land and similar to the N input with synthetic fertilizers (103 Mt N y^{-1}). For the basic situation in 2050 most N flows are more or less increased by 60% (for instance the N input with synthetic fertilizers increases to 181 Mt N y^{-1}), except a few that are kept constant at their 2010 values, such as the N output of *Other uses* from the *Food balance*.

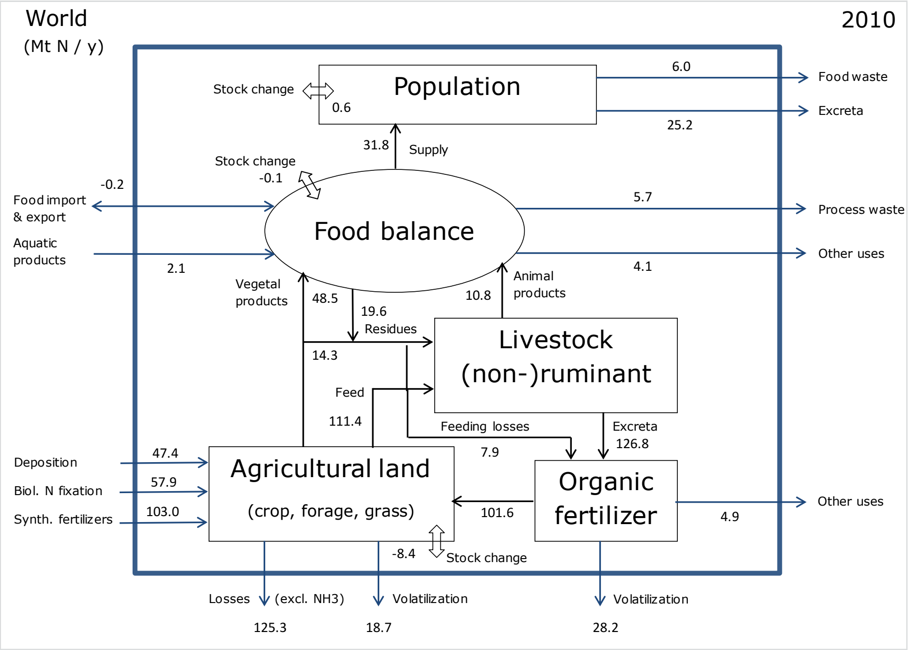

Figure 1. Nitrogen flows in the food system of the world in 2010 (in Mt N per year). Volatilization from organic fertilizer refers to total N-NH$_3$ emissions from manure storage and application, whereas volatilization from agricultural land is due to application of synthetic fertilizers. Other uses refer to non-food use such as fuel.

N loss ratio

Results from all scenarios show large variation in the *N loss* (84 – 307 Mt N y^{-1}), only modest variation in *Food N* (42 – 53 Mt N y^{-1}) and therefore considerable variation in the N loss ratio (2.0 – 5.8 ; Figure 2). The N loss ratio is higher in the basic scenario for 2050 (5.8) compared to the situation in 2010 (5.4). Reducing food waste has effect on *N loss* but almost not on the N loss ratio due to a similar relative decrease in purchased *Food N*. Higher yields cause a slight increase in both the *N loss* and the *Food N* without changing the N loss ratio. As for the other measures, their effects on the N loss ratio decrease in the order: decreasing N losses from agricultural land > less animal-based products > improving feed conversion > reducing NH$_3$ volatilization. The lowest *N loss* and N loss ratio are realised when all measures are applied simultaneously. The difference between the *N loss* of the basic scenario for 2050 and the N losses of all single measures amounts to in total 319 Mt N y^{-1}, whereas the difference with combined measures equals 208 Mt N y^{-1}.

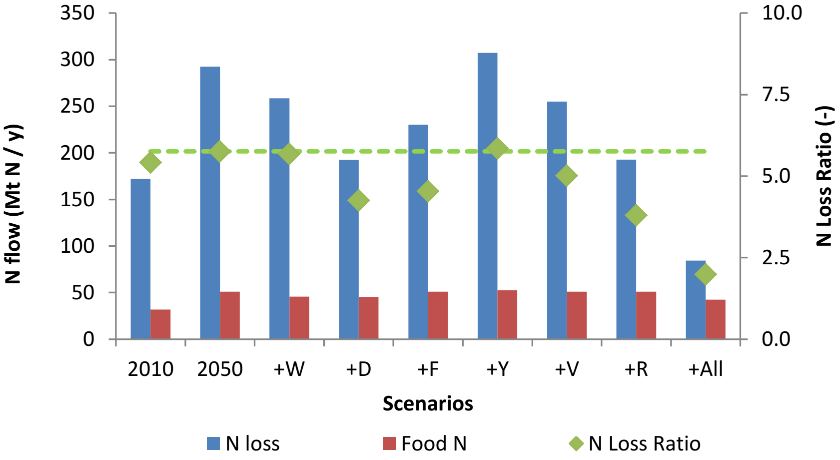

Figure 2. Total *N loss* from agricultural land and NH$_3$ volatilization and *Food N* purchased by households on the left axis and the N Loss ratio (*N loss / Food N*) on the right axis for different scenarios (see Table 1). The dashed line illustrates the N loss ratio of the basic scenario for 2050.

Discussion

The results for 2010 compare reasonably well with other estimates of global N flows (Sutton *et al.*, 2013; Billen *et al.*, 2014; Bodirsky *et al.*, 2014) and are consistent with the statistical data from FAOSTAT that were used for parametrization of the input–output relations. The large difference between the decrease in *N* *loss* of combined measures relative to summed *N loss* of separate measures (viz. 208 vs. 319 Mt N y^{-1}), illustrates the synergistic effects due to the feedback mechanisms that occur when single measures are combined. It underlines the need to evaluate measures in an integrated manner. We did not include wastes (right-hand side of Figure 1) in our *N loss* because the ultimate fate of the N in these waste streams is insufficiently known. However, it is worthwhile investigating this further because the total amount of N in wastes in 2010 is 20% of the total N input and amounts to 24% of the total *N loss*. Part of the N lost from agricultural land is N_2 emitted to the atmosphere, which is not detrimental to the environment. According to Bouwman *et al*. (2013) 40% of the amount of N lost from agricultural land (excluding the NH_3 volatilization) is emitted as N_2, which is substantially reducing the adverse effects of lost N on the environment. However, every lost kg of N needs replenishment by biological or industrial N fixation, incurring various types of environmental pressure. Our results indicate that relative decreases in *N loss* are larger than those in N inputs, e.g. -60% for N input with synthetic fertilizers and -71% for *N loss* in the scenario of combined measures relative to the basic scenario for 2050. The N loss ratio seems therefore a better indicator for the environmental effects of N use in agriculture compared to the N use efficiency which is based on N input(s). The *N loss* drops from 293 Mt N y^{-1} in the basic scenario for 2050 to 84 Mt N y^{-1} in the scenario of combined measures which is even significantly below 172 Mt N y^{-1} calculated for 2010. Next step is to assess feasible levels for the proposed measures and use these to calculate the amount of N lost in future scenarios.

Conclusions

On average 6 kg N is lost to the environment for every kg N in purchased food entering households at the global level in the basic scenario for 2050. Due to feedback mechanisms a comprehensive analysis is needed to obtain realistic estimates of the effectiveness of improvement measures on global N loss. Our analysis indicates that single measures may reduce the N loss ratio up to 3.8, but if all measures are applied simultaneously the N loss ratio decreases drastically to 2.0 without affecting the projected food demand for 2050. These dramatic effects merit further detailing our analysis by more realistic parameterizing of improvement measures.

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