Impacts of dietary changes on global scale nitrogen losses to air and water

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Abstract
A simple fast calculation approach has been developed that gives insight in the overall effects of dietary changes on nitrogen (N) emission to air and water by 2050 for ten identified world regions. The impact of dietary change on N fertilizer and N manure applications and related emissions was based on the consumption of crop and animal commodities, making use of the FAO data from 1961 to 2005 and extrapolating the data towards 2050 in response to five dietary change scenarios. Scenarios included a 'North American Diet' (NAD), a 'Same Diet' (SD), a 'Business-as-Usual' (BAU) diet; a 'Demitarian Diet' (DD) and a 'Vegan Diet' (VD). The calculated N_2O and NH_3 emissions and N leaching/runoff for the reference year (i.e. 2005) showed good agreement with various literature estimates. N_2O was the most persistent problem, even increasing under the VD scenario, due to the increased use of N fertilizer to cultivate food crops and the assumed high contribution of N fertilizer to N_2O emission. NH_3 emissions increased three times in the NAD scenario, while it decreased by 13% in the VD scenario. This happens because NH_3 emissions mainly follow the N manure trends. In the VD scenario, N leaching/runoff remains equal to 2005, while it increases by 145% in the NAD scenario. Overall, results show that dietary change affects most strongly NH_3 emissions, followed by N leaching/runoff and then N_2O emissions. Only a severe reduction in meat consumption can substantially reduce N losses with the exception of N_2O emissions.

Key Words: nitrogen, ammonia, nitrous oxide, food demand, losses, global scale

Introduction
The population has increased rapidly over the last 50 years from about 3 billion in 1960 to 7 billion in 2010. Tilman et al (2011) pointed out that the world population may further increase from 7 billion in 2010 to 9.5 to 10 billion by 2050 while Bongaarts (2016) even makes projections up to 11.2 billion. The expected population growth, in combination with an expected strong economic growth increasing people's demand of meat, implies an expected doubling of food productivity to satisfy people's demand (Tilman et al., 2011). Many measures have been taken to increase the food production, including conversion of forest land to agricultural land and fertilization, especially of nitrogen (N) of the soil which largely increased since 1950. Bouwman et al. (2011) estimated global scale mineral N fertilizer inputs at 4, 83 and 104 Tg N yr^{-1} in 1950, 2000 and 2050 with a related N manure input of 48, 92 and 139 Tg N yr^{-1}, respectively. There is ample evidence confirming that anthropogenic intervention of the N cycle has negative impacts on both human health and environment (Erisman et al., 2013). Nitrogen losses to air and water cause a number of ecological and human health effects, such as: (i) global climate change induced by emissions of nitrous oxide (N_2O), (ii) biodiversity change caused by eutrophication and acidification of terrestrial ecosystems, freshwater ecosystems and coastal ecosystems, and (iii) increased nitrate (NO_3^-) leaching to ground water, leading to elevated NO_3^- concentrations in drinking water, that have given cause for concern in some industrialized regions.

There are two main approaches to mitigate N emissions from agriculture. The first one is to increase the N use efficiency (NUE) in the complete chain from application to consumption (from farm to fork) by e.g. increasing the NUE in crop production and animal production, increasing the recycling of animal manure, food waste and human waste and reducing food waste (Sutton et al., 2013). The other approach is to reduce N demand by lowering the animal product consumption in developed regions with high meat consumption rates, since the NUE is quite low in livestock production sector compared with crops (Sutton et al., 2013). Several authors have already proved the effects of changing diet on human health and climate (e.g. Stehfest et al., 2009) based on global models such as IMAGE and Global NEWS. A fast calculation approach assessing the overall effects of dietary changes on N emissions to air and water at global scale is, however, still lacking. Here we present such an approach, quantifying overall global effects of dietary changes on N emissions to air and water at global scale up to 2050 for ten study regions. The study includes impacts of changing N inputs by fertilizers and manure on the N_2O emission and NH_3 emissions to the air and N leaching and/or runoff to groundwater and/or surface water.

Methods

Calculation approach

We developed a simple and transparent calculation scheme to assess N inputs by fertilizer and manure in response to changes in the consumption of crop and animal commodities under different diet change scenarios. The procedure was based on using FAO databases on current crop and animal food production that were extrapolated to the future making a number of assumptions, while distinguishing ten study regions (Figure 1). The FAO food group statistics provides hundreds of different food commodities. Some types of foods are consumed in small quantities and some others are only relevant at a regional scale. To allow fast calculation, ten food commodities were aggregated from the FAO-Food-Groups, as shown in Figure 2.

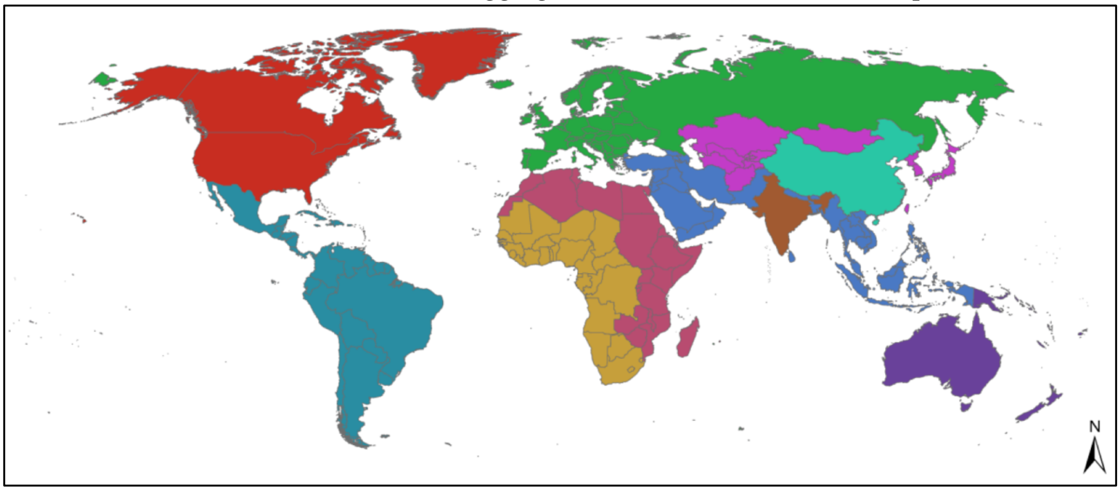

Figure 1 The identified ten study regions

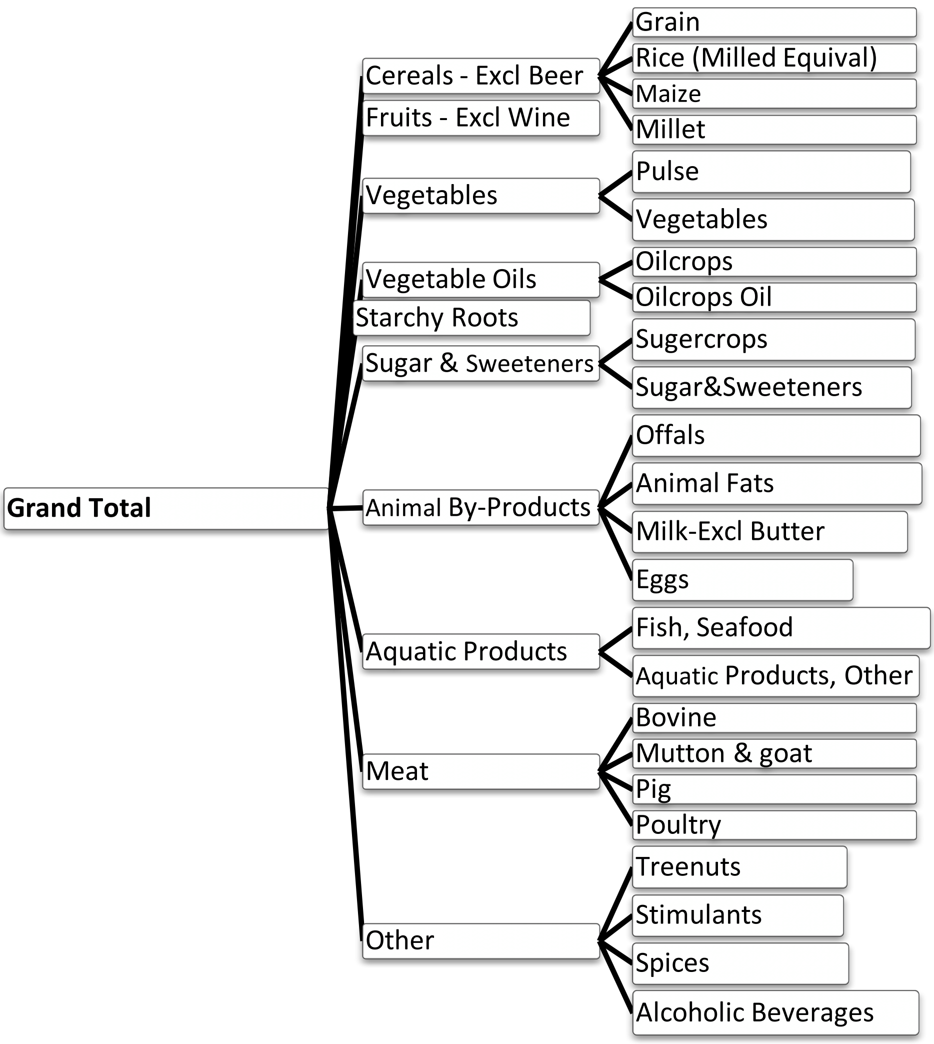

Figure 2 The aggregated ten food groups based on 182 FAO food commodities

The overall calculation procedure to assess the impacts of changes in human diet on N losses to air and water in each study region consisted of eight steps, as shown in Figure 3.

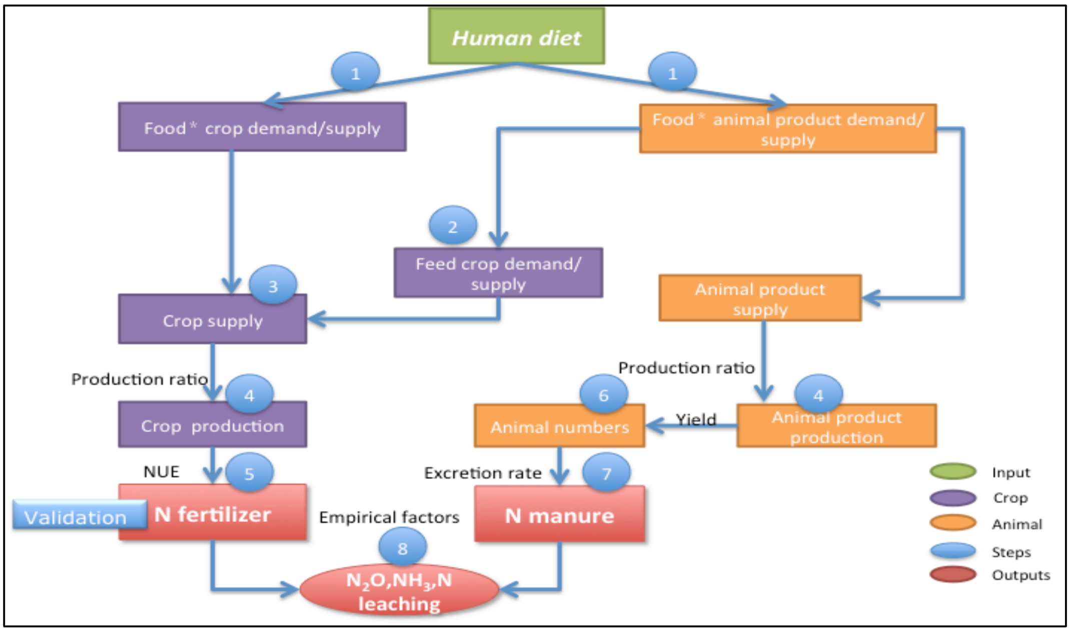

Figure 3. Nitrogen emissions calculation steps due to diet change. Food* includes food, seed, processing and other utilities.

The future food supply in response to diet change was calculated by accounting for the combined effect of population change and diet change. Diet change was included by a scenario dependent trend in food supply, expressed as a change per capita per year, to extrapolate the diet pattern until 2050 (step 1). We then calculated the future feed supply in the study regions by multiplying the future supply of animal products in each region with a region averaged feed conversion ratio, which was calculated as the ratio of the current supply of feed (including feed import) and of animal products in a region (step 2). In step 3, we calculated the total food and feed crop supply in the study regions by summing up. Based on thus calculated regional food and feed demands, the required production of food/feed crops and animal products for each region was assessed using a regional to global production ratio, implicitly including regional imports and exports (step 4). Next, the fertilizer application rate was calculated based on the N use efficiency (NUE in kg N/kg crop) per crop and per region (step 5). The manure excretion was derived by multiplying animal numbers in defined animal categories, estimated by dividing animal production by the animal yield (step 6), with the N excretion rate per animal category (step 7). Finally, the N_2O and NH_3 emissions and N leaching/runoff were estimated as a fraction of N fertilizer and manure inputs using empirical factors derived from different studies (step 8).

Scenarios
Five diet scenarios were used to explore amount of fertilizer and manure from 2006 to 2050 i.e. Business As Usual (BAU), North American Diet (NAD), Same Diet (SD), Demitarian Diet (DD) and Vegan Diet (VD). The BAU scenario is based on the assumption that the trend in diet pattern between 1996 and 2005 continues until 2050. In the (extreme) NAD scenario, we assumed that the other nine regions will linearly shift their food consumption till 2050 to those of North Americans in 2005 while the diet in North America stays the same as in 2005. In the SD scenario, the diet pattern per capita in 2005 is assumed to stay the same until 2050. Only the population increase changes the total food consumption till 2050, comparable to the BAU scenario. The DD scenario is equal to the BAU scenario, but we assumed that half of the energy provided by meat in Europe, Oceania and North America, will be replaced by pulses by 2050. In the extreme VD scenario, we assumed that the energy requirement by all world inhabitants is fulfilled by a vegan diet completely replacing the consumption of all animal products (meat, fish, dairy and eggs) by pulses. Both the DD and VD scenario are equal to the BAU scenario in terms of energy requirements.

Results
Estimates of global N_2O emission, NH3 emission and N leaching from fertilizer and manure for the current situation and the five diet change scenarios are presented in Figure 4.

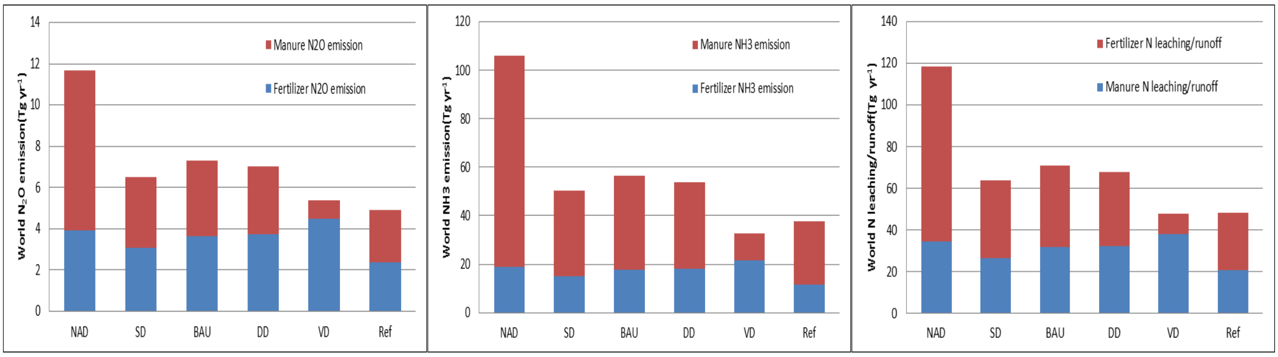

Figure 4 World N_2O emissions (left), NH_3 emissions (middle) and N leaching/runoff (right) due to fertilizer application and manure excretion in the reference year (2005) and in 2050 under five diet change scenarios.

The global N_2O emission in 2005 was estimated at 4.9 Tg N yr^{-1}, being highly comparable to Syakila and Kroeze (2011) and Davidson (2009) who gave estimates of 5.3 and 5.0 Tg N yr^{-1}, respectively. In general, the N_2O emission in 2050 was higher than for the reference year under all the scenarios. The predicted total N_2O emission increased to 11.6 Tg N yr^{-1} under the NAD scenario, mainly due to an increase in manure excretion. Under the SD scenario, manure contributed slightly more than fertilizer, while in the BAU scenario fertilizer and manure application basically caused the same N_2O emission. Even in the VD scenario, the total N_2O emission was higher than in the reference year, but the contribution of fertilizer was higher than manure in response to the decreased consumption of meat and increased consumption of pulses. The global scale NH_3 emission in 2005 was estimated at 37.5 Tg N, being nearly the same as predicted by Bouwman et al. (2011) for the year 2000, i.e. 34 Tg N yr^{-1}. Similar to the N_2O emission, the largest increase occurred in the NAD scenario. NH_3 emission from excreted manure contributed almost 82% to the total NH_3 emission (87 Tg N yr^{-1}), while fertilizer contributed 18% (19 Tg N yr^{-1}). The only scenario with a lower NH_3 emission than in the reference year was the VD scenario, with 32.7 Tg N yr^{-1}. The global total N leaching/ runoff in 2005 was estimated at 48 Tg N yr^{-1} being higher than the estimate by Bouwman et al. (2011) for the year 2000, i.e. 39 Tg N yr^{-1}. In the future, only the VD scenario would cause a comparable N leaching/runoff as in 2005 (47.8 Tg yr^{-1}). All other four scenarios had a higher N leaching/runoff than the reference year.

Conclusion

Overall, results show that dietary change affects most strongly NH_3 emissions, followed by N leaching/runoff and then N_2O emissions. Even a vegan diet in 2050 is not leading to a clear N_2O emission reduction when one accounts for the expected population increase. This is due to the assumed higher N_2O emission factor from fertilizer which increases in this scenario. Only a severe reduction in meat consumption can substantially reduce future NH_3 emission and N leaching and runoff losses to air and water.

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