Assessment of current and critical nitrogen inputs on European agricultural soils

Wim de Vries[1,2], Johannes Kros[2]

[1] Alterra Wageningen University and Research Centre, PO Box 47, 6700 AA Wageningen, the Netherlands, www.wageningenur.nl, wim.devries@wur.nl
[2] Environmental Systems Analysis Group, Wageningen University, PO Box 47, 6700 AA Wageningen, the Netherlands.

Abstract
The intensification of European agriculture, including large inputs of nitrogen (N) to soil by fertilizers and manure, has led to an increase in crop growth but also in various adverse effects. This includes: (i) loss of biodiversity in natural terrestrial ecosystems due to increased emission and deposition of ammonia (NH_3), (ii) eutrophication of surface waters due to increased N runoff and (iii) increased nitrate (NO_3) levels in drinking water reservoirs due to elevated N leaching. In this study we identified agricultural regions where current N inputs exceed critical N inputs at a high spatial resolution for the entire European Union using the INTEGRATOR model. Critical N inputs were derived on the basis of critical N losses, which in turn were based on critical levels of NH_3 emission and critical N concentrations in leaching to ground water or runoff to surface water in view of the adverse impacts listed above. Results show that at EU-27 level, current N inputs slightly exceed critical N inputs in view of eutrophication by 15% for aquatic ecosystems and 25% for terrestrial ecosystems. We identified those places where there is a need to lower N losses to acceptable levels by increasing the nitrogen use efficiency (NUE).

Key Words
nitrogen, budgets, critical inputs, agricultural soils, nitrogen use efficiency

Introduction

Since the early 1940s, European agriculture has intensified greatly resulting in large inputs of nitrogen (N) to soil by mineral fertilizers and organic fertilizers (manure, compost and biosolids). Beneficial effects include both an increase in crop growth as well as soil fertility status in terms of N contents. However, the increased application of fertilizers and manure also induced unwanted environmental effects including: (i) elevated runoff of N, causing an exceedance of ecological limits resulting in eutrophication of nearby surface waters, (ii) increased leaching rates of nitrate to ground water affecting drinking water quality, (iii) increased emission of NH_3 and deposition on nearby terrestrial ecosystems causing their eutrophication and (iv) elevated emissions of nitrous oxide (N_2O) causing global warming. Inversely, in some regions in Europe there is still need for additional N inputs in view of crop yield gaps induced by nutrient limitation, besides other yield limiting factors. Considering the occurrence of both an excess N input, associated with adverse environmental effects, and N limitation, associated with crop yield reductions, EU-27 is an interesting region to assess both needed and critical N inputs (input levels) and compare them with current inputs. When critical inputs are below needed inputs in view of attainable crop production, it would cause a loss in that production unless the nutrient use efficiency (NUE) is increased. When the NUE is increased, the needed input decreases, since the attainable crop yield can be reached with less N fertilizer, due an enhanced uptake fraction, while the critical input increases since a lower fraction of N is lost to the environment. In this context, it is highly relevant to calculate the NUE at which the needed inputs are equal to the critical inputs, and to compare these NUEs with the current NUEs to assess the needed improvement in efficiency. By calculating the NUE at which the needed inputs are equal to the critical inputs it indicates the way towards sustainable mineral fertilizer use by defining NUE targets that meet production and environmental goals at the same time.

In this study we calculated spatial explicit current (year 2010) N losses from agro- ecosystems and compared those with critical N losses in view of eutrophication of aquatic and terrestrial ecosystems, being the most important threats (De Vries et al., 2013), based on critical limits for N in surface water and critical NH_3 emissions. When protecting surface water quality, impacts on ground water quality, in view of drinking water quality, are also accounted for, since the N targets for surface water are more stringent than for ground water (drinking water). Furthermore, the NUE values were calculated at which current N inputs cause N losses at acceptable levels. In a next study, needed inputs in view of attainable crop production and NUE values at which N losses at these inputs are acceptable will be calculated.

Methods

Assumption and calculation

We used the INTEGRATOR model calculate spatial explicit critical N inputs to air and water and compare them with current N inputs (the year 2010) at the same spatial scale. The assessment was made at EU level, country level and at the level of NitroEurope Classification Units (NCUs). NCUs are unique combinations of soil type, administrative region, slope class and altitude class composed of polygons that are a cluster of 1 km x 1 km pixels. The derivation of a critical N input at each calculation unit, in view of adverse environmental impacts, consisted of three consecutive steps, i.e.: (i) identification of critical values for defined N indicators, (ii) back calculation of critical N losses to surface water or air that correspond to critical values for N indicators and (iii) back calculation of critical N inputs and related mineral N fertilization rates from critical N losses.

Critical N losses were related to: (i) NH_3 deposition on neighbouring nature areas in view of habitat quality and biodiversity and (ii) N runoff/leaching in view of surface water quality (eutrophication). Critical inputs related to NO_3 leaching in view of drinking water quality were not included since the criteria for N in surface water are more stringent (see below). Although N inputs also cause N_2O emissions this aspect was not included in the assessment since there are no specific limits for N_2O emissions. One could use radiative forcing as a criterion but N_2O is only one of the greenhouse gases that affect radiative forcing (others being carbon dioxide, methane, ozone etc.), making the assessment of a critical input highly trivial (Steffen et al., 2015). Furthermore, NH_3 emission from agricultural land also reduces radiative forcing by increasing forest growth enhancing dioxide uptake, thereby almost completely counteracting the warming effect of N_2O (De Vries et al., 2011).

The critical N input to the soil was derived from the critical levels of either NH_3 emission or N losses to water (by leaching and runoff) by applying the model INTEGRATOR This model calculates the various N flows by empirical simple linear relationships between the different N fluxes while using a steady state approach, by neglecting changes in soil N pools, taking an (infinite) long time perspective in line with the critical input concept used in air quality control. The calculated critical N inputs depend on the N loss fractions for emission, denitrification, leaching, runoff and the NUE of N fertilizer and N manure. The critical input calculations were made with current N loss fractions and NUE values. Furthermore, the NUE values were calculated at which current N inputs cause N losses at acceptable levels.

Critical levels for nitrogen concentrations or losses to air and water

Surface water quality: The critical N losses to water and air were calculated from critical values for defined N indicators. Critical N runoff rates were calculated by multiplying an annual average critical concentration of dissolved total N in stagnant surface water of 1.0 and 2.5 mg N l^{-1} with the current water precipitation surplus (i.e. not accounting for impacts of climate change). The range of 1.0-2.5 mg N l^{-1} was based on (i) an extensive study on the ecological and toxicological effects of inorganic N pollution (Camargo and Alonso, 2006), (ii) an overview of maximum allowable N concentrations in surface waters in national surface water quality standards (Liu et al., 2011) and (iii) different European objectives for N compounds (Laane, 2005). When protecting surface water quality, impacts on ground water quality, in view of drinking water quality, are also accounted for since the critical NO_3 concentration in groundwater is equal to the drinking water limits of the World Health Organization of 50 mg NO_3 l^{-1} being equal to 11.3 mg NO_3-N l^{-1} (WHO, 2011), which is higher than the ecologically based standard for surface water, 2.5 mg N l^{-1}.

Air quality: Critical levels of NH_3 emission were calculated as the area-weighted mean critical total N (NH_3 and NO_x) load on nature areas (terrestrial ecosystems) at county (NUTS3) level level, assuming that (i) the current NH_3 and NO_x contribution to N deposition also holds for the critical inputs and (ii) the total NH_3 deposition on both agricultural and non-agricultural land equals the total NH_3 emission from agricultural land at NUTS3 level. In a previous global-scale study, De Vries et al. (2013) used uniform critical atmospheric NH_3 concentrations in view of adverse biodiversity impacts. However, this approach requires the use of an atmospheric dispersion model. Furthermore, the diversity in local circumstances affecting the critical input of nitrogen on terrestrial ecosystems is not taken into account. Consequently, we based the critical NH_3 emissions on the spatially explicit differences in critical inputs at NUTS3 level, aggregated (averaged) from high spatial resolution critical N inputs in view of biodiversity impacts presented in Slootweg et al (2014).

Results

Average current (year 2010) and critical annual N budgets of agricultural land at EU-27 level, as calculated by INTEGRATOR, are given in Table 1. Results show that at EU 27 level, average current N inputs (year 2010) exceed critical N inputs by 15% in view of eutrophication of aquatic ecosystems, using a critical N concentration in runoff 2.5 mg N l^{-1}, and 25% for terrestrial ecosystems when using the critical N deposition as criterion. When using a critical N concentration in leaching of 11.3 mg N l^{-1}, average critical N inputs are twice as high as the current N inputs (not shown in Table 1). Large critical N input exceedances occur at several places when using a critical NH_3 emission rate or a critical N concentration in surface water of 2.5 mg N l^{-1}. Inversely, critical N inputs can also be much larger in areas where the current NH_3 emission or N leaching is much lower than the acceptable losses.

Table 1 Average current (2010) and critical annual N budgets of agricultural land in EU-27 calculated by INTEGRATOR

Source	N budget EU-27 (kg N ha^{-1} yr^{-1})		
	Current	Critical N runoff 2.5 mg N l^{-1}	Critical NH_3-N emission
Input to land			
Fertilizer +fixation	63.0	56.7	63.5
Excretion+ biosolids	47.3	34.8	24.7
Total input	110.3	91.5	88.3
Output from land			
Crop uptake [1]	76.8	65.2	53.3
Total surplus [2]	33.5	26.3	35.0
Denitrification[3]	26.4	20.5	24.7
Leaching + runoff	13.9	5.8	10.3
Accumulation[4]	-6.8	0	0
Total output	110.3	91.5	88.3

[1] Uptake includes the net removal (crop or grass) from arable land or grassland.
[2] Total surplus is formally not an output from land. It equals the total input minus crop uptake
[3] Note that denitrification stands for the N_2O, NO_x and N_2) emissions from housing systems and from soil.
[4] N accumulation is negative due to the net N mineralization from well drained peat soils of 7.8 kg N ha^{-1} yr^{-1}. In the calculation of the current inputs, we include the difference between N deposition 9.8 kg N ha^{-1} yr^{-1}) and NH_3 emission (10.8 kg N ha^{-1} yr^{-1}), while these terms are assumed equal in the critical input calculation.

The relationship between critical inputs and current inputs of total N is presented in Figure 1 for a critical N concentration in surface water of 2.5 mg N l^{-1} and a critical NH_3 emission rate. Results show that large exceedances occur at several places when using a critical NH_3 emission rate or a critical N concentration in surface water of 2.5 mg N l^{-1}. Inversely, critical inputs can also be much larger in areas where the current NH_3 emission or N leaching is much lower than the acceptable losses.

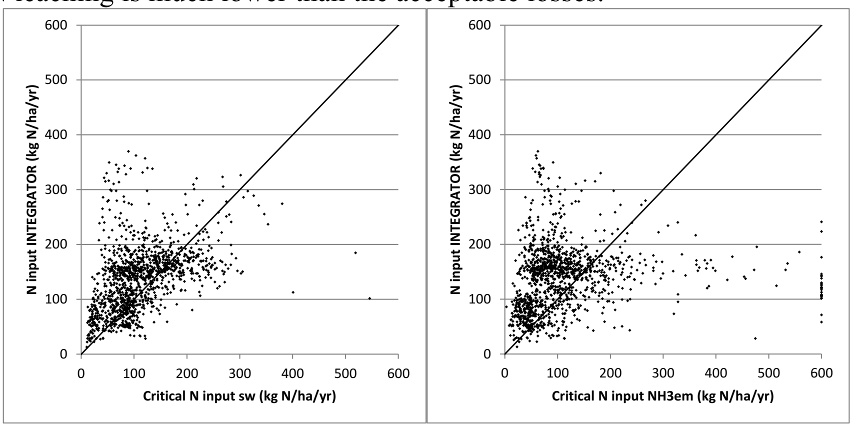

Figure 1. The relationship between critical inputs and current inputs of total N (left panel), the sum of N fertilizer and N fixation (middle panel) and the sum of N excretion and N biosolids (right panel) using a critical N concentration in surface water of 2.5 mg N l^{-1} (top) and a critical NH_3 emission rate (middle).

Maps of the geographic variation of the exceedances of critical inputs of total N are given Figure 2 for a critical total N concentration in surface water of 2.5 mg N l^{-1} and a critical NH_3 emission rate as criterion. Results show high total N inputs in Ireland and western UK (partly caused by intensive sheep grazing), the Netherlands, Belgium and Luxembourg, Bretagne in France and the the Po valley in Italy, while critical N inputs are only partly correlated with the current N inputs. While e.g. highest N inputs occur in western UK, highest N exceedances occur in eastern UK when using a critical total N concentration in surface water of

2.5 mg N l^{-1}, but in general the largest exceedances occur in regions with the largest inputs. Remarkable is the relative high exceedance of the critical N fertilizer input in eastern Germany, being almost similar to the Netherlands, while the exceedance of the critical total N input is much less. This illustrates the N manure problem in the latter country. The maps also show significant regions where the current input is less than the critical input, especially in central and eastern Europe which can partly be due to under fertilization.

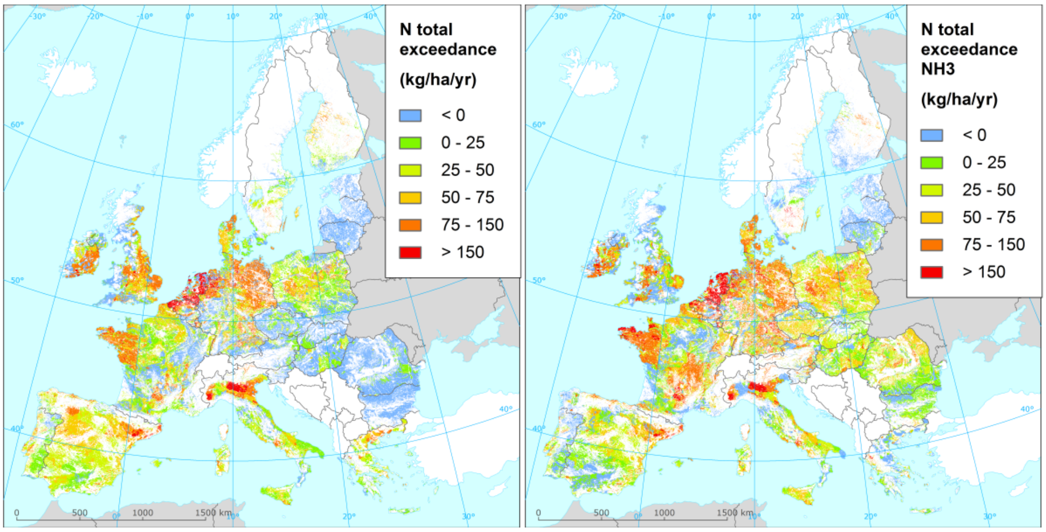

Figure 2. Maps of exceedances of critical N inputs using a critical total N concentration in surface water of 2.5 mg N l^{-1} (left) and a critical NH_3 emission rate (right).

Conclusion

At EU-27 level, the average critical N inputs in view of eutrophication of aquatic or terrestrial ecosystems are approximately 15% and 25% lower, respectively, than current (year 2010) N inputs using either a critical N concentration in runoff 2.5 mg N l^{-1} or the critical N deposition as criterion, respectively. At regional level, there are very limited exceedances of critical N inputs when using the ground water criterion of 11.3 mg NO_3-N l^{-1} but large exceedances occur at several places when using a critical N concentration in surface water of 2.5 mg N l^{-1} or a critical NH_3 emission rate. Relative high exceedances are found in regions with high total N inputs, such as Ireland, the Netherlands, Belgium and Luxembourg, Brittany in France and the the Po valley in Italy.

References

Camargo JA and Alonso A (2006). Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. Environment International 32:831-849.

Carpenter SR. and Bennet E (2011). Reconsideration of the planetary boundary for phosphorus. Environ. Res. Lett. 6, doi:10.1088/1748-9326/6/1/014009.

De Vries W, Kros J, Kroeze C and Seitzinger SP (2013). Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Current Opinion in Environmental Sustainability 5:392–402.

Laane RWPM (2005). Applying the critical load concept to the nitrogen load of the river Rhine to the Dutch coastal zone. Estuarine, Coastal and Shelf Science 62:487–493.

Liu C, Kroeze C, Hoekstra AY, Gerbens-Leenes W (2011). Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers. Ecological Indicators 18:42-49.

Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, Folke C, Gerten D, Heinke J, Mace GM, Persson LM, Ramanathan V, Reyers B, Sörlin S (2015). Planetary Boundaries: Guiding human development on a changing planet. Science 347, 1259855 (2015). DOI: 10.1126/science.1259855.

Slootweg, J, Posch M, Hettelingh J.-P and Mathijssen L (2014). Modelling and Mapping the impacts of atmospheric deposition on plant species diversity in Europe: CCE Status Report 2014. RIVM Report 2014-0075, Coordination Centre for Effects, National Institute for Public Health and the Environment, Bilthoven, Netherlands.

WHO (2011). Nitrate and Nitrite in Drinking-water Background document for development of WHO Guidelines for Drinking-water. WHO/SDE/WSH/07.01/16/Rev/1