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Wim de Vries[1,2], Lena Schulte-Uebbing[2], Hans Kros[1], Jan Cees Voogd[1]

1 Wageningen University & Research, Environmental Research, PO Box 47, 6700 AA Wageningen, the Netherlands

2 Wageningen University & Research, Environmental Systems Analysis Group, PO Box 47, 6700 AA Wageningen, the Netherlands

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Approved for publication:
Gert Jan Reinds, teamleader of Sustainable Soil Use

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In this study we investigated critical nitrogen (N) inputs and N losses and their exceedances (actual inputs or losses minus critical inputs or losses) for agricultural soils in the EU-27 region in view of adverse effects. Critical N inputs were calculated based on a critical (i) ammonia emission rate related to critical N loads in view of biodiversity protection, (ii) N concentration in runoff to surface water of 2.5 mg N l^{-1}, related to the protection of aquatic ecosystems and (iii) nitrate (NO_3^-) concentration in leachate to groundwater of 50 mg NO_3^- l^{-1}, based on the safe limit for drinking water. In addition, we calculated the required N inputs to achieve target crop yields, which were set at 80% of the water-limited yield potential. Calculations were performed with the INTEGRATOR model for ca 40,000 unique soil-slope-climate combinations and then aggregated at NUTS3-, country- or EU-27 level. Results show that critical N inputs at EU-27 level as compared to actual (year 2010) N inputs are 31% lower to protect biodiversity and 43% lower to protect surface water quality. Critical N inputs are most strongly exceeded in regions with high livestock densities, such as Ireland, the Netherlands, Flanders in Belgium, Brittany in France and the Po valley in Italy. Inversely, required N inputs to attain target crop yields at EU-27 level are ca. 40% higher. Especially in Eastern Europe, there is a large potential to increase yields by increasing N fertilization, but this generally requires strongly improved N use efficiency (NUE), since critical N inputs are mostly lower. Using a maximum plausible NUE, the surface water criterion cannot be achieved on 17% and 25% of all agricultural land at actual crop yield and target crop yields, respectively. Similarly, a maximum plausible reduction in NH_3 emission fractions also still causes exceedances of critical N loads in view of biodiversity protection. Reducing agricultural production is needed to protect biodiversity and/or water quality in those regions.

Keywords: agriculture, ammonia, nitrate, nitrogen, nitrogen use efficiency, crop yield, yield gap, required inputs, eutrophication, critical inputs

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name: Rene Rietra

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Approved team leader responsible for the contents,

name: Gert Jan Reinds

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Preface

The growth of human activities over the last century has led to large pressures on the Earth System. In this context, the concept of planetary boundaries was introduced, including one for anthropogenic nitrogen (N) fixation. An N boundary gives insight in the acceptable use of N as compared to the current use. However, when setting such a boundary one has to account for both required N inputs in view of agricultural production and critical N inputs in view of adverse environmental impacts. Furthermore, such an N boundary needs to account for spatial variation in both required and critical N inputs.

Since the introduction of the planetary boundary concept, both the International Fertilizer Association and Fertilizers Europe were interested in a more accurate calculation of N boundaries, accounting for the spatial variation in the sensitivity of terrestrial and aquatic ecosystems and in climate, land use and soil properties affecting the fate of N. Simple downscaling of planetary boundaries to regions, as often applied, neglects this variation. The same risk holds for the use of the targets given in the EU 'From Farm to Fork' strategy (FFS), including a reduction in N losses by at least 50% and a reduction in the use of N fertilisers by at least 20% in 2030. Flat rate reductions in N losses and N inputs are inappropriate since N concentrations in air and water vary in space, depending on application rate, climate, crop type and soil type. Nitrogen inputs and losses should be reduced where ecosystems are most at risk. Inversely, in some regions in Europe, crop yields are limited by N availability (besides other factors) and additional N inputs may thus be required to close yield gaps, unless the nitrogen use efficiency (NUE) is increased. Both agronomy and the environment are linked here. Consequently, not only Fertilizers Europe and the International Fertilizer Association but also the European Environmental Agency were interested in spatially explicit information on critical inputs, required inputs and needed improvements in NUE to reconcile environmental and agronomic goals.

In this study, we quantified and compared spatially explicit current inputs and losses of N with required N inputs for crop production and with critical N inputs and N losses in view of adverse environmental effects at EU-27 level with a focus on ammonia (NH_3) emissions to air and nitrate (NO_3) leaching and runoff to groundwater and surface water. We also quantified the required NUE at which the current or even target crop yield can be reached with acceptable N losses to either air or water and the degree to which these NUEs can be attained by improved management. The results of this study can be used to develop region-specific mitigation policies.

We thankfully acknowledge Fertilizers Europe, the International Fertilizer Association and the European Environmental Agency who funded this research.

Summary

Reactive forms of nitrogen, which include all forms of N except di-nitrogen (N_2), are crucial for life on earth, since nitrogen (N) is an essential nutrient for the growth and functioning of plants, animals and humans. In Europe, agricultural production and especially livestock farming have increased rapidly since the early 1940s, associated with a significant increase in N fertilizer and N manure inputs. Only 60% of the applied N to agricultural land in Europe is, however, taken up by crops, while the remainder is lost to the environment. Since the 1990s, the nitrogen use efficiency (NUE) of European agriculture has increased but by far not enough to reduce N losses sufficiently to meet environmental targets. Nitrogen that is lost to the environment leads to substantial unwanted side-effects including an increase in: (i) ammonia (NH_3) emission and deposition on terrestrial ecosystems, causing decreases in plant species diversity, (ii) runoff of N, causing eutrophication of surface waters, (iii) leaching of nitrate (NO_3^-) to groundwater, causing degradation in drinking water quality and (iv) emissions of nitrous oxide (N_2O), a greenhouse gas, causing climate change.

Several policies at European and national level have attempted to reduce the negative side effects of excess N in agriculture since 1990, including (i) the National emission ceilings (NEC) directive and the Birds Directive and Habitats Directive affecting N emissions, (iii) the Nitrates Directive and the Water Framework Directive with critical N concentration limits for groundwater and surface waterbodies. These directives limit the inputs of N to agricultural land, but integrated information on the needed reduction in N losses and related N surpluses and N inputs to protect the environment is lacking. The need for such information is illustrated by targets given in the 'From Farm to Fork' strategy (FFS), including the reduction of nutrient losses by at least 50% and of the use of fertilisers by at least 20% in 2030. Generic use of flat-rate reductions in N losses and N inputs is, however, inappropriate since N concentrations in air and water vary with location depending on application rate, climate, crop type and soil type, and N inputs should be reduced where ecosystems are most at risk. In addition, in large regions across Europe (especially in eastern Europe) an increase in agricultural production can be achieved by closing the gap between actual yields and the "yield potential", which may require a further increase in nitrogen (N) inputs.

In this study we investigated critical N inputs and N losses and their exceedances (actual inputs or losses minus critical inputs or losses) for agricultural soils in the EU-27 region in view of those adverse effects on terrestrial and aquatic ecosystems and on drinking water quality. Critical N inputs were calculated based on a critical: (i) ammonia emission rate related to critical N loads in view of biodiversity protection, (ii) N concentration in both surface and subsurface runoff to surface water of 2.5 mg N l^{-1}, related to the protection of aquatic ecosystems and (iii) nitrate (NO_3^-) concentration in leachate to groundwater of 50 mg NO_3^- l^{-1}, considered the safe limit for drinking water. In addition we calculated the required N inputs to achieve target crop yields, which were set at 80% of the water-limited yield potential, which is considered a maximum exploitable yield for farmers under most circumstances given economic and environmental constraints.

The calculated critical and required N inputs were based on the assumption that the N use efficiency (NUE), defined as crop N offtake divided by total N input We also calculated the necessary increase NUE and the necessary decrease in NH_3 emission fractions from manure and fertilizer to reconcile actual (or target) crop production with environmental targets. The INTEGRATOR model, including a full soil N balance, was further developed to calculate not only actual, but also required and critical N inputs to the soil by fertiliser, manure, biosolids, biological N fixation and N deposition, and the related losses to the environment, at the actual N use efficiency (NUE). Calculations were performed for ca 40.000 unique soil-slope-climate combination and then aggregated at NUTS3-, country- or EU-27-level.

Required overall reductions in NH_3 emissions and N runoff at EU level to protect terrestrial and aquatic ecosystems are 38% and 50%, respectively, the latter value being equal to the mentioned reduction in nutrient losses by the 'From Farm to Fork' strategy (FFS) of the European Green Deal. At current NUE, the

required reduction in N inputs to protect terrestrial and aquatic ecosystems, is 31% and 43%, respectively. However, if NUE is increased to such a level that current crop yields are reconciled with the protection of surface water quality, the required reduction is only 19-22%. This coincides fully with the mentioned 20% reduction in N fertilizer inputs by the FFS.

Critical N inputs are most strongly exceeded in regions with high livestock density, such as Ireland, the Netherlands, Belgium, Luxembourg, Brittany in France and the Po valley in Italy. Inversely, required N inputs to attain target crop yields are ca. 40% higher than current N inputs. Especially in Eastern Europe, there is a large potential to increase yields by increasing N fertilization, but this generally requires strongly improved N management, since critical N inputs are mostly lower.

At increased NUE, a given crop yield can be obtained with less N input, while the critical N input increases since a lower fraction of N is lost to the environment. The NUE increase that is required to attain actual or target crop yields at acceptable N losses varies strongly. Using a maximum plausible NUE of 0.9, the surface water criterion cannot be reconciled with actual crop yields on 17% of all agricultural land, and with target crop yields on 25% of all agricultural land. Similarly, even if NH_3 emission fractions are reduced to the lowest plausible value, current production levels would still cause exceedances of critical N loads in view of biodiversity protection. Reductions in crop or animal production is needed to protect biodiversity and/or water quality in those regions. There is a need to develop region-specific mitigation policies based on regional information on critical N inputs and their exceedances with related environmental and health impacts. Results of this study could be used for such policies.

1 Introduction

Past trends in enhanced food production and elevated nitrogen cycling
Nitrogen (N) is an essential nutrient for the growth and functioning of plants, animals and humans. The Earth's atmosphere consists for 78% of di-nitrogen (N_2), but in this form N is unavailable to most living organisms. Instead, reactive forms of nitrogen (Nr), which include all forms of N except N_2, are crucial for life on Earth. Since the late nineteenth century, human activities have approximately doubled Nr inputs to the environment (Galloway et al., 2004). This increase has mainly been driven by increased N fertilizer use, an increase in the cultivated area of N-fixing crops (Erisman et al., 2008; Fowler et al., 2013; Smil, 2001) and increased use of fossil fuels, to fulfil the food and energy demand of a growing world population (Galloway et al., 2008). Supply of N fertilizer, produced by industrial synthesis of ammonia (NH_3) from atmospheric N_2 and hydrogen, is essential to feed an ever increasing world population (Eickhout et al., 2006; Erisman et al., 2008; Robertson & Vitousek, 2009; Sutton et al., 2013). The approximately 105 million tons of mineral N fertilizer currently applied (FAO, 2010) are estimated to feed about 50% of the human population (Erisman et al., 2008; Smil, 2002, 2011).

In Europe, agricultural production and especially livestock farming have increased rapidly since the early 1940s, associated with a large increase in fertilizer and manure inputs. N inputs to EU agriculture reached a maximum around 1985 and have decreased since then (e.g., Sutton et al., 2011) thanks to better practices implemented by farmers and to European legislation enforcement. In addition, this is partly due to reduced fertilizer application and partly because the number of dairy cattle has decreased by about 1% per year since the implementation of the milk quota system in the EU-15 in 1984 (Oenema et al., 2007).

Expected increase in food production and required nitrogen inputs
Even though Europe is one of the most food secure regions worldwide (per capita food availability is only higher in North America; FAOSTAT), agricultural productivity in Europe will probably need to increase in the future. Increasing European agricultural production is necessary both to maintain or increase food self-sufficiency, to help meeting global food demands, and to provide biomass resources for energy and other uses (De Wit et al., 2011). In recent years, Europe has shifted from a situation where it produced enough calories to meet domestic demand to one where it relies on trade to fulfil demands (Sadowski & Baer-Nawrocka, 2016). Many countries produce less than 70% of the food they require, and reliance on trade is has increased in many European countries over the last 20 years (FAO, 2012; Puma et al., 2015; Sadowski & Baer-Nawrocka, 2016). Europe is also a net importer of vegetal proteins, mainly in the form of feed (Lassaletta et al., 2014). This makes Europe vulnerable in case a disruption leads to scarcity on global crop markets (Puma et al., 2015).

While Europe's food demand is only projected to increase by a few percent between now and 2050 (Bruinsma, 2012), rising global population and shift towards higher shares of animal protein in diets will lead to large increases in global food demand. Predictions vary from an increase in demand by approximately 60% (FAO, 2017) to a doubling (Tilman et al., 2011) of the current demand by 2050. There is strong concern that historical rates of crop yield growth are not sufficient to meet growing demands (Ray et al., 2012; Ray et al., 2013), especially in Sub-Saharan Africa (Van Ittersum et al., 2016) and some regions in Asia and South America (Fader et al., 2013). In today's globalized world it is likely that Europe will play a role in meeting global demands.

Increasing Europe's agricultural output requires either dedicating more land to agriculture, or increasing yields on already existing agricultural land. The latter approach is more realistic considering the large competition on land use by nature protection, biodiversity maintenance, renewable energies or soil sealing. An increase in yields on already existing agricultural land can be done by closing the gap between actual yields and the biophysical 'yield potential (Yp)', defined as the maximum possible yield for a given climate and soil, assuming optimal management either under rainfed conditions (water-limited yield potential) or irrigated conditions (Van Ittersum et al., 2013). Yield gaps for major grains in Europe are highly variable (www.yieldgapatlas.org). Closing yield gaps usually requires increasing inputs, such as water or nutrients, such as nitrogen (N). Several studies have shown that especially in Eastern Europe, there is a large potential to increase yields by increasing N fertilization (Mueller et al., 2012; Pradhan et al., 2015).

Unwanted side-effects of nitrogen application and critical nitrogen inputs

At the European scale, only 60% of the nitrogen applied to agricultural land in manures, fertilisers, deposition and from fixation is taken up by crops while the remainder increases the N-fluxes to the environment, herein termed 'lost' to the environment (Leip et al., 2011). Since the 1990s, the nitrogen use efficiency (NUE) of European agriculture has increased (Van Grinsven et al., 2014) but by far not enough to reduce N losses sufficiently to meet environmental targets. Nitrogen that is lost to the environment leads to substantial unwanted side-effects including: an increase in: (i) ammonia (NH_3) emission (e.g. Oenema et al., 2007; Webb et al., 2005) and deposition on nearby terrestrial ecosystems, causing N enrichment and decreases in plant species diversity (e.g. De Vries et al., 2010; Spranger et al., 2008), (ii) runoff of N, causing eutrophication of surface waters (e.g. Camargo & Alonso, 2006), (iii) leaching of nitrate (NO_3^-) to groundwater, causing degradation in drinking water quality (e.g. Powlson et al., 2008; Van Grinsven et al., 2006) and (iv) emissions of nitrous oxide (N_2O), a greenhouse gas, causing climate change (Freibauer, 2003). Following the same trend as N inputs, N losses to air by NH_3 and N_2O emission and to water by NO_3 leaching and N runoff have increased in Europe up to 1985 and decreased thereafter, also because of improved manure management in grasslands (Sutton et al., 2011).

The notion that increased N inputs to agriculture drive multiple, interacting global effects has led to the concept of a 'planetary N boundary'. Planetary boundaries have been defined for several other environmental issues and can be seen as planet-wide environmental 'tipping points' beyond which humanity is at risk (Rockström et al., 2009a; Rockström et al., 2009b). The planetary N boundary has, however, been criticized for focussing only on the ecological consequences of the disturbance of the N cycle, while neglecting the need for N to feed the current world population (Nordhaus et al., 2012). Opportunities exist to reduce the environmental impact of agriculture by eliminating N overuse, and improving NUE, while still allowing an increase in production of major cereals (Mueller et al., 2012). Furthermore, defining a global threshold for the N boundary is arbitrary, due to the spatial variability in impacts both in terms of N limitation and N overuse (Lewis, 2012; Nordhaus et al., 2012). Especially on a global scale, N fertilizer application is highly unevenly distributed. In many African countries (Liu et al., 2010), as well large areas of Latin America and South East Asia (MacDonald et al., 2011), N inputs are insufficient to maintain soil fertility, posing risks of land degradation (Sutton et al., 2013). Many developed and rapidly growing economies, on the other hand, have large N surpluses (Vitousek et al., 2009). Hence, in many parts of the world an increase in N input is needed to avoid land degradation and increase crop yields, while in other parts N application can be reduced while simultaneously maintaining or even enhancing yields and reducing environmental impacts (Ju et al., 2009).

To meet food demands of a growing population, N fertilizers are thus needed, but at the same time the impacts of agricultural N use on water quality, biodiversity and climate have to be reduced (Foley et al., 2005; Foley et al., 2011). Considering those aspects, De Vries et al. (2013) calculated both N inputs that are required to meet global food demands and planetary N boundaries for adverse environmental impacts. The assessment of the planetary N boundary was based on a threshold for NH_3 concentration in air in view of biodiversity decline in terrestrial ecosystems and a threshold for N concentration in runoff in view of eutrophication of aquatic ecosystems. De Vries et al. (2013), however, only accounted for spatial variations in a very approximate way.

Need for spatially explicit critical nitrogen inputs in policy making

Several policies at European and national level have attempted to reduce the negative side effects of excess N since 1990, including (i) the National emission ceilings (NEC) directive with NH_3 and NO_x emission targets, (ii) the Birds Directive and Habitats Directive affecting N emissions, (iii) the Nitrates Directive and the Water Framework Directive with critical N concentration limits for ground water and surface water and (iv) the Paris Climate Agreement with emission targets for N_2O. These directives limit the inputs of N to agricultural land as illustrated in Figure 1. However, integrated information on the needed reduction in N losses and related N surpluses and N inputs to protect the environment is lacking. The need for such information is illustrated by targets given in the 'From Farm to Fork' strategy (FFS) of the European Green Deal. The FSS aims for a sustainable food production system by reducing food waste, enhancing circularity (recycling of plant, animal and human waste) and improving the efficiency of nutrient application methods to 'protect the environment, preserve biodiversity and tackle climate change' (European Commission, 2020). One of targets of the FSS, linked to integrated nutrient management actions plans, is the reduction of nutrient losses by at least 50% and of the use of fertilisers by at least 20% at 2030.

The background of the above mentioned flat rate reductions in nutrients (nitrogen and phosphorous) in the FFS is not given. For N, it is most likely related to downscaling the calculated planetary N boundary. In a recent EEA study, a consumption-based approach (N pollution caused by European consumption) was used to assess an N boundary for EU 27, regardless of where consumed goods are produced (EEA, 2020). A share of the planetary N boundary is allocated to Europe, based on different allocation principles. In this context, it is however, needed to realize that a planetary N boundary is totally different from a planetary boundary for greenhouse gas emissions in view of climate change. There the only important thing is to reduce the total emission of greenhouse gases, independent of location, since concentrations of greenhouse gases (carbon dioxide, methane and nitrous oxide) are similar all over the world. However, nitrogen concentrations in air and water vary with location depending on application rate, climate, crop type and soil type and N inputs should be reduced where it is needed, while there may be locations where inputs can increase, in view of crop yield gaps, without exceeding environmental thresholds. The EEA study explicitly mentions that: "there are large differences in the nitrogen surplus across Europe .. and the sensitivity of the receiving ecosystems also varies. Thus, the scale matching of the nitrogen boundaries to Europe should in principle be made spatially explicit to account for local contexts and effects" (EEA, 2020). This big paradigmatic difference is crucial to include in European policy. There is a need to identify regional hot spots for N-related environmental and health impacts, by a spatially explicit assessment of critical N inputs and their exceedances, for developing targeted mitigation policies. In addition, estimating an boundary for Europe or EU as a whole can better be done by upscaling local critical nitrogen inputs than by downscaling a planetary N boundary.

Aim of this study

The present study addresses the need for a more sophisticated spatially explicit assessment of both required N inputs to meet target yields and critical N inputs to not exceed environmental thresholds and the required improvement in management to reconcile the difference. We derived critical N inputs and N losses and their exceedances (actual inputs or losses minus critical inputs or losses) for agricultural land in the EU-27 in view of the above-mentioned adverse effects on terrestrial ecosystems caused by NH_3 emissions, on aquatic ecosystems caused by N runoff and on drinking water caused by leaching to ground water. In addition, we calculated the required N inputs to achieve target crop yields. Target crop yields were set at 80% of the water-limited yield potential, which is considered a maximum exploitable yield for farmers under most circumstances given economic and environmental constraints (Lobell et al., 2009; Van Ittersum et al., 2013). The calculated critical and required N inputs were based on the assumption that the N use efficiency (NUE), defined as crop N offtake divided by total N input (EU Nitrogen Expert Panel, 2015), is constant. We also calculated the necessary increase NUE and the necessary decrease in NH_3 emission fractions from manure and fertilizer to reconcile actual (or target) crop production with environmental targets. In this context, we also investigated the regions where technological improvements, changing the NUE or NH_3 emission fraction to the highest and lowest plausible values, respectively, are not sufficient to protect biodiversity and/or water quality. In those regions, a reduction in the production is needed to fully protect the environment.

2 Methods and data

2.1 Overall approach and concepts

Calculation of actual, required and critical N inputs
The model INTEGRATOR (De Vries et al., 2011b) was used to calculate:
1. **Actual N inputs** and associated N losses for the year 2010,
2. **Required N inputs**, i.e. inputs that are required to obtain target crop yields, set to 80% of the water limited yield potential, and associated N losses, and
3. **Critical N inputs**, i.e. N inputs to the soil at which critical N losses to air and water calculated from critical values for defined N indicators are not exceed.

We first calculated required and critical N inputs, using the actual N use efficiency (NUE_{act}) derived for the year 2010, as illustrated in Figure 1. We also calculated necessary NUEs to reconcile actual crop yields or target crop yields with acceptable environmental N losses.

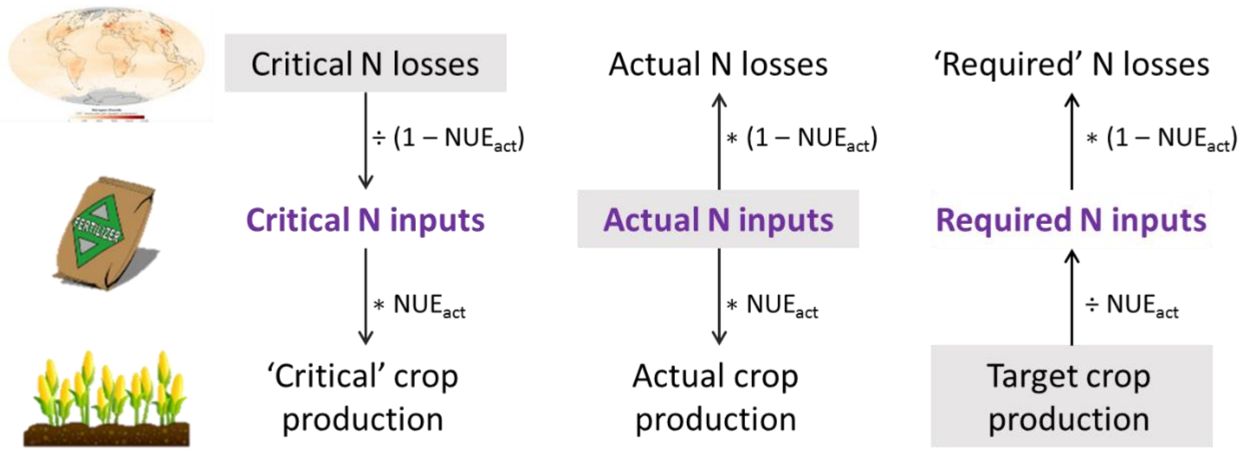

Figure 1 *The drivers behind the calculation of (i) actual N inputs, based on current fertilizer consumption and livestock numbers, (ii) required N inputs, based on target crop yields and (iii) critical N inputs, based on critical N losses to air and water based on critical values for defined N indicators.*

INTEGRATOR is based on the model MITERRA-EUROPE, which is a deterministic and static model that calculates (among other things) N balances, emissions of NH_3, N_2O and NO_x to the atmosphere, and leaching and runoff of N to groundwater and surface waters for so-called NUTS (administrative areas in the EU of 160–440 km^2) regions (Velthof et al., 2009). As with MITERRA-EUROPE, INTEGRATOR calculates various N flows from empirical linear relationships between the different N fluxes. Actual, required and critical N inputs and N losses (budgets) and actual and necessary NUEs were calculated with INTEGRATOR for approximately 30 crops and 40,000 NCUs, being 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 (De Vries et al., 2011b; De Vries et al., 2011c). The results are aggregated for all agricultural land (crops + grassland), different crop groups (C3 cereals, maize, other crops, grassland + fodder crops) and major soil types (sand, clay and peat) and are also presented for various geographic regions, varying from NCUs to NUTS regions, countries and EU-27 (25 EU countries, as it excludes Cyprus and Malta; Croatia is also not included). Details on the calculations for actual, required and critical inputs and losses of nitrogen are given in sections 2.2, 2.3 and 2.4 and Annex 1, Annex 2 and Annex 3, respectively.

Used concepts (terms) and indicators

A definition of used terms and indicators with respect to nitrogen impacts and limits in this study is given in Table 1.

Table 1 *Definition of used concepts (terms) and indicators with respect to nitrogen impacts and limits.*

Term	Definition	Indicators
Critical impacts	Environmental impacts of N that are considered detrimental to ecosystem or human health	Species shifts due to N enrichment; eutrophication of surface water; health effects due to nitrate pollution in drinking water
Critical limits	Thresholds for N concentration in environmental compartments that are not to be exceeded to avoid critical environmental impacts	N deposition on natural ecosystems, N concentration surface water; N concentration in groundwater
Critical losses	N losses from agriculture at which critical environmental limits are reached	NH_3 emissions from agriculture, N runoff from agriculture to surface water, N leaching from agriculture to groundwater
Critical inputs	N inputs to agriculture that lead to critical N losses	N fertilizer addition; N excretion; N fixation; N biosolids

Critical N inputs are defined as N inputs to agriculture at which environmental thresholds are reached, but not exceeded (see Table 1). They can be seen as 'maximum allowable inputs' that do not lead to adverse environmental effects. To back-calculate critical N inputs, we first define critical environmental impacts (see Table 1 and Figure 2). From these impacts, we derive critical limits for N compounds in different environmental compartments (e.g. NO_3^- concentrations in groundwater; see step 1 in Figure 2). Those critical limits are reached at certain N losses from agriculture (step 2 in Figure 2). From those critical N losses we can back-calculate critical N inputs, assuming a constant nitrogen use efficiency (step 3 in Figure 2). The N use efficiency also determines the production at critical N inputs ('critical production'). We can then compare critical production with the desired production (step 4 in Figure 2). If critical N production is below desired (actual or target) production, this implies that environmental objectives can only be reached at a lower N input.

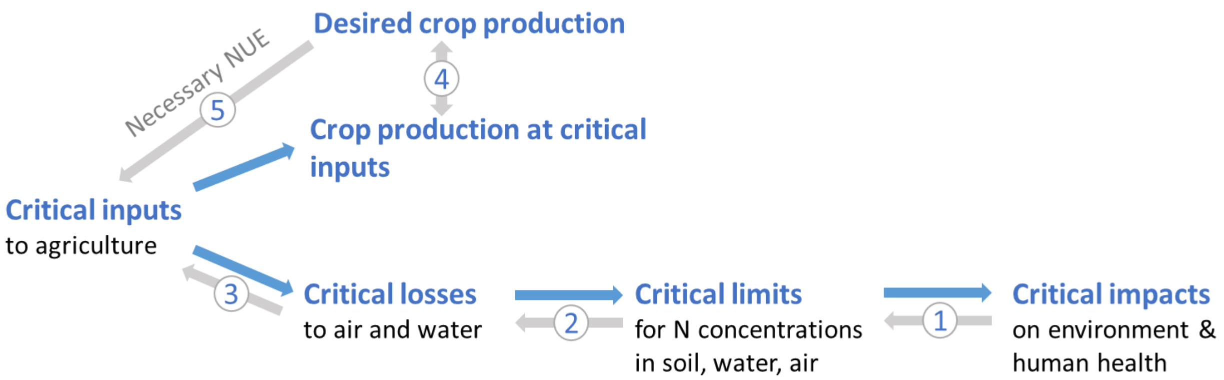

Figure 2 *Schematic representation of the back-calculation of critical N inputs from critical impacts and the necessary NUE to reconcile desired food production with environmental goals. Blue arrows indicate direction of the N flows: Nitrogen inputs lead to crop production, the remainder is lost to the environment. The N lost from agriculture enters the environment and leads to a change in N concentrations in soil, air and water. If N concentrations exceed certain critical limits, this can lead to impacts on the environment and human health. Grey arrows indicate the steps in the back-calculation of critical inputs from critical impacts and of the necessary NUE from a desired crop production.*

A lower N input, however, likely causes a loss in crop production, unless the nitrogen use efficiency (NUE) is increased. This holds even stronger when target yields are aimed for, as these are generally higher than actual yields. By increasing NUE, actual yields or target yields can be reached with less N fertilizer. Firstly, at a higher NUE, a larger fraction of the applied N is taken up (leading to a higher yield for equal inputs).

Secondly, at a higher NUE a lower fraction of the applied N is lost to the environment, thus leading to higher critical inputs for the same critical losses. Following this reasoning, we calculated the (increase in) NUE that is necessary to obtain actual yields or target yields without exceeding critical N losses. If the critical production is lower than the desired production, we thus calculate the NUE at which desired production can be obtained at critical inputs ('necessary NUE', step 5 in Figure 2). A glossary of all terms further used in this study is given at the end of this report.

2.2 Assessment of actual inputs and losses of nitrogen

2.2.1 Overall approach

Nitrogen (N) flows in agricultural soils are calculated by an empirical linear model predicting (i) N (NH_3, N_2O and NO_x) emissions from housing systems in response to N excretion, followed by (ii) N offtake, N (NH_3, N_2O and NO_x) emissions from soils and N surface runoff, and by denitrification and leaching to groundwater in response to inputs by fertilizers, animal manure, biosolids, atmospheric N deposition and biological N fixation. A schematic overview of this approach, which is an elaboration of the MITERRA-Europe approach (Velthof et al., 2009), is presented in Figure 3. The figure specifically illustrates the approach to calculate N (NH_3, N_2O and NO_x) emissions from housing systems and soils and leaching/runoff of N to groundwater and surface water, using linear relationships.

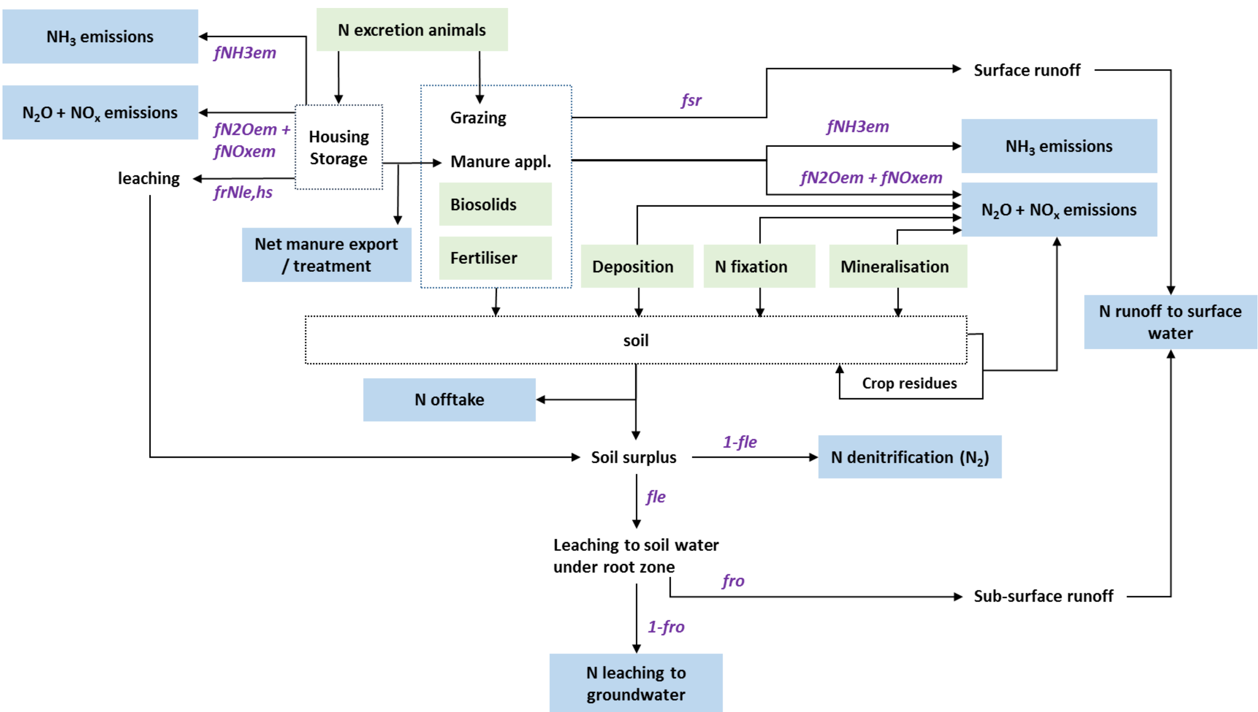

Figure 3 *Schematic presentation of the calculated N flows in INTEGRATOR (adapted after the MITERRA-EUROPE model by(Velthof et al., 2009); see text for description of calculation methods). At NCU level, the sum of total gross N inputs (green boxes) equals the sum of all N outputs (blue boxes). The sum of all green boxes equals the sum of all blue boxes.*

The NH_3 emissions for fertilizer vary for different fertilizer types and for manure they vary between animal categories (mainly cattle, pig and poultry) and the type of manure (solid or liquid). The empirical fractions for N_2O emission, N surface runoff and N leaching are a function of land use (grassland, arable land), climate (precipitation, temperature), slope and soil texture and/or soil organic carbon. More details on the calculation of inputs, offtake and losses to air and water are given below.

2.2.2 Spatially explicit inputs, offtake and surpluses of nitrogen

Calculation of actual N inputs

The total N input to agricultural soils is calculated as the sum of inputs via animal manure (either manure application or grazing), fertilizer, biosolids, atmospheric deposition, biological N fixation and N mineralization. N offtake (or uptake or removal) is N that is removed from in the harvested part of the crop. Table 2 summarizes the approaches and data used to calculate N inputs and N offtake. More information on the spatially explicit assessment of N excretion (and related N manure input) and N fertilizer application for the reference year 2010 is given below.

Table 2 *Assessment of N inputs and N offtake in INTEGRATOR.*

Model inputs	Assessment
N excretion	Sum of animal numbers x N excretion rates per animal.
- Livestock numbers	FAO livestock statistics from the EUROSTAT EUROFARM database at NUTS3 level; downscaled to 1km x 1km and aggregated to NCU level.
- N excretion rates	Country-specific N excretion rates for 8 animal categories based on GAINS model.
N fertilizer application	FAOSTAT data at country level, downscaled to NCU level based on crop N demand accounting for all non-fertilizer N inputs and using a balanced N fertilization approach.
Biological N fixation rates	2 kg N ha^{-1} yr^{-1} for arable land except pulses and legumes and 5 kg N ha^{-1} yr^{-1} for grassland. 1.3 times harvested N for pulses and legumes and 25 kg N ha^{-1} yr^{-1} for rice.
Biosolids application	National application data downscaled to NCU level based on distribution of N inputs via manure.
N deposition	Emission-deposition matrix, based on the EMEP model, using N emission estimates from INTEGRATOR.
N mineralization	Calculated for peat soil as a function of water table depth and soil C-N ratio.
N offtake	Downscaled crop yields (or grassland yields) x N content in harvested crop parts.
- Crop yields	FAOSTAT data at country level on the harvested crop yields; downscaled to NCU level based on spatial variation in actual crop yield from the global yield gap atlas (GYGA).
- Grassland yield	Publication by Smit et al. (2008) on production at field level. Removal by consumption of grass is calculated by multiplying the grassland production with a consumption ratio of 0.8 for intensively managed grasslands and of 0.4 for extensively managed grasslands. Grassland with yields lower than 4.5 t dry matter ha^{-1} yr^{-1} are considered extensive grasslands, above 4.5 t dry matter ha^{-1} yr^{-1} intensive grasslands.
- Crop N content	Crop-specific N contents varying with N input (see Table A.1.2.1).

N excretion and N manure input

Total manure N production is calculated at NCU level from N excretion, correcting for losses (gaseous emissions and leaching) in housing and manure storage systems (see Table 2). Total N excreted is calculated by multiplying downscaled animal numbers at NCU level, from the FAO livestock statistics at NUTS3 level, with N excretion rates per animal per country for 8 animal categories (dairy cows, other cows, pigs, laying hens, other poultry, sheep and goats, horses, and fur animals). More details are given in Annex A1.1. A division is made between excretion of animals in housing systems and by grazing animals in pastures, based on country-level data on the number of grazing days. Nitrogen excreted in housing systems is derived by multiplying total N manure excretion with a housing fraction, while the N excreted on land during grazing is calculated by subtracting N excreted in housing systems from total N manure excretion.

Total manure N application to land is equal to N excretion in housing systems minus N emissions and leaching from housing and manure storage systems. Total N manure application rates are distributed over grassland and arable land (including fodder maize) based on assumptions used by Velthof et al. (2009). More details on the approach are given in Annex A1.1.

N inputs by biosolids, fixation, deposition and mineralization

N inputs by biosolids (compost, sludge), N fixation and N deposition at NCU level were derived by downscaling data (mostly at national level) to NCU level. Biosolids (compost, sludge) N inputs were calculated by multiplying application rates of biosolids with N contents in biosolids (dry matter basis). For compost, national data (if available) were used; for sludge, generic data (median value at EU level) were used.

Biological N fixation by pulses and soybeans was calculated as 1.3 times the amount of N in harvested products. This ratio was calculated according to Herridge et al. (2008) as N_{shoots}/N_{grain} x 1/HI x SR_{ratio} x frN_{fix} where, N_{shoots} and N_{grain} is the N content in shoots and grain (%), HI is harvest index, being the crop specific ratio of seed dry matter to above-ground dry matter, SR_{ratio} is the (shoot + root) / shoot ratio to account for N fixation in roots and frN_{fix} is a crop-specific fraction of N in the crop that is derived from N fixation. Using data from Herridge et al. (2008) on harvest index, shoot root ratio and N fixation retention fraction, a value of 1.3 was derived for both dry pulses and soybean. Biological N fixation in all other arable soils (except legumes and pulses) was set to 2 kg N ha^{-1} yr^{-1}, as free-living soil bacteria only fix a few kg of N per ha (Paul & Clark, 1996). In grassland, N fixation is determined by the clover fraction, which in turn is influenced by N inputs. The contribution of biological N fixation by clover is negligible at an annual fertilizer and manure input near 250 kg N ha^{-1} (Van der Meer & Baan Hofman, 1989, 2004). When external inputs to grasslands are high, N is only fixed by free-living soil bacteria at rates of circa 2 kg N ha^{-1} yr^{-1}. As we do not have information on the clover fraction in grasslands, we assumed an average biological N_2 fixation rate of 5 kg N ha^{-1} yr^{-1} for grasslands, similar to Velthof et al. (2009).

Atmospheric N deposition for 2010 were derived from modelled results with the EMEP model (Simpson et al., 2012) for that year (Fagerli et al., 2012) at 50 km x 50 km resolution, which were subsequently downscaled to NCU level. The N deposition data thus derived varied from about 3 kg N ha^{-1} yr^{-1} for parts of Scandinavia and southern Europe to more than 30 kg N ha^{-1} yr^{-1} for parts of Belgium and the Netherlands.

Nitrogen inputs by net N mineralization (loss of soil N pool) are only assumed to occur on arable land or grassland on peat soils. For mineral soils, long-term changes in soil N pool were neglected (neither mineralization nor accumulation of soil organic matter was considered). N mineralization rates are calculated by dividing the net C mineralization in peat soils (derived as a function of groundwater level) by the soil C-N ratio. Information of water table depths of peat soils was related to land use. Soil C-N ratios were set to 30 for oligotrophic peat soils (Dystric Histosols,Od) and to 15 for eutrophic peat soils (Eutric Histosols, Oe) based on mean calculated C-N ratios for those peats soils in the WISE3 database (Batjes, 2009) for Europe.

Fertilizer N input
Nitrogen fertilizer inputs at NCU level were derived by a balanced N fertilization approach, based on the total crop N demand, the available non-fertilizer N inputs (i.e., N inputs by animal manure, biosolids, crop residues, N mineralization, N deposition and N fixation) and the N use efficiency (NUE) of the effective N input. The fertilizer inputs thus derived were scaled to national fertilizer consumption rates from FAOSTAT by multiplying the values with the ratio of FAO country data and the aggregated country level data. The results thus obtained were compared with N fertilizer input data at crop and country level by Fertilizers Europe for the reference year (2010). These data were derived from expert judgments by country experts, combining country N production figures with country information on relative use per crop.

For the balanced N fertilization approach, first total N demand of each crop was calculated as the sum of N in harvested products and in N crop residues. The N removal in harvested crops is calculated by multiplying crop yield (in terms of harvest) with crop N content, which in turn is a function of the N input. Total fertilizer demand in a NUTS2 region is calculated by multiplying the N removal of each crop by the total area of the crops in each NUTS2 region. The area of crops in NUTS2 regions were derived from CAPRI. Yields of arable crops for each country were derived from FAOSTAT (http://faostat.fao.org/). Nitrogen contents of harvested crop products and the amount of crop residues and the relation with N input are based on literature (Fink et al., 1999; Greenwood & Draycott, 1989; Velthof & Kuikman, 2000). The N in crop residues is calculated by dividing the N removed in harvested crops by an N harvest index.

Second, the effective (plant-available) non-fertilizer N input was calculated, distinguishing between less available organic N inputs from animal manure, crop residues and N mineralization, and more available inorganic N inputs from animal manure, deposition and fixation. Third, the needed remaining fertilizer N input is calculated by subtracting the effective non-fertilizer N input from the crop N demand and dividing this amount by the NUE. We assumed that no N fertilizer is applied to rough grazing areas. Fourth, the N fertilizer estimates for each location (NCU) are aggregated at country level and the resulting national fertilizer application rates are compared with country-level N fertilizer consumption from FAOSTAT. Finally, the fertilizer N input at NCU level are scaled (multiplied) with the ratio of the national N fertilizer consumption from FAOSTAT and the aggregated calculated country-level N fertilizer consumption based on the balanced N fertilization approach. Details of the calculation of fertilizer N input are given in Annex A1.2.

N removal in harvested products and crop yields

Cropland: N removal from the field with harvested crops (here denoted as N offtake, but often referred to as N uptake or removal) is calculated by multiplying statistical data on crop yields for specified major crops (approximately 30) with crop-specific N contents in harvested products, which are a function of N input. INTEGRATOR uses national average yields from FAOSTAT and thus does not reflect within-country variations in crop yields. The global yield gap atlas (GYGA, www.yieldgap.org), however, provides estimates of actual yields for a variety of staple crops at sub-country (regional) level (for zones of similar climate). These sub-national estimates of actual yields are multi-year average yields obtained by farmers under dominant management practices, and are gathered from sub-national statistics, farm surveys and/or local agronomists. For wheat, differences between actual yield estimates for climate zones within a country are up to a factor 3.5, though much more commonly around 1-1.5. To introduce sub-national variation in actual crop yields in INTEGRATOR, we used sub-national wheat yields from GYGA to scale yields of all crops in INTEGRATOR, assuming that: (i) the relative differences in wheat yields also reflect differences in yields of other crops and (ii) the total national crop yield should be equal to the yield estimate from FAOSTAT (as currently used in INTEGRATOR). Details of the calculation of sub-national actual crop yields are given in Annex A1.3.

Grassland: Statistical databases of e.g. FAO and Eurostat do not present grassland yields. Therefore, grassland yields were derived from Smit et al. (2008), who analysed spatially explicit data on grassland productivity and land use across regions in Europe by extracting data from various regional, national and international census statistics for Europe. Regional differences in grassland productivity are analysed considering selected climatic and agronomic parameters. Results show that grassland productivity is highly correlated with annual precipitation and less with annual temperature sum and growing season length. The derived spatially explicit grassland yields were used in INTEGRATOR (no further scaling was applied).

Three types of grasslands were distinguished: intensively managed grasslands, extensively managed grasslands and rough grazing areas (the distinction is used for the allocation of manure to these land use classes). The total area of managed grassland (intensive + extensive) in INTEGRATOR was derived from the CLUE model and includes the CLUE category pasture (2). Grasslands with yields above 4.5 t DM ha^{-1} yr^{-1} were classified as intensively managed grasslands; otherwise they were classified as extensively managed grasslands. Rough grazing is considered non-agricultural area and was not included in the assessments in this study.

N removal by consumption of grass was calculated by multiplying the grassland production with a consumption ratio of 0.8 for intensively managed grasslands and of 0.4 for extensively managed grasslands, leading to a EU 27 average consumption ratio of 0.63. The latter ratio was based on the calculation of N intake by beef and dairy cattle from grassland for the year 2010 by the GLEAM model (Gerber et al., 2013) for the EU-27 countries divided by the total grassland production.

Crop and soil N surplus

The difference between total N input and crop N removal is denoted in this report as the N crop surplus, to differentiate it from an N soil surplus, being equal to the N crop surplus minus N emissions minus N surface runoff. The latter N surplus was used to assess N leaching and N runoff (see Section 2.2.3).

2.2.3 Spatially explicit losses of nitrogen from soil to air and water

Emission of gaseous N compounds (NH_3-N, N_2O-N, NO_x-N and N_2-N; in the following denoted as NH_3, N_2O, NO_x and N_2) and leaching and surface and subsurface runoff of N to surface water are due to N inputs from faeces and urine during storage in manure storage systems, by grazing of free ranging animals, after application of manure and fertilizers to agricultural land, due to atmospheric N deposition, N fixation and crop residue input. These losses are calculated in INTEGRATOR by multiplying N inputs by emission, leaching or runoff fractions (see Figure 3).

The fate of N in the agricultural system is calculated as a sequence of occurrences: ammonia (NH_3), nitrogen oxides (NO_x) and nitrous oxide (N_2O) emissions, followed by N surface runoff, N offtake and N leaching to groundwater and surface water. Total denitrification in the soil is calculated by subtracting all N outputs from the system (gaseous emissions, offtake, runoff and leaching) from all N inputs to the soil (plus net release/mineralization in case of peat soils). All N transformation processes were assumed to linearly relate to N inputs. This implies that NH_3, N_2O and NO_x emissions depend linearly on the N input to the soil from fertilizer and manure, N surface runoff depends linearly on the N inputs from fertilizer, manure and biosolids, N offtake depends linearly on the N input minus N (NH_3, N_2O and NO_x) emissions and N surface runoff, and N losses to water (leaching plus runoff) depend linearly on N soil surplus, defined as N input - N offtake - N emissions - N surface runoff (see above). Leaching of NO_3-N (in the following denoted as NO_3) below the rooting zone was partitioned over subsurface runoff to surface water and leaching to groundwater by multiplying N leaching with a subsurface runoff fraction and a groundwater-leaching fraction (equal to 1 – subsurface runoff fraction), respectively. An overview of the assessment of the N loss fractions, determining the N losses to air (NH_3, N_2O, NO_x and N_2 emissions) and water (N leaching to groundwater and N runoff to surface water) is given in Table 3.

Table 3 *Assessment of N loss fractions to air (NH_3, N_2O, NO_x and N_2 emissions) and water (N leaching and runoff) in INTEGRATOR.*

Model inputs	**Assessment**
NH_3 emission fractions	Grazing: average emission fraction at country level based on GAINS model (see Table A1.4.1). Housing and manure storage systems: Country-specific N emission fractions distinguished per animal type and manure type (solid and liquid) for different housing systems (see Table A1.4.6) and manure storage systems (see Table A1.4.5) based on the GAINS model. Soils: Country-specific data from GAINS model. For manure, emission fractions are distinguished between animal categories and manure type of manure (solid and liquid) and manure application technique (see Table A1.4.3 and Table A1.4.7). For fertilizer, emission fractions are distinguished between urea-based fertilizers and nitrate-based fertilizers (see Table A1.4.4).
N_2O emission fractions	Housing and manure storage systems: country specific fractions based on GAINS model data as given in Table A1.5.1. Soils: function of N source (manure type, fertilizer type, crop residue type, grazing, mineralisation, fixation and deposition) application technique, soil type, land use and precipitation and temperature, based on Lesschen et al. (2011) as given in Table A1.5.2.
NO_x emission fractions	Grazing: average emission fraction at country level based on GAINS model (see Table A1.4.1). Housing and manure storage systems: 0.3% of N excretion. Soils: similar approach as N_2O emission as given in Table A1.5.3.
N_2 emission fractions	Housing and manure storage: 9 x NO_x emission, i.e. 2.7% of N excretion (Oenema et al., 2000). Soils: set equal to denitrification rates, being equal to N surplus-N leaching -N runoff.
N leaching fractions	Housing and manure storage systems: fraction of N excreted in these systems that depends on the type of manure system and the type of floor (Velthof et al., 2009). Soils: fraction of soil N surplus (includes N input by grazing) depending on soil type, land use, soil organic content, precipitation surplus, temperature and rooting depth (Velthof et al., 2009).
N surface runoff fractions	Fraction of N input to soil by inorganic and organic fertilizers, calculated as a function of slope class, land use, precipitation surplus, soil type and depth to rock (Velthof et al., 2009).
N subsurface runoff fractions	Fraction of N leaching below the root zone, calculated as a function of soil type, moisture class and slope, derived from the IMAGE groundwater model described in Keuskamp et al. (2012).

The linear transformation constants (emission fractions, offtake fractions, leaching fractions and runoff fractions) are a function of the type of fertilizer or manure, land use, soil type, application method and/or hydrological regime as given in Table 3. Details on the derivation of the NH_3-N emissions fractions, the N_2O-N emissions fractions and on the runoff and leaching fractions are given in Annex A1.4, Annex A1.5 and Annex A1.6, respectively The N_2 emissions from soil were set equal to the denitrification loss (see Table 3) since N_2 O and NOx emissions are already included by linear relationships. The denitrification loss was calculated as a residual flux, being equal to N input, including the change in soil N pool, minus N emissions minus N surface runoff minus N offtake minus N leaching below the rooting zone.

To enable comparison of results with measurements in view of the Nitrate Directive, we also calculated NO_3 concentrations in the leaching flux to groundwater and N concentrations in the total runoff (including surface runoff and subsurface runoff) to surface water. Details on the derivation are given in Annex A1.7.

The precipitation surplus is taken from the IMAGE groundwater model described in Keuskamp et al. (2012). More specifically, the precipitation surplus was set equal to the calculated total runoff which was determined by using the empirical relations derived by Turc (1954) and validated for a large number of catchments inside and outside Europe (see Keuskamp et al., 2012). The model includes irrigation but spatial explicit information on irrigation is scarce. Leng et al. (2017), however, found that irrigation may increase runoff in case of flood irrigation, as water is applied in large volumes within short durations, whereas drip irrigation and sprinkler irrigation cause lower runoff since the highly efficient application method causes an enhanced evapotranspiration. Since there is no precise information on the method and source of irrigation, we assume no overall effect of irrigation on the runoff (precipitation surplus).

2.3 Assessment of required inputs and losses of nitrogen

2.3.1 Region- and crop-specific yield potentials and target yields

Yield gaps for wheat, barley and maize

The global yield gap atlas (GYGA, www.yieldgap.org) provides estimates of yield potentials for a variety of staple crops and countries. Estimates of yield potentials are obtained from crop models for specific weather stations that are scaled up to the country level by using zones of similar climate (Grassini et al., 2015; Van Bussel et al., 2015). These bottom-up estimates are more accurate than estimates of yield potentials that use global datasets on weather, soil and crop management (Van Ittersum et al., 2013); however, they are currently only available for selected countries and crops. For Europe, GYGA currently provides yield gap estimates for wheat for all EU-27 countries except Cyprus and Malta, for barley for all countries except Cyprus, Malta, Italy and Portugal, and for maize for several important maize-growing countries.

Scaling yield gaps for wheat to other crops

In order to obtain estimates for yield potentials for other crops than wheat (for which data is available from GYGA for almost all EU-27 countries), we used a scaling approach. In this approach, we multiplied actual yields per climate zone with yield gaps per climate zone for wheat and then multiplied this with the ratio of the maximum country-level yield for this crop in Europe and the actual crop yield in the respective climate zone.

$$Yw_{crop_n,cz_{ij}} = Ya_{crop_n,cz_{ij}} * YRw_{wheat,cz_{ij}} * \left(\frac{YRm_{crop_n,co_j}}{YRm_{wheat,co_j}}\right) \tag{1}$$

Where:

$Yw_{crop_n,cz_{ij}}$ = the water-limited yield potential for crop n in climate zone i and country j

$Ya_{crop_n,cz_{ij}}$ = the actual crop yield in INTEGRATOR for crop n in climate zone i and country j (as derived by downscaling described in Annex A1.3)

$YRw_{wheat,cz_{ij}}$ = the potential yield ratio defined as $\left(\frac{Yw_{wheat,cz_{ij}}}{Ya_{wheat,cz_{ij}}}\right)$ in GYGA, with $Yw_{wheat,cz_{ij}}$ = water-limited wheat yield potential for climate zone i in country j from GYGA and $Ya_{wheat,cz_{ij}}$ = actual wheat yield for climate zone i in country j from GYGA.

YRm_{wheat,co_j} = the maximum yield ratio for wheat in country j, defined as $\frac{Y_{max,wheat,EU}}{Ya_{wheat,co_j}}$, where $Y_{max,wheat,EU}$ is the is maximum value for the actual yield for wheat in the EU (using country-level data in INTEGRATOR) and $Ya_{wheat,country_j}$ is the actual wheat yield for country j in INTEGRATOR

YRm_{crop_n,co_j} = the maximum yield ratio for crop n in country j, defined as $\frac{Y_{max,crop_n,EU}}{Ya_{crop_n,co_j}}$, where $Y_{max,crop_n,EU}$ is the is maximum value for the actual yield for crop n in the EU (using country-level data in INTEGRATOR) and Ya_{crop_n,co_j} is the actual country-level yield for crop n in country j in INTEGRATOR.

The maximum yield ratio for other crops as compared to wheat (YRm_{crop}/YRm_{wheat}) was added to account for differences in yield variability between wheat and other crops. We also considered scaling without using this correction and checked the potential improvement by comparing the results with given crop yield gap data for barley and maize (see Annex A2.1). For a few crop groups, and for those NCUs where no climate zone with wheat yield data could be assigned, we made exceptions to this scaling procedure (see Annex A2.2 and Annex A2.3). For grassland, we only applied the scaling to intensive grassland, as we assumed that extensive grasslands will not be managed by farmers to maximise yields (as grass from these grasslands is not a commodity traded on markets, it does not make sense for farmers to increase production unless they keep more animals).

As it is unrealistic to expect that farmers will increase yields until the biophysical potential, we perform all calculations for required N inputs for a target yield that is set to 80% of the water-limited yield potential, which is considered the maximum exploitable yield for farmers under most circumstances given economic and environmental considerations (Lobell et al., 2009; Van Ittersum et al., 2013). The target yield for crop n in climate zone i of country j was thus calculated as:

$$Ytarget_{crop_n,cz_{ij}} = 0.8 * Yw_{crop_n,cz_{ij}} \quad (2)$$

For certain crop-country combinations, 80% of the scaled yield potential was smaller than the actual yield in INTEGRATOR (see Annex A2.4). In those cases, we set the target yield to the actual yield.

2.3.2 Required nitrogen inputs

Calculations of required N inputs to achieve target yields
In order to calculate required N inputs (N inputs that are needed to achieve target yields), we multiplied actual N inputs with the ratio of target yield and the actual yield:

$$Nin_{req} = \frac{Ytarget}{Ya} * Nin_{act} \quad (3)$$

Where:

Nin_{req} = Total required N input (kg N ha^{-1} yr^{-1})
Ytarget = Target yield (see Section 2.3.1) (kg dry matter ha^{-1} yr^{-1})
Ya = Actual yield (kg dry matter ha^{-1} yr^{-1})
Nin_{act} = Total actual N inputs, the sum of actual N inputs from fertilizer, N fixation, excretion, biosolids, deposition and mineralization (kg N ha^{-1} yr^{-1})

We assumed that all required additional N is fertilizer N, and all other inputs stay constant. Required N inputs from fertilizer were thus calculated as:

$$Nfert_{req} = Nin_{req} - Nex - Nbs - Nfix - Ndep - Nmin \quad (4)$$

Where:

$Nfert_{req}$ = Total required N inputs from fertilizer to achieve target yields (kg N ha^{-1} yr^{-1})
Nex = Total actual (year 2010) N excretion (kg N ha^{-1} yr^{-1})
Nbs = Total actual (year 2010) N biosolids inputs (kg N ha^{-1} yr^{-1})
Nfix = Total actual (year 2010) biological N fixation (kg N ha^{-1} yr^{-1})
Ndep = Total actual (year 2010) N deposition (kg N ha^{-1} yr^{-1})
Nmin = Total actual (year 2010) N mineralization (kg N ha^{-1} yr^{-1})

N uptake and N losses at required N inputs were derived by scaling actual uptake and losses with ratio of target yield and the actual yield.

This calculation of required N inputs and associated losses implicitly assumes that the NUE of the required N inputs is the same as the NUE of the actual N inputs. On the one hand, this may represent an overestimation of required N inputs, since all additional inputs are from fertilizer and fertilizer N inputs have a higher NUE than N inputs from other sources (mainly manure. On the other hand, the yield response to higher N inputs is lower at high yields (law of diminishing returns), which implies a decrease in NUE at higher N inputs, which compensates for this underestimation of the NUE of added N fertilizer.

2.4 Assessment of critical inputs and losses of nitrogen

Critical N inputs in view of adverse environmental impacts were derived in three steps:

1. Identification of critical values (critical limits) for defined N indicators related to N concentrations in air and water (see Section 2.4.1),
2. Assessment (back-calculation) of critical N losses to air and water that correspond to the critical values of the identified N indicators (see Section 2.4.2), and
3. Assessment (back-calculation) of critical N inputs and related N fertilization and N excretion rates that correspond to the critical N losses (see Section 2.4.2).

'Critical' nitrogen inputs refer to N sources that can be managed by the farmer: manure, fertilizer, biosolids and biological N fixation, being determined by the sown crops. We distinguished three N thresholds or indicators for which critical N inputs were calculated: (i) critical N deposition on natural ecosystems, (ii) critical nitrate (NO_3^-) concentration in leachate to groundwater and (iii) critical nitrogen concentration in runoff to surface water (See Figure 4). The identification of critical values, the back-calculation approaches and input data that were used to perform the calculations are described below.

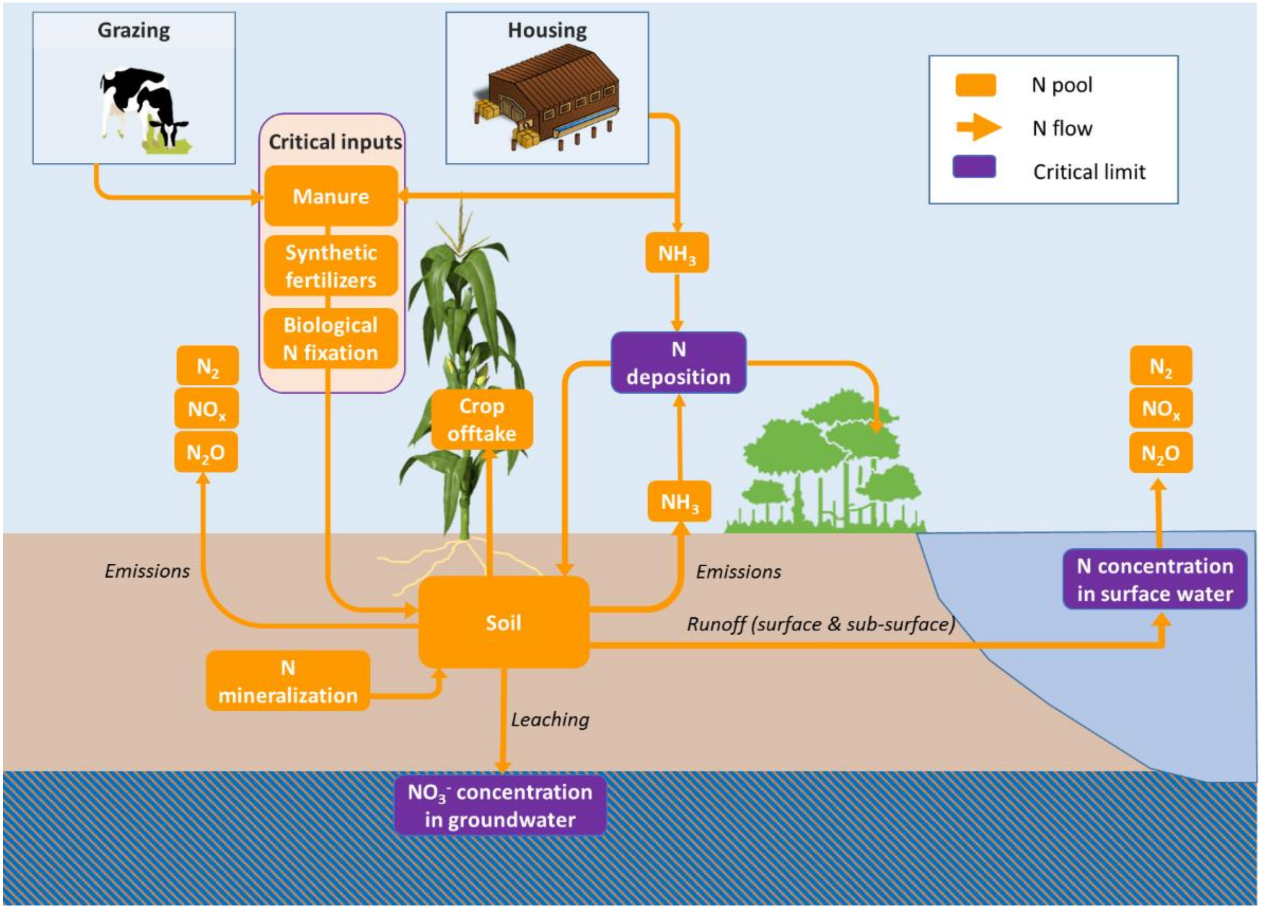

Figure 4 *Simplified scheme of the N flows and N indicators considered in the calculations of critical nitrogen inputs. Nitrogen indicators for which critical limits are set are shown as purple boxes.*

2.4.1 Critical values for nitrogen indicators and related critical N losses

Figure 5 gives a summary of the used nitrogen indicators for which critical limits / thresholds were assessed and their use in is assessing critical N losses and ultimately critical N inputs.

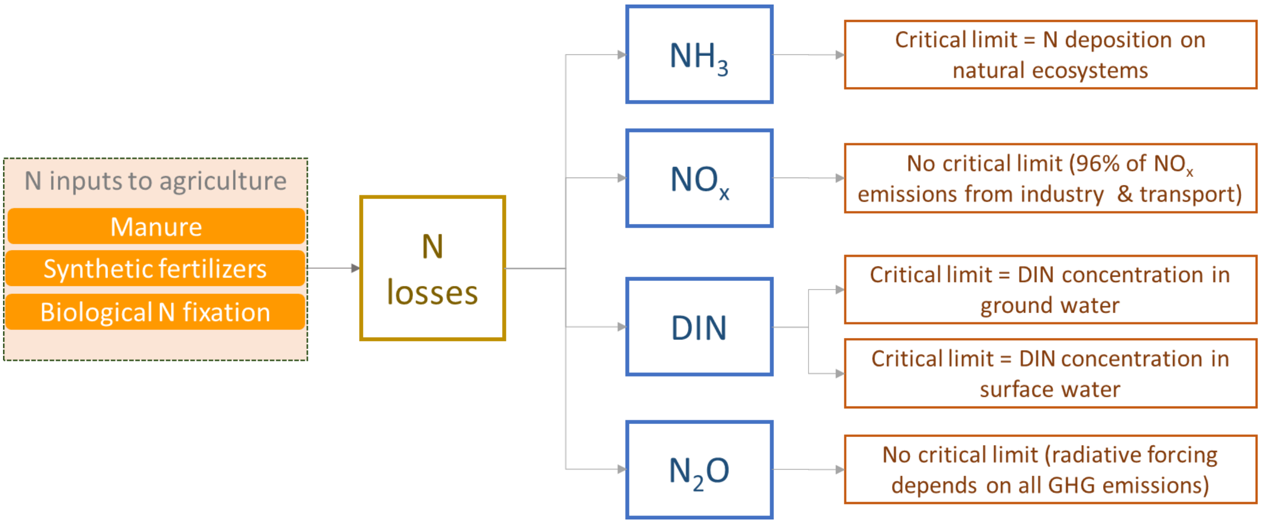

Figure 5 *Schematic overview of the nitrogen indicators used with critical limits and their relationship with calculated N losses. DIN is dissolved inorganic nitrogen. For N in ground water, it is nitrate, but this practically comparable to DIN since NH4 in ground water is nearly always negligible.*

Critical N deposition in view of eutrophication of terrestrial ecosystems

Critical levels of NH_3 emission from agricultural land were derived from the critical N deposition on natural terrestrial ecosystems, while correcting for the fraction NH_3 in total N deposition and the fraction agricultural land in an NCU (see Section 2.4.2). To assess N deposition levels that cause eutrophication and related biodiversity decline in terrestrial ecosystems (especially declines in plant species diversity), we used the so-called critical N loads. More specifically, area-weighted mean critical N loads at NUTS3 resolution were used to assess critical NH_3 emission rates from agriculture. In Europe, the critical N loads for terrestrial ecosystems in nature areas are based on either empirical values, as described in Bobbink et al. (2003), or on model calculations, as the sum of the current N offtake, a critical N leaching rate and a related critical N denitrification rate (e.g. De Vries et al., 2007). Both methods have their advantages and disadvantages as summarized in De Vries et al. (2010). Maps of critical N loads for Europe thus derived have been published in various reports and papers (e.g. Hettelingh et al., 2014; Hettelingh et al., 2015).

The disadvantage of using those maps is the difference in methods used by different countries, i.e. empirical values, or model calculations or a combination of both methods, sometimes leading to relative large differences in critical N loads at country borders. We thus used a consistent model based approach over Europe to calculate critical N loads, using a critical N concentration in soil solution of 3 mg N l^{-1} for forests and 3.5 mg N l^{-1} for semi-natural vegetation, being values in which changes in vegetation are to be expected (De Vries et al., 2007). The input data for the calculations on the European scale consisted of spatial information describing land cover, soils and climate variables that were derived by overlaying and combining maps and data bases of (i) land cover, using a harmonised land cover map for Europe (Slootweg et al., 2005), (ii) soils, using the European Soil Database v2 polygon map (JRC, 2006) and (iii) a high resolution European data base with meteorological data (Mitchell et al., 2004). Only in areas with high rainfall where the model based approach lead to implausible high critical N loads, we used the formally accepted critical N loads as presented in e.g. Hettelingh et al. (2014). Results based on this approach gave comparable patters for critical N inputs at EU level as the officially published data sets, but patterns did not show the abrupt country differences due to methodological differences.

Critical N concentration in runoff in view of eutrophication of surface water
As N indicator for eutrophication of aquatic ecosystems, and related impacts on aquatic species, we identified critical concentrations of dissolved total N in surface water in the range of 1.0-2.5 mg N l^{-1}. This range is based on (i) an extensive study on the ecological and toxicological effects of inorganic N pollution (Camargo & 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). For this study, we used the upper limit of 2.5 mg N l^{-1}.

Critical N concentration in leaching to groundwater in view of health impacts
The critical NO_3^- concentration in groundwater was set to the WHO drinking water limit of 50 mg NO_3 l^{-1} or 11.3 mg NO_3-N l^{-1}. This value is based on epidemiological evidence for methemoglobinemia in infants (WHO, 2011). As with runoff, critical N leaching rates from agriculture were calculated by multiplying the precipitation surplus with a critical N concentration, using 11.3 mg NO_3-N l^{-1}.

Critical nitrous oxide emissions in the context of climate change
N inputs also cause N_2O emissions, but as there are no limits for N_2O emissions, apart from a required reduction target, this aspect is not included in the assessment. Another argument for not including N_2O emissions is the fact that NH_3 emissions due to agricultural N inputs cause an enhanced CO_2 sequestration in response to elevated NH_3 deposition, largely compensating for the increase in radiative forcing caused by N_2O emissions, so that the overall effect of N use in agriculture in Europe is near neutral (De Vries et al., 2011a).

2.4.2 Back-calculation of critical nitrogen inputs and critical N losses

Overall approach
Total critical N inputs are the sum of the N inputs by fertilizer, animal manure, biosolids, biological fixation, deposition and mineralisation (see Eq. (5)). Critical inputs were calculated as the sum of N uptake, critical N emissions to air (NH_3, N_2O, NO_x and N_2 emissions) and critical N losses to water (leaching and runoff), using criteria related to either NH_3 emissions N leaching or N runoff (Eq. (6)).

$$N_{in(crit)} = N_{fe+fix(crit)} + N_{ex+bs(crit)} + N_{dep(crit)} + N_{min} \quad (5)$$

$$N_{in(crit)} = N_{off(crit)} + N_{de(crit)} + N_{em(crit)} + N_{sw(crit)} + N_{gw(crit)} \quad (6)$$

Where:

$N_{in(crit)}$	=	Critical nitrogen input (critical N load) (kg N ha^{-1} yr^{-1})
$N_{fe+fix(crit)}$	=	Critical N inputs from mineral fertilizers and biological N fixation (kg N ha^{-1} yr^{-1})
$N_{ex+bs(crit)}$	=	Critical N inputs from manure excretion and biosolids application (kg N ha^{-1} yr^{-1})
$N_{dep(crit)}$	=	N deposition at critical inputs from fertilizer, BNF, excretion and biosolids (kg N ha^{-1} yr^{-1})
N_{min}	=	N inputs from mineralization (only on peat soils) (kg N ha^{-1} yr^{-1})
$N_{off(crit)}$	=	Nitrogen crop offtake (removal by harvest) at critical N input (kg N ha^{-1} yr^{-1})
$N_{de(crit)}$	=	N denitrification (set equal to N_2 emission) from the soil at critical N input (kg N ha^{-1} yr^{-1})
$N_{em(crit)}$	=	Total N (NH_3+N_2O+NO_x) emissions from agriculture at critical N inputs (kg N ha^{-1} yr^{-1})
$N_{sw(crit)}$	=	Critical nitrogen runoff (surface + sub-surface) to surface water (kg N ha^{-1} yr^{-1})
$N_{gw(crit)}$	=	Critical nitrogen leaching to groundwater (kg N ha^{-1} yr^{-1})

Based on a critical limit for either NH_3 emission, $NH3_{em(crit)}$, N concentration in runoff to surface water (determining $N_{sw(crit)}$) or NO_3 in leaching to groundwater (determining $N_{le(crit))}$), the critical N input is calculated by a back-calculation approach.

The back-calculation approach is based on a slightly simplified version of the forward calculations in INTEGRATOR. Figure 6 illustrates the linkage between N inputs, N offtake and N losses.

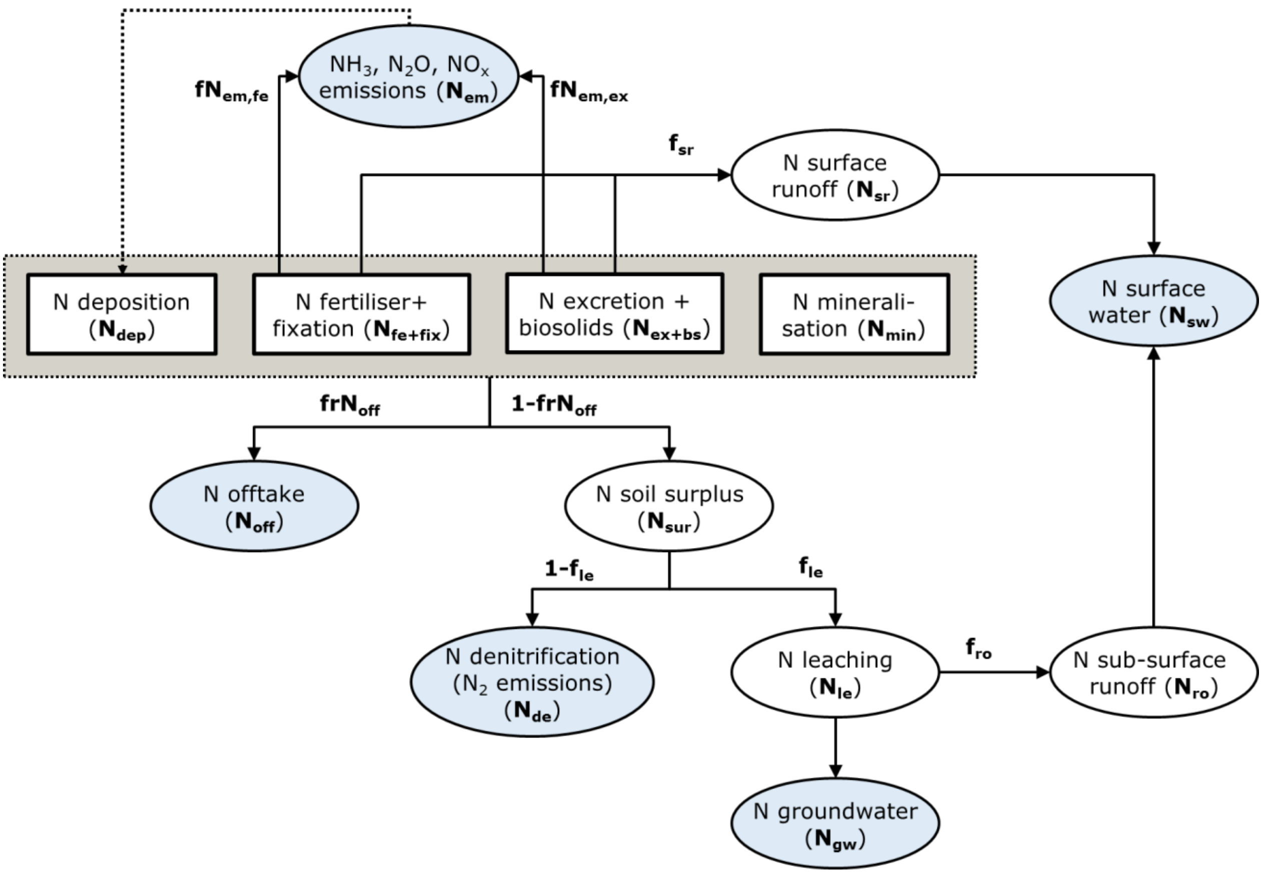

Figure 6 *Illustration of simplified model version used for calculating critical N input, showing links between N inputs, N losses to air as N emissions (NH_3, N_2O and NO_x) and denitrification (N_2 emissions) and N losses to groundwater and surface water due to N leaching and N runoff. All N flows are expressed in kg N ha^{-1} yr^{-1}. The grey box shows total N inputs, the blue circles show total N outputs. Total N inputs are equal to total N outputs (assuming no soil accumulation). Critical N inputs are calculated for thresholds for NH_3-N emissions, N runoff to surface water or NO_3-N leaching to groundwater.*

Total N inputs consist of N inputs from fertilizer, biological fixation, excreted manure[1], biosolids, deposition and mineralisation (grey box with dashed outline in Figure 6). Total N outputs consist of N offtake, N losses to air due to N emissions and denitrification, and N losses to water due to N surface runoff, N leaching and N runoff (blue circles in Figure 6).

In the back-calculations we lumped N fixation and N fertilizer together, and also lumped N biosolids and N excretion together. Inputs from N deposition are assumed to be a function NH_3 emissions, as indicated by the dashed arrow in in Figure 6, and inputs from N mineralization (only on peat soils) are considered constant. We further assumed that (i) the N offtake fraction (frN_{off}), calculated as N offtake divided by total inputs minus N emissions and N surface runoff, is constant and equal to the 2010 value, and that the relative contribution of fertilizer plus fixation to total farmer-managed inputs (i.e., the sum of fertilizer, fixation, manure and biosolids) is constant and equal to the 2010 value. Below we first describe how each N flux is calculated in the back-calculations, and then present the calculations of critical N inputs related to critical NH_3 emissions, critical N runoff to surface water and critical N leaching to groundwater.

[1] A 'Gross Nutrient Balance' (GNB) approach takes an 'extended' soil surface (or land) as system boundary and includes also the N losses from housing and manure management systems to obtain a proxy for the overall environmental pressure including the pollution of soil, water and air (OECD, 2008). The difference between a soil budget and a land budget according to this reference is the definition of manure input. Since land is defined as the soil plus the housing systems on it, the manure input is equal to excretion, while the manure input in a soil budget is equal to the applied manure excluding the NH_3 emitted from housing systems.

In calculating critical N inputs to agriculture, we assumed that the relative contribution of N fertilizer and N fixation (N_{fe+fix}) and N manure and N biosolids (N_{ex+bs}) is constant.

$$N_{fe+fix(crit)} = fN_{fe} * (N_{fe+fix(crit)} + N_{ex+bs(crit)}) \tag{7}$$

Where:

fN_{fe} = Fraction N inputs from fertilizer and fixation in total critical N inputs (constant) (-)

The **fraction N inputs from fertilizer and fixation** in total critical N inputs (fN_{fe}) is calculated by dividing actual N inputs from fertilizer and fixation by actual N inputs from fertilizer, fixation, manure and biosolids for each crop/NCU combination:

$$fN_{fe} = \frac{N_{fe(2010)}+N_{fix(2010)}}{N_{fe(2010)}+N_{fix(2010)}+N_{am(2010)}+N_{bs(2010)}} \tag{8}$$

Where:

$N_{fe(2010)}$ = Total N mineral fertilizers inputs to soil for the year 2010 (kg N ha^{-1} yr^{-1})

$N_{am(2010)}$ = Total N manure inputs to soil (application + grazing) for the year 2010 (kg N ha^{-1} yr^{-1})

$N_{fix(2010)}$ = Total biological N fixation for the year 2010 (kg N ha^{-1} yr^{-1})

$N_{bs(2010)}$ = Total N biosolids inputs for the year 2010 (kg N ha^{-1} yr^{-1})

N offtake by harvest at critical inputs ('critical offtake') is assumed to be a fixed fraction of total N inputs minus surface runoff and emissions:

$$N_{off(crit)} = frN_{off} * \left(N_{fe+fix(crit)} + N_{ex+bs(crit)} + N_{dep(crit)} + N_{\min} - N_{sr(crit)} - N_{em(crit)}\right) \tag{9}$$

Where:

frN_{off} = N offtake fraction (constant) (kg N ha^{-1} yr^{-1})

$N_{sr(crit)}$ = N surface runoff at critical N inputs (kg N ha^{-1} yr^{-1})

The **offtake fraction** is assumed to be equal to the offtake fraction for the year 2010. The offtake fraction is thus calculated for each crop-NCU combination as:

$$frN_{off} = \frac{N_{off}(2010)}{N_{fe(2010)}+N_{am(2010)}+N_{fix(2010)}+N_{bs(2010)}+N_{min(2010)}+N_{dep(2010)}-N_{sr}(2010)-N_{em(2010)}} \tag{10}$$

Where:

$N_{off(2010)}$ = Total N offtake by harvest for the year 2010 (kg N ha^{-1} yr^{-1})

$N_{min(2010)}$ = Total N mineralisation for the year 2010 (peat soils only) (kg N ha^{-1} yr^{-1})

$N_{dep(2010)}$ = Total N inputs from N deposition for the year 2010 (kg N ha^{-1} yr^{-1})

$N_{sr(2010)}$ = Surface runoff for the year 2010 (kg N ha^{-1} yr^{-1})

$N_{em(2010)}$ = Total N (NH_3, NO_x, N_2O) emissions for the year 2010 (kg N ha^{-1} yr^{-1})

N emissions (NH_3, N_2O, NO_x) at critical inputs ('critical emissions') are calculated as a fraction of critical N inputs from fertilizer and fixation, and from excretion + biosolids:

$$NH3_{em(crit)} = N_{fe+fix(crit)} * fNH3_{em,fe} + N_{ex+bs(crit)} * fNH3_{em,ex} \tag{11}$$

$$N2O_{em(crit)} = N_{fe+fix} * fN2O_{em,fe} + N_{ex+bs(crit)} * fN2O_{em,ex} \tag{12}$$

$$NOx_{em(crit)} = N_{fe+fix(crit)} * fNOx_{em,fe} + N_{ex+bs(crit)} * fNOx_{em,ex} \tag{13}$$

$$N_{em(crit)} = N_{fe+fix(crit)} * fN_{em,fe} + N_{ex+bs(crit)} * fN_{em,ex} \tag{14}$$

Where:
$NH_{3em(crit)}$ = NH_3 emissions from agriculture at critical N inputs (kg N ha^{-1} yr^{-1})
$N_2O_{em(crit)}$ = N_2O emissions from agriculture at critical N inputs (kg N ha^{-1} yr^{-1})
$NO_{xem(crit)}$ = NO_x emissions from agriculture at critical N inputs (kg N ha^{-1} yr^{-1})
$fNH3_{em,fe}$ / $fN2O_{em,fe}$ / $fNOx_{em,fe}$ = NH_3 / N_2O / NO_x emission fraction from fertiliser applied to land (-)
$fNH3_{em,ex}$ / $fN2O_{em,ex}$ / $fNOx_{em,ex}$ = NH_3 / N_2O / NO_x emission fraction from manure excretion (-)
$fN_{em,fe}$ = Total N (NH_3+N_2O+NO_x) emission fraction from fertiliser applied to land (-)
$fN_{em,ex}$ = Total N (NH_3+N_2O+NO_x) emission fraction from manure excretion (-)

Values for $fNH3_{em,fe}$ ($fN2O_{em,fe}$, $fNOx_{em,fe}$) were derived by dividing total NH_3 (N_2O, NO_x) emissions from fertilizer by total N inputs from fertilizer per crop and NCU. Values for $fNH3_{em,ex}$ ($fN2O_{em,ex}$, $fNOx_{em,ex}$) were derived by dividing total NH_3 (N_2O, NO_x) emissions from housing and manure storage, application and grazing by total N excretion at country level.

N deposition at critical N inputs ('critical deposition') is assumed to be a fixed fraction of NH_3 emissions at critical N inputs and the (constant) fraction agricultural land (f_{ag}) and the fraction NH_3 deposition in total deposition (fNH_3) (see further Eq. (23) and Annex A3.1 for the assumptions and derivation):

$$N_{dep(crit)} = NH3_{em(crit)} * \frac{f_{ag}}{f_{NH3}} \tag{15}$$

N surface runoff at critical N inputs ('critical surface runoff') is calculated as a fixed fraction of critical N inputs. The runoff fraction (f_{sr}) is the same value as in the forward calculations (see Annex A1.5).

$$N_{sr(crit)} = f_{sr} * (N_{fe+fix(crit)} + N_{ex+bs(crit)}) \tag{16}$$

N leaching below the rooting zone at critical N inputs ('critical leaching') is calculated as a fixed fraction of the critical N surplus, which in turn is calculated as the sum of critical N inputs minus surface runoff, emissions and offtake. The leaching fraction (f_{le}) is the same value as in the forward calculations (see Annex A1.5). Denitrification is calculated by multiplying the soil N surplus by 1 minus the leaching fraction.

$$N_{le(crit)} = f_{le} * N_{sur(crit)} \tag{17}$$

$$N_{de(crit)} = (1 - f_{le}) * N_{sur(crit)} \tag{18}$$

$$N_{sur(crit)} = N_{fe+fix(crit)} + N_{ex+bs(crit)} + N_{dep(crit)} + N_{min} - N_{sr(crit)} - N_{em(crit)} - N_{off(crit)} \tag{19}$$

N sub-surface runoff to surface water ('critical sub-surface runoff') is calculated as a fixed fraction of critical leaching. The sub-surface runoff fraction (f_{ro}) is the same value as in the forward calculations (see Annex A1.5).

$$N_{ro(crit)} = f_{ro} * N_{le(crit)} \tag{20}$$

The remainder of leaching (N_{le}-N_{ro}) is assumed to be N flux to groundwater (N_{gw}):

$$N_{gw(crit)} = (1 - f_{ro}) * N_{le(crit)} \tag{21}$$

Total N inputs to surface water (N_{sw}) are the sum of N surface runoff and N sub-surface runoff:

$$N_{sw(crit)} = N_{sr(crit)} + N_{ro(crit)} \tag{22}$$

Calculation of critical NH_3 emissions and associated critical N inputs from critical levels of N deposition

NH_3 emissions from agriculture to air are diluted by emission from non-agricultural land in the area. Therefore we accounted for differences in the fraction agricultural land in an NCU in assessing critical NH_3 emissions. Critical levels of NH_3 emission from agricultural land were calculated as:

$$NH3em_{(crit)} = Ndep_{tot(crit)} * \frac{f_{NH3}}{f_{ag}} \tag{23}$$

Where:

$Ndep_{tot(crit)}$ = Critical N deposition on non-agricultural terrestrial ecosystems, calculated as the area-weighted average critical N load for those ecosystems in nature areas (see Section 2.4.1) (kg N ha^{-1} yr^{-1})

The calculated NH_3 emissions are based on the assumptions that within an NCU (i) the average N deposition rate on agricultural land equals the average N deposition rate on non-agricultural land (both in kg N ha^{-1}), (ii) the amount of NH_3 that is emitted (coming from agriculture) is deposited in the same region, but then on all (agricultural land and non-agricultural) land (both in kg N) and (iii) the current shares of NH_3 and NO_x in total N deposition stay constant (and thus NOx emissions/deposition increase or decrease in the same proportion as NH_3 emissions/deposition). The derivation of Eq. (23), based on these assumption is given in Annex A3.1.

As shown in Equation (11), critical NH_3 emissions are a function of critical N inputs from fertilizer (+ fixation) and from excretion (+ biosolids), and (constant) emission fractions for both inputs. Once critical NH_3 emissions, $NH3em_{(crit)}$, are calculated with Eq. (23), Eq. (11) contains two unknowns, i.e. $N_{fe+fix(crit)}$ and $N_{ex+bs(crit)}$. By assuming that the relative contribution of N fertilizer and N fixation (N_{fe+fix}) and N excretion by animals and N biosolids (N_{ex+bs}) is equal to the 2010 value (see Eq. 7), we can express $N_{fe+fix(crit)}$ as a function of $N_{ex+bs(crit)}$:

$$N_{fe+fix(crit)} = \frac{fN_{fe}}{1-fN_{fe}} * N_{ex+bs(crit)} \tag{24}$$

The value for fN_{fe} is derived in Eq. (8). Replacing $N_{fe+fix(crit)}$ in Eq. (11) with the right-hand side of Eq. (24) and solving the equation for $N_{ex+bs(crit)}$, critical N inputs from excretion in view of critical NH_3 emission can be derived as

$$N_{ex+bs(crit,NH3)} = \frac{NH3em_{(crit)}}{fNH3_{em,ex}+fNH3_{em,fe}*\frac{fN_{fe}}{1-fN_{fe}}} \quad (25)$$

Where:

$N_{ex+bs(crit,NH3)}$ = Critical N inputs from excretion and biosolids in view of a critical ammonia emission rate (kg N ha^{-1} yr^{-1})

The related critical N input from fertilizer and fixation can be calculated with equation (24).

Equation (25) implies that the critical nitrogen input to the soil via fertiliser ($N_{fe+fix(crit,NH3)}$) and excretion ($N_{ex+bs(crit,NH3)}$) in view of critical NH_3 emissions depends on (i) the NH_3 emission fraction for fertiliser applied to land ($fNH3_{em,fe}$), (ii) the NH_3 emission fraction for excretion ($fNH3_{em,ex}$) and the share of N fertilizer + fixation in total critical inputs (fN_{fe}). The total critical N inputs also include the N deposition at critical inputs ($N_{dep(crit,NH3)}$; calculated with Eq. (15)) and N inputs from mineralization for peat soils (N_{min}), which are assumed constant.

The related offtake $N_{off(crit,NH3)}$ was calculated with Eq. (9), while related N flux to groundwater $N_{gw(crit,NH3)}$ and surface water $N_{sw(crit,NH3)}$ were calculated with Eqs. (21) and (22). While calculations were made assuming that emission fractions remain the same at critical inputs, calculations could also be made with estimated future fractions, based on expected changes.

Equations for estimating N (NH_3, N_2O and NO_x) emissions were parameterized in such a way that emission fractions include all losses, including those from animal housing and manure storage systems and from the application of animal manure, fertilizers and dung and urine from grazing animals to the soil. The approach implicitly assumes that manure applied to the soil in a given grid cell (external data) comes from the farms in the same grid cell (which is not always true, as manure excreted in housing systems is sometimes allocated for application in neighbouring NCUs if otherwise maximum application rates are exceeded).

Calculation of critical N runoff and associated critical N inputs from critical N concentrations in surface water

Nitrogen inputs from fertilizer and manure are susceptible to runoff. Total runoff consists of two components: (i) surface runoff (or direct runoff) (N_{sr}), being a fraction of N inputs and (ii) sub-surface runoff (N_{ro}), being a fraction of N leaching below the root zone (see Figure 7, left). Similarly, total precipitation surplus (Q_{tot}) is distributed over surface runoff (Q_{sr}), sub-surface runoff (Q_{ro}) and leaching to groundwater (Q_{gw}) (see Figure 7, right).

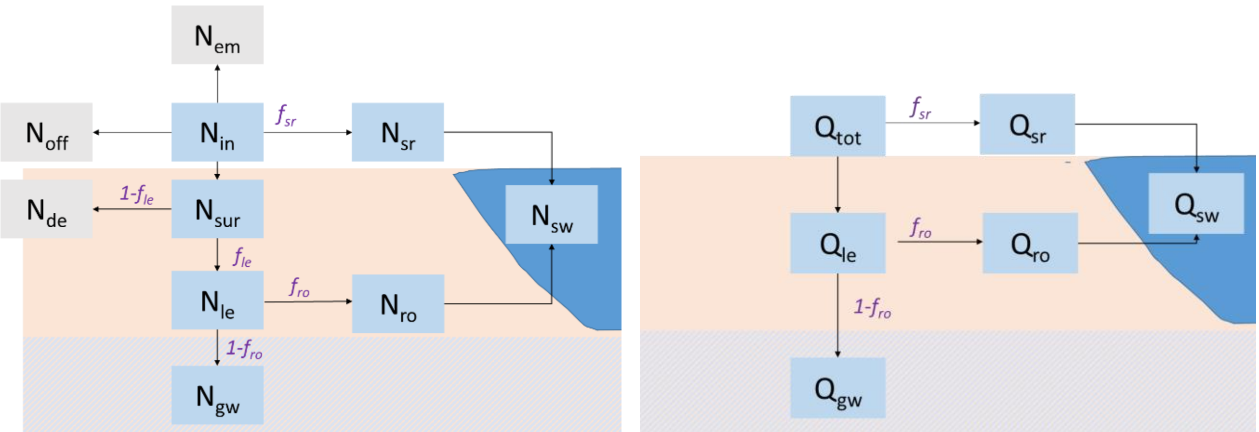

Figure 7 *Illustration of approach used for back-calculating N flows to surface water and groundwater. Left scheme shows N flows and fractions, right scheme shows water flows and fractions that determine how total runoff (Q_{tot}) is distributed over the various flows.*

Runoff to surface water comes both from agricultural and non-agricultural land. Runoff from non-agricultural land usually has a lower N concentration and thus dilutes the N concentration in runoff from agricultural land. As with critical NH_3 emissions, we thus account for differences in the fraction agricultural land in a region, according to:

$$[N]_{water} = f_{ag} * [N]_{ag} + \left(1 - f_{ag}\right) * [N]_{nag} \qquad (26)$$

Where:

$[N]_{water}$ = N concentrations in total runoff to surface water (mg N l^{-1})
$[N]_{ag}$ = N concentrations in runoff from agricultural land (mg N l^{-1})
$[N]_{nag}$ = N concentrations in runoff from natural land (mg N l^{-1})

The critical N concentration in runoff from agricultural land, $[N_{ag}]_{(crit)}$, can thus be calculated as:

$$[N]_{ag(crit)} = \frac{[N]_{water(crit)} - (1 - f_{ag}) * [N]_{nag}}{f_{ag}} \qquad (27)$$

We used an average value of 0.5 mg N l^{-1} for the N concentration in runoff from non-agricultural land, $[N]_{nag}$. A value of 0.5 mg N l^{-1} for streams/catchments in forests has been suggested by Gundersen et al. (2006) as the level at which a forest ecosystem can be considered 'leaky'. Their assessment is based on an overview of current water quality in forests by compiling studies from the 1990s on nitrate concentration in seepage water from temperate forests, including >500 sites from Europe. On the basis of data from 128 forested plots, De Vries et al. (2007) calculated a median N output near 1 kg N ha^{-1} yr^{-1}, which equals an N concentration of 0.5 mg N l^{-1} for a median precipitation surplus of 200 mm yr^{-1}.

For the critical N concentration in runoff to surface water, we used a value of 2.5 mg N l^{-1} (see Section 2.4.1). When using a critical concentration for total runoff to surface water of 2.5 mg N l^{-1} and concentration of 0.5 mg N l^{-1} for runoff from natural land, equation (27) becomes:

$$[N]_{ag(crit)} = \frac{2 + 0.5 * f_{ag}}{f_{ag}} \qquad (28)$$

The total critical N runoff flux towards surface water, $N_{sw(crit)}$, is the sum of surface and sub-surface runoff:

$$N_{sw(crit)} = N_{sr(crit)} + N_{ro(crit)} \qquad (29)$$

Where

$N_{ro(crit)}$ = Critical N sub-surface runoff to surface water (kg N ha^{-1} yr^{-1})

The total critical N runoff flux can be derived from the critical N concentration in runoff from agricultural land by multiplying the critical N concentration with the total water runoff volume to surface water (the sum of surface runoff Q_{sr} + sub-surface runoff Q_{ro}) and a correction factor:

$$N_{sw(crit)} = [N]_{ag(crit)} * cF_{cN} \; * (Q_{sr} + Q_{ro}) \qquad (30)$$

Where

Q_{sr} = Water flux to surface water via surface runoff (m^3 m^{-2} yr^{-1})
Q_{ro} = Water flux to surface water via sub-surface runoff (m^3 m^{-2} yr^{-1})
cf_{cN} = Conversion factor from mg N l^{-1} to kg N ha^{-1} /(m^3 m^{-2}), i.e. 10

$[N]_{ag(crit)}$ is given from equation (9); Q_{sr}, Q_{ro} and cf_{cN} are also given. By combining equations (17), (19) and (20), sub-surface runoff is calculated as:

$$N_{ro(crit)} = \left(N_{fe+fix(crit)} + N_{ex+bs(crit)} + N_{dep(crit)} + N_{min} - N_{em(crit)} - N_{sr(crit)} - N_{off(crit)}\right) * f_{le} * f_{ro} \qquad (31)$$

By substituting equation (15) into equation (31) for $N_{dep(crit)}$, equation (14) for $N_{em(crit)}$, equation (16) for $N_{sr(crit)}$ and equation (9) for $N_{off(crit)}$, we can calculate critical N inputs in view of critical N runoff to surface water as a function of the leaching fraction (fN_{le}), the N mineralization rate (for peat soils), the N offtake fraction (fN_{off}), N emission fractions for fertilizer and manure ($fN_{em,fe}$ and $fN_{em,ex}$), NH_3 emission fractions for fertilizer and manure ($fNH3_{em,fe}$, $frNH3_{em,ex}$), the surface runoff fraction (f_{sr}), fraction agricultural land (f_{ag}), the fraction NH_3 deposition in total deposition (f_{NH3}), the fraction of N fertilizer application compared to the sum of N fertilizer application and N excretion (fN_{fe}). Annex A3.2 shows the steps for the derivation of the formula to calculate critical N inputs from excretion and biosolids ($N_{ex+bs(crit,sw)}$), Eq. (A 3.2.1)). Critical N inputs from fertilizer and fixation ($N_{fe+fix(crit,sw)}$) are calculated with Eq. (24). Total critical N inputs also include inputs from N deposition ($N_{dep(crit,sw)}$; calculated with Eq. 15) and inputs from mineralization for peat soils (N_{min}), which are assumed constant.

Calculation of critical N leaching and associated critical N inputs from critical N concentrations in groundwater

The critical N concentration in groundwater is defined as 50 mg NO_3 l^{-1} (11.3 mg NO_3-N l^{-1}). This critical concentration can be related to a critical amount of N leaching to groundwater (N_{gw}) as follows:

$$[NO3]_{gw(crit)} = \frac{N_{gw(crit)}}{Q_{gw}} * cF_{cNO3} \qquad (32)$$

Or

$$N_{gw(crit)} = \frac{[NO3]_{gw(crit)}}{cF_{cNO3}} * Q_{gw} \qquad (33)$$

Where:

$[NO3]_{gw(crit)}$	=	Critical nitrate concentration in leaching flux towards groundwater (mg NO_3 l^{-1})
$N_{gw(crit)}$	=	Critical N leaching flux towards groundwater (kg N ha^{-1} yr^{-1})
Q_{gw}	=	Water flux leaching towards groundwater (m^3 m^{-2} yr^{-1})
cf_{cNO3}	=	Conversion factor from (kg N ha^{-1})/(m^3 m^{-2}) to mg NO_3 l^{-1}, i.e. (62/14)/10

Q_{gw} and cf_{cNO3} are known. The critical N leaching flux towards groundwater can be related to N inputs as:

$$N_{gw(crit)} = \left(N_{fe+fix(crit)} + N_{ex+bs(crit)} + N_{dep(crit)} + N_{min} - N_{em(crit)} - N_{sr(crit)} - N_{off(crit)}\right) * f_{le} * (1 - f_{ro}) \qquad (34)$$

By substituting equations (15) into equation (34) for $N_{dep(crit)}$, equation (14) for $N_{em(crit)}$, equation (16) for $N_{sr(crit)}$ and equation (9) for $N_{off(crit)}$, we can calculate critical N inputs in view of critical N leaching to groundwater as a function of the leaching fraction (fN_{le}), the N mineralization rate (for peat soils), the N offtake fraction (fN_{off}), N emission fractions for fertilizer and manure ($fN_{em,fe}$ and $fN_{em,ex}$), NH_3 emission fractions for fertilizer and manure ($fNH3_{em,fe}$, $fNH3_{em,ex}$), the surface runoff fraction (f_{sr}), the sub-surface runoff fraction (f_{ro}), the fraction agricultural land (f_{ag}), the fraction NH_3 deposition in total deposition (fNH_3), the fraction of N fertilizer application compared to the sum of N fertilizer application and N excretion (fN_{fe}). Annex A3.2 shows the steps for the derivation of the formula to calculate critical N inputs from excretion and biosolids ($N_{ex+bs(crit,gw)}$), Eq. (A 3.2.2)). Critical N inputs from fertilizer and fixation ($N_{fe+fix(crit,sw)}$) are calculated with Eq. (24). Total critical N inputs also include inputs to agricultural soils from N deposition ($N_{dep(crit,gw)}$; calculated with Eq. 15) and inputs from mineralization for peat soils (N_{min}), which are assumed constant.

2.4.3 Use of cut-off values in the calculation of critical N inputs

In areas where environmental constraints do not limit critical N inputs, critical N inputs need to be constrained by a maximum value, in order to avoid unrealistically high critical N inputs. We chose to cut-off critical N inputs at the N input that is needed to obtain a 'maximum' N uptake at current NUE. The maximum N uptake, in turn, is defined as the dry matter yield for the year 2010 multiplied by the maximum N content (see Table A1.2.1):

$$N_{in(max)} = \frac{N_{off(max)}}{NUE_{(2010)}} \quad (35)$$

$$N_{off(max)} = Yield_{(2010)} * Ncont, max \quad (36)$$

Where:
$N_{in(max)}$ = maximum N input (kg N ha^{-1} yr^{-1})
$N_{off(max)}$ = maximum N offtake (kg N ha^{-1} yr^{-1})
$NUE_{(2010)}$ = NUE for the year 2010 (-)
$Yield_{(2010)}$ = Crop dry matter yield for the year 2010 (kg DM ha^{-1} yr^{-1})
Ncont,max = maximum crop N content (kg N kg DM^{-1}); see Table A1.2.1

The maximum N uptake fraction ($fNup_{max}$) is calculated as:

$$fNup_{max} = \frac{N_{in(max)}}{N_{in(crit)}} \quad (37)$$

If $fNup_{max}$ is lower than one (i.e., if the critical N input is larger than the maximum N input), all terms of the N balance are re-calculated according to:

$$N_{in(crit,cutoff)} = N_{in(crit)} * fNup_{max} \quad (38)$$

$$N_{off(crit,cutoff)} = N_{off(crit)} * fNup_{max} \quad (39)$$

$$N_{loss(crit,cutoff)} = N_{loss(crit)} * fNup_{max} \quad (40)$$

Where:
$N_{in(crit,cutoff)}$ = Total critical N inputs (sum of N inputs from manure + biosolids, fertilize + fixation, deposition and mineralization) after cut-off (kg N ha^{-1} yr^{-1})
$N_{off(crit,cutoff)}$ = Crop N offtake at critical N inputs after cut-off (kg N ha^{-1} yr^{-1})
$N_{loss(crit,cutoff)}$ = N losses at critical inputs after cut-off. N losses can refer to either N emissions, N leaching, N runoff or N denitrification (kg N ha^{-1} yr^{-1})

Total critical N inputs after cutoff ($Nin_{(crit,cutoff)}$)are the sum of N inputs from manure + biosolids, fertilizer + BNF, deposition and mineralization. However, N inputs from mineralization are assumed to be constant. Therefore, critical N inputs from the other three terms after cutoff are calculated as:

$$N_{fe+fix(crit,cutoff)} = N_{fe+fix(crit)} * fN_{corr} \quad (41)$$

$$N_{ex+bs(crit,cutoff)} = N_{ex+bs(crit)} * fN_{corr} \quad (42)$$

$$N_{dep(crit,cutoff)} = N_{dep(crit)} * fN_{corr} \quad (43)$$

$$fN_{corr} = \frac{\left(N_{fe+fix(crit)}+N_{ex+bs(crit)}+N_{dep(crit)}\right)*fNup_{max}-N_{min}}{N_{fe+fix(crit)}+N_{ex+bs(crit)}+N_{dep(crit)}} \quad (44)$$

In areas where N inputs from mineralization alone exceeded maximum N inputs, N inputs from fertilizer +fixation, manure + biosolids and deposition are set to zero, and N inputs from mineralization are reduced according to:

$$N_{min(crit,cutoff)} = N_{min} * fNup_{max} \tag{45}$$

Due to this procedure (conducted so that balances close at critical N inputs), N mineralization at critical inputs can be lower than current N mineralization, even though N mineralization is in principle assumed to remain constant.

The impact of alternative choices for a cut-off value are explored in Section 4.1.

2.5 Assessment of necessary changes in ammonia emission fractions and nitrogen use efficiencies

The calculation of critical and required N inputs, described above, were all based on the assumption that the nitrogen use efficiency (NUE, defined as the ratio of N taken up by crops and the N inputs) as well as NH_3 emission fractions from fertilizer and manure are equal to the actual (year 2010) values. If critical N inputs are below actual N inputs, this implies that environmental objectives can only be reached at a lower N input, which likely would cause a loss in crop production, unless: (i) the NH_3 emission fractions are reduced (this allows a higher N input in the context of NH_3 emission and related N loads to ecosystems) or (ii) the nitrogen use efficiency (NUE) is increased (this allows a higher N input in the context of N loses to groundwater and surface water). This holds even stronger when target yields above actual yields are aimed for. We thus calculated necessary reductions in NH_3 emission reduction fractions and necessary increases in NUE to reconcile food production and environmental N losses, as described below.

2.5.1 Calculation of necessary (reductions in) ammonia emission fractions

For all NCUs where actual NH_3 emissions exceeded critical NH_3 emissions; we calculated 'necessary NH_3 emission fractions'. 'Necessary' emission fractions are defined as emission fraction at which we can achieve actual offtake (or target offtake) without exceeding critical NH_3 emission. The necessary NH_3 emission fraction related to all inputs per crop and NCU was calculated according to:

$$fNH3_{em(nec)} = \frac{NH3em_{(crit)}}{N_{fe(2010)}+N_{fix(2010)}+N_{bs(2010)}+N_{ex(2010)}-N_{export(2010)}} \tag{46}$$

Where:

$fNH3_{em(nec)}$ = Necessary NH_3 emission fraction for all inputs (-)
$NH3em_{(crit)}$ = Critical NH_3 emissions (kg N ha^{-1} yr^{-1})
$N_{fe(2010)}$ = Total N fertilizers inputs to soil for the year 2010 (kg N ha^{-1} yr^{-1})
$N_{fix(2010)}$ = Total biological N fixation for the year 2010 (kg N ha^{-1} yr^{-1})
$N_{bs(2010)}$ = Total N biosolids inputs for the year 2010 (kg N ha^{-1} yr^{-1})
$N_{ex(2010)}$ = Total N excretion (in housing systems + by grazing animals) for the year 2010 (kg N ha^{-1} yr^{-1})
$N_{export(2010)}$ = Total net manure export for the year 2010 (kg N ha^{-1} yr^{-1})

We also calculated the necessary NH_3 emission fraction for N excretion (including emissions from housing systems, manure application and grazing), assuming constant NH_3 emission fractions for fertilizer, according to:

$$fNH3_{em,ex(nec)} = \frac{fNH3_{em(nec)} - fN_{fe} * fNH3_{em,fe}}{1 - fN_{fe}} \tag{47}$$

Where:

$fNH3_{em,ex(nec)}$ = Necessary NH_3 emission fraction for N excretion (-)
$fNH3_{em,fe}$ = Actual NH_3 emission fraction from fertiliser applied to land (-)
fN_{fe} = Fraction N inputs from fertilizer and fixation in total critical N inputs (-)

We assumed a minimum NH_3 emission fraction for excretion of 0.05. The average necessary NH_3 emission fraction for N excretion was thus calculated by excluding all NCUs where $fNH3_{em,ex(nec)}$ was smaller than 0.05. For all NCUs where the necessary emission fraction was larger than the actual emission fraction (those NCUs where critical NH_3 emissions exceed actual NH_3 emissions), we set the necessary NH_3 emission fraction to the actual NH_3 emission fraction before calculating the average necessary emission fraction.

Finally, we calculate the necessary NH_3 emission fraction for N excretion, assuming that all fertilizer is replaced by nitrate fertilizers and that the emission fraction for all fertilizers is thus 2% as:

$$fNH3_{em,ex(nec,impr)} = \frac{fNH3_{em(nec)} - fN_{fe} * 0.02}{1 - fN_{fe}} \tag{48}$$

Again, we calculated the average necessary NH_3 emission fraction for N excretion at improved fertilizer by excluding all plots where $fNH3_{em,ex(nec,impr)}$ was smaller than 0.05, and by setting necessary to actual when $fNH3_{em,ex(nec,impr)}$ is larger than the actual emission fraction. Necessary NH_3 emission fractions were calculated both for current N inputs and required N inputs (inputs that are needed to achieve target yields).

Necessary reductions were then derived by comparing 'necessary' emission fractions for total N inputs and N excretion to actual emission fractions.

2.5.2 Calculation of necessary (increases in) nitrogen use efficiencies

If the NUE is increased, the actual or target crop yields can be reached at lower N inputs, due an enhanced N offtake fraction, while the critical N input increases since a lower fraction of N is lost to the environment (see Figure 8).

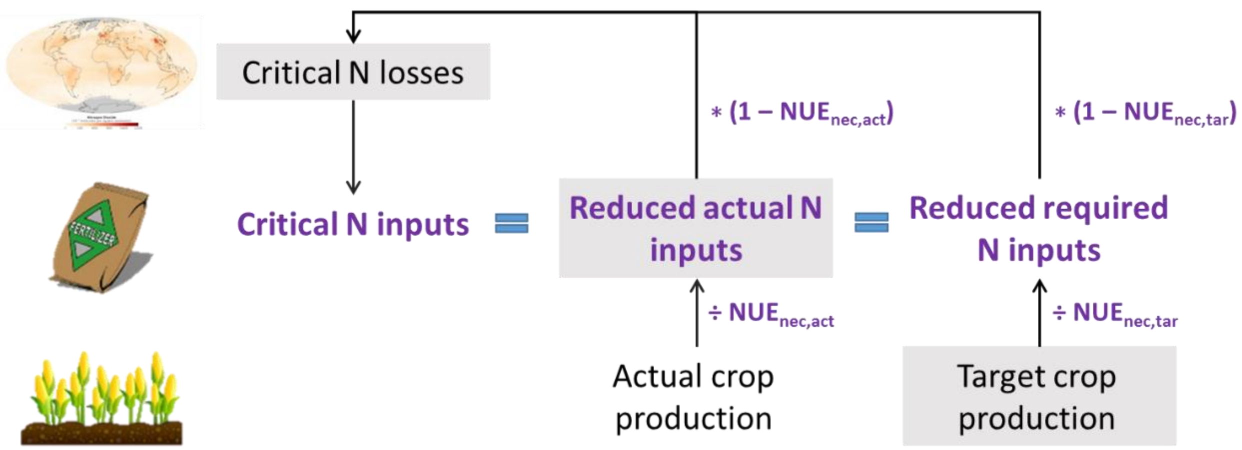

Figure 8 *Illustration of necessary NUE changes to reconcile crop production and environmental targets.*

For all cases where actual N runoff to surface water and/or actual N leaching to groundwater exceeded critical N values, we calculated the necessary NUE at which actual yields or target yields are attained without exceeding environmental limits. The necessary NUE was calculated using an iterative approach where we first calculate the necessary NUE as:

$$NUE_{(nec,act)} = \frac{N_{off(2010)}}{N_{off(2010)}+N_{de(crit)}+N_{sw(crit)}+N_{gw(crit)}+N_{em(crit)}} \quad (49)$$

Where

$N_{off(2010)}$ = Actual N offtake for the year 2010 (kg N ha^{-1} yr^{-1})

$N_{de(crit)}$ = N denitrification at critical N inputs (kg N ha^{-1} yr^{-1})

$N_{sw(crit)}$ = N runoff to surface water at critical N inputs (kg N ha^{-1} yr^{-1})

$N_{gw(crit)}$ = N leaching to groundwater at critical N inputs (kg N ha^{-1} yr^{-1})

$N_{em(crit)}$ = N emissions at critical N inputs (kg N ha^{-1} yr^{-1})

We then calculate the N inputs at the new NUE by dividing the actual (or target) offtake by the preliminary NUE, and then calculated the associated emissions and runoff + leaching belonging to these new inputs with the equations described in Section 2.4.2, and compare runoff + leaching to critical runoff or leaching. If the calculated value deviates more than 1%, we lower or increase the necessary NUE until critical runoff + leaching associated with the 'necessary' NUE is within 1% of critical runoff + leaching.

We calculate necessary NUEs both for actual and for target yields; and both for all agricultural land (crops + grassland). As N surface runoff is a function of N inputs (rather than N soil surplus), the necessary NUE can become larger than 1. We considered a maximum plausible NUE that farmers can achieve to be 0.9 (EU Nitrogen Expert Panel, 2015) considering unavoidable minimal losses of N to air and water. NCUs where the necessary NUE was larger than 0.9 were excluded when calculating the mean necessary NUE at country-level or EU-27 level. For all NCUs where the necessary NUE was lower than the actual NUE, we set necessary to actual before calculating the average necessary NUE. We also calculated the average necessary NUE by including all plots, but setting the maximum value for necessary NUE to 0.9.

3 Results

The calculated required N input, actual N input, and critical N inputs for all agricultural land at EU-27 level are given in Figure 9. The calculated critical N inputs are given separately for NH_3 emissions in view of critical N deposition and related eutrophication of terrestrial ecosystems, surface water eutrophication (N runoff) and groundwater quality (NO_3 leaching). Separate results for arable land vs. grassland & fodder, and for various arable crops are given in Annex A4.1. Actual, required and critical nitrogen inputs at country level are given in Annex 5. In all cases, a cut-off value is used for maximum critical N inputs.

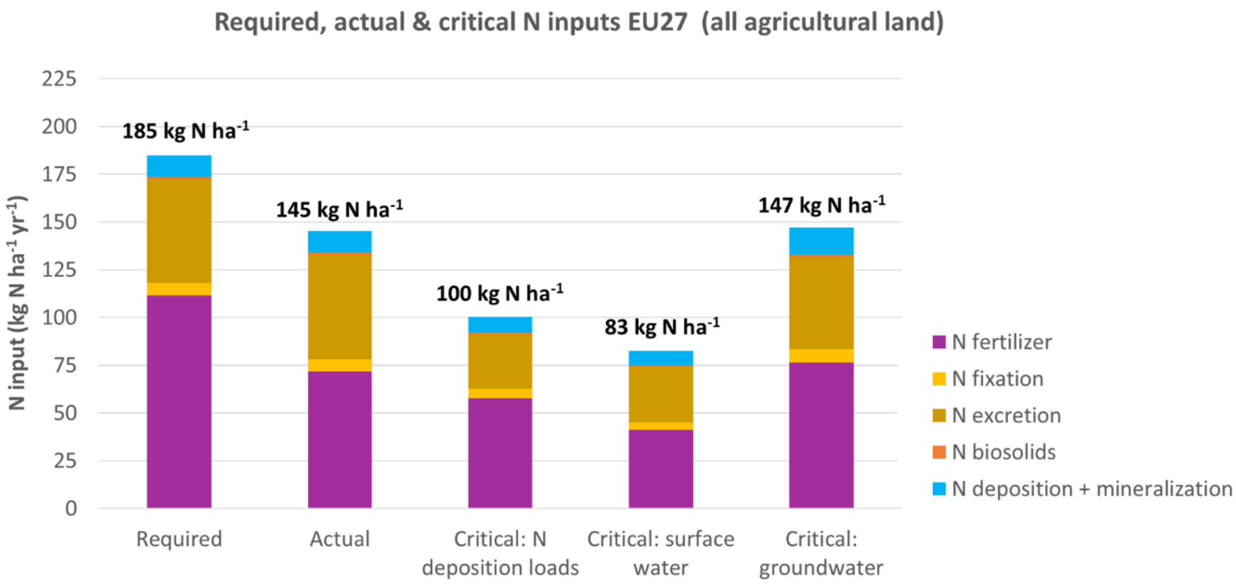

Figure 9 *Average required, actual and critical nitrogen inputs for all agricultural land for EU-27.*

Required N inputs are on average 27% higher than actual N inputs. The difference between the average required and actual N input is higher for arable land (33%) than for grassland plus fodder (21%) which is mainly due to the fact that we assumed that target crop yields will not be "targeted" for extensive grasslands but only for intensive grasslands (see Figure A4.1.1). Within arable land, there are strong variations between crops regarding the differences between required and actual N inputs (see Figure A4.1.2).

Critical N inputs for surface water quality (83 kg N ha^{-1} yr^{-1}) are on average 43% lower than actual N inputs (145 kg N ha^{-1} yr^{-1}), whereas critical N inputs for N deposition (100 kg N ha^{-1} yr^{-1}) are on average 31% lower. Critical N inputs for groundwater quality, however, are on average 1% higher than actual N inputs. The risk of adverse impacts of N inputs on the environment is thus highest for surface water quality, followed by air quality and then groundwater quality. This is also illustrated in Table 4, showing that the agricultural area where actual N inputs exceed critical N inputs. This share is highest for N runoff to surface water (74%), followed by NH_3 emissions to air (66%) and lowest for N leaching to groundwater (18%). Note that N leaching to groundwater is still exceeded on 18% of the agricultural area, despite the fact that the average critical N input exceeds the actual N input.

For all crops, the critical N input in view of N runoff is lower than those in view of NH_3 emission, except for maize, illustrating the higher fraction of manure application on this crop type (Annex A4.1, Figure A4.1.2). On arable land, critical N inputs in view of N runoff are lower than those in view of critical NH_3 emissions, whereas the reverse was true for grassland (Figure A4.1.1). This is to be expected in view of the higher NH_3 emission fractions of manure, mostly applied to grassland, as compared to fertilizers, mostly applied to arable land.

Table 4 *Percent of area where actual N inputs exceed critical N inputs in view of critical NH_3 emissions, critical N runoff to surface water and critical N leaching to groundwater.*

	Arable	Fodder	Grass	Fodder + Grass	Total
NH_3 emissions to air	62%	71%	72%	72%	66%
Runoff to surface water	88%	64%	45%	51%	74%
Leaching to groundwater	22%	6%	14%	11%	18%

3.1 Comparison of required and actual nitrogen budgets

Average actual (year 2010) N budgets for all agricultural land, further subdivided in arable land, and grassland (including fodder) are given in in Table 5. Average required N budgets of all agricultural land, further subdivided in arable land, and grassland (including fodder) are given in *Table 5*. Comparison with the actual N inputs in Table 5 show that required N inputs (185 kg N ha^{-1} yr^{-1}) are on average ca 27% higher than actual inputs (145 kg N ha^{-1} yr^{-1}), with values being 33% higher for arable land and ca 21% higher for grassland. As mentioned above, this difference is because we assumed that there is no reason for farmers to produce more grass in extensively managed grassland (not economic as the livestock does not require much more), but only in intensively managed grassland where it is relevant to reduce the input of external feed.

Table 5 *Average annual actual (2010) and required N inputs, N offtake and N losses for total agricultural land, arable land and grassland (including fodder) in the EU-27 calculated by INTEGRATOR.*

Source	N budget for all agricultural land EU-27 (kg N ha-1 yr-1)		N budget for arable land EU-27 (kg N ha-1 yr-1)		N budget for grassland + fodder EU-27 (kg N ha-1 yr-1)	
	Actual	Required	Actual	Required	Actual	Required
Input to land						
Fertilizer	71.8	111.5	75.2	117.5	66.5	102.1
Fixation	6.5	6.5	8.1	8.1	3.9	3.9
Excretion	54.4	54.4	35.0	35.0	85.2	85.2
Biosolids	1.2	1.2	1.6	1.6	0.8	0.8
N deposition	10.5	10.5	10.1	10.1	11.2	11.2
N mineralization[1]	0.8	0.8	0.2	0.2	1.7	1.7
Total input	***145.3***	***185.0***	***130.1***	***172.4***	***169.2***	***204.9***
Output from land						
Crop offtake[2]	92.3	116.6	76.8	100.6	116.8	141.7
N crop surplus[3]	*53.0*	*68.4*	*53.4*	*71.8*	*52.4*	*63.1*
N emission (NH_3, N_2O, NO_x)	19.2	24.3	15.8	21.0	24.5	29.7
Denitrification[4]	17.3	22.6	18.7	25.7	15.1	17.7
Runoff to surface water	7.8	10.2	8.8	11.8	6.3	7.7
Leaching to groundwater	8.7	11.3	10.1	13.4	6.5	8.0
Total output	***145.3***	***185.0***	***130.1***	***172.4***	***169.2***	***204.9***

1 Net N mineralization is only calculated for (drained) peat soils as we assumed no change in soil N pool (neither mineralization nor accumulation) for mineral soils. The results, however, only refer to part of the peat soils. For approximately 2500 crop-NCU combinations on peat soils, accounting for 1.6 million hectares or 1.1% of all agricultural land, calculated critical inputs from fertilizer and excretion are negative because mineralization alone leads to the exceedance of critical limits for runoff and/or leaching. These crop-NCU combinations were excluded in the presentation of the results for critical N inputs and (for comparability) thus also for actual and required N inputs. This does lower mean mineralization rates from 4.9 kg N ha^{-1} yr^{-1} to 0.8 kg N ha^{-1} yr^{-1} (for all agricultural land).

2 Offtake includes the net removal (crop or grass) from arable land or grassland.

3 The N crop surplus (or deficit, when negative), defined as the difference between total N input and N offtake, is formally not an output from land, but equals the sum of N emissions, denitrification, runoff to surface water and leaching to groundwater.

4 Note that denitrification comprises N_2 emissions from soil.

N input rates are ca. 30% higher on grassland than on arable land due to much higher manure N inputs, reflected by higher NH_3 emissions. The N crop surplus, however, is comparable due to much higher N offtake by grass compared to crops. However, N leaching rates from arable land are on average higher than from grassland, mainly due a higher denitrification below grassland (Table 5).

The relationship between required N inputs and actual N inputs for all agricultural land, arable land and grassland (including fodder) is shown in Figure 10. By definition, required N inputs always exceed actual N inputs (as in cases where calculated target yields were below actual crop yields, we set target yield to actual yield). In most cases, the extra required N input in arable land equals less than 50 kg N ha^{-1} yr^{-1}, whereas it is mostly less than 100 kg N ha^{-1} yr^{-1} for grassland and fodder, but in some regions, a doubling of the N input is required.

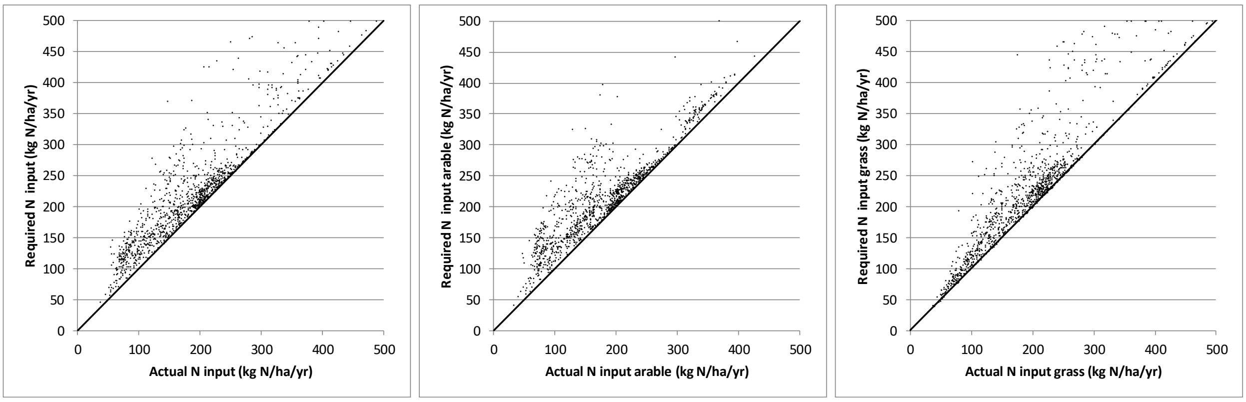

Figure 10 *The relationship between required N inputs and actual N inputs for all agricultural land (left panel), arable land (middle panel) and grassland (including fodder) (right panel).*

Figure 11 shows the geographic variation of total N inputs to all agricultural land, including a division over fertilizer, manure and other N sources (biosolids, fixation, deposition and mineralization from peat soils). Results show high N inputs by animal manure in Ireland and western UK (partly caused by intensive sheep grazing), the Netherlands, Belgium and Luxembourg, Brittany in France and the Po valley in Italy. Fertilizer N inputs are specifically high in the Netherlands, Belgium and Luxembourg, Germany, Poland and parts of France, implying that total N inputs are specifically high in the Netherlands, Belgium and Luxembourg (Figure 11).

Maps of the geographic variation of the required inputs and the exceedances of actual N inputs to arable land are shown in Figure 12. Required additional N inputs to achieve target yields are mostly below 50 kg N ha^{-1} yr^{-1}, except for large parts of Eastern Europe (especially Poland and the Baltic states) as well as Portugal, where yield gaps are high. In the Netherlands, the required N inputs are high, but this also holds for the actual N input and consequently the additional N inputs to achieve target yields are low (actual yields are often equal to or even above target yields in this country).

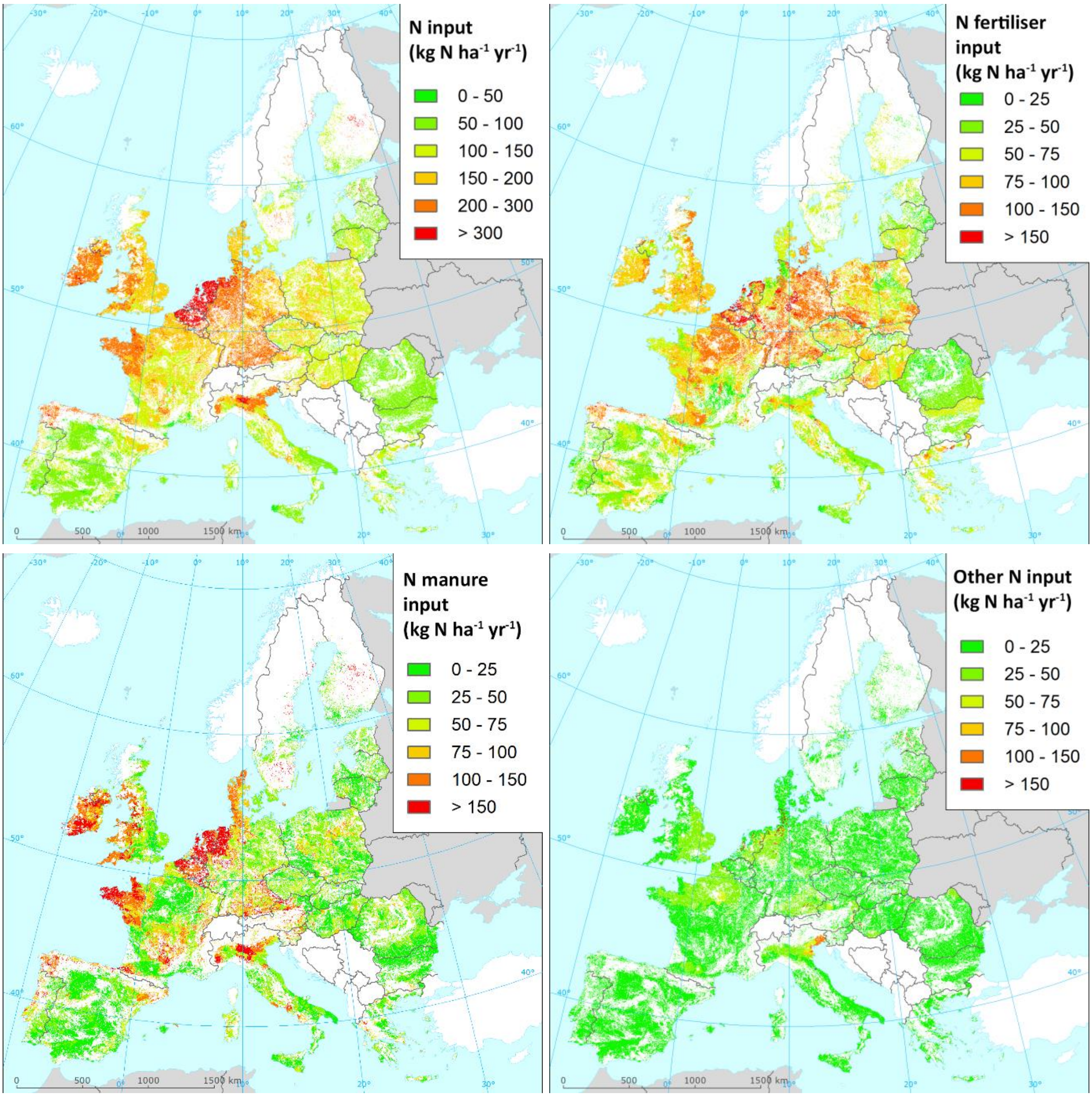

Figure 11 *Maps of the spatial variation of actual (year 2010) total N input (top left), N input by fertilizer (top right), manure (bottom left) and other sources (biosolids, fixation, deposition and mineralization; bottom right) for all agricultural land.*

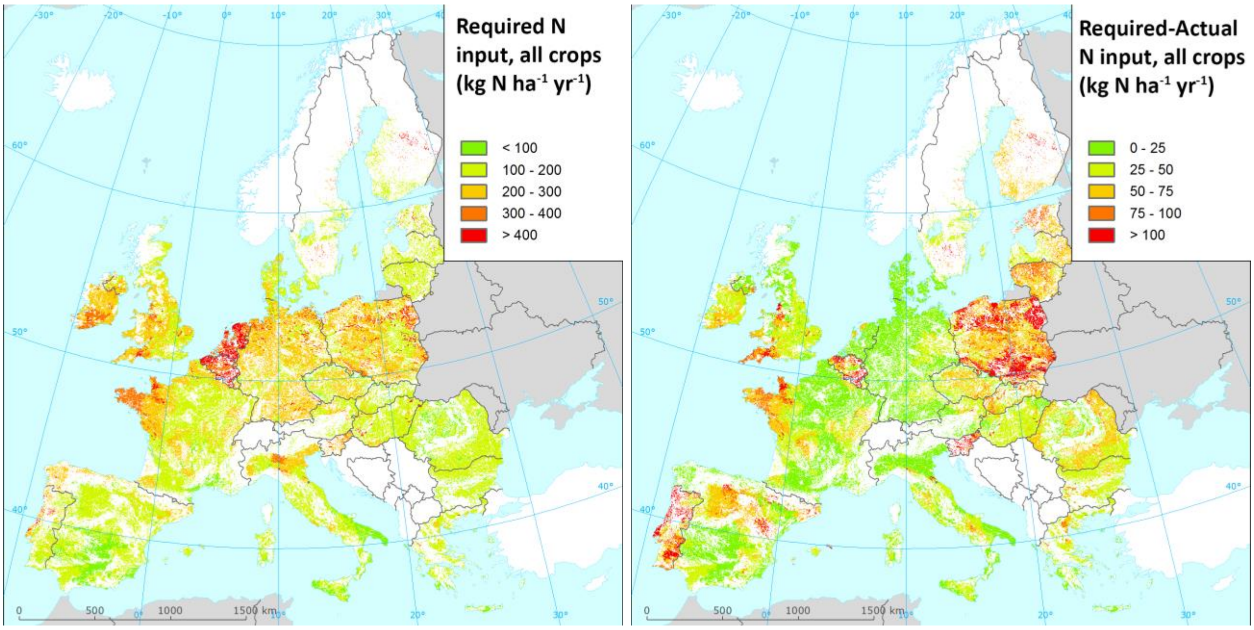

Figure 12 *Maps of the required N input (left) and exceedance of the actual N input by required N input (right) for all agricultural land.*

3.2 Comparison of actual and critical nitrogen budgets

3.2.1 Comparison at EU level

Actual N budgets (year 2010) and critical N budgets for agricultural land at EU-27 level, using critical NH_3 emission, critical N runoff and critical N leaching as criterion, are given in Table 6.

Table 6 *Average annual actual (2010) and critical N inputs for all agricultural land in EU-27 for different criteria as calculated by INTEGRATOR.*

Source	**N budget EU-27 (kg N ha^{-1} yr^{-1})**			
	Actual	**At critical NH_3 emission**	**At critical N runoff to surface water**	**At critical N leaching to groundwater**
Input to land				
Fertilizer +fixation	78	639	45	83
Excretion+ biosolids	56	29	30	49
N deposition	11	7.6	7.0	14
N mineralisation[1]	0.8	0.8	0.8	0.8
Total input	***145***	***100***	***83***	***147***
Output from land				
Crop offtake[2]	92	66	56	97
N crop surplus[3]	*53*	*35*	*26*	*50*
N emission (NH_3, N_2O, NO_x)	19	12	12	20
Denitrification	17	11	7.5	15
Runoff to surface water	7.8	11[2]	4.0	7.7
Leaching to groundwater	8.7		3.2	7.0
Total output	***145***	***100***	***837***	***147***

1 Net N mineralisation is only calculated for (drained) peat soils as we assumed no change in soil N pool (neither mineralization nor accumulation) for mineral soils. The results, however, only refer to part of the peat soils, since approximately 2500 crop-NCU combinations on peat soils were excluded because critical N inputs were negative because mineralization alone leads to the exceedance of critical limits for runoff and/or leaching. This does not significantly affect results for critical N inputs, but reduces mean mineralization rates from 4.9 kg N ha-1 yr-1 to 0.8 kg N ha-1 yr-1 (for all agricultural land).

2 Offtake includes the net removal (crop or grass) from arable land or grassland. For the N budget at critical NH_3 emissions, runoff and leaching are not provided separately – the value presents the sum of N runoff + N leaching.

3 The N crop surplus given here is defined as the difference between total N input and N offtake.

Results show that at EU-27 level, average critical N inputs in view of eutrophication of aquatic ecosystems due to runoff (83 kg N ha^{-1} yr^{-1}) are 43% lower than actual (year 2010) N inputs (145 kg N ha^{-1} yr^{-1}). Critical N inputs in view of eutrophication of terrestrial ecosystems due to NH_3 emission (100 kg N ha^{-1} yr^{-1}) and 31% lower, whereas critical N inputs in view of N leaching to groundwater (147 kg N ha^{-1} yr^{-1}) and 1% higher (Table 6).

Reducing emissions to critical NH_3 emission implies an N emission that is approximately 36% lower than the actual (year 2010) N emission (12.2 vs 19.2 kg N ha^{-1} yr^{-1}; see Table 6) and a critical N crop surplus (further denoted as N surplus) that is approximately 35% lower (34.7 vs 53.0 kg N ha^{-1} yr^{-1}). The use of a critical N concentration in runoff of 2.5 mg N l^{-1} causes a European average critical runoff that is approximately 49% lower than the actual runoff (4.0 vs 7.8 kg N ha^{-1} yr^{-1}), while the related "critical" denitrification is approximately 57% lower than the actual denitrification (7.5 vs 17.3 kg N ha^{-1} yr^{-1}). This is possible because of spatial differences in the denitrification fraction, which is related to soil type, land use and precipitation. The critical N surplus is also about 50% lower than the actual surplus (26.4 vs 53.0 kg N ha^{-1} yr^{-1}; see Table 6). The European average critical N leaching rate, based on a NO_3-N concentration of 11.3 mg N l^{-1} is approximately 20% lower than the average actual N leaching (7.0 vs 8.7 kg N ha^{-1} yr^{-1}; see Table 6) but the N surpluses are comparable, due to a higher N emission, illustrating that N inputs that are acceptable for groundwater will not only exceed the critical N runoff but also critical NH_3 emissions.

The EU average critical N inputs by excretion + biosolids are nearly equal when using a critical NH_3 emission rate and a critical N concentration in runoff of 2.5 mg N l^{-1} (29.0 and 30.0 kg N ha^{-1} yr^{-1}), but the critical N inputs by fertilizer + fixation are lower for N runoff (45.0 kg N ha^{-1} yr^{-1}) than for NH_3 emissions (62.9 kg N ha^{-1} yr^{-1}) (Table 6). The higher critical N inputs by fertilizer + fixation in case of NH_3 emission is mainly due to the lower NH_3 emission fractions of fertilizers as compared to manure.

The importance of soil type on N budgets is illustrated in Table A4.3.1. Average EU-27 current (2010) N budgets for major soil types show that the NUEs decrease going from clay soils (0.64) to sandy soils (0.61) to peat soils (0.55) whereas the denitrification fractions (denitrification/N surplus) increase going from sandy soils (0.23) to clay soils (0.34) to peat soils (0.67). On average the fraction of incoming N that is lost to water ((N runoff + N leaching)/N input) thus decreases from sandy soils (0.16) to clay soils (0.10) to peat soils (0.03).

3.2.2 Comparison at NUTS3 level

Figure 13 shows the relationship between actual and critical N losses, N surpluses and N inputs, divided in NH_3 emissions, N runoff and NO_3 leaching.

The relationships between actual and critical NH_3 emissions (Figure 13, top row left) shows strong exceedances of critical NH_3 emission. This implies that actual NH_3 emissions lead to an exceedance of critical N deposition limits in view eutrophication of terrestrial ecosystems, in many NUTS3 regions, especially in regions with high livestock density. Similarly, actual N surpluses and N inputs largely exceed critical N surpluses and N inputs in view of NH_3 emissions (Figure 13, middle and bottom row left). Only in few NUTS3 regions critical NH_3 emissions exceed actual emissions, meaning there is 'room' for additional NH_3 emissions without exceeding critical N loads on nature, and thus also for additional N inputs. Note that 'maximum' critical N inputs are constrained by a defined 'maximum' crop N offtake. Without this 'cut off-value', critical N inputs would become very high in areas with a low share of agricultural land, and/or a large contribution of N fertilizer with low NH_3 emission fractions.

The relationships between actual and critical values for N runoff and related N surpluses and N inputs at NUTS3 level (Figure 13, middle column) indicate that the critical N runoff, based on an N concentration in surface water of 2.5 mg N l^{-1}, is also exceeded at most plots, while the exceedance of the critical N leaching to groundwater and the related critical N surpluses and N inputs (Figure 13, left column) occurs at much less plots. As mentioned before, the critical N offtake and the related critical N input has been constrained by a maximum value in those cases. Otherwise, the critical N input can become extremely high in areas with a high precipitation surplus and/or denitrification fraction.

The relationships between actual and critical N inputs from fertilizer and fixation, and the relationship between actual and critical N inputs from manure and biosolids (both in view of critical NH_3 emissions, critical runoff and critical leaching) are shown in Figure A4.2.1. It illustrates that critical N inputs from manure and biosolids view of critical NH_3 emissions are exceeded more often than those for fertilizer and fixation.

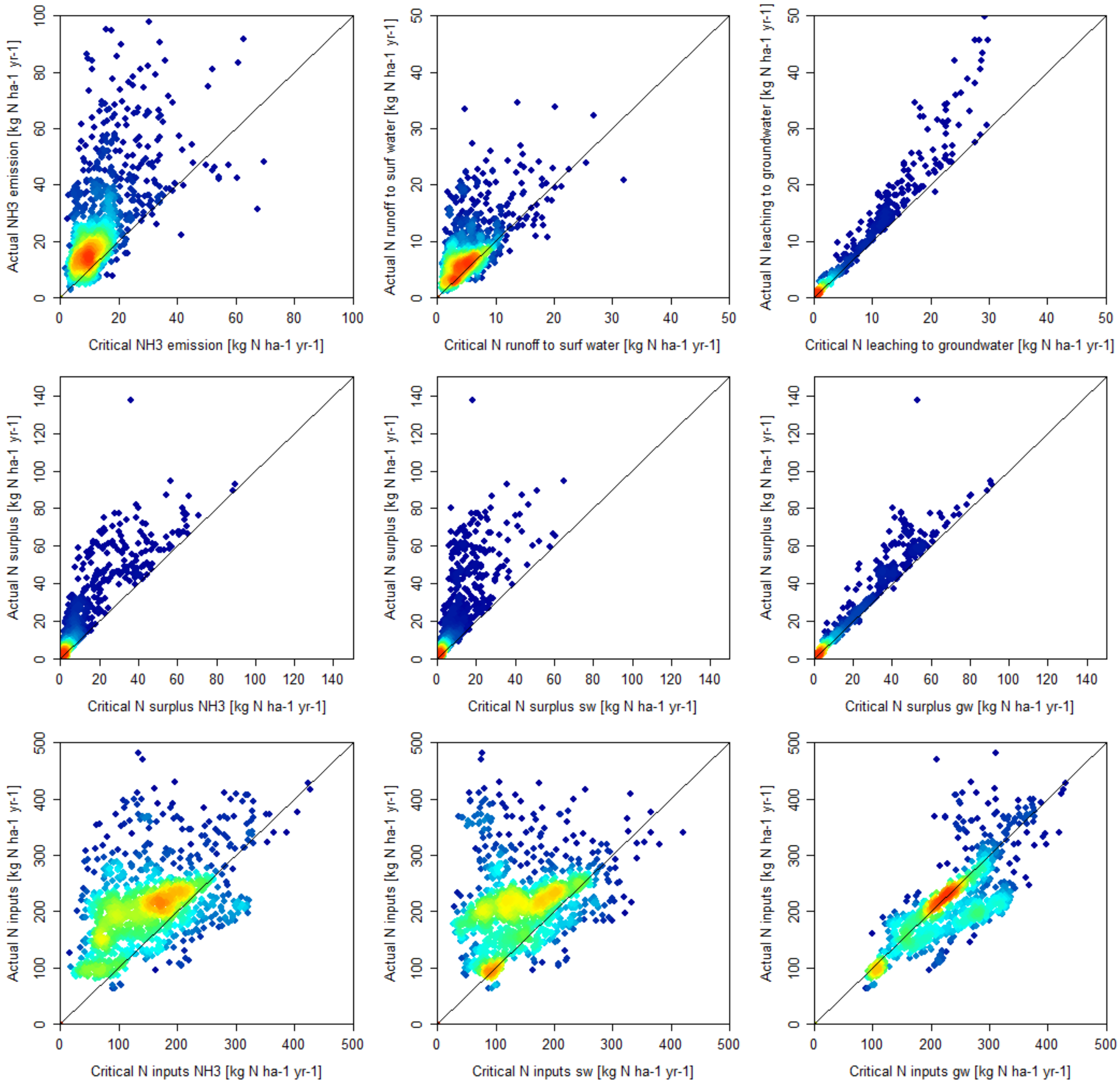

Figure 13 *Top row: Relationship between actual N losses and critical N losses – actual vs. critical NH_3 emissions (left), actual vs. critical N runoff to surface water (middle) and actual vs. critical N leaching to groundwater (right). Middle row: Relationship between actual N surpluses and critical N surpluses – actual N surplus vs. N surplus at critical NH_3 emissions (left), actual N surplus vs. N surplus at critical runoff to surface water (middle), and actual N surplus vs. N surplus at critical leaching to groundwater (right). Bottom row: Relationship between actual N inputs and critical N inputs – actual vs. critical N inputs in view of critical NH_3 emissions (left), actual vs. critical N inputs in view of critical runoff to surface water (middle), and actual vs. critical N inputs in view of critical leaching to groundwater (right). All graphs refer to all agricultural land.*

3.2.3 Comparison at NCU level

The spatial variation in N fluxes in the year 2010, i.e. the total actual N inputs, N offtake, N crop surplus (note that the N crop surplus, i.e. total N input minus N offtake, differs from the N soil surplus, i.e. total N input minus N offtake minus emissions minus surface runoff), as used in the comparison with the critical N surplus, as illustrate in Figure 14) and the N losses to air and water including NH_3 emissions, N runoff to surface water and N leaching to groundwater are given in Figure 15.

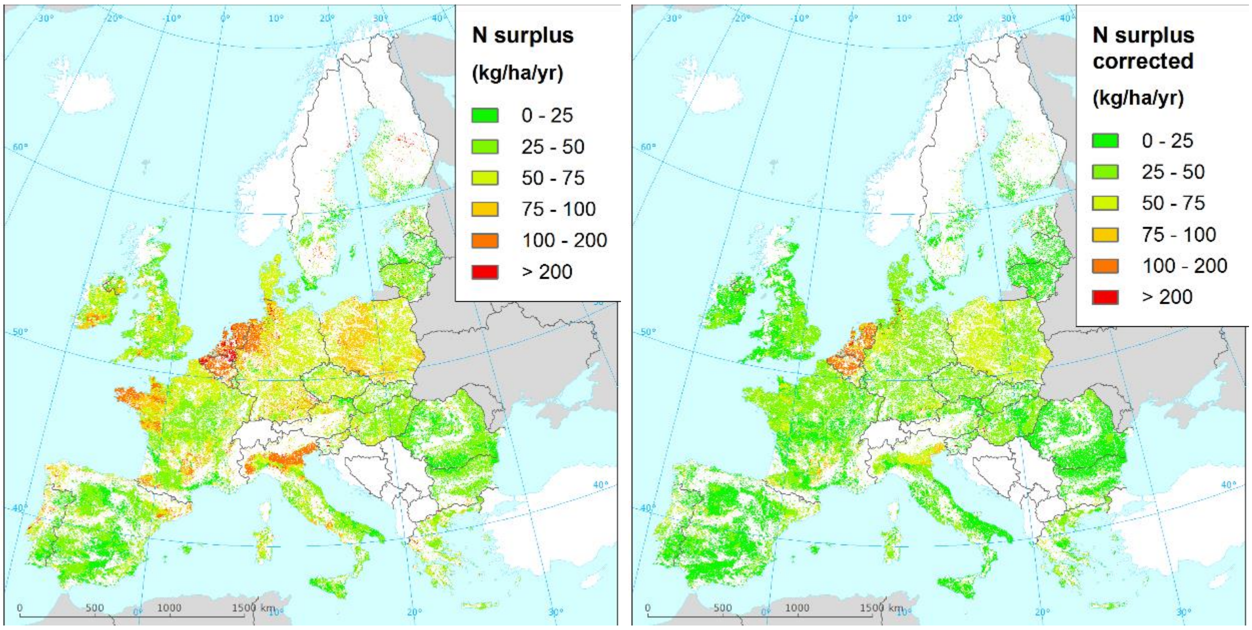

Figure 14 *Maps of the spatial variation in: (i) N crop surplus as used in the N budgets (total N inputs minus N offtake, left) and (ii) N soil surplus, as used in the comparison with the critical N surplus (total N input minus N offtake minus emissions minus surface runoff) (right) for the year 2010 on all agricultural land.*

Maps of the spatial variation in EU-27 in critical N losses and exceedances of those critical N losses by actual N losses, with the related critical N surpluses and critical N inputs and their exceedances by actual N surpluses and actual N inputs are given in Figure 16 for NH_3 emissions, in Figure 17 for N runoff to surface water and in Figure 18 for N leaching to groundwater. Critical N inputs vary strongly over EU-27, mainly due to differences in soil type, affecting the net N mineralization (peat soils) and denitrification (peat>clay>sand) and in precipitation surplus in case of N runoff to surface water and N leaching to groundwater (see also Annex A4.3).For NH_3 emissions, the largest exceedances occur in regions with the largest N manure inputs, including Ireland and western UK, the Netherlands, Belgium and Luxembourg, Brittany in France and the Po valley in Italy (Figure 16). The largest exceedances of critical N runoff (implying an exceedance of a critical total N concentration in surface water of 2.5 mg N l^{-1}) by actual N runoff, occur mostly in regions with the largest total N inputs. This includes regions high manure N inputs combined with high fertilizer N inputs such as the Netherlands, Belgium and Luxembourg, Germany, Poland and parts of France (Figure 17). Exceedances of critical N leaching and related critical N inputs are mainly predicted for the Netherlands, Germany, Poland and Austria, but also in region with a low precipitation surplus such as Spain (Figure 18).

The geographic variation in critical values for NH_3-N emissions (Figure 16), critical N runoff (Figure 17) and critical N leaching (Figure 18 shows much les variation than actual values (Figure 15). This is not so surprising for N runoff and NH_3-N emissions since actual values are determined by spatial variation in N inputs, in combination with variations in N uptake and N leaching factors (N runoff) or ammonia emission factors (NH_3-N emissions), whereas critical values are determined by variations in precipitation surplus (N runoff) or critical N deposition levels (NH_3-N emissions). For crop N surplus (critical values not given) the difference in variation is less distinct since actual values are determined by spatial variations in N input and N uptake, whereas critical values are determined by variations in precipitation surpluses and denitrification fractions.

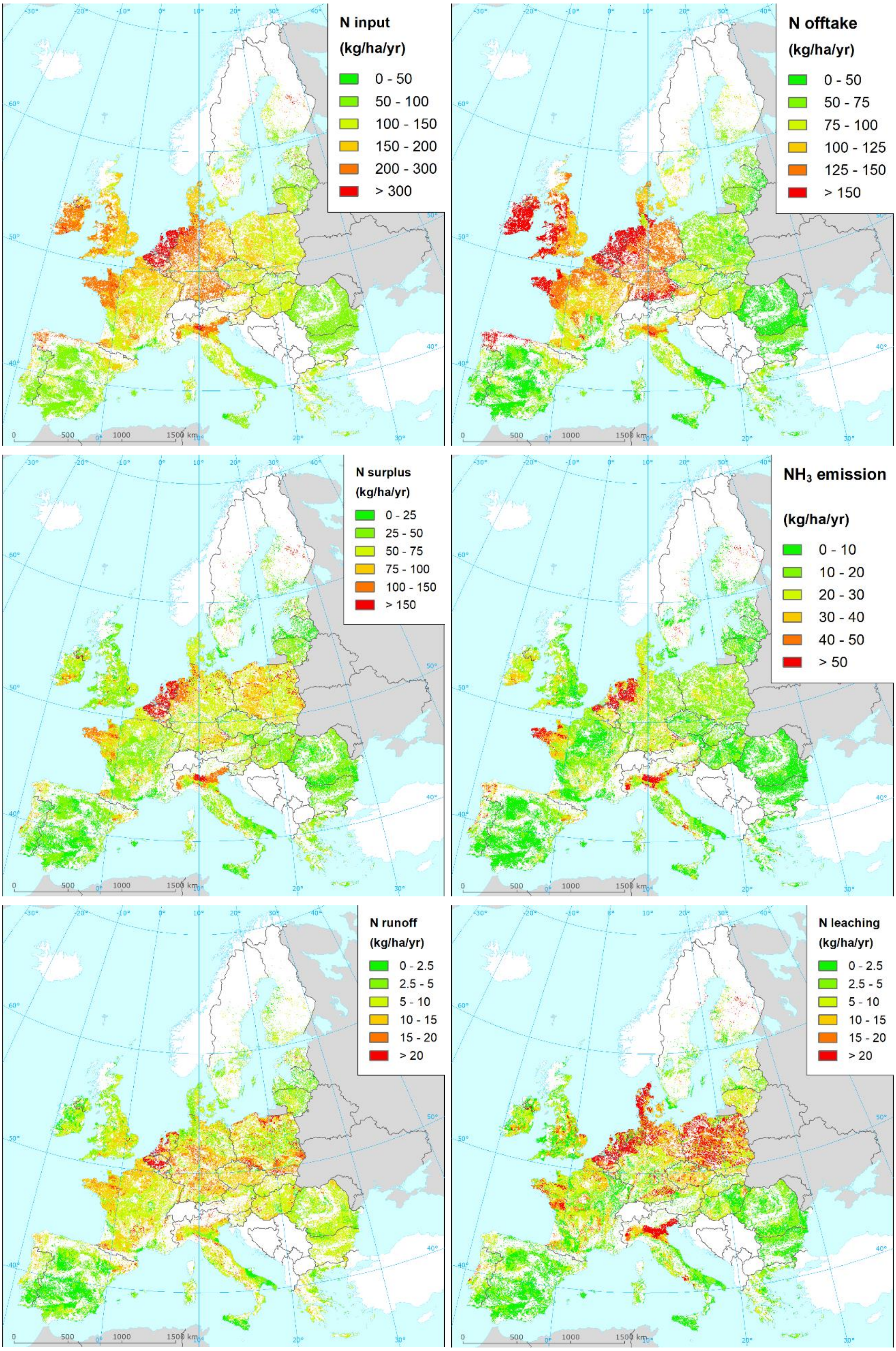

Figure 15 *Maps of the spatial variation of actual (year 2010) total N input, being the external N input plus net N mineralisation (top left), N offtake (top right), N crop surplus (total N input minus N offtake, middle left), NH_3 emissions (middle right), N runoff to surface water (bottom left) and N leaching to groundwater (bottom right) for all agricultural land. Note the strong difference in N offtake between the border of Germany and Poland, most likely due to inadequate P supply in Poland, limiting crop yields.*

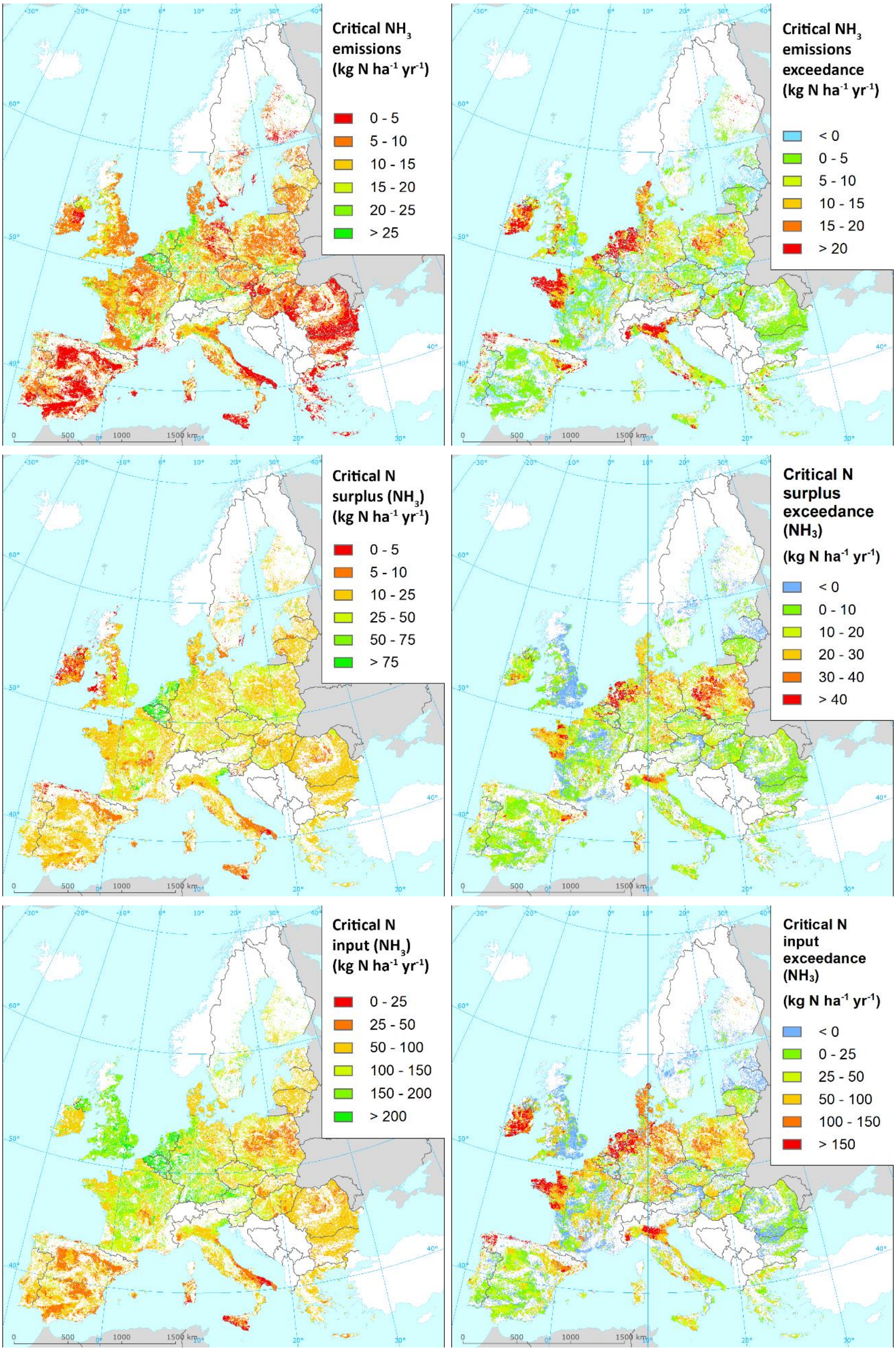

Figure 16 *Maps of the spatial variation in EU-27 of (i) critical NH_3 emissions (top left), (ii) exceedance of critical NH_3 emissions by actual (year 2010) NH_3 emissions (top right), (iii) critical N surplus in view of critical NH_3 emissions (middle left) and (iv) exceedance of critical N surplus in view of critical NH_3 emissions by actual (year 2010) N surpluses (middle right) (v) critical N inputs with regards to critical NH_3 emissions (bottom left) and (vi) exceedance critical N inputs with regards to critical NH_3 emissions by actual (year 2010) N inputs (bottom right).*

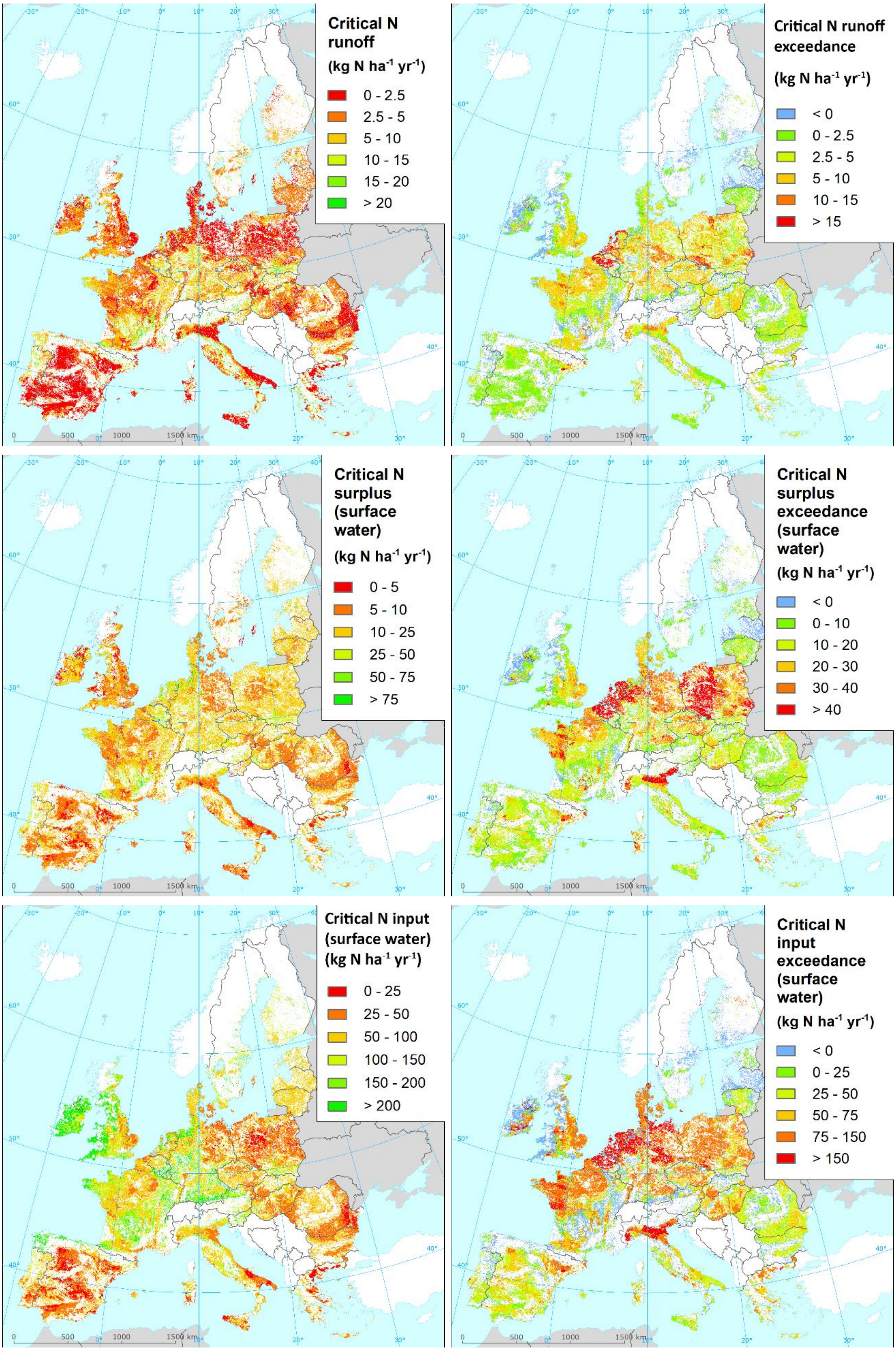

Figure 17 *Maps of the spatial variation in EU-27 of (i) critical N runoff to surface water (top left), (ii) exceedance of critical N runoff to surface water by actual (year 2010) N runoff to surface water (top right), (iii) critical N surplus in view critical N runoff (middle left) and (iv) exceedance of critical N surplus in view of critical N runoff by actual (year 2010) N surplus (middle right) (v) critical N inputs with regards to critical N runoff to surface water (bottom left) and (vi) exceedance critical N inputs with regards to critical N runoff to surface water by actual (year 2010) N inputs (bottom right).*

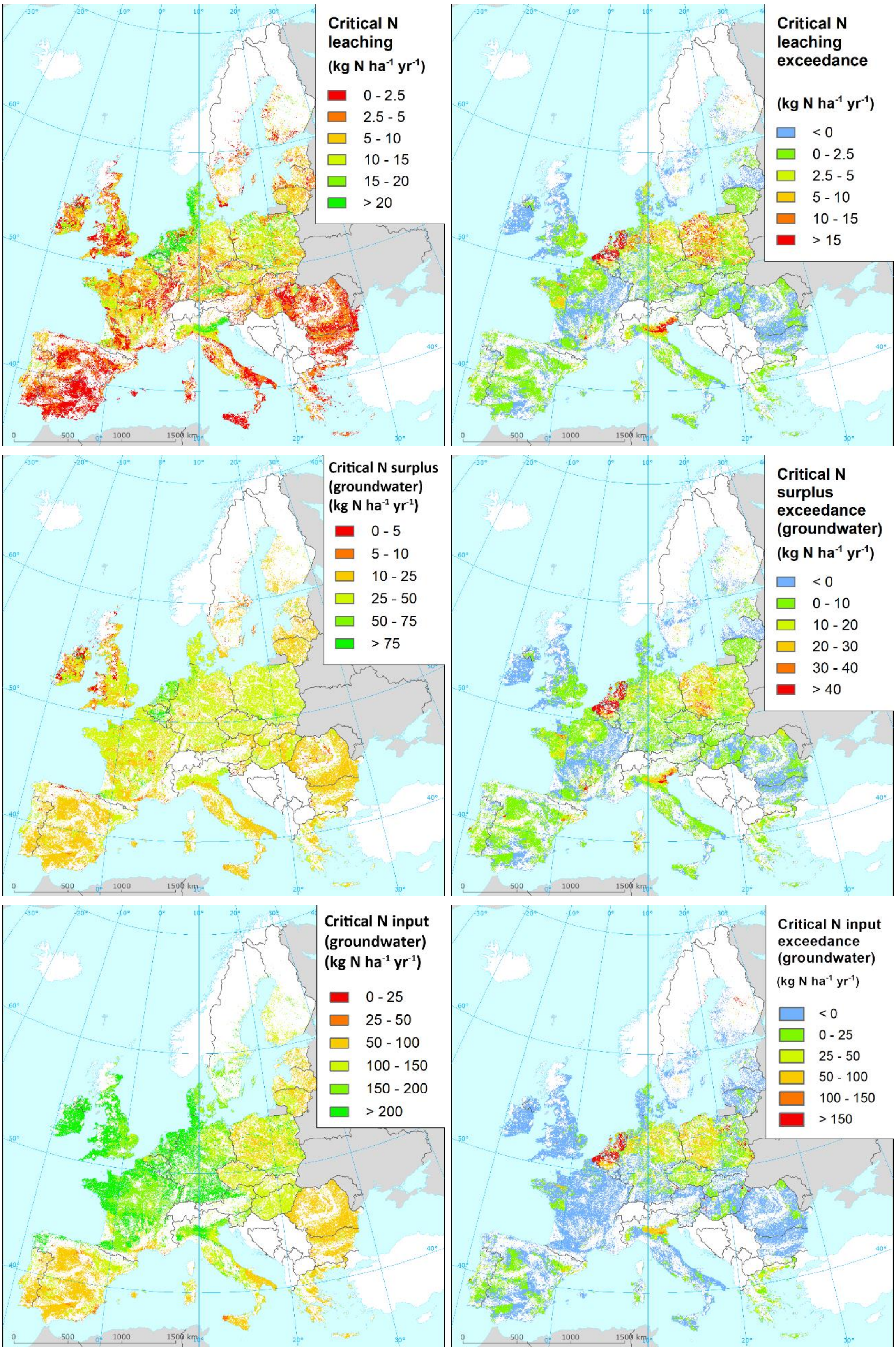

Figure 18 *Maps of the spatial variation in EU-27 of (i) critical N leaching to groundwater (top left), (ii) exceedance of critical N leaching to groundwater by actual (year 2010) N leaching (top right), (iii) critical N surplus in view critical N leaching (middle left) and (iv) exceedance of critical surplus in view of N leaching by actual N surplus (middle right) (v) critical N inputs with regards to critical N leaching to groundwater (bottom left) and (vi) exceedance critical N inputs with regards to critical N leaching to groundwater by actual (year 2010) N inputs (bottom right).*

3.3 Necessary ammonia emission fractions and nitrogen use efficiencies to reconcile food production and environment

3.3.1 Necessary NH_3 emission fractions

Manure excretion in housing systems and by grazing animals, and application of manure or mineral fertilizer to arable land, leads to NH_3 emissions. The average NH_3 emission fraction in the EU-27 is 0.12 (0.04 for fertilizer application, 0.26 for manure excretion and application). Current NH_3 emissions exceed critical NH_3 emissions on 66% of all agricultural land in the EU-27. On this land, environmental objectives can only be reached at a lower N input, causing a loss in crop production, unless ammonia emission fractions are reduced.

The necessary NH_3 emission fraction for all inputs in order to stay below critical NH_3 emissions at current N inputs (and offtake) is 0.07, implying a reduction of 39%. At required N inputs (target offtake), the necessary NH_3 emission fraction for all N inputs is 0.06, implying a reduction of 51%. NH_3 emissions are mainly caused by manure application and housing systems and to a much lesser extent by mineral fertilizer application. Assuming constant emission fractions for fertilizer application, NH_3 emission fraction for manure excretion and application needs to be reduced by 80%, from 0.26 to 0.05. However, this includes NCUs where the necessary emission fraction for excretion is unrealistically low, or even negative (because emissions from fertilizer application alone exceed critical emissions). If we assume that the emission fraction for manure excretion and application can be lowered to a minimum of 0.05, it is not possible to stay below critical NH_3 emissions on 27% of the land at current N input, and on 45% of the land at required N input (see Table 7). In the remaining NCUs, we need to reduce the average emission fraction for manure by 35%, from 0.25 to 0.16 for actual N input and by 44% (from 0.24 to 0.13) for required N input (see Table 7).

Assuming an improved emission fraction for fertilizer application of 0.02 and a minimum EF of 0.05, it is not possible to stay below critical NH_3 emissions on 10% of the land at actual N input, and on 17% at required N input. The average necessary NH_3 EF for manure excretion and application is 0.19 (a 27% decrease from the current value of 0.26) for actual N inputs, and 0.16 (39% lower than the current value) for required N inputs (see Table 7).

Table 7 *Share of agricultural land where it is possible to stay below critical NH_3 emissions by reducing the EF for manure, considering a plausible minimum of 0.05, for (i) actual N input and (ii) required N input and at (i) current NH_3 EF for fertilizer and (ii) improved NH_3 EF for fertilizer of 2%.*

	At current NH_3 EF for fertilizer		**At improved NH_3 EF for fertilizer (2%)**	
	Actual input	**Required input**	**Actual input**	**Required input**
Share of agricultural land where it is possible to stay below critical NH_3 emission by reducing NH_3 EF manure (minimum = 0.05)	73%	55%	90%	83%
Current NH_3 EF manure	0.25	0.24	0.26	0.26
Necessary NH_3 EF manure	0.16	0.13	0.19	0.16

Figure 19 shows the share of agricultural land where (i) no reduction in NH_3 EF is necessary (because current or required N inputs are lower than critical N inputs), (ii) where reductions in NH_3 EF is necessary to stay below critical NH_3 emissions at current or required N inputs and the necessary NH_3 EF is > 0.2; between 0.1 and 0.2, between 0.05 and 0.1, or below 0.05 (considered not possible). Assuming that the EF for fertilizer is improved (0.02 everywhere) reduces the share of land where the NH_3 EF for manure needs to be reduced to below 0.2 from 67% to 50% (actual N input) or from 83% to 68% (required N input). Scatter plots showing the relationship between actual and necessary NH_3-N emission fractions for each NUTS3 region are presented in Annex 6 (Figure A6.1).

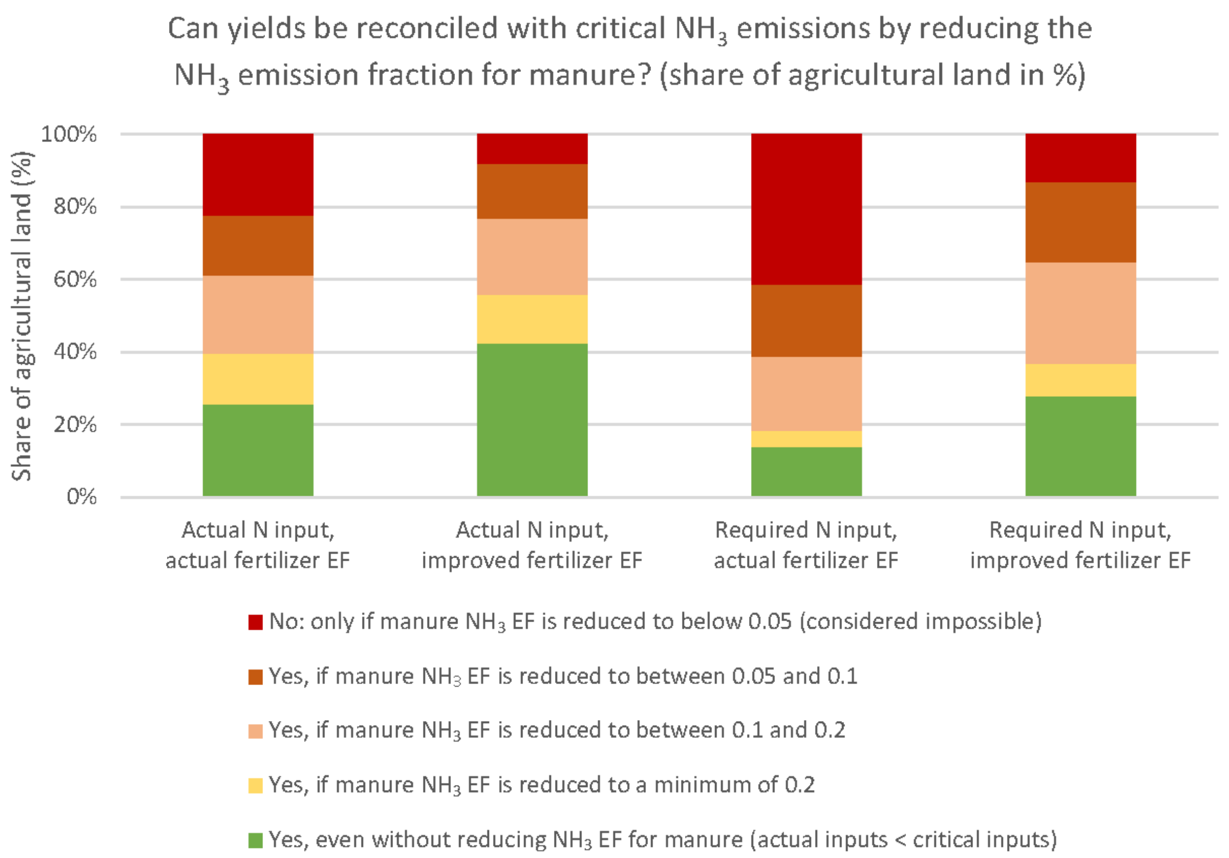

Figure 19 *Share of agricultural land for different reduction targets for the NH_3 emission fraction for manure, for actual yields and target yields and assuming current or improved EF for fertilizer.*

Maps of the geographic variation of the necessary NH_3 emission fractions for N excretion at actual and target crop yields, and the difference with current NH_3 emission fractions are given in Figure 20. Large decreases in NH_3 emission fractions are required in Italy, Spain, Ireland, Poland and Eastern Germany. This is both because critical N loads in many of these regions are low (see Figure A3.1.2), leading to low critical NH_3 emissions (between 0-10 kg NH_3-N ha^{-1} yr^{-1}) in these regions (Figure 16).

3.3.2 Necessary nitrogen use efficiencies

When critical N inputs in the context of critical N runoff and/or critical N leaching are below actual N inputs, environmental objectives can only be reached at a lower N input, unless the nitrogen use efficiency (NUE) is increased. The necessary NUEs to attain the actual or target crop yield at acceptable N runoff to surface water and N leaching to groundwater are shown in shown in Table 8, averaged at EU level. Table 8 presents results for all agriculture; results for different land use types (arable land, fodder, grassland) are given in Annex 6 (Table A6.1).

As we considered 0.9 as the maximum plausible NUE that farmers can achieve, on 17% of all agricultural land the surface water criterion cannot be achieved at actual N inputs, and on 25% it is impossible to stay below critical N runoff to surface water at required N input (see Table 8 and Figure 21). On the remaining land, the average NUE has to increase from 0.61 to 0.72 for actual N inputs (actual yields), and from 0.61 to 0.74 for required N inputs (target yields). Reaching an NUE above 0.75 is, however, already hard although it is plausible with technological progress (Bodirsky et al., 2014; Zhang et al., 2015), by adopting well-proven mostly low-cost measures such as balanced N fertilization and precision farming (N application at the right time and right place). The area where the surface water criterion cannot be achieved when using an NUE of 0.75 is much higher, being 50% at actual N inputs and 60% at required N inputs (Figure 21).

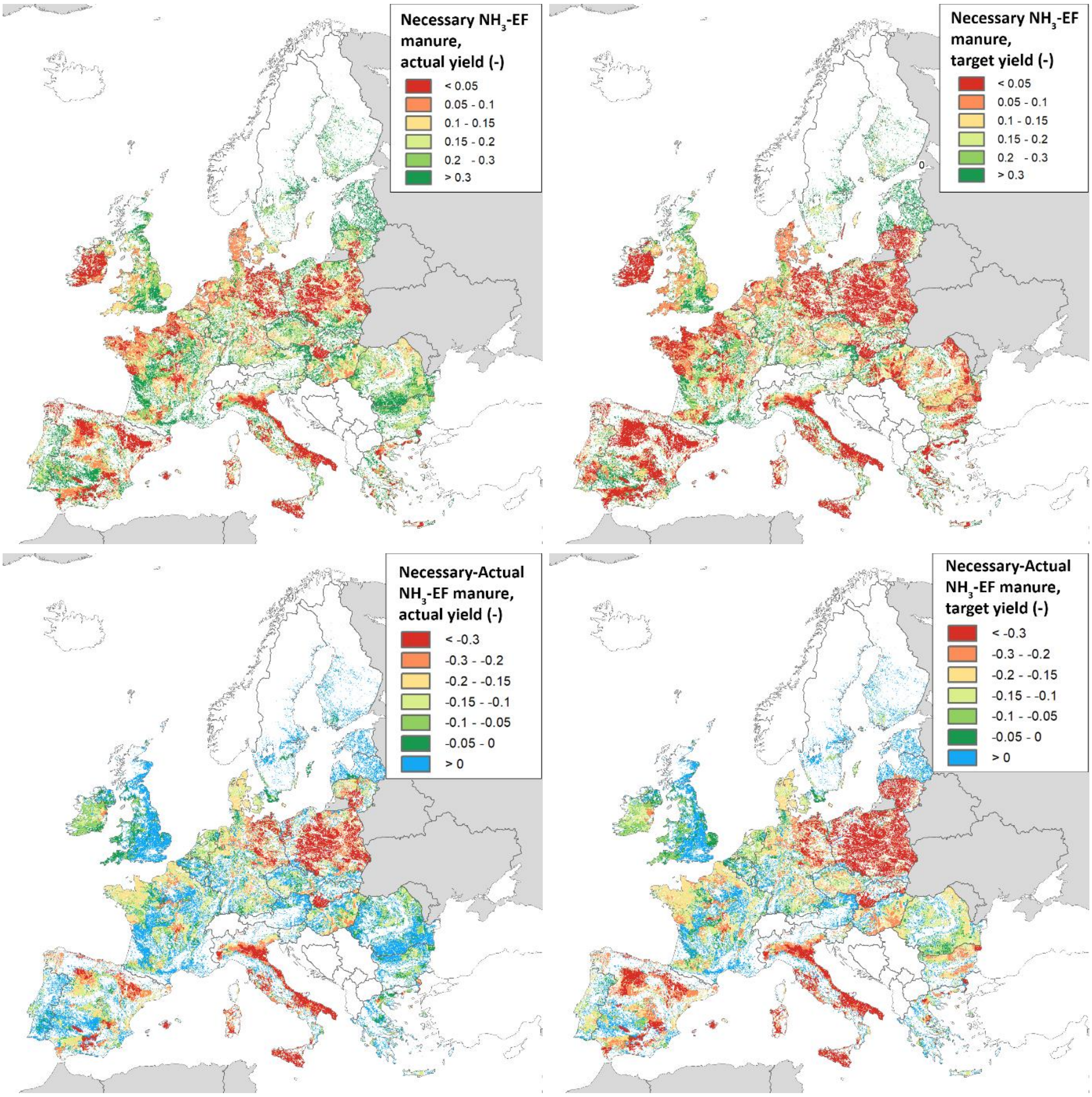

Figure 20 *Maps showing spatial variation in necessary NH_3 emission fractions for excretion at current yield (left, middle) and at target yield (right, middle), and exceedance of actual NH_3 emission fractions by necessary NH_3 emission fractions at current yield (left, bottom) and at target yield (right, bottom).*

For groundwater, on the other hand, it is possible to stay below critical N leaching by increasing the NUE to a max. of 0.9 on 98% of all agricultural land (both at actual and required N inputs). For actual N inputs, the average NUE has to increase from 0.62 to 0.64, and the necessary NUE is lower than 0.9 on 98% of agricultural land (see Table 8 and Figure 21). For required N inputs, the average NUE has to increase from 0.62 to 0.67, and the necessary NUE is also than 0.9 on 98% of the land. Using a plausible NUE of 0.75, however, the area where the ground water criterion cannot be achieved is near 80% at actual N inputs and near 70% at required N inputs (Figure 21).

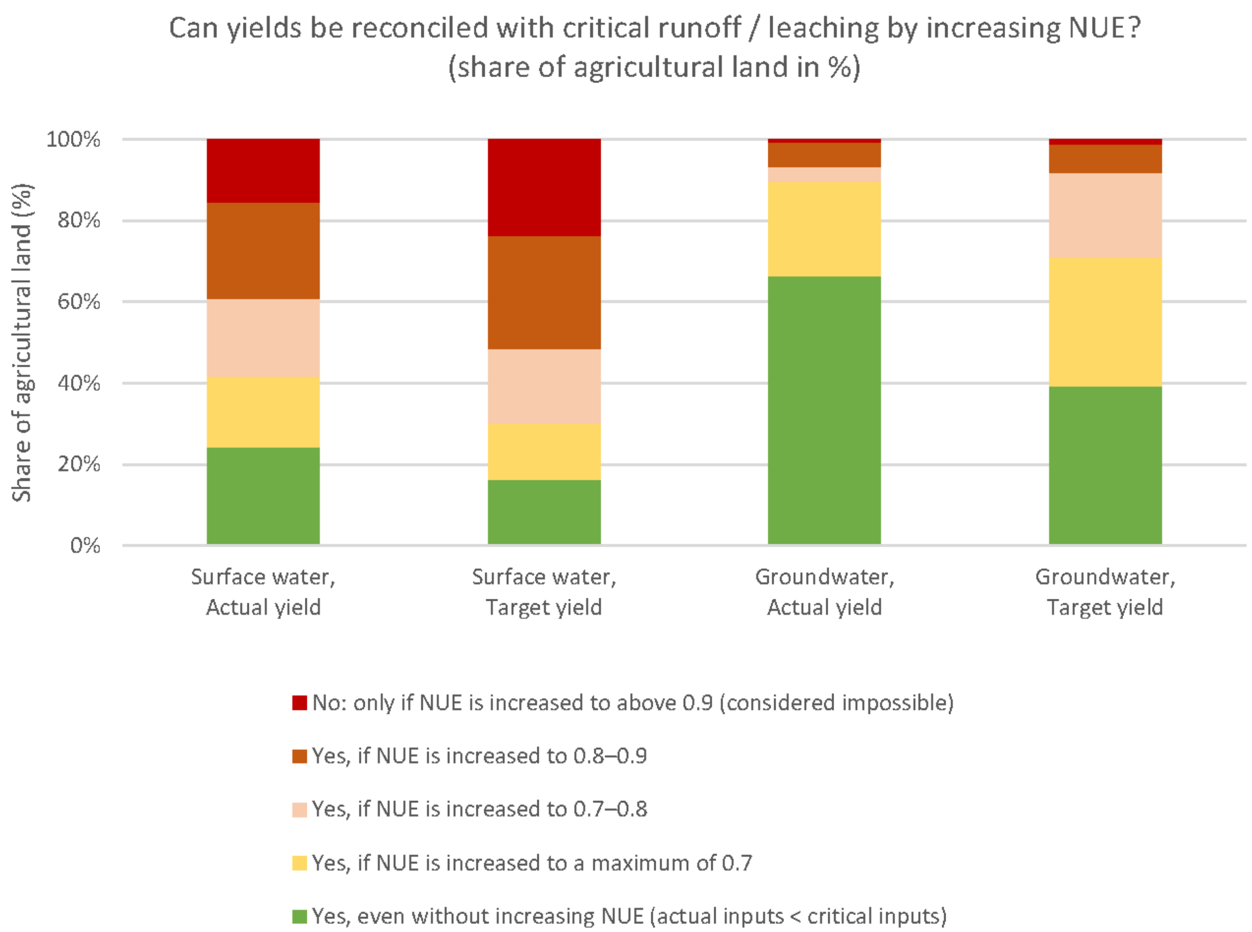

Figure 21 *Share of agricultural land for different NUE targets, for actual yields and target yields and for critical N runoff to surface water and critical N leaching to groundwater.*

If we calculate the average necessary NUE considering all plots (also those where NUE,nec > 0.9), but set the maximum for NUE,nec to 0.9, necessary NUEs for the surface water criterion are slightly (about 1-5%) higher (see Table 8).

Table 8 *Share of agricultural land where it is possible to respect thresholds for N runoff to surface water or N leaching to groundwater, while also obtaining actual or target yields by increasing NUE, considering a plausible maximum of 0.9. Furthermore, the table shows current and necessary NUEs (i) only for those plots where NUE,nec <= 0.9, (ii) for all plots but cutting off NUE,nec at 0.9 and (iii) for all plots and without cutting off NUE,nec.*

	N runoff to surface water		**N leaching to groundwater**	
	Actual yield	**Target yield**	**Actual yield**	**Target yield**
ALL AGRICULTURE				
Share of agricultural land where it is possible to stay below critical N losses by increasing NUE (NUE,nec = max. 0.9)	85%	77%	100%	100%
*(i) ... for **those** plots:*				
Current NUE	0.62	0.62	0.64	0.64
Necessary NUE	0.74	0.76	0.66	0.67
*(ii) ... for **all** plots (cutting off NUE,nec at 0.9)*				
Current NUE	0.64	0.64	0.64	0.64
Necessary NUE	0.76	0.78	0.66	0.67
*(iii) ... for **all** plots (no cut-off)*				
Current NUE	0.64	0.64	0.64	0.64
Necessary NUE	0.78	0.80	0.66	0.67

Scatter plots showing the relation between N inputs and N uptake at current and necessary NUEs at NUTS 3 level, and thus implicitly the NUE increases that are needed to attain the actual crop yield or target crop yield at acceptable N losses, are shown in Figure 22 and Figure 23. The current NUE is around 60-70% for the majority of NUTS3 regions, and between 0.5 and 0.9 for almost all. For the surface water criterion, necessary NUEs in most plots are between 0.8 and 0.9, and even above 0.9. Note that necessary NUEs can become larger than 1 (because surface runoff is a function of input and not dependent on the offtake), but we set 1 as the maximum value in our calculations and thus these values are not shown.

The relationship between actual and necessary nitrogen use efficiencies for arable land at actual crop yields and at target crop yields when all criteria are to be fulfilled are given Annex 6 (Figure A6.2). The figures presents the actual NUE per NUTS region as compared to the needed NUE to stay within environmental limits, considering leaching to groundwater and runoff to surface water. Results show that the calculated current NUE at NUTS3 level is generally between 40 and 90%. The necessary NUE to stay within environmental boundaries is nearly always between 60 and 90%. In several cases it is lower than the current NUE. This are the areas where the current production does not lead to N losses to either air and/or water exceeding critical limits.

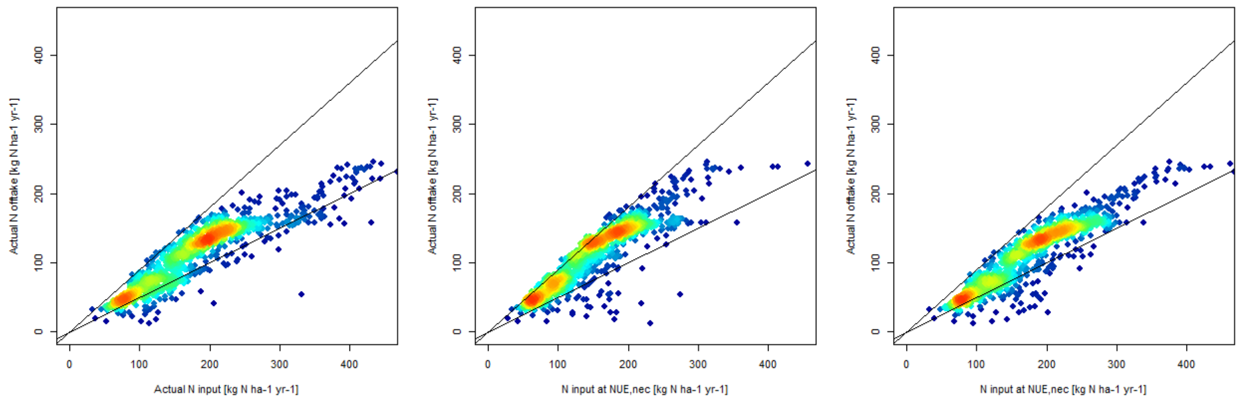

Figure 22 *The ratio between (i) actual N offtake and actual N input (NUE) (left), (ii) actual N offtake and N input at necessary NUE to attain actual crop yields with acceptable N losses to surface water (middle), and (iii) actual N offtake and N input at necessary NUE to attain actual crop yields with acceptable nitrate losses to ground water (right). Bottom line shows NUE of 50%, top line shows NUE of 90%.*

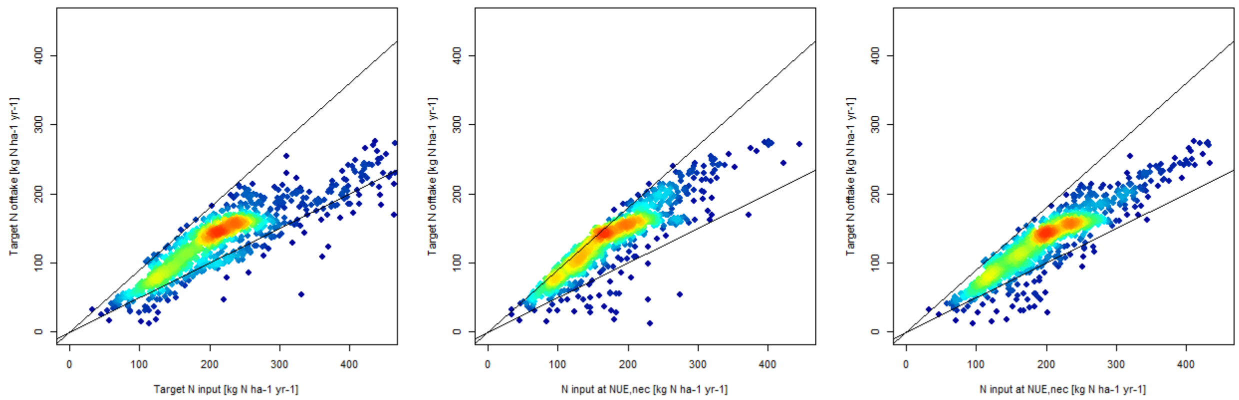

Figure 23 *The ratio between (i) target N offtake and target N input (NUE) (left), (ii) target N offtake and N input at necessary NUE to attain target crop yields with acceptable N losses to surface water (middle), and (iii) target N offtake and N input at necessary NUE to attain target crop yields with acceptable nitrate losses to ground water (right). Bottom line shows NUE of 50%, top line shows NUE of 90%.*

Maps of the geographic variation in actual NUEs and necessary NUEs for surface water and groundwater and the difference with the current NUE are given in Figure 24 (for actual crop yields) and Figure 25 (for target crop yields).

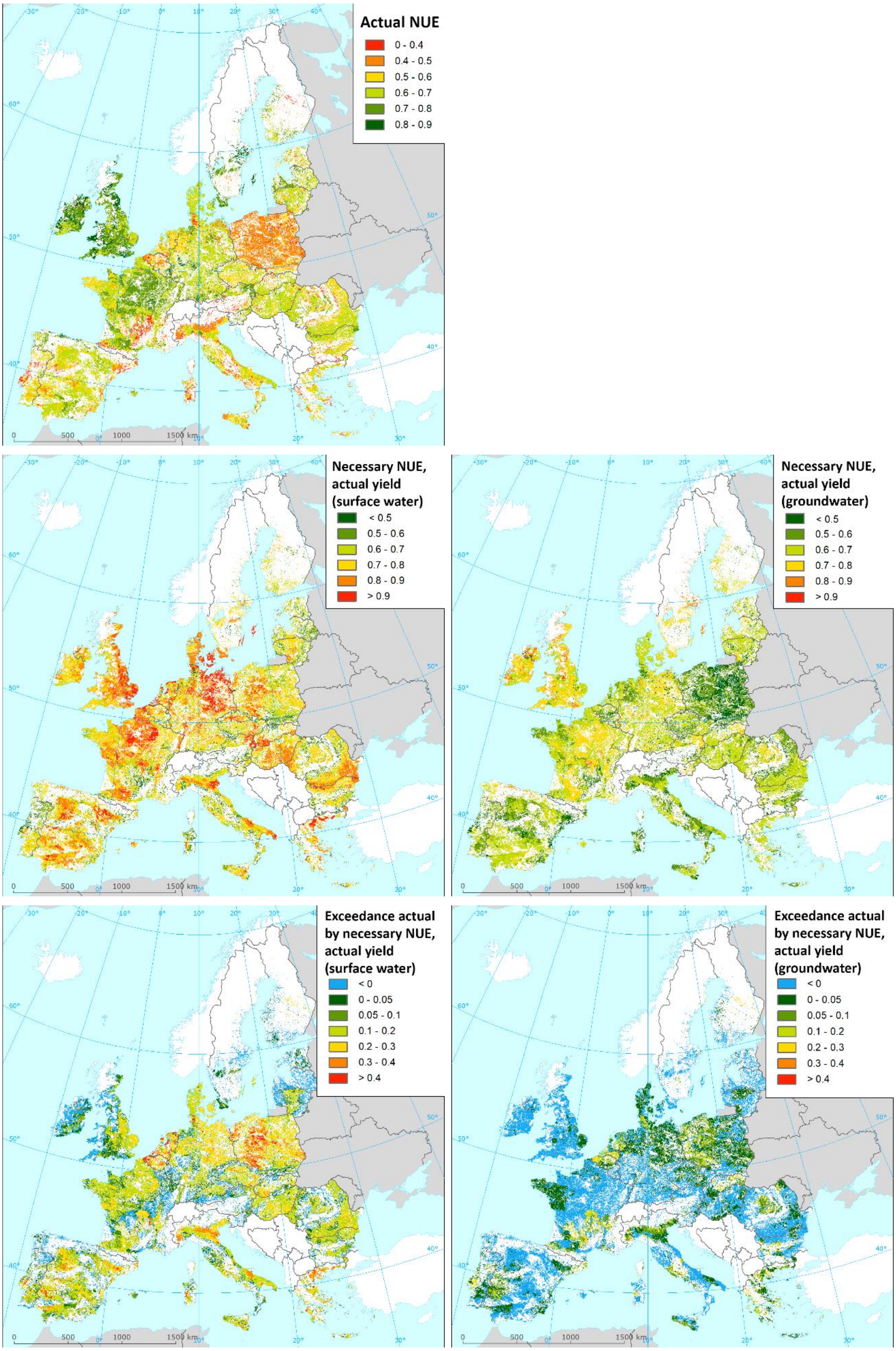

Figure 24 *Maps showing the spatial variation in actual NUE (top), necessary NUE at actual crop yields (middle) for surface water (left) and groundwater (right), and difference between actual NUE and necessary NUE (bottom) for surface water (left) and groundwater (right), for all agricultural land.*

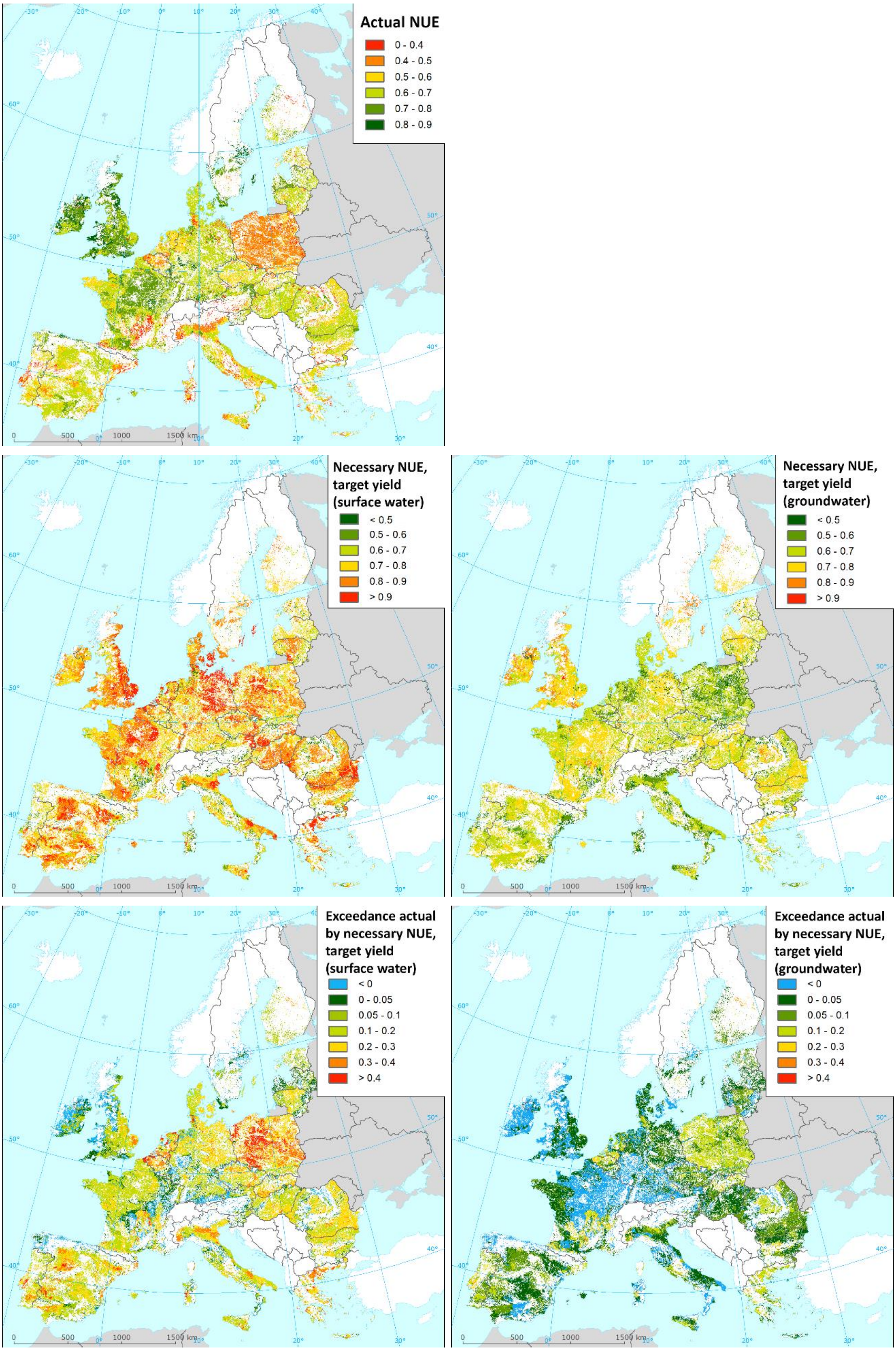

Figure 25 *Maps showing the spatial variation in actual NUE (top), necessary NUE at target crop yields (middle) for surface water (left) and groundwater (right), and difference between actual NUE and necessary NUE (bottom) for surface water (left) and groundwater (right), for all agricultural land.*

For surface water, large increases in NUE (>30 percentage points) are necessary in parts of Poland, Greece, Italy and Spain, while for groundwater NUEs hardly need to increase more than 10 percentage points. In order to achieve target yields at critical losses, necessary NUEs are around 90% for almost the whole of Europe for surface water, while they rarely exceed 70-80% for groundwater.

3.3.3 Nitrogen inputs at necessary N use efficiencies

With an increase in NUE, the N inputs that are needed to attain a given crop yield decrease (Table 9).If for example NUE is increased to the level required to reconcile actual crop yields with surface water protection (0.78, see Table 8), the required N input to attain current production levels drops by 19% (from 145 to 118 kg N ha^{-1} yr^{-1}). The required N input to obtain target yields drops by 22% (from 185 to 145 kg N ha^{-1} yr^{-1}). These values are very close to the Farm to Fork Strategy (FFS) goal of reducing N inputs by 20%.

Table 9 *Calculated average N inputs at EU-27 level that are needed to attain actual and target crop yields when using the current NUE and the necessary NUE to reconcile actual or target crop yield protection of either surface water quality or groundwater quality.*

Type of NUE applied	**N input (kg N ha^{-1} yr^{-1})**	
	Actual yield	**Target yield**
Current NUE[1]	145	185
Necessary NUE for surface water quality[2]	118	145
Necessary NUE for groundwater quality[3]	139	173

1 The current NUE is 0.64.

2 The necessary NUE to reconcile crop yield with surface water quality is 0.78 at actual yield and 0.80 at target yield (Table 8).

3 The necessary NUE to reconcile crop yield with ground water quality is 0.66 at actual yield and 0.67 at target yield (Table 8).

4 Discussion and conclusions

4.1 Uncertainties in the approach

Critical limits used

Critical ammonia emission rates: The critical ammonia emission rates are set equal to average critical N loads (deposition levels) at NUTS3 level. In a previous global study, De Vries et al. (2013) used uniform critical atmospheric NH_3 concentrations to assess N impacts on biodiversity. However, this approach requires the use of an atmospheric dispersion model, and does not account for the diversity in local circumstances affecting the critical load of nitrogen on terrestrial ecosystems. Critical N loads for terrestrial ecosystems used in this study are derived from critical N concentrations in soil solution related to risks for plant species diversity decline in forests and semi-natural vegetation (see Section 2.4.1), being comparable to empirical critical loads based on observed plant species diversity shifts in response to experimental N addition (Hettelingh et al., 2014).

Calculations of critical NH_3 emissions from critical N loads assume that N deposition rates on agricultural land and natural land are similar, which is substantiated by data (see Figure A3.1.1), and that the contribution of NH_3 to total N deposition stays constant, implying that NO_x emissions are reduced in the same proportion as NH_3. Another assumption in the calculation is that NH_3 emitted in a NUTS3 region is also deposited in the same region, while in fact only 50% of NH_3 emissions are deposited within a radius of ca. 75 km and the remainder is transported over several hundreds of kilometres (Ferm, 1998). The size of NUTS3 regions varies substantially (20–100,000 km^2, with a median of 1,850 km^2 and an average of 3,800 km^2). In smaller NUTS3 regions with high NH_3 emissions relative to surrounding regions (i.e., regions where the amount of NH_3 emissions exported to other regions exceeds the amount of NH_3 emissions received from other regions), needed reductions to respect N deposition thresholds may have been over-estimated, while the reverse is true for regions with low NH_3 emissions.

Critical N concentrations in runoff and leachate: The approach that was taken to assess critical N inputs to agriculture was that the maximum dissolved critical N concentration should not exceed 50 mg NO_3.l^{-1} (11.3 mg NO_3.-N l^{-1}) in leaching to groundwater (a limit related to health effects of nitrate in drinking water) or 2.5 mg N.l^{-1} in runoff to surface water (a limit related to ecological effects of nitrogen concentrations in water bodies). Use of a limit value for runoff water from agriculture is, however, only a surrogate in terms of the surface water quality. Higher values can be acceptable due to dilution with fresh water from non-agricultural areas and denitrification in surface water, while lower values may be needed because of mixing of runoff water with point loads of N into surface water. In this study, the dilution with fresh water from non-agricultural areas was included, assuming an N concentration in runoff from non-agricultural land of 0.5 mg N l^{-1}.Consequently the critical N concentration in runoff from agriculture was higher if the share of agriculture in an area is lower. It even exceeded the groundwater criterion when agriculture occupied less than 18% of the area in an NCU, which was the case in only less than 5% of all NCUs. The other above mentioned processes, i.e. denitrification in surface water and mixing of runoff water with point loads, were, however, not included. A higher could thus be acceptable The occurrence of denitrification in shallow groundwater, in riparian zones and in surface water, increases the limit value in runoff water from agriculture, whereas the reverse is true for mixing of runoff water with point loads of N into surface water and both effects were assumed to compensate, although it may cause deviations at local scale.

The uniform threshold value of 2.5 mg N l^{-1} used in this study does not reflect variation in ecological criteria for different surface water types (e.g., rivers, lakes, coastal waters). The Water Framework Directive (WFD) does not provide targets for surface water N concentrations itself, but requires countries to determine criteria for ‘good ecological status’. A recent review of nutrient criteria used by EU Member States to support good ecological status under the WFD shows that used thresholds vary widely, even within shared water body types (Poikane et al., 2019), partly due to different approaches used to determine critical concentrations. Overall, median values for critical N concentrations in lakes and rivers based on expert judgements or percentile distributions of N concentrations in water bodies (2.5–4.0 mg N l^{-1}) are higher than median thresholds based on data-driven methods related to biological criteria (0.68–1.5 mg N l^{-1}) (Poikane et al., 2019). This indicates that the used threshold of 2.5 mg N l^{-1} might be too lenient and that an ecologically relevant criterion may be closer to 1.0 mg N l^{-1}. However, as shown in Section 4.1.2, our model currently seems to overestimate actual N concentrations in surface water, and using a more lenient threshold for the critical concentration may compensate for this.

Some countries do not set targets at all for N concentrations for certain water body types, but focus only on P. Despite the widely held belief that P limits primary production in freshwaters and N in coastal waters, ample evidence shows that N can equally limit primary production in lakes and rivers (Conley et al., 2009; Poikane et al., 2019). Both critical N and P load thus need to be considered when assessing surface water eutrophication risk.

Cut-off values for critical N inputs

In some regions, critical N inputs might be very high. For example, critical N inputs in view of critical ammonia emissions are very high in NCUs with a very low share of agricultural land, and critical N inputs in view of critical runoff to surface water are very high in NCUs with a high precipitation surplus. To avoid distortion of the aggregated critical N inputs by very high critical N inputs that will never be given in practice, we used a cut-off value for Nin,crit which was set at the N input that will lead to a maximum offtake, calculated as actual yield * maximum N content. This 'maximum N offtake' is on average 10% higher than the actual N offtake at EU level for arable crops (excl. fodder), 24% higher for fodder crops and 86% higher for grassland. These differences in cut-off value probably explain a large share of the variation in differences between actual inputs and critical inputs for different crop groups – for example, the fact that for grassland the critical N inputs are higher (compared to actual inputs) might be due to the fact that the cut-off value is higher, rather than that there is actually less exceedance of critical losses! This also applied to comparisons between countries.

Other options to use as cut-off value could have been the actual N input or the required N input at target yield. The potential impact of using different choices is illustrated in Figure 26 for all agricultural land, further divided over arable land, fodder and grassland in Table 10.

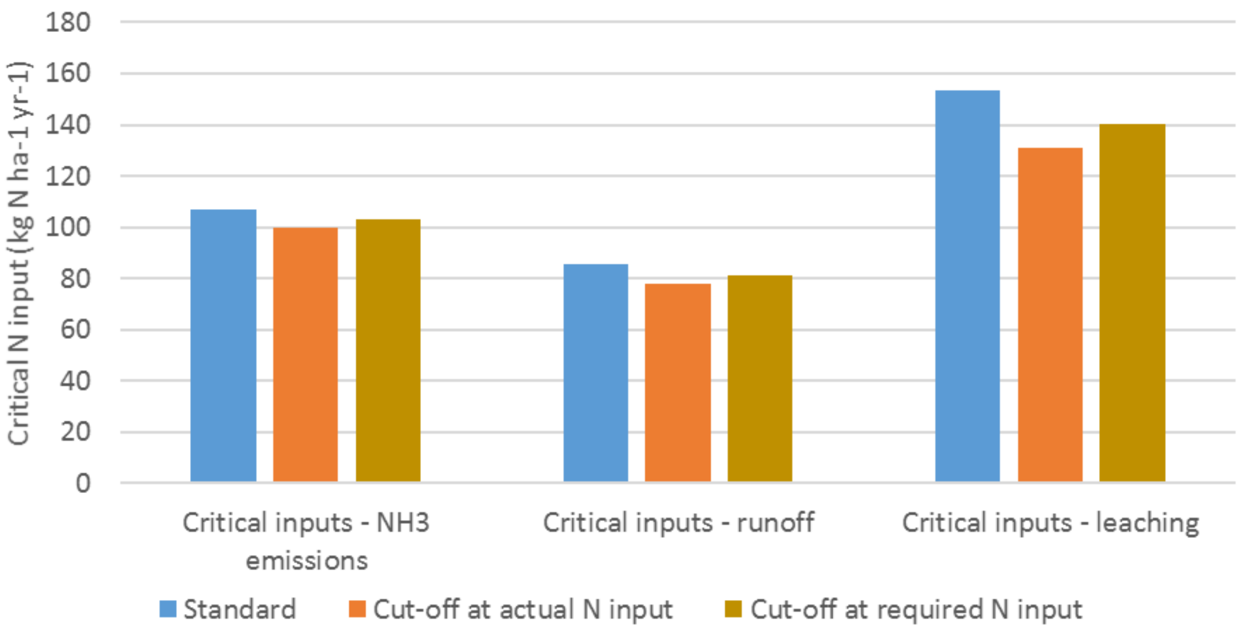

Figure 26 *Critical inputs (kg N ha^{-1} yr^{-1}) in view of critical NH_3 emissions (left), critical N runoff to surface water (middle) and critical N leaching to groundwater (right) calculated with different cut-off values for all agricultural land in EU-27.*

Table 10 *Critical N inputs (kg N ha^{-1} yr^{-1}) in view of critical NH_3 emissions, critical N runoff to surface water and critical N leaching to groundwater calculated with different cut-off values for different crops and all agricultural land in EU-27.*

Land use	Critical N inputs at standard approach: cut-off at actual yield * max. N content			Critical N inputs for cut-off at actual N input			Critical N inputs for cut-off at required N input		
	Critical - NH_3	Critical - runoff	Critical - leaching	Critical - NH_3	Critical - runoff	Critical - leaching	Critical - NH_3	Critical - runoff	Critical - leaching
Arable land	103	52	123	98	51	112	101	52	119
Fodder	128	135	220	120	123	181	124	130	199
Grassland	105	140	191	95	118	149	96	125	161
All agriculture	107	86	153	100	78	131	103	81	140

Results show that the standard approach that we used lead to somewhat higher values than approaches in which we would actual N input or the required N input at target yield, but the impacts are small (less that 5-10%).

Low precipitation areas, chalk – karst regions and steep slopes
The use of surface water quality criteria can lead to very low critical loads in areas with a low precipitation surplus). This in turn will lead to a relative low denitrification rate and consequently also a low N offtake, especially in areas with a low NUE (. In those regions, there is already a problem with low N inputs, as illustrated for e.g. Greece and Portugal. To avoid extremely low critical N inputs, we applied an arbitrary minimum value for the precipitation surplus of 5% of precipitation with an absolute minimum of 25 mm in the semi-arid regions in the Southern and Eastern part of the EU.

Furthermore, there are regions where there is no connection between precipitation surplus and recharge of aquifers or surface waters, such chalk – karst regions in UK, France and central Europe. One might also argue that the approach is less meaningful for regions where surface runoff and erosion are the main loss route for N to surface water bodies, since these fluxes are rather related to N application than to N surplus. Unlike P, however, surface runoff and erosion are only main loss routes for N to surface water bodies in areas where the slopes are extremely steep which is unlikely for arable land. We currently have not excluded karst regions or regions with steep slopes.

4.2 Plausibility of results

Plausibility of the calculated nitrogen inputs
Relationships between calculated N fertilizer application rates with INTEGRATOR and Fertilizer Europe expert estimates for major crops are shown in Figure 27. Overall, results are reasonably comparable for grain crops (wheat, barley, rice and maize), while there is a tendency of overestimating the N fertilizer inputs for sugar beet and sunflower/soybean/linseed and overestimating the N fertilizer inputs for potatoes and especially oilseed rape. The area of the latter crops is however much more limited and does much less affect the spatial distribution of N inputs that those of grain crops. One reason for the deviations between INTEGRATOR and expert estimates could be differences in the used areas for the various crops, but those areas are quite comparable as shown in Figure 28. It should be realized, however, that the expert estimates per crop per country also have considerable uncertainties and consequently the comparison indicates that the inputs per crop seem reasonable.

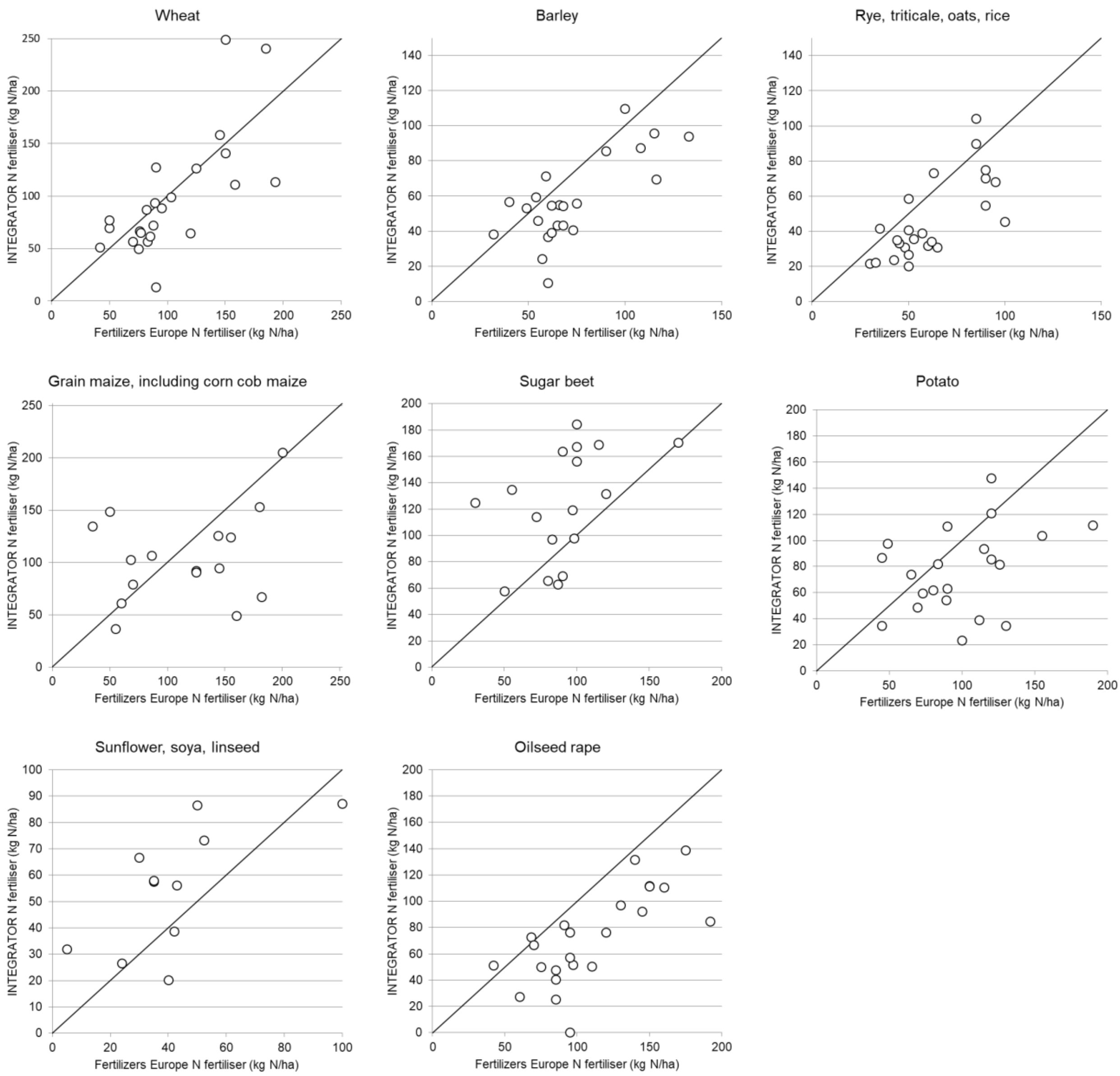

Figure 27 *Comparison of calculated N fertilizer application rates with INTEGRATOR (y-axis) and Fertilizer Europe expert estimates (x-axis) for major crops.*

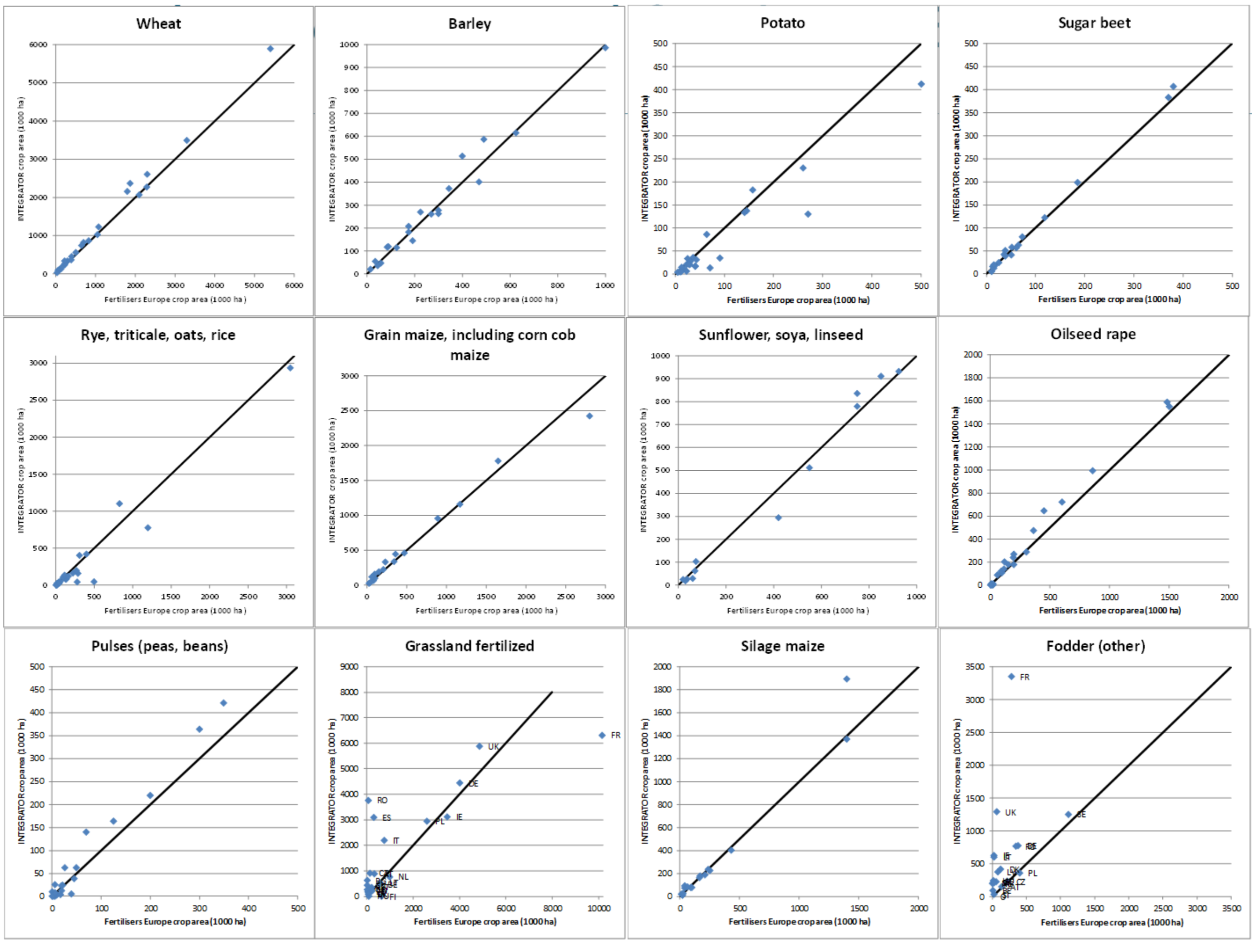

Figure 28 *Comparison of crop areas in INTEGRATOR (y-axis) and provided by Fertilizer Europe expert estimates (x-axis) for major crops.*

Plausibility of the calculated nitrogen use efficiencies

In this study, we calculated actual NUEs based on a land N balance. The NUE was thus estimated as N offtake divided by all N inputs including fertilizer inputs, manure excretion, biosolid application, biological fixation and deposition, while most studies assess NUE by accounting for manure application, thus excluding N emissions during housing and manure storage.

The plausibility of the resulting NUEs can be derived for arable land from European wide data on farm N balances (Quemada et al., 2018). These authors collected farm level data for arable farms in Spain, Germany and Denmark and for livestock farms (dairy farms, pig farms and beef farms) in The Netherlands, Denmark and Ireland. These data can only be used to assess the plausibility of the NUE of the land N balance for arable farms, since land N inputs and N outputs are comparable. For dairy farms, a major input is net N input by feed and fodder and a major output is N in animal products (milk, egg, wool, meat), whereas this is manure N input and grass N output in the land N balance. A small difference in the land N balance calculated in this study compared to the arable farm N balance calculated by Quemada et al. (2018) is that we included inputs by compost and sludge whereas they includes N inputs by seed and planting material, bedding material (straw, saw dust) and irrigation water (where relevant), but these amounts are small compared to the N input by fertilizer and manure.

Relationships between N outputs (crop N removal) and N inputs for 64 irrigated arable farms in Spain are shown in Figure 29. Results show that the NUE varies mostly between 60 and 90% with some values being higher than 100%. This is in line with the range in actual NUES in arable land over Europe (see Figure 24 top left). As with the measured farm level NUEs, the calculated actual NUE at NUTS3 level are generally between 50 and 90%, with values above 100% at some places, implying that the soil is mined with N. This is only the case in areas with a total manageable N input below 200 kg N ha^{-1} yr^{-1}, often being the case in drained peat soils where a large N mineralisation takes place.

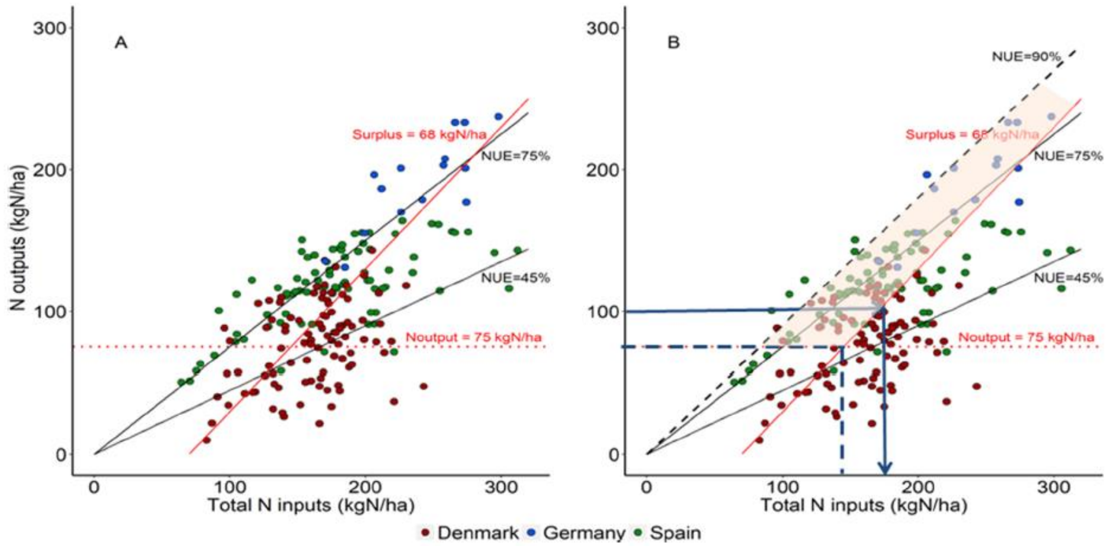

Figure 29 *Relationships between N outputs (crop N removal) and N inputs in farm N balances of arable farms in Denmark, Germany and Spain (from Quemada et al., 2020).*

Plausibility of the calculated ammonia emissions

Country-level NH_3 emissions estimated with INTEGRATOR for 2010 compare well with country-level NH_3 emission estimates from EMEP (officially reported emission data level 2 for the year 2010 obtained from EMEP database). This holds specifically for emissions from total agriculture and for manure application + grazing, whereas the comparison for emissions from fertilizer application and from housing and manure storage systems is slightly less (Figure 30). Compared to EMEP, ammonia emissions at EU level are very similar from manure application + grazing (INTEGRATOR = 868 Gg N yr^{-1}, EMEP = 878 Gg N yr^{-1} -> INTEGRATOR 1% lower), slightly higher from fertilizer application (INTEGRATOR = 530 Gg N yr^{-1}, EMEP = 459 Gg N yr-1 -> INTEGRATOR 16% higher), but significantly lower from manure storage and housing systems (INTEGRATOR = 1094 Gg N yr-1, vs. 1468 Gg N yr-1 for EMEP -> INTEGRATOR 25% lower). Consequently, the estimated emission from total agriculture by INTEGRATOR (2493 Gg N yr^{-1}) is 11% lower than from EMEP (2872 Gg N yr^{-1}).

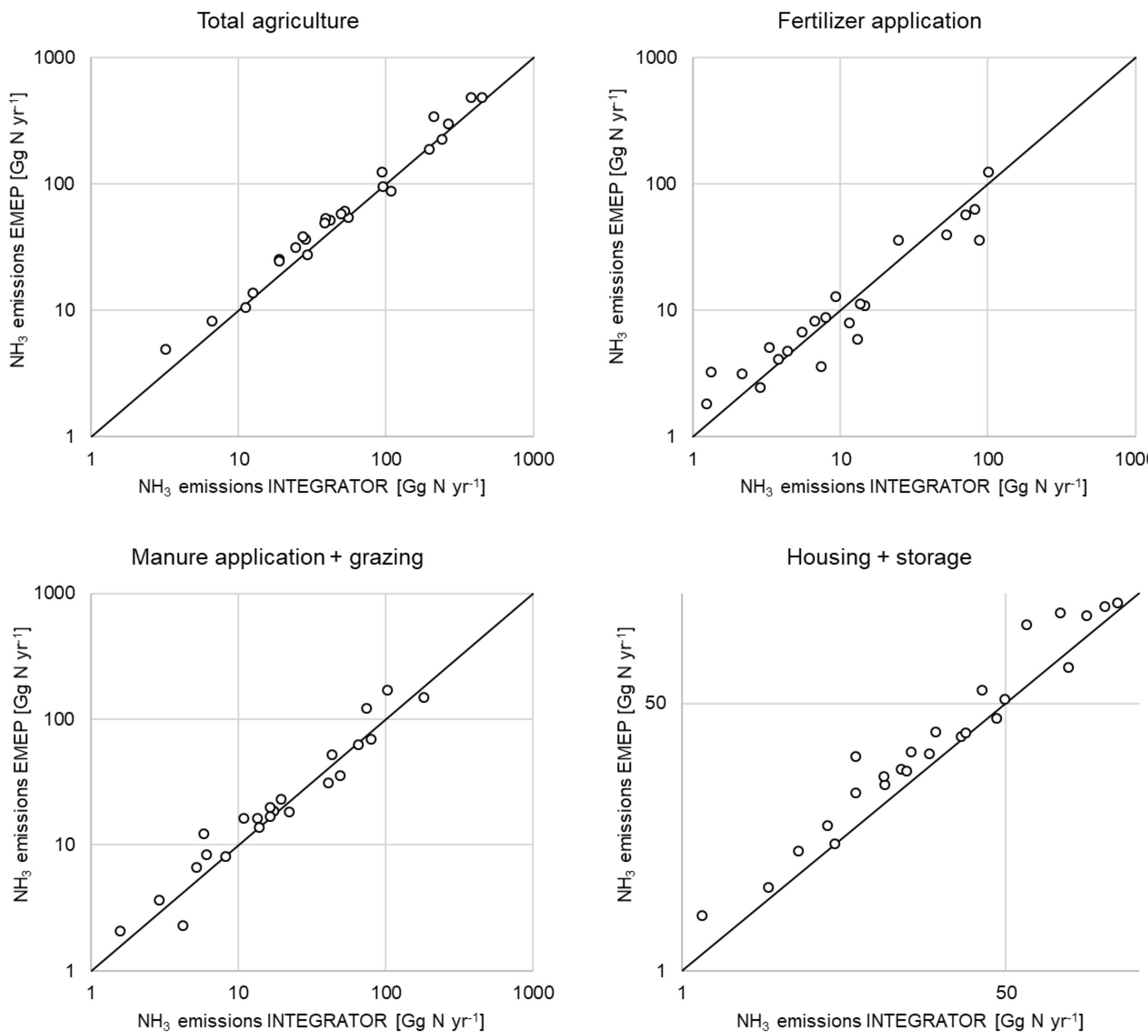

Figure 30 *Comparison of country-level NH_3 emission estimates from EMEP (officially reported emission data level 2 for the year 2010 obtained from EMEP database) vs. country-level NH_3 emissions from INTEGRATOR for (i) total agriculture (top left), fertilizer application (top right), manure application + grazing (bottom left) and housing and manure storage (bottom right).*

Plausibility of the calculated nitrate concentrations in groundwater

A comparison of calculated NO_3 concentrations in groundwater with NO_3 measurements in groundwater at country level for the year 2010 is given in Figure 31. At EU level the estimated NO_3 concentrations in different classes and the area exceeding the critical limit of 50 mg NO_3 l^{-1} are quite comparable, but there are significant differences at country level, especially in the Netherlands, Belgium, Denmark and Poland where predictions are much larger than observations, while the reverse is true for Germany.

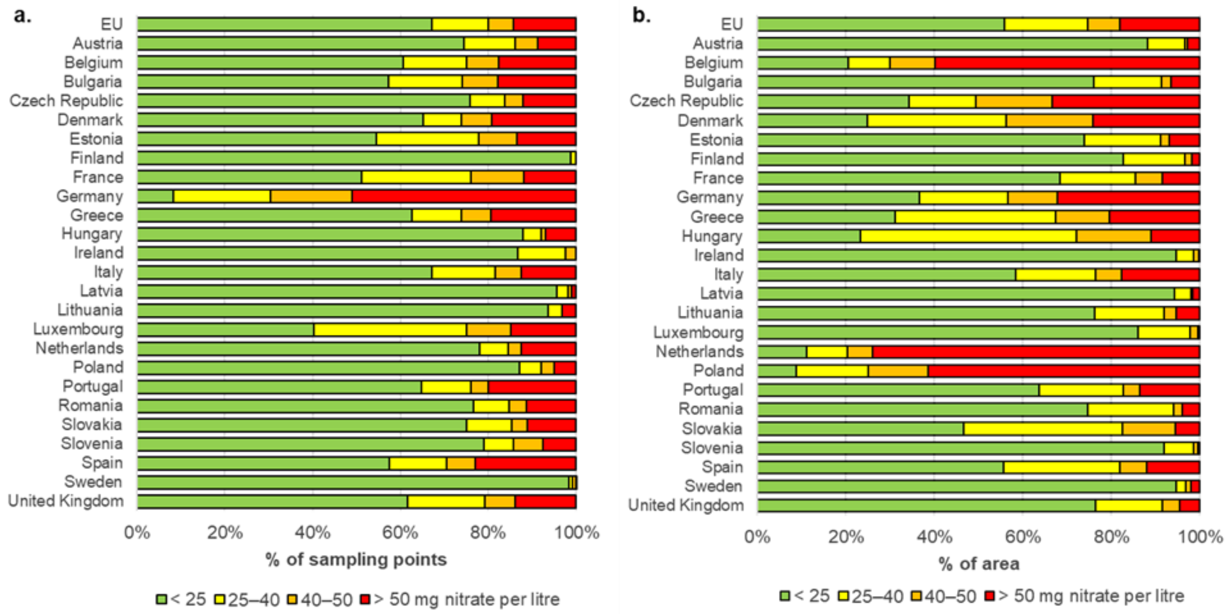

Figure 31 *Share of sampling points in a given NO3- concentration range reported by countries under the Nitrates Directive (EC, 2013) and b) share of area in a given NO3- concentration range in N leachate to groundwater calculated with INTEGRATOR.*

4.3 Possibilities to attain necessary ammonia emission fractions and nitrogen use efficiencies

Possibilities to attain necessary ammonia emission fractions

As shown above, the necessary NH_3 emission fraction for all inputs in order to stay below critical NH_3 emissions at current N inputs is 0.07, with a significant area where it should be lower than 0.05. It should also be realized that attaining a minimum emission fraction of 0.05 for N manure excretion is highly challenging. The NH_3 emission fraction for N excretion refers to the total NH_3 emission of excreted manure on land by grazing and manure excreted in housing systems, followed manure application. For manure excreted on land by grazing, there is no way to reduce the emissions, but an emission fraction of 0.05 is the minimum value attained while it can be up 10% (Table A1.4.1). The NH_3 emission fractions for manure storage (in housing or manure storage systems) can be reduced by with 40-80% compared to current standard housing systems (see Annex 1.4) where 40% can be attained in in cattle housing systems, while 80% (70-90%) can be attained in poultry and pig housing systems by ammonia removal effectiveness with air scrubbers (Melse et al., 2009). Finally, reduction of NH_3 emission to 5% of manure application is only possible by manure injection (Van Bruggen et al., 2016). In other words, a minimum emission fraction of 5% is attainable but will in practice not be reached.

Using a minimum NH_3 emission fraction for manure N excretion of 0.1 and of 0.02 for fertilizer, the share of crop area where actual crop yields (top) or target crop yields (bottom) can be achieved at acceptable (critical) NH_3 emissions is 81% at actual crop yields and 69% at target crop yields and only is 56% and 29%, respectively when using the current N fertilizer emission fractions.

Possibilities to attain necessary nitrogen use efficiencies

The necessary NUE to stay within environmental boundaries at actual crop yield and target crop yields was nearly always between 65 and 95%. The necessary NUE to stay within environmental boundaries at actual crop yields was in several regions lower than the actual NUE. This occurred in areas where the current production does not lead to N losses to either air and/or water exceeding critical limits. In case of target crop yields, the necessary NUE was nearly everywhere higher than the than the actual NUE.

There are various options to increase the NUE. Apart from proper water management, this includes: (i) ensuring an adequate soil status and /or supply of non-N nutrients, (ii) practicing balanced N fertilization based on crop N demand and accounting for non-fertilizer N sources (right rate) and (iii) giving nitrogen at the right time and right place with the right type of fertilizer. The latter two aspects are related to the so-called 4 R strategy (placement of fertilizers at the right rate, with the right type at the right time and the right place), implying precision fertilization management. A recent meta-analyses of 376 studies (1166 observations) on the effects of N management practices on crop productivity and NUE suggest that including the right type of fertilizer at the right rate, place and time may cause an overall increase of approximately 50% in NUE of wheat, maize and rice (Xia et al., 2017) in China. NUEs that may ultimately be reached in Europe in arable land may be based on farm NUEs. A range in those NUEs has been assembled by Quemada et al. (2018) to (i) identify factors that influence differences in NUE between farms and regions, (ii) derive information for reference values and (iii) come up with recommendations for enhancing NUE performance. A procedure to set targets

could be the 80% value of NUE values for a combination of a region, possibly subdivided over crop type and soil type, being the performance of the 20% best farmers. This information would be relevant to assess the plausibility of attaining necessary nitrogen use efficiencies in different regions.

4.4 Conclusions

Actual, required and critical nitrogen inputs and losses at EU level

In most regions in the EU-27 actual annual N inputs (year 2010) are lower than required N inputs to reach target crop yields and higher that critical N inputs to protect the environment. At EU-27 level, the average critical N inputs in view of eutrophication of aquatic ecosystems are 43% lower than the actual (year 2010) N inputs (83 kg N ha^{-1} yr^{-1} vs 145 kg N ha^{-1} yr^{-1}). Average critical N inputs in view of nutrient enrichment of terrestrial ecosystems are 31% lower than actual N inputs. Required N inputs to obtain target yields (185 kg N ha^{-1} yr^{-1}) are on average 27% higher than actual N inputs, with strong variations between crops.

Protecting terrestrial and aquatic ecosystems requires reducing EU NH_3 emissions and N runoff to surface water by 38% and 50%, respectively. These values are similar to the goal to reduce nutrient losses by 50% stated in the 'Farm to Fork' strategy (FFS) of the European Green Deal. Required reductions in N inputs to protect terrestrial and aquatic ecosystems (31% and 43%, respectively) are higher than the 20% reduction goal for fertiliser use in the FFS. However, those reductions are needed at current NUE. If NUE is increased to such a level that current crop yields are reconciled with the protection of surface water quality, the required reduction in N inputs is only 19%, which is similar to the FFS target of reducing fertilizer use by 20% in 2030.

Variation in actual, required and critical nitrogen inputs at country level

At country level, variation in critical N inputs in view of eutrophication of aquatic ecosystems are mainly determined by variations in the precipitation surplus and denitrification fraction. Low critical N inputs are thus calculated for countries with a low precipitation surplus, such as Spain, Greece and Portugal, whereas the reverse is true for countries with a high precipitation surplus, such as Ireland and the UK and/or a high denitrification level, such as Luxembourg and Slovenia. The variations in critical N inputs between countries in view of eutrophication of terrestrial ecosystems is mainly determined by variations in the critical NH_3 emission rate. At NUTS3 and NCU level, there are large exceedances at many 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 Po valley in Italy, regions also characterized by a high livestock density.

Variation in actual and required nitrogen use efficiencies

The NUE increase that is required to attain actual or target crop yields at acceptable N losses varies strongly. The actual NUE for all agricultural land, averaged over EU-27 is 0.64. Necessary NUEs to reconcile crop production with groundwater protection for all agricultural land, averaged over EU-27, vary between 0.66 (actual yields) and 0.67 (target yields). For reconciling crop production with surface water protection, necessary NUEs vary between 0.78 (actual yields) and 0.80 (target yields). On average the difference in necessary NUE values at actual crop yields and target crop yields is small.

Using a maximum plausible NUE of 0.9, the surface water criterion cannot be achieved on 17% and 25% of all agricultural land at actual crop yield and target crop yields, respectively. Similarly, a maximum plausible reduction in NH_3 emission fractions also still causes exceedances of critical N loads in view of biodiversity protection. Reduction in crop or animal production is needed to protect biodiversity and/or water quality in those regions

Implications of the study
This study indicates that the FFS goals to reduce nutrient losses by 50% and nutrient inputs by 20% are in principle appropriate to protect air and water quality and related biodiversity. It also shows that these reductions can in most cases be attained by better N management, resulting in higher NUEs and/or lower NH_3 emissions fractions. Use of generic flat rate targets for reductions in N losses and N inputs is, however, inappropriate, since no reductions are needed (or even increased N inputs are possible) in regions with low crop yields and limited N losses, whereas higher reductions are needed in hot spot areas with high N losses to air and water. In such regions, mostly dominated by intensive livestock, technical measures to improve the situation may not always be enough to fully protect air and water quality, thus requiring livestock reductions to attain environmental goals.

This highlights the need for region-specific mitigation policies based on regional information on critical N inputs and their exceedances with related environmental and health impacts. Results of this study could be used to develop such policies, while spatially explicit calculations of differences in actual and critical N inputs and N losses would then be relevant to evaluate the proposed mitigation measures. In addition, this report provides an elaborate documentation of the methodology and calculation steps, thus allowing the approach to calculate critical inputs to be applied in national or regional assessments using more detailed models and input data.

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Glossary of terms

Term	Variable name or acronym	Definition (the terms marked in purple are terms that are explained in the glossary).
Actual N input	Nin(act)	**N inputs** for the year 2010
Actual yield	Y(act)	Crop yield for the year 2010, expressed in kg dry matter content per hectare
Critical N input	Nin(crit)	**N inputs** at which critical thresholds for defined nitrogen indicators are reached, but not exceeded
Critical N leaching	Ngw(crit,gw)	N leaching to groundwater at which critical N concentrations in waterflow to groundwater are reached but not exceeded
Critical N losses	Nloss(crit)	Total N losses to the environment (as emissions, surface runoff, sub-surface runoff, and leaching) at **critical N inputs**
Critical N offtake	Noff(crit)	**N offtake** at **critical N inputs**
Critical N runoff	Nsw(crit,sw)	N runoff to surface water at which critical N concentrations in waterflow to surface water are reached but nut exceeded
Critical NH_3 emissions	NH3em(crit,NH3)	Ammonia emissions at which critical N deposition levels on natural ecosystems are reached but not exceeded
Farm N inputs	Nin,farm	Nitrogen inputs managed by the farmer, i.e. N fertilizer, N fixation, N manure application, N excreted by grazing animals, N biosolids (or total **N inputs** minus N deposition and net N mineralization)
N excretion	Nex	Total manure N excreted by animals in housing systems and by grazing animals
N inputs	Nin	All nitrogen inputs to agriculture, including N fertilizer, N fixation, N manure application, N excreted by grazing animals, N biosolids, N deposition and net N mineralization
N leaching	Nle	Total N leaching below the root zone (**N surplus** multiplied with a leaching fraction)
N leaching to groundwater	Ngw	N leaching to groundwater (Total N **leaching** below the root zone minus sub-surface runoff / lateral transport to surface water)
N offtake	Noff	Nitrogen in harvested part of the crop
N runoff to surface water	Nsw	Total N runoff to surface water (sum of surface runoff and sub-surface runoff)
N crop surplus	Nsurplus	Total nitrogen inputs minus **N offtake**
N soil surplus	Nsur	Total nitrogen inputs minus **N offtake**, N emissions and N surface runoff
N uptake	Nup	Total nitrogen uptake by the plant, including crop residues, below-ground parts and harvested part
N use efficiency	NUE	Nitrogen use efficiency, defined as **N offtake** divided by total **N inputs**
Necessary NH_3 EF	fNH3em(nec)	Maximum NH_3 emission fraction at which actual yield can be obtained without exceeding critical N deposition on natural ecosystems
Necessary NH_3 EF for excretion	fNH3emex(nec)	Maximum NH_3 emission fraction for excreted manure at which actual yield can be obtained without exceeding critical N deposition on natural ecosystems, assuming a constant emission fraction for fertilizer
Necessary NUE for actual yield	NUE(nec,act)	Minimum NUE at which **actual yield** can be obtained without exceeding critical runoff to surface water or critical leaching to groundwater
Necessary NUE for target yield	NUE(nec,tar)	Minimum NUE at which **target yield** can be obtained without exceeding critical runoff to surface water or critical leaching to groundwater
Required N input	Nin(req)	**N input** required to obtain target yield at actual NUE
Target yield	Ytarget	Defined as 80% of the water-limited yield potential derived by scaling, but not lower than the actual yield
Water-limited yield potential	Yw	maximum possible yield for a rainfed crop for a given climate, soil and topography (most relevant benchmark for rainfed crops)
Yield potential	Yp, Yw	maximum possible yield for a given crop, climate and soil, assuming optimal management and assuming that water is not limited (most relevant benchmark for irrigated crops)

Annex 1 Methods and data to calculate the spatially explicit actual inputs, uptake and losses of nitrogen

A1.1 Calculation of N excretion and manure application rates

Downscaling of livestock data
Statistical data on livestock numbers in various animal categories at NUTS2 level, needed to assess N excretion, were downscaled to a 1 km^2 resolution using expert based judgment with spatial data sources on land use, slope, altitude and soil characteristics influencing the livestock carrying capacity. A major distinction was made between grazing animals and other animals. Dairy cows, beef cattle, sheep and goats were assumed to be highly dependent on local land resources for grazing or feed production. Pigs and poultry were assumed to be held in more land independent systems. For more detailed information on the downscaling of livestock, we refer to Neumann et al. (2009). The livestock numbers thus derived at a 1 km^2 resolution were aggregated to numbers at NCU level, since NCUs are clusters of 1 km2 grid cells that are characterized by similar environmental and/or agronomic conditions.

N excretion rates
Table A1.1.1 presents N excretion rates per animal for dairy cows, other cattle, pigs, horses, sheep and goats, laying hens, other poultry and fur animals, according to GAINS for the year 2010 as used in INTEGRATOR (Asman et al., 2011). Average excretion rates for the EU-27 and absolute and relative standard deviations per animal category are presented as a measure of the variation in N excretion rates between countries. Relative differences are largest (>30%) for other poultry and fur animals and smallest (<14%) for pigs and horses.

Distribution of manure
Manure produced by grazing animals all enters grassland. The grazing intensity, and thereby the N excretion by grazing animals, decreases from intensively managed grassland to extensively managed grassland to rough grazing. This is included by using weighing factors of 1.0, 0.5 and 0.1, except for sheep and goats where no weighting was applied. Manure produced in housing systems by sheep and goats is completely applied to grassland. For other manure, a fraction is applied to arable land and the remaining fraction is applied to grassland/fodder crops, based on data of Menzi (2002). A distinction is made between (i) liquid manure of dairy cattle, other cattle and pigs, (ii) solid manure of dairy cattle, other cattle and pigs and (iii) poultry manure (See Table A1.1.2).

For the distribution of manure application on arable land, we distinguish three arable crop groups: group I with a relatively high use of manure (sugar beet, barley, rape, and soft wheat), group II with an intermediate use of manure (potatoes, durum wheat, rye, oats, grain maize, other cereals including triticale, and sunflower), and group III with low use of manure (fruits, citrus, olives, oil crops, citrus, grapes and other crops). Finally, no manure is allocated to dry pulses and rice, in view of assumed N fixation, fibre crops, other root crops and vegetables. First, the average manure application rate (in kg N per ha) over all arable crops is calculated. The application rate (kg N/ha) for the three arable crop groups is then assessed by using weighing factors of 0.25 for group III, 0.50 for group II and 1.0 for group I. Group I thus receives the highest manure application rates, based on Velthof et al. (2009).

Table A1.1.1 *Mean N excretion of for dairy cows, other cattle, pigs, horses, sheep and goats, laying hens, other poultry and fur animals in European Countries, in kg per animal per year, for the year 2010, according to the RAINS database (after Asman et al., 2011).*

Country	Dairy cows*	Other cattle	Pigs	Horses	Sheep and goats	Laying hens	Other poultry	Fur animals
Austria	106	46	9	48	13	0.7	0.4	4.1
Belgium	118	50	11	50	7	0.7	0.5	4.1
Bulgaria	75	45	12	50	12	0.8	0.7	1.5
Cyprus	103	40	12	50	12	0.8	0.7	4.1
Czech	131	45	12	50	12	0.8	0.6	1.5
Denmark	132	37	10	43	17	0.7	0.5	4.6
Estonia	113	45	12	50	14	0.8	0.5	4.1
Finland	121	53	10	50	16	0.8	0.4	1.9
France	112	50	12	50	12	0.8	0.9	4.1
Germany	130	40	15	48	8	0.8	0.6	4.1
Greece	111	45	12	50	12	0.8	0.7	4.1
Hungary	146	45	9	50	12	1.5	1.5	4.1
Ireland	105	69	12	50	8	0.8	0.5	4.1
Italy	112	47	12	50	16	0.7	0.5	4.1
Latvia	88	51	10	51	7	0.9	0.9	4.1
Lithuania	95	50	12	50	12	0.8	0.5	4.1
Luxembourg	114	42	10	50	12	0.8	0.7	4.1
Malta	98	40	12	50	12	0.8	0.7	0.7
Netherlands	147	40	9	50	12	0.7	0.6	2.2
Poland	81	35	11	50	14	0.7	0.6	4.1
Portugal	102	50	9	39	7	0.6	0.9	0.7
Romania	67	45	12	50	12	0.8	0.7	4.1
Slovakia	135	45	12	50	12	0.8	0.7	4.1
Slovenia	110	40	12	50	11	0.7	0.5	4.1
Spain	71	52	9	40	5	0.8	0.6	4.1
Sweden	132	39	11	50	6	0.6	0.3	4.1
United Kingdom	133	49	12	50	6	0.9	0.7	4.1
Mean	111	46	11	49	11	0.8	0.6	3.5
St. Deviation	21	7	1	3	3	0.2	0.2	1.2
St. Deviation (% of the Mean)	19%	14%	13%	6%	29%	20%	35%	33%

For the distribution of manure application on grassland, we distinguish intensive grassland, including fodder, extensive grassland and rough grazing, using weighing factors of 1.0, 0.50 and 0.12 respectively. The parameterization of these weighting factors was based on comparison of calculated N fertilizer input data per crop per country with those estimated by country experts of Fertilizers Europe for the reference year 2010 (see Section 4.2).

The maximum amount of N manure application was set to a legal maximum of 170 kg N ha^{-1} yr^{-1} for all agricultural land (crop land and grassland), except for Denmark and the Netherland where the acceptable amounts for grassland and fodder 250 kg N ha^{-1} yr^{-1}. When N manure application exceeds these amounts, the excess manure is distributed over nearby NCUs within a NUTS region, or over nearby NUTS regions within a country if application rates are still exceeded.

Table A1.1.2 *Proportion of different types of manure (%) used on arable land in European Countries as used in INTEGRATOR (After Menzi, 2002). The remaining percentage is allocated to grassland.*

Country	Slurry/liquid manure of dairy/other cattle, pigs	Solid manure of dairy/ other cattle, pigs	Poultry manure
Austria	40	60	95
Belgium	80	100	100
Bulgaria	80	80	80
Croatia	80	80	80
Cyprus	80	80	80
Czech Republic	20	80	90
Denmark	75	75	97
Estonia	80	80	80
Finland	80	90	100
France	80	95	98
Germany	85	85	100
Greece	20	20	50
Hungary	63	95	75
Ireland	5	0	0
Italy	74	90	80
Latvia	80	80	80
Lithuania	10	90	100
Luxembourg	30	90	100
Malta	80	80	80
Netherlands	35	50	100
Norway	22	30	100
Poland	80	90	89
Portugal	100	100	100
Romania	80	80	80
Slovakia	80	100	100
Slovenia	80	80	80
Spain	75	100	100
Sweden	22	70	100
Switzerland	10	50	63
United Kingdom	25	50	56

A1.2 Calculation of N fertilizer application rates

The amount of N fertilizer input at NCU level is derived by a balanced N fertilization approach, based on total crop N demand, available non-fertilizer inputs (N inputs by animal manure, crop residues, N mineralization, N deposition and N fixation) and N use efficiency (NUE) of the effective N input.

Offtake requirements: First, total N demand of each crop (= N in harvested products + N in crop residues) is calculated according to:

$$N_{up} = N_{off} * \left(1 + \frac{1}{N_{index}}\right) \qquad \text{(A1.2.1)}$$

Where:

N_{up} = Total plant N uptake (above- and belowground parts) (kg N ha^{-1} yr^{-1})
N_{off} = N removed in harvested crops (kg N ha^{-1} yr^{-1})
N_{index} = N removed in harvested crop divided by N amount in crop residues; (N_{off}/N_{cr}) (-)

The aboveground N offtake (N removed in harvested crops) is calculated as the product of the crop yield (in terms of harvest) and the N content in harvested crops:

$$N_{off} = Yield * N_{cont} \tag{A1.2.2}$$

Where:

Yield = dry matter yield (kg DM ha^{-1} yr^{-1})

N_{cont} = crop N content (g N kg DM^{-1})

The N content, in turn, is a function of the effective N input, according to:

$$N_{cont} = frN_{min} * N_{cont,max} + \frac{(1-frN_{min})*N_{cont,max}}{N_{in,eff,max}} * N_{in,eff} \tag{A1.2.3}$$

Where

frN_{min} = a fraction being equal to the ratio of the minimum/maximum crop N content (-)

$N_{cont,max}$ = maximum crop N content (g N kg DM^{-1})

$N_{in,eff,max}$ = maximum effective N input, being the effective N input where the content in the crop is at is maximum and does not increase anymore (kg N ha^{-1} yr^{-1})

The minimum N content, i.e. the content at negligible effective N input ($N_{in,eff}$) has been set at 0, since there is (in the long term) a negligible N uptake when there is no N fertilizer input (See Lassaletta et al., 2014). In reality, this is due to combination of effects of reduced N inputs on both crop yields and N contents, which we include in the N content only. This implies that frN_{min} is set to 0 and Eq. (A 1.2.3) thus simplifies to:

$$N_{cont} = \frac{N_{cont,max}}{N_{in,eff,max}} * N_{in,eff} \tag{A1.2.4}$$

The maximum effective N input is calculated as a function of the maximum N uptake (defined as yield times maximum N content) and uptake efficiency, according to:

$$N_{in,eff,max} = (Yield * N_{cont,max})/frN_{up} \tag{A1.2.5}$$

Where

fr_{Nup} = the efficiency factor of the effective N applied (-)

<u>The effective N input</u> (total amount of plant-available N) is calculated by distinguishing between organic nitrogen inputs by animal manure, crop residues and N mineralization, and more readily available nitrogen inputs (mineral N) from animal manure, N deposition and N fixation, according to:

$$N_{in,eff} = N_{fe} + N_{min,am} + f_{av,am} * N_{org,am} + N_{min,gr} + f_{av,gr} * N_{org,gr} + f_{av,bs} * N_{bs} + f_{av,cr} * N_{cr} + f_{av,min} * N_{min} + f_{av,dep} * N_{dep} + N_{fix} - N_{em,ap} \tag{A1.2.6}$$

Where:

N_{fe} = Input of N by fertilizer (kg N ha^{-1} yr^{-1})

$N_{min,am}$ = Input of mineral (inorganic) N in applied animal manure (kg N ha^{-1} yr^{-1})

$N_{org,am}$ = Input of organic N in applied animal manure (kg N ha^{-1} yr^{-1})

$N_{min,gr}$ = Input of mineral (inorganic) N in manure excreted by grazing (kg N ha^{-1} yr^{-1})

$N_{org,gr}$ = Input of organic N in manure excreted by grazing (kg N ha^{-1} yr^{-1})

N_{bs} = Input of N by biosolids (kg N ha^{-1} yr^{-1})

N_{cr} = N mineralized from crop residues (kg N ha^{-1} yr^{-1})

N_{min} = N mineralized from soil organic matter (change in soil N pool, which is only included for peat soils) (kg N ha^{-1} yr^{-1})
N_{dep} = Input of N by deposition (kg N ha^{-1} yr^{-1})
N_{fix} = Input of N by fixation (kg N ha^{-1} yr^{-1})
$N_{em,ap}$ = Emission of N due to application of N by fertilizer, manure, grazing, biosolids (NH_3, N_2O and NO_x), fixation and deposition (N_2O and NO_x only) (kg N ha^{-1} yr^{-1})
$f_{av,am}$ = Availability fraction of organic N in applied animal manure compared to N fertilizer (-)
$f_{av,gr}$ = Availability fraction of organic N in animal manure excreted by grazing animals compared to N fertilizer (-)
$f_{av,bs}$ = Availability fraction of N in biosolids compared to N fertilizer (-)
$f_{av,cr}$ = Availability fraction of N in crop residues compared to N fertilizer (-)
$f_{av,min}$ = Availability fraction of N mineralized from soil compared to N fertilizer (-)
$f_{av,dep}$ = Availability fraction of N deposition compared to N fertilizer (-)

The N in crop residues is calculated by dividing N offtake by an N index, calculated as N offtake divided by N crop residue ($N_{index} = N_{off}/N_{cr}$). The availability of the mineral part of animal manure is determined by its input minus the calculated N emission. As with fertilizer, the availability fraction of the mineral part of animal manure is set equal to 1. The availability fraction of organic N compared to N fertilizer varies for the different organic N sources and is set equal to:

- organic N in animal manure and mineralized N from (peat) soil: fav,am and fav,min are 0.7 for arable land and 0.9 for grassland
- organic N from grazing and N from biosolids: fav,gr and fav,bs are 0.4.
- organic N from crop residues: fav,cr is 0.9
- N from deposition: fav,dep is 0.75.

N fertilizer input is finally derived according to (see Eq. A1.2.7):

$$N_{fe} = \frac{N_{up}}{fr_{Nup}} - \left(N_{min,am} + f_{av,am} * N_{org,am} + N_{min,gr} + f_{av,gr} * N_{org,gr} + f_{av,bs} * N_{bs} + f_{av,cr} * N_{cr} + f_{av,min} * N_{min} + f_{av,dep} * N_{dep} + N_{fix} - N_{em,ap}\right) \quad \text{(A1.2.7)}$$

Initially, a maximum N content ($N_{cont,max}$) is used to assess N_{fe}. The $N_{fe,max}$ thus calculated is summed up and compared with the N_{fe} available according to national fertilizer consumption rates (FAO data). The fertilizer input N_{fe} at each NCU is then scaled by the ratio $N_{fe,used}/N_{fe,max}$. When $N_{fe,used} > N_{fe,max}$, there is a case of over-fertilization and the N content will not change (is at its maximum). When $N_{fe,used} < N_{fe,max}$, there is a case of under-fertilization. In this case the new value of N_{fe} is included in $N_{in,eff}$ thus leading to a change in N content (Eq. A 1.2.4) and thereby in N offtake. In the case of a balanced N fertilizer approach, there is neither over-fertilization nor under fertilization. In all countries where $N_{fe,used} > N_{fe,max}$ or $N_{fe,used} < N_{fe,max}$, we reduce or increase the N use according to $N_{fe,used} = N_{fe,max}$.

Input data to assess N uptake: Input data to assess N uptake include maximum N contents in harvested products, crop residue ratios and uptake fractions. The maximum N content in (intensively managed) grassland was set at 3%. The N contents of crop products and the N index and C/N ratio of crop residues were based on a literature review of Velthof & Kuikman (2000) for the Netherlands (Table A1.2.1). The results presented in Table A1.2.1 were derived from Dutch studies of the nineties. The value of frN_{up} are set at 0.8 for arable land and at 1.0 for grassland (Velthof et al., 2009).

Table A1.2.1 *Crops distinguished by INTEGRATOR, maximum nitrogen contents (fresh weight) and nitrogen indices used in the uptake calculation (source: Velthof & Kuikman, 2000; Velthof et al., 2009), and total crop area for each crop. Table shows categorization of crops into either arable land or fodder/grassland used for aggregation of results.*

CAPRI CODE	CAPRI ID	CAPRI description	N content max (g kg^{-1})	N index (N_{off}/N_{cr}) (-)	frN_{up} (-)	Area (km^2)
Arable land						
SWHE	1	Common wheat	20	3.02	0.8	249,796
DWHE	2	Durum Wheat	20	3.02	0.8	36,812
BARL	3	Barley	17	2.37	0.8	139,898
RYEM	4	Rye	14	1.79	0.8	24,060
OATS	5	Oats	17	2.08	0.8	42,116
MAIZ	6	Maize (= grain maize)	14	1.53	0.8	87,980
PARI	7	Rice	20	3.02	0.8	4,853
OCER	8	Other cereals	15	2.02	0.8	31,823
POTA	9	Potatoes	3.5	3.13	0.8	16,262
SUGB	10	Sugar beet	1.8	0.67	0.8	16,371
SUNF	12	Sunflower	32	1.79	0.8	41,417
RAPE	13	Rape and turnip rape	35	1.79	0.8	76,525
SOYA	14	Soya	58	1.06[1]	0.8	3,849
TEXT	15	Fibre and oleaginous crops; Cotton	4	1.11	0.8	3,513
TOBA	16	Tobacco	30	2.05	0.8	960
PULS	18	Dry pulses	42	1.10[1]	0.8	15,993
OVEG	20	Other fresh vegetables	2.5	1.16	0.8	15,227
FRUI	24	Other Fruit	6.7	3.0	0.8	25,435
CITR	25	Citrus fruits: Oranges	2.7	2.05	0.8	5,342
OLIV	26	Olive groves	20	2.05	0.8	47,681
TWIN	27	Vineyards /table wine	4.6	2.05	0.8	22,645
OCRO	29	Other crops; Permanent industrial crops	5	2.05	0.8	1,680
OWIN	31	Other wine	0.5	2.1	0.8	9,917
TAGR	35	Table grapes	4.6	2.1	0.8	961
TABO	36	Table olives	20	2.1	0.8	2,848
OOIL	37	Other oil	34	1.3	0.8	2,048
Fodder + Grassland						
OFAR	22	Fodder other on arable land; Temporary grasslands	5.8	2.43	1.0	153,833
GRAS	33	Grassland	30[2]	2.0	1.0	382,486
MAIF	34	Fodder maize	15	4.9	1.0	54,038

1 Soy and pulses are based on Herridge et al (2008). Data on N index by (Velthof & Kuikman, 2000; Velthof et al., 2009) are 2.05 for soya and 4.97 for pulses.

2 N contents in grass are given in dry weight since grassland yields are in dry weight.

A1.3 Calculation of actual crop yields

Scaling of subnational variation in wheat yields to all crops in INTEGRATOR

National yields per crop were derived from FAOSTAT. Sub-national variation in actual crop yields in INTEGRATOR was derived by using sub-national wheat yields from the Global Yield Gap Atlas (GYGA) and scaling those yields to all crops in INTEGRATOR, assuming that: (i) the relative differences in wheat yields also reflect differences in yields of other crops and (ii) the total national crop yield should be equal to the yield estimate from FAOSTAT. GYGA provides estimates of actual yields for a variety of staple crops at sub-country (regional) level (for zones of similar climate). These sub-national estimates of actual yields are multi-year average yields obtained by farmers under dominant management practices, and are gathered from sub-national statistics, farm surveys and/or local agronomists. Sub-national rainfed wheat yields are available for all EU-27 countries except Malta and Cyprus.

Assuming that the variation in rainfed wheat yields between climate zones within a country from GYGA is a good representation of spatial variations in yields of all other INTEGRATOR crops, we applied a scaling factor per climate zone, according to:

$$Ya\_p_{crop_n,cz_{ij}} = Ya_{crop_n,co_j} * \frac{Ya_{wheat,cz_{ij}}}{Ya_{wheat,co_j}} \qquad \text{(A1.3.1)}$$

Where:

$Ya\_p_{crop_n,cz_{ij}}$	=	the preliminary scaled actual yield of crop n for climate zone i in country j
Ya_{crop_n,co_j}	=	the average actual crop yield for country j from FAO (data in INTEGRATOR)
$Ya_{wheat,cz_{ij}}$	=	the actual wheat yield for climate zone i in country j from GYGA
Ya_{wheat,co_j}	=	the area-weighted average actual wheat yield for country j from GYGA

The ratio $\frac{Ya_{wheat,cz_{ij}}}{Ya_{wheat,ave_j}}$ (the wheat yield in climate zone i within country j as compared to average wheat yield in country j from GYGA) was used to multiply the country average crop yields in INTEGRATOR. This fulfilled the first assumption that relative sub-national variations in wheat yields also reflect differences in yields of other crops.

The crop yields in each climate zone calculated with Eq. (A 1.3.1) were then multiplied with a fixed factor, i.e. the INTEGRATOR crop production/scaled crop production, to ensure that the total crop production values in a country stay equal to those used in INTEGRATOR (from FAOSTAT):

$$Ya_{crop_n,cz_{ij}} = Ya\_p_{crop_n,cz_{ij}} * \frac{Ya_{crop_n,co_j} * A_{crop_n,co_j}}{\Sigma\left(Ya\_p_{crop_n,cz_{ij}} * A_{crop_n,cz_{ij}}\right)} \qquad \text{(A1.3.2)}$$

Where:

$Ya_{crop_n,cz_{ij}}$	=	the final scaled actual yield of crop n for climate zone i in country j
$A_{crop_n,cz_{ij}}$	=	the crop area for crop n in climate zone i in country j, derived by an overlay of climate zones in GYGA and crop areas per NCU in INTEGRATOR (based on Eurostat data for crop areas per NUTS region).
A_{crop_n,co_j}	=	the country-level crop area for crop n in country j in INTEGRATOR.

The area of arable land in INTEGRATOR is derived from the CLUE model and includes the CLUE categories non-irrigated arable land (1), irrigated arable land (6) and permanent crops (8). The area of each crop in NUTS 2 regions are derived from CAPRI, by using the CAPRI crop shares and multiplying these shares with the area of arable land as derived with CLUE. Crop areas are derived from the Lucas survey. Crop area of each NCU are then scaled by using data from Eurostat (derived from: http://ec.europa.eu/eurostat/data/database). Yields of arable crops were derived from FAO statistics.

Before we could apply this procedure, we needed to make sure that each NCU was assigned to a climate zone with available data on wheat yield, as GYGA only provides estimates for actual wheat yield and yield potentials for climate zones containing more than 5% of the national crop area. The steps to assign a climate zone with wheat data to each NCU are presented in detail below.

Assign each NCU to a climate region based on overlay
First, we made an overlay of a map of climate zones (http://www.yieldgap.org/web/guest/methods-upscaling) with a map of NCUs and calculated the share of the area of each climate zone within each NCU. Each of the 40,000 NCUs was then assigned to one of the 77 climate zones that occupied the largest share of the area of the respective NCU, OR to “non-classified” (CZ 0). (In the procedure of assigning climate zones in GYGA, only grid cells with sum of the harvested area of major food crops > 0.5% of the grid cell area were accounted for. Therefore all countries that have a coastline have non-classified regions along fringes of the coasts. These areas were assigned the default national average yield.)

Important for the quality of our approach is that for the majority of NCUs, the assigned climate zone is indeed dominant within the NCU (rather than that several climate zones occupy almost equal shares of the area within a NCU). Indeed, 70% of the NCUs (in terms of area) was assigned a climate zone that occupied more than 60% of the area in this climate zone (see Table A1.3.1). Very few NCUs (less than 6% in terms of area) were assigned to a climate zone that occupied less than 40% of a NCU's territory.

Table A1.3.1 *Results of quality check for assigning climate zones to NCUs.*

	Number of NCUs	Total area dominant CZ (ha)	Total area NCUs (ha)	% of total (area)
Area of assigned CZ < 25% of total area NCU	41	2,918	13,355	0.3%
Area of assigned CZ 25-40% of total area NCU	1,220	80,565	231,997	5.5%
Area of assigned CZ 40-60% of total area NCU	7,329	512,703	1,002,664	23.9%
Area of assigned CZ 60-85% of total area NCU	10,237	912,253	1,257,133	30.0%
Area of assigned CZ > 85% of total area NCU	24,110	1,618,387	1,685,139	40.2%
Grand Total	42,937	3,126,826	4,190,289	100.0%

Assign a "wheat climate zone" to all NCUs

After assigning a climate zone to each NCU based on the principle of "dominant CZ within NCU", there are many climate zones that occur in countries but for which GYGA does not provide wheat yield data. For example, for the Netherlands, wheat yield data is available for all climate zones, but for countries like Bulgaria, Spain and Greece, wheat yield data is only available for about 20-25% of climate zones (see Table A1.3.2). We thus needed to re-assign a new climate zone to these NCUs that (i) does have data on wheat yields in this country and (ii) is as similar as possible to the original climate zone.

We re-classified all climate zones for which wheat yield data were not available based on similarities in classification parameters: Temperature Seasonality (TS), Aridity Index (AI) and Growing Degree Days (GDD), see Table A1.3.3. As neighbouring classes within each category are often quite similar, climate zones for which no wheat data was available were classified according to the following rules:

1. Assign climate zone with neighbouring TS class (same AI and GDD), otherwise:
2. Assign climate zone with neighbouring AI class (same TS and GDD), otherwise:
3. Assign climate zone with neighbouring GDD class (same TS and AI), otherwise:
4. Assign climate zone with neighbouring TS and AI class (same GDD), otherwise:
5. Assign climate zone with neighbouring AI and GDD class (same TS), otherwise:
6. Assign climate zone with neighbouring TS and GDD class (same AI), otherwise:
7. Assign climate zone with neighbouring TS and GDD and AI class, otherwise:
8. Assign default climate zone "99999"

Table A1.3.4 shows how often each of the 8 re-classification rules was applied per country and in total. After re-classification, the share of climate zones with no wheat data was reduced from 64% to 13%.

Table A1.3.2 *Number of climate zones that occur in each country; number of climate zones for which wheat yield data is available in the respective country, and share of climate zones in a country for which wheat yield data is available.*

Country	**number of CZs that occur in country**	**number of CZs wheat yield data available**	**% of CZ in country for which wheat yield data is available**
AT	12	8	67%
BE	5	3	60%
BG	25	5	20%
CZ	14	6	43%
DE	16	9	56%
DK	3	2	67%
EE	4	2	50%
EL	38	8	21%
ES	48	13	27%
FI	6	3	50%
FR	26	10	38%
HU	9	6	67%
IE	5	3	60%
IT	33	9	27%
LT	11	3	27%
LU	4	1	25%
LV	7	2	29%
NL	2	2	100%
PL	17	9	53%
PT	34	8	24%
RO	26	7	27%
SE	11	5	45%
SI	10	5	50%
SK	15	7	47%
UK	13	6	46%
TOTAL	**394**	**142**	**36%**

Table A1.3.3 *Parameters used in the classification of climate zones in GYGA.*

GGD (◦Cd)	**GYGA ED Value**	**AI (-)**	**GYGA ED Value**	**Temperature seasonality**	**GYGA ED Value**
0–2670	1000	0–2695	0	0–3832	1
2671–3169	2000	2696–3893	100	3833–8355	2
3170–3791	3000	3894–4791	200	>= 8656	3
3792–4829	4000	4792–5689	300		
4830–5949	5000	5690–6588	400		
5950–7111	6000	6589–7785	500		
7112–8564	7000	7786–8685	600		
8565–9311	8000	8686–10181	700		
9321–9850	9000	10182–12876	800		
>=9851	10000	>=12877	900		

Table A1.3.4 Amount of times that each classification rule was applied, per country.

	Number of times that classification rule was applied									
Country	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
AT	8		4							12
BE	3			2						5
BG	5	1	4	3		3			9	25
CZ	6		5	1					2	14
DE	9		3	4						16
DK	2		1							3
EE	2		2							4
EL	8		6	9		3			12	38
ES	13	2	10	6	1	5	2	1	8	48
FI	3	1	2							6
FR	10	1	4	6		2			3	26
HU	6		2			1				9
IE	3	2								5
IT	9		6	7		3			8	33
LT	3	3	4			1				11
LU	1		1	1		1				4
LV	2		3	1		1				7
NL	2									2
PL	9	1	3	3		1				17
PT	8	6	8	3	4	4		1		34
RO	7	1	4	1		2	1		10	26
SE	5	3	2			1				11
SI	5		2	3						10
SK	7		4	3		1				15
UK	6	2		4			1			13
Grand Total	**142**	**23**	**80**	**57**	**5**	**29**	**4**	**2**	**52**	**394**
%	**36%**	**6%**	**20%**	**14%**	**1%**	**8%**	**1%**	**1%**	**13%**	

Quality check

Important for the quality of our results is how many NCUs had to be assigned to a different climate zone because there was no data on wheat yields for the originally assigned climate zone. But the properties of these NCUs are also relevant: if these "newly assigned" NCUs are NCUs with almost no arable land, assigning an alternative climate zone will not affect our results. Overall 29% of the NCUs got reassigned (20% of total area, 8% of agricultural area) (see Table A1.3.5).

Table A1.3.5 *Number and area of NCUs that were assigned to a new climate zone and totals for comparison.*

Country	Total number of NCUs (#)	Number of NCUs that were assigned a new CZ (#)	Total area (km^2)	Total area of NCUs that were assigned a new CZ (ha)	Total arable land (km^2)	Arable land within NCUs that were assigned a new CZ (ha)
AT	1829	86	83828	2559	14365	365
BE	461	63	30201	5058	8582	208
BG	1379	485	109532	17770	32246	560
CZ	855	250	78472	13251	25545	671
DE	6627	640	349860	20264	120454	2050
DK	107	0	40345	0	24470	0
EE	121	2	41621	450	6432	70
EL	3138	1736	123756	63866	27182	8138
ES	4365	1634	493626	125918	153417	18057
FI	324	57	315417	9843	22580	1368
FR	5623	1608	540574	88779	193181	8080
HU	589	24	91967	1258	39487	413
IE	435	38	67119	2225	10127	470
IT	5012	2036	293947	98659	93889	17581
LT	299	51	64518	8827	21367	3141
LU	48	12	2592	1032	635	288
LV	149	16	62629	1803	11285	508
NL	311	0	33705	0	10590	0
PL	1887	253	308190	15514	111871	3901
PT	961	522	87758	34076	18450	5795
RO	3244	1957	234207	88887	86178	9570
SE	539	106	436040	161498	26144	3502
SI	968	154	20039	2651	1959	37
SK	595	227	49008	13135	13632	1021
UK	3071	696	231336	57492	59817	1551
total	42937	12653	4190289	834815	1133883	87345

A1.4 Calculation of ammonia emissions

Figure A1.4.1 presents an overview of the calculation of NH_3 emissions from animal manure (housing, storage, grazing, application) in INTEGRATOR. Calculations are made per animal category and manure type (liquid/solid) for certain animal categories. Emission fractions also vary per country. Below, we present central estimates for the emission fractions (Table A1.4.1 to Table A1.4.7).

Emissions from grazing

Emission fractions for NH_3 emissions from grazing are not further distinguished per animal category. The average emission fraction at country level is 8% and varies between 5 and 10% (see Table A1.4.1).

Table A1.4.1 *NH_3 emission fractions for manure excreted by grazing animals.*

Country	EF	Country	EF	Country	EF	Country	EF	Country	EF
AT	0.08	**DK**	0.07	**GR**	0.08	**LU**	0.08	**RO**	0.1
BE	0.08	**EE**	0.08	**HU**	0.08	**LV**	0.08	**SE**	0.1
BG	0.08	**ES**	0.10	**IE**	0.05	**NL**	0.1	**SI**	0.1
CZ	0.08	**FI**	0.06	**IT**	0.08	**PL**	0.1	**SK**	0.1
DE	0.08	**FR**	0.08	**LT**	0.08	**PT**	0.1	**UK**	0.1

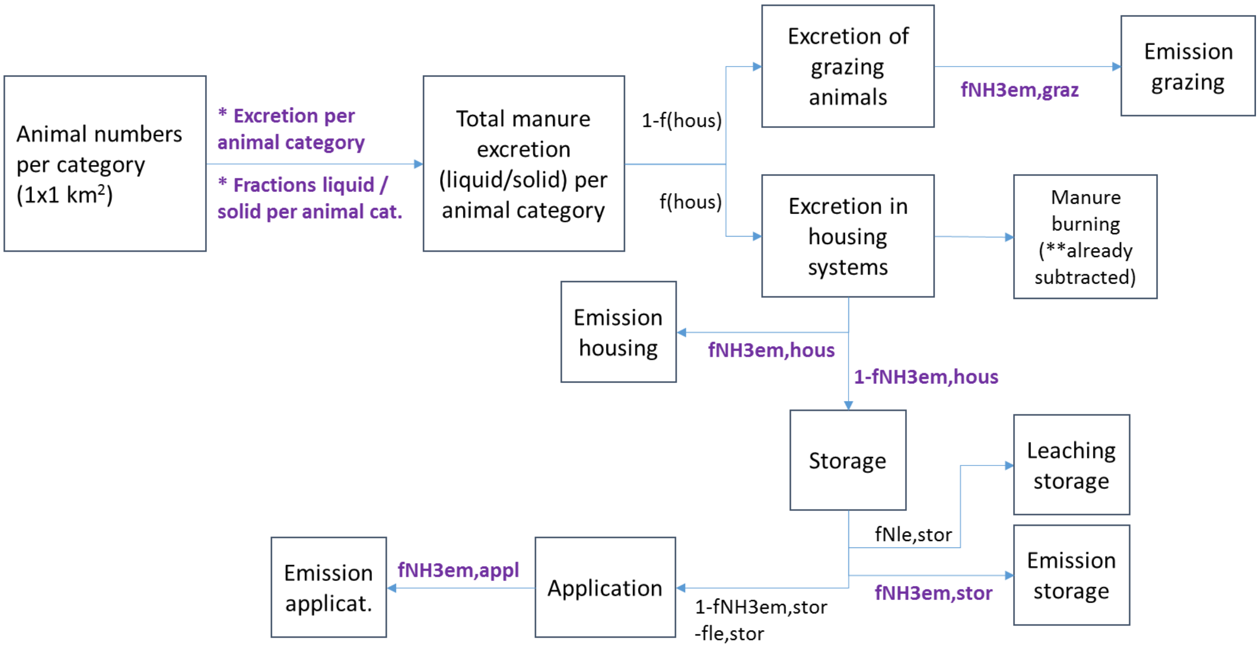

Figure A1.4.1 *Overview of the calculation of NH_3 emissions from animal manure. Fhous = fraction manure excreted in housing systems. fNH3em,graz = NH_3 emission fraction for manure excreted by grazing animals. fNH3em,hous = NH_3 emission fraction for manure excreted in housing systems. fNH3em,stor = NH_3 emission fraction for manure storage. fNle,stor = N leaching fraction for manure in storage systems. fNH3em,appl = NH_3 emission fraction for manure application.*

Emissions from housing and manure storage

Emission fractions for NH_3 emissions from housing and manure storage are distinguished per animal type (6 categories) and manure type (liquid vs. solid for 3 animal categories); see Table A1.4.2. For some countries, the basic emission fractions are modified based on assumptions on the implementation of low-emission manure storage or housing systems. For these countries, a new emission fraction is calculated based on the degree of implementation of emission-reducing technologies, and the reduction efficiency of the technology (see Table A1.4.5 and Table A1.4.6).

Table A1.4.2 *Ranges in NH_3-N emission fractions for housing and manure storage per animal type and manure type. Value is simple arithmetic mean over 25 EU countries; ranges in brackets indicate lowest and highest value. In some cases, emission fractions presented here include the effect of implementation of low-emission techniques. For more details, see Table A1.4.5 (manure storage) and Table A1.4.6 (housing).*

Type of emission	Dairy cows		Other cows		Pigs		Laying hens	Other Poultry	Sheep & goats
	Liquid	Solid	Liquid	Solid	Liquid	Solid			
Housing	0.13 (0.07-0.22)	0.12 (0.07-0.19)	0.12 (0.03-0.19)	0.11 (0.00-0.19)	0.15 (0.09-0.23)	0.17 (0.13-0.23)	0.17 (0.09-0.36)	0.17 (0.00-0.40)	0.11 (0.10-0.15)
Manure storage	0.05 (0.01-0.09)	0.07 (0.04-0.16)	0.05 (0.01-0.10)	0.06 (0.04-0.12)	0.06 (0.01-0.11)	0.06 (0.01-0.14)	0.05 (0.00-0.15)	0.04 (0.00-0.15)	0.01 (0.00-0.14)

Emissions from manure application

Emission fractions for NH_3 emissions from manure application are distinguished for three animal categories (cattle, pigs and poultry) and manure type (liquid and solid manure), being distinguished for cattle and pigs only (see Table A1.4.3 for ranges over Europe). The values are country dependent, in view of differences in manure application techniques. For more detail on the derivation of the country dependent values, see Table A1.4.7.

Table A1.4.3 *Ranges in NH_3-N emission fractions for manure application. Value is simple arithmetic mean over 25 EU countries; ranges in brackets indicate lowest and highest value. In some cases, emission fractions presented here include the effect of implementation of low-emission techniques. For more details, see Table A1.4.7.*

	Cattle		Pigs		Poultry
	Liquid	Solid	Liquid	Solid	
Manure application	0.19 (0.12-0.24)	0.17 (0.05-0.22)	0.15 (0.06-0.25)	0.17 (0.06-0.25)	0.13 (0.04-0.23)

Emissions from fertilizer application

Emission fractions for NH_3 emissions from fertilizer application are distinguished for two types of fertilizers: urea-based fertilizers and nitrate-based fertilizers. The average emission fraction is 15% (range: 12-20%) for urea-based fertilizers and 3% (range: 1-7%) for nitrate based fertilizers (see Table A1.4.4). Nitrate-based fertilizers are dominant in almost all countries, and therefore the average emission fraction for fertilizers is 4%.

Table A1.4.4 *NH_3 emission fractions from fertilizer application.*

Country	EF urea-based fertilizer	EF nitrate-based fertilizer	Share urea-based fertilizer	Share nitrate-based fertilizer	EF final
AT	0.15	0.02	0.01	0.99	0.02
BE	0.15	0.02	0.01	0.99	0.02
BG	0.15	0.03	0.05	0.95	0.04
CZ	0.15	0.03	0.02	0.98	0.03
DE	0.15	0.03	0.16	0.84	0.05
DK	0.15	0.02	0.01	0.99	0.02
EE	0.15	0.02	0.02	0.98	0.02
ES	0.16	0.04	0.26	0.74	0.07
FI	0.15	0.01	0.01	0.99	0.01
FR	0.15	0.04	0.09	0.91	0.05
GR	0.20	0.04	0.02	0.98	0.04
HU	0.15	0.03	0.13	0.87	0.04
IE	0.12	0.03	0.14	0.86	0.04
IT	0.15	0.03	0.48	0.52	0.09
LT	0.15	0.07	0.30	0.70	0.09
LU	0.15	0.02	0.05	0.95	0.03
LV	0.15	0.02	0.32	0.68	0.06
NL	0.15	0.02	0.00	1.00	0.02
PL	0.15	0.04	0.35	0.66	0.08
PT	0.15	0.03	0.12	0.89	0.04
RO	0.15	0.03	0.05	0.95	0.04
SE	0.15	0.01	0.00	1.00	0.01
SI	0.15	0.02	0.15	0.85	0.04
SK	0.15	0.06	0.10	0.90	0.07
UK	0.15	0.01	0.09	0.91	0.02

Table A1.4.5 *NH_3 emission fractions for manure storage. EF = basic emission fraction, "Red low" = degree of implementation of emission-reducing techniques with low emission reduction (emissions are reduced by 40%), "Red high" = degree of implementation of emission-reducing techniques with high emission reduction (emissions are reduced by 80%).*

	Dairy cow liquid				Dairy cow solid	Other cow liquid				Other cow solid	Pigs liquid				Pigs solid	Laying hens				Other poultry				Sheep & goats
CO	**EF**	**Red low (-40%)**	**Red high (-80%)**	**EF final**	**EF**	**EF**	**Red low (-40%)**	**Red high (-80%)**	**EF final**	**EF**	**EF**	**Red low (-40%)**	**Red high (-80%)**	**EF final**	**EF**	**EF**	**Red low (-40%)**	**Red high (-80%)**	**EF final**	**EF**	**Red low (-40%)**	**Red high (-80%)**	**EF final**	**EF**
AT	0.08	0.26	0.20	0.06	0.05	0.08	0.34	0.10	0.06	0.05	0.08	0.33	0.10	0.06	0.06	0.04			0.04	0.03			0.03	0.00
BE	0.06	0.30	0.48	0.03	0.06	0.06	0.30	0.47	0.03	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
BG	0.04			0.04	0.06	0.06			0.06	0.06	0.03			0.03	0.06	0.04			0.04	0.03			0.03	0.00
CZ	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
DE	0.06	0.09	0.28	0.04	0.06	0.11	0.06	0.65	0.05	0.11	0.09			0.09	0.06	0.03			0.03	0.04			0.04	0.06
DK	0.06		0.84	0.02	0.07	0.06		0.83	0.02	0.07	0.05		0.58	0.03	0.06	0.07			0.07	0.13			0.13	0.06
EE	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
ES	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
FI	0.06	0.40	0.15	0.04	0.06	0.06		0.15	0.05	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
FR	0.06	0.20	0.04	0.05	0.04	0.06	0.10	0.05	0.06	0.04	0.04	0.25		0.04	0.04	0.04			0.04	0.03			0.03	0.00
GR	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
HU	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
IE	0.02	0.77		0.01	0.16	0.02	0.78		0.01	0.04	0.01	0.47	0.15	0.01	0.01	0.00			0.00	0.00			0.00	0.00
IT	0.13	0.01	0.32	0.09	0.13	0.12		0.20	0.10	0.12	0.10	0.12	0.09	0.09	0.10	0.15			0.15	0.15			0.15	0.00
LT	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
LU	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
LV	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
NL	0.05		0.20	0.04	0.04	0.05	0.05	0.95	0.01	0.05	0.11			0.11	0.05	0.04		0.10	0.04	0.03		0.13	0.03	0.01
PL	0.08		0.35	0.06	0.04	0.10		0.35	0.07	0.04	0.10		0.23	0.08	0.04	0.04			0.04	0.03			0.03	0.00
PT	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
RO	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
SE	0.08	0.10	0.28	0.06	0.10	0.08	0.11	0.27	0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
SI	0.08		0.50	0.05	0.09	0.08		0.50	0.05	0.09	0.13		0.41	0.09	0.12	0.07			0.07	0.03			0.03	0.00
SK	0.06			0.06	0.06	0.06			0.06	0.06	0.06			0.06	0.06	0.04			0.04	0.03			0.03	0.00
UK	0.06	0.80		0.04	0.07	0.06	0.80		0.04	0.07	0.09			0.09	0.14	0.10			0.10	0.07			0.07	0.14

Table A1.4.6 *NH_3 emission fractions for housing systems. EF = basic emission fraction, "Red low" = degree of implementation of emission-reducing techniques with low emission reduction (emission reduction of 25%, 40 or 65%, depending on the animal category). Emission-reducing techniques with high emission reduction (-80%) do not occur in any country.*

	Dairy cow liquid			Dairy cow solid	Other cow liquid			Other cow solid	Pigs liquid			Pigs solid	Layhens			Other poultry			Sheep & goats
CO	**EF**	**Red low (-25%)***	**EF final**	**EF**	**EF**	**Red low (-25%)**	**EF final**	**EF**	**EF**	**Red low (-40%)**	**EF final**	**EF**	**EF**	**Red low (-65%)**	**EF final**	**EF**	**Red low (-65%)**	**EF final**	**EF**
AT	0.12		0.12	0.12	0.12		0.12	0.12	0.15		0.15	0.15	0.20	0.19	0.19	0.20	0.28	0.18	0.10
BE	0.15		0.15	0.14	0.09		0.09	0.10	0.17	0.20	0.15	0.17	0.14	0.84	0.10	0.11	0.10	0.11	0.10
BG	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.17	0.15	0.17	0.20	0.34	0.18	0.20	0.40	0.17	0.10
CZ	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.34	0.14	0.17	0.20	0.90	0.14	0.20	0.75	0.15	0.10
DE	0.09		0.09	0.09	0.06		0.06	0.06	0.25	0.16	0.23	0.20	0.22	0.70	0.17	0.40	0.65	0.31	0.15
DK	0.08	0.15	0.07	0.07	0.08	0.15	0.07	0.07	0.17	0.40	0.13	0.18	0.25	0.55	0.20	0.20	0.85	0.14	0.15
EE	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.36	0.13	0.17	0.20	0.72	0.15	0.20		0.20	0.10
ES	0.12		0.12	0.12	0.03		0.03	0.03	0.17	0.41	0.13	0.17	0.20	0.77	0.15	0.20	0.48	0.17	0.10
FI	0.12		0.12	0.12	0.12		0.12	0.12	0.13	0.05	0.12	0.13	0.20	0.18	0.19	0.20	0.60	0.16	0.10
FR	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.13	0.16	0.17	0.20	0.66	0.15	0.20	0.30	0.18	0.10
GR	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.17	0.15	0.17	0.20	0.23	0.18	0.20	0.40	0.17	0.10
HU	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.45	0.12	0.17	0.20	0.36	0.17	0.20	0.65	0.15	0.10
IE	0.19		0.19	0.19	0.19		0.19	0.19	0.18	0.20	0.15	0.18	0.20	0.25	0.18	0.20	0.38	0.17	0.10
IT	0.08		0.08	0.08	0.12		0.12	0.12	0.17	0.22	0.15	0.17	0.23	0.60	0.18	0.20	0.50	0.17	0.12
LT	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.34	0.11	0.17	0.20	0.55	0.09	0.20	0.60	0.08	0.10
LU	0.12		0.12	0.12	0.12		0.12	0.12	0.17		0.17	0.17	0.20		0.20	0.20		0.20	0.10
LV	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.40	0.13	0.17	0.20	0.65	0.15	0.20		0.20	0.10
NL	0.14	0.80	0.08	0.14	0.14		0.14	0.10	0.18	0.85	0.09	0.18	0.20	0.90	0.14	0.20	0.82	0.14	0.10
PL	0.22		0.22	0.13	0.18		0.18	0.13	0.18	0.13	0.17	0.22	0.20	0.45	0.17		0.55	0.00	0.10
PT	0.12		0.12	0.12	0.12		0.12	0.00	0.17	0.23	0.15	0.17	0.20	0.73	0.15	0.20	0.40	0.17	0.10
RO	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.10	0.16	0.17	0.20	0.15	0.19	0.20	0.70	0.15	0.10
SE	0.12		0.12	0.13	0.12		0.12	0.13	0.17	0.17	0.15	0.17	0.20	0.54	0.16	0.20	0.85	0.14	0.10
SI	0.15		0.15	0.07	0.15		0.15	0.07	0.24	0.08	0.23	0.15	0.36		0.36	0.40		0.40	0.10
SK	0.12		0.12	0.12	0.12		0.12	0.12	0.17	0.40	0.13	0.17	0.20	0.82	0.14	0.20	0.80	0.14	0.10
UK	0.19		0.19	0.13	0.19		0.19	0.13	0.17	0.40	0.13	0.23	0.24	0.35	0.21	0.14	0.50	0.12	0.15

*Except Netherlands: -50%.

Table A1.4.7 *NH_3 emission fractions for manure application. EF = basic emission fraction, "Red low" = degree of implementation of emission-reducing techniques with low emission reduction (emissions are reduced by 20 or 40%), "Red high" = degree of implementation of emission-reducing techniques with high emission reduction (emissions are reduced by 80%).*

	Cattle liquid				Cattle solid				Pigs liquid				Pigs solid				Poultry			
CO	EF	Red low (-40%)	Red high (-80%)	EF final	EF	Red low (-20%)	Red high (-80%)	EF final	EF	Red low (-40%)	Red high (-80%)	EF final	EF	Red low (-20%)	Red high (-80%)	EF final	EF	Red low (-40%)	Red high (-80%)	EF final
AT	0.30	0.10	0.00	0.29	0.16	0.13	0.05	0.15	0.16	0.10	0.00	0.16	0.14	0.10	0.10	0.12	0.20	0.01	0.22	0.16
BE	0.28	0.48	0.12	0.20	0.08	0.34	0.32	0.05	0.30	0.78	0.11	0.18	0.10	0.12	0.63	0.05	0.34	0.03	0.82	0.11
BG	0.20			0.20	0.20			0.20	0.20	0.03	0.14	0.18	0.20			0.20	0.20	0.11	0.25	0.15
CZ	0.20	0.15	0.10	0.17	0.20	0.40	0.10	0.17	0.20	0.36	0.28	0.13	0.20			0.20	0.20	0.29	0.55	0.09
DE	0.20	0.54	0.24	0.12	0.20	0.89	0.20	0.13	0.16	0.85	0.15	0.09	0.20	0.84	0.16	0.14	0.24	0.19	0.81	0.07
DK	0.20	0.03	0.47	0.12	0.15	0.17	0.81	0.05	0.20	0.00	0.55	0.11	0.20	0.18	0.80	0.06	0.16	0.17	0.82	0.04
EE	0.20			0.20	0.20			0.20	0.20	0.13	0.23	0.15	0.20			0.20	0.20	0.07	0.65	0.09
ES	0.20			0.20	0.20			0.20	0.20	0.02	0.39	0.14	0.20			0.20	0.20	0.00	0.64	0.10
FI	0.20	0.53	0.18	0.13	0.15	0.57	0.17	0.11	0.14	0.68	0.05	0.10	0.14	0.68	0.00	0.12	0.20	0.38	0.20	0.14
FR	0.20	0.00	0.00	0.20	0.20			0.20	0.20	0.11	0.12	0.17	0.20			0.20	0.20	0.02	0.52	0.12
GR	0.20			0.20	0.20			0.20	0.20	0.01	0.16	0.17	0.20			0.20	0.20	0.00	0.32	0.15
HU	0.20	1.00	0.00	0.12	0.20			0.20	0.20	0.74	0.26	0.10	0.20			0.20	0.20	0.06	0.44	0.13
IE	0.24	0.01	0.00	0.24	0.08			0.08	0.09	0.19	0.04	0.08	0.09			0.09	0.16	0.00	0.19	0.13
IT	0.23	0.07	0.20	0.18	0.23	0.26	0.09	0.20	0.25	0.00	0.21	0.21	0.25			0.25	0.23	0.40	0.32	0.13
LT	0.20			0.20	0.20			0.20	0.20	0.12	0.22	0.16	0.20			0.20	0.20	0.04	0.53	0.11
LU	0.20			0.20	0.20			0.20	0.20			0.20	0.20			0.20	0.20			0.20
LV	0.20			0.20	0.20			0.20	0.20	0.16	0.24	0.15	0.20			0.20	0.20	0.06	0.59	0.10
NL	0.34	0.48	0.48	0.15	0.14	0.85	0.00	0.11	0.41	0.00	0.99	0.08	0.17	0.75	0.00	0.14	0.31	0.00	0.86	0.09
PL	0.20	0.00	0.00	0.20	0.16	0.96	0.05	0.12	0.23	0.03	0.10	0.21	0.20	0.94	0.06	0.15	0.20	0.47	0.43	0.09
PT	0.20			0.20	0.20			0.20	0.20	0.03	0.20	0.17	0.20			0.20	0.20	0.24	0.21	0.15
RO	0.20			0.20	0.20			0.20	0.20	0.02	0.08	0.19	0.20			0.20	0.20	0.08	0.33	0.14
SE	0.21	0.14	0.16	0.17	0.16	0.10	0.35	0.11	0.18	0.43	0.09	0.14	0.15	0.10	0.45	0.10	0.10	0.05	0.64	0.05
SI	0.24	0.20	0.00	0.22	0.23	0.20	0.00	0.22	0.28	0.05	0.10	0.25	0.19	0.00	0.11	0.17	0.23	0.08	0.00	0.23
SK	0.20			0.20	0.20			0.20	0.20	0.15	0.25	0.15	0.20			0.20	0.20	0.00	0.81	0.07
UK	0.23	0.02	0.01	0.22	0.08	0.18	0.03	0.08	0.16	0.20	0.70	0.06	0.24	0.20	0.75	0.09	0.36	0.13	0.56	0.18

A1.5 Calculation of N_2O, NO_x and N_2 emissions from housing and manure storage systems

As with fractions for NH_3 emissions, N_2O emission, NOx and N_2 emissions are derived for (i) housing and manure storage systems and (ii) soils, based on N inputs by fertilizer and manure application, grazing and other inputs (crop residues, fixation, deposition, mineralisation)

Emissions from housing and manure storage

Emission of NO_x from housing and manure storage systems is calculated in a generic way as 0.3% of the N excretion while N_2 emissions is also is calculated in a generic way as 9 times the NO_x emissions (Oenema et al., 2000), implying that the combination of NO_x and N2 emissions is calculates as 3% of the N excretion.

As with NH_3, N_2O-N emissions from housing and manure storage are distinguished per animal type (6 categories) and manure type (liquid vs. solid for 3 animal categories) as given in Table A1.5.1. For some countries, the emission fractions lay hens, other poultry and sheep and goats vary.

Table A1.5.1 *N_2O-N emission percentages used for housing and manure storage per animal type and manure type.*

Type of emission	Dairy cows		Other cows		Pigs		Laying hens	Other Poultry	Sheep & goats
	Liquid	Solid	Liquid	Solid	Liquid	Solid			
Housing	0.1%	2%	0.1%	2%	0.1%	2%	0.4-0.5% [1)]	0.4-0.5% [1)]	0.5-0.7% [2)]

1) 0.4% for BG, CZ, EE, HR, HU, LT, LV, PL, RO, SI, SK; 0.5% for AT, BE, CY, DE, DK, ES, FI, FR, GR, IE, IT, MT, NL, PT, SE, UK, LU.

2) 0.5% for BG, CZ, EE, HR, HU, LT, LV, PL, RO, SI, SK, LU; 0.7% for AT, BE, CY, DE, DK, ES, FI, FR, GR, IE, IT, MT, NL, PT, SE, UK.

Emissions from soils

Emissions of N_2O and for NO_x from soils are calculated as a percentage of function of the N input, depending on the N source (manure type, fertilizer type, crop residue type, grazing, mineralisation, fixation and deposition) application technique, soil type, land use and precipitation and temperature, based on Lesschen et al. (2011), as given in Table A1.5.2 for N_2O and in Table A1.5.3 for NO_x.

The emission of N_2 from soils is simply set equal to the denitrification flux, which is calculated as the N surplus -NO3-N leaching.

Table A1.5.2 *N_2O-N emission percentages as a function of N source (manure type, fertilizer type, crop residue type, grazing, mineralisation, fixation and deposition) application technique, soil type, land use and precipitation and temperature.*

Soil[1)]	Lu[2)]	pH[3)]	fNemfeNit 1,*	fNemfeUr 2,*	fNemap cattle liquid	cattle solid	pigs liquid	pigs solid	poultry	fNemgr	fNemmi	fNemdep	fNemfix	fNemcrcer cereals fNemcr	fNemcrveg vegetables	fNemcrres others
1	1	1	0.750%	0.375%	0.313%	0.125%	0.469%	0.188%	0.156%	1.500%	0.375%	0.375%	0.281%	0.000%	0.000%	0.000%
1	1	2	1.000%	0.500%	0.417%	0.167%	0.625%	0.250%	0.208%	2.000%	0.500%	0.500%	0.375%	0.000%	0.000%	0.000%
1	2	1	0.375%	0.300%	0.469%	0.188%	0.703%	0.281%	0.234%	0.000%	0.375%	0.375%	0.281%	0.150%	1.500%	0.750%
1	2	2	0.500%	0.400%	0.625%	0.250%	0.938%	0.375%	0.313%	0.000%	0.500%	0.500%	0.375%	0.200%	2.000%	1.000%
2	1	1	1.125%	0.563%	0.469%	0.188%	0.703%	0.281%	0.234%	2.250%	0.563%	0.563%	0.422%	0.000%	0.000%	0.000%
2	1	2	1.500%	0.750%	0.625%	0.250%	0.938%	0.375%	0.313%	3.000%	0.750%	0.750%	0.563%	0.000%	0.000%	0.000%
2	2	2	0.750%	0.600%	0.938%	0.375%	1.406%	0.563%	0.469%	0.000%	0.750%	0.750%	0.563%	0.300%	3.000%	1.500%
2	2	1	0.563%	0.450%	0.703%	0.281%	1.055%	0.422%	0.352%	0.000%	0.563%	0.563%	0.422%	0.225%	2.250%	1.125%
3	1	1	1.500%	0.750%	0.625%	0.250%	0.938%	0.375%	0.313%	3.000%	1.950%	0.750%	0.563%	0.000%	0.000%	0.000%
3	2	1	0.750%	0.600%	0.938%	0.375%	1.406%	0.563%	0.469%	0.000%	3.900%	0.750%	0.563%	0.300%	3.000%	1.500%
3	1	2	2.000%	1.000%	0.833%	0.333%	1.250%	0.500%	0.417%	4.000%	2.600%	1.000%	0.750%	0.000%	0.000%	0.000%
3	2	2	1.000%	0.800%	1.250%	0.500%	1.875%	0.750%	0.625%	0.000%	5.200%	1.000%	0.750%	0.400%	4.000%	2.000%

1) 1:sand, 2:clay/unknown, 3:peat.
2) 1:grass, 2: arable, 3: nature.
3) 1: acid/peat, 2: intermediate, basic, calcareous.

Table A1.5.3 *NO_x-N emission percentages as a function of N source (manure type, fertilizer type, crop residue type, grazing, mineralisation, fixation and deposition) application technique, soil type, land use and precipitation and temperature.*

Soil[1)]	Lu[2)]	Prec[3)]	pH[4)]	Temp[5)]	fNemfeNit 1,*	fNemfeUr 2,*	fNemap cattle liquid	cattle solid	pigs liquid	pigs solid	poultry	fNemgr	fNemmi	fNemdep	fNemfix	fNemcrcer cereals fNemcr	fNemcrveg vegetables	fNemcrres others
1	1	1	1	1	0.140%	0.110%	0.040%	0.020%	0.075%	0.030%	0.015%	0.280%	0.070%	0.070%	0.070%	0.000%	0.000%	0.000%
1	1	1	1	2	0.190%	0.140%	0.050%	0.020%	0.105%	0.040%	0.025%	0.380%	0.090%	0.090%	0.090%	0.000%	0.000%	0.000%
1	1	1	1	3	0.230%	0.180%	0.065%	0.030%	0.130%	0.050%	0.025%	0.470%	0.120%	0.120%	0.120%	0.000%	0.000%	0.000%
1	1	1	2	1	0.190%	0.140%	0.050%	0.020%	0.105%	0.040%	0.025%	0.380%	0.090%	0.090%	0.090%	0.000%	0.000%	0.000%
1	1	1	2	2	0.250%	0.190%	0.070%	0.030%	0.140%	0.060%	0.025%	0.500%	0.130%	0.130%	0.130%	0.000%	0.000%	0.000%
1	1	1	2	3	0.310%	0.230%	0.085%	0.030%	0.175%	0.070%	0.035%	0.630%	0.160%	0.160%	0.160%	0.000%	0.000%	0.000%
1	1	2	1	1	0.280%	0.140%	0.075%	0.030%	0.160%	0.060%	0.035%	0.560%	0.140%	0.140%	0.140%	0.000%	0.000%	0.000%
1	1	2	1	2	0.380%	0.190%	0.105%	0.040%	0.210%	0.080%	0.040%	0.750%	0.190%	0.190%	0.190%	0.000%	0.000%	0.000%
1	1	2	1	3	0.470%	0.230%	0.130%	0.050%	0.260%	0.100%	0.050%	0.940%	0.230%	0.230%	0.230%	0.000%	0.000%	0.000%

Soil[1)]	Lu[2)]	Prec[3)]	pH[4)]	Temp[5)]	fNemfeNit 1,*	fNemfeUr 2,*	fNemap cattle liquid	cattle solid	pigs liquid	pigs solid	poultry	fNemgr	fNemmi	fNemdep	fNemfix	fNemcrcer cereals fNemcr	fNemcrveg vegetables	fNemcrres others
1	1	2	2	1	0.380%	0.190%	0.105%	0.040%	0.210%	0.080%	0.040%	0.750%	0.190%	0.190%	0.190%	0.000%	0.000%	0.000%
1	1	2	2	2	0.500%	0.250%	0.140%	0.060%	0.275%	0.110%	0.055%	1.000%	0.250%	0.250%	0.250%	0.000%	0.000%	0.000%
1	1	2	2	3	0.630%	0.310%	0.175%	0.070%	0.350%	0.140%	0.070%	1.250%	0.310%	0.310%	0.310%	0.000%	0.000%	0.000%
1	1	3	1	1	0.560%	0.280%	0.160%	0.060%	0.315%	0.130%	0.065%	1.130%	0.280%	0.280%	0.280%	0.000%	0.000%	0.000%
1	1	3	1	2	0.750%	0.380%	0.210%	0.080%	0.415%	0.170%	0.085%	1.500%	0.380%	0.380%	0.380%	0.000%	0.000%	0.000%
1	1	3	1	3	0.940%	0.470%	0.260%	0.100%	0.525%	0.210%	0.105%	1.880%	0.470%	0.470%	0.470%	0.000%	0.000%	0.000%
1	1	3	2	1	0.750%	0.380%	0.210%	0.080%	0.415%	0.170%	0.085%	1.500%	0.380%	0.380%	0.380%	0.000%	0.000%	0.000%
1	1	3	2	2	1.000%	0.500%	0.275%	0.110%	0.555%	0.220%	0.110%	2.000%	0.500%	0.500%	0.500%	0.000%	0.000%	0.000%
1	1	3	2	3	1.250%	0.630%	0.350%	0.140%	0.695%	0.280%	0.140%	2.500%	0.630%	0.630%	0.630%	0.000%	0.000%	0.000%
1	2	1	1	1	0.070%	0.110%	0.060%	0.020%	0.115%	0.050%	0.025%	0.000%	0.070%	0.060%	0.060%	0.030%	0.280%	0.140%
1	2	1	1	2	0.090%	0.140%	0.075%	0.030%	0.160%	0.060%	0.035%	0.000%	0.090%	0.090%	0.090%	0.040%	0.380%	0.190%
1	2	1	1	3	0.120%	0.180%	0.100%	0.040%	0.195%	0.080%	0.040%	0.000%	0.120%	0.190%	0.190%	0.050%	0.470%	0.230%
1	2	1	2	1	0.090%	0.140%	0.075%	0.030%	0.160%	0.060%	0.035%	0.000%	0.090%	0.080%	0.080%	0.040%	0.380%	0.190%
1	2	1	2	2	0.130%	0.190%	0.105%	0.040%	0.210%	0.080%	0.040%	0.000%	0.130%	0.130%	0.130%	0.050%	0.500%	0.250%
1	2	1	2	3	0.160%	0.230%	0.130%	0.050%	0.260%	0.100%	0.050%	0.000%	0.160%	0.250%	0.250%	0.060%	0.630%	0.310%
1	2	2	1	1	0.140%	0.140%	0.115%	0.050%	0.235%	0.090%	0.050%	0.000%	0.140%	0.130%	0.130%	0.060%	0.560%	0.280%
1	2	2	1	2	0.190%	0.190%	0.160%	0.060%	0.315%	0.130%	0.065%	0.000%	0.190%	0.190%	0.190%	0.080%	0.750%	0.380%
1	2	2	1	3	0.230%	0.230%	0.195%	0.080%	0.390%	0.160%	0.075%	0.000%	0.230%	0.380%	0.380%	0.090%	0.940%	0.470%
1	2	2	2	1	0.190%	0.190%	0.160%	0.060%	0.315%	0.130%	0.065%	0.000%	0.190%	0.170%	0.170%	0.080%	0.750%	0.380%
1	2	2	2	2	0.250%	0.250%	0.210%	0.080%	0.415%	0.170%	0.085%	0.000%	0.250%	0.250%	0.250%	0.100%	1.000%	0.500%
1	2	2	2	3	0.310%	0.310%	0.260%	0.100%	0.525%	0.210%	0.105%	0.000%	0.310%	0.500%	0.500%	0.130%	1.250%	0.630%
1	2	3	1	1	0.280%	0.280%	0.235%	0.090%	0.470%	0.190%	0.095%	0.000%	0.280%	0.250%	0.250%	0.110%	1.130%	0.560%
1	2	3	1	2	0.380%	0.380%	0.315%	0.130%	0.625%	0.250%	0.125%	0.000%	0.380%	0.380%	0.380%	0.150%	1.500%	0.750%
1	2	3	1	3	0.470%	0.470%	0.390%	0.160%	0.785%	0.310%	0.160%	0.000%	0.470%	0.750%	0.750%	0.190%	1.880%	0.940%
1	2	3	2	1	0.380%	0.380%	0.315%	0.130%	0.625%	0.250%	0.125%	0.000%	0.380%	0.330%	0.330%	0.150%	1.500%	0.750%
1	2	3	2	2	0.500%	0.500%	0.415%	0.170%	0.835%	0.330%	0.165%	0.000%	0.500%	0.500%	0.500%	0.200%	2.000%	1.000%
1	2	3	2	3	0.630%	0.630%	0.525%	0.210%	1.040%	0.420%	0.210%	0.000%	0.630%	1.000%	1.000%	0.250%	2.500%	1.250%
2	1	1	1	1	0.210%	0.160%	0.060%	0.020%	0.115%	0.050%	0.025%	0.420%	0.110%	0.110%	0.110%	0.000%	0.000%	0.000%
2	1	1	1	2	0.280%	0.210%	0.075%	0.030%	0.160%	0.060%	0.035%	0.560%	0.140%	0.140%	0.140%	0.000%	0.000%	0.000%
2	1	1	1	3	0.350%	0.260%	0.100%	0.040%	0.195%	0.080%	0.040%	0.700%	0.180%	0.180%	0.180%	0.000%	0.000%	0.000%
2	1	1	2	1	0.280%	0.210%	0.075%	0.030%	0.160%	0.060%	0.035%	0.560%	0.140%	0.140%	0.140%	0.000%	0.000%	0.000%
2	1	1	2	2	0.380%	0.280%	0.105%	0.040%	0.210%	0.080%	0.040%	0.750%	0.190%	0.190%	0.190%	0.000%	0.000%	0.000%
2	1	1	2	3	0.470%	0.350%	0.130%	0.050%	0.260%	0.100%	0.050%	0.940%	0.230%	0.230%	0.230%	0.000%	0.000%	0.000%
2	1	2	1	1	0.420%	0.210%	0.115%	0.050%	0.235%	0.090%	0.050%	0.840%	0.210%	0.210%	0.210%	0.000%	0.000%	0.000%
2	1	2	1	2	0.560%	0.280%	0.160%	0.060%	0.315%	0.130%	0.065%	1.130%	0.280%	0.280%	0.280%	0.000%	0.000%	0.000%

Soil[1)]	Lu[2)]	Prec[3)]	pH[4)]	Temp[5)]	fNemfeNit 1,*	fNemfeUr 2,*	fNemap cattle liquid	cattle solid	pigs liquid	pigs solid	poultry	fNemgr	fNemmi	fNemdep	fNemfix	fNemcrcer cereals fNemcr	fNemcrveg vegetables	fNemcrres others
2	1	2	1	3	0.700%	0.350%	0.195%	0.080%	0.390%	0.160%	0.075%	1.410%	0.350%	0.350%	0.350%	0.000%	0.000%	0.000%
2	1	2	2	1	0.560%	0.280%	0.160%	0.060%	0.315%	0.130%	0.065%	1.130%	0.280%	0.280%	0.280%	0.000%	0.000%	0.000%
2	1	2	2	2	0.750%	0.380%	0.210%	0.080%	0.415%	0.170%	0.085%	1.500%	0.380%	0.380%	0.380%	0.000%	0.000%	0.000%
2	1	2	2	3	0.940%	0.470%	0.260%	0.100%	0.525%	0.210%	0.105%	1.880%	0.470%	0.470%	0.470%	0.000%	0.000%	0.000%
2	1	3	1	1	0.840%	0.420%	0.235%	0.090%	0.470%	0.190%	0.095%	1.690%	0.420%	0.420%	0.420%	0.000%	0.000%	0.000%
2	1	3	1	2	1.130%	0.560%	0.315%	0.130%	0.625%	0.250%	0.125%	2.250%	0.560%	0.560%	0.560%	0.000%	0.000%	0.000%
2	1	3	1	3	1.410%	0.700%	0.390%	0.160%	0.785%	0.310%	0.160%	2.810%	0.700%	0.700%	0.700%	0.000%	0.000%	0.000%
2	1	3	2	1	1.130%	0.560%	0.315%	0.130%	0.625%	0.250%	0.125%	2.250%	0.560%	0.560%	0.560%	0.000%	0.000%	0.000%
2	1	3	2	2	1.500%	0.750%	0.415%	0.170%	0.835%	0.330%	0.165%	3.000%	0.750%	0.750%	0.750%	0.000%	0.000%	0.000%
2	1	3	2	3	1.880%	0.940%	0.525%	0.210%	1.040%	0.420%	0.210%	3.750%	0.940%	0.940%	0.940%	0.000%	0.000%	0.000%
2	2	1	1	1	0.110%	0.160%	0.090%	0.040%	0.175%	0.070%	0.035%	0.000%	0.110%	0.090%	0.090%	0.040%	0.420%	0.210%
2	2	1	1	2	0.140%	0.210%	0.115%	0.050%	0.235%	0.090%	0.050%	0.000%	0.140%	0.140%	0.140%	0.060%	0.560%	0.280%
2	2	1	1	3	0.180%	0.260%	0.150%	0.060%	0.290%	0.120%	0.060%	0.000%	0.180%	0.280%	0.280%	0.070%	0.700%	0.350%
2	2	1	2	1	0.140%	0.210%	0.115%	0.050%	0.235%	0.090%	0.050%	0.000%	0.140%	0.130%	0.130%	0.060%	0.560%	0.280%
2	2	1	2	2	0.190%	0.280%	0.160%	0.060%	0.315%	0.130%	0.065%	0.000%	0.190%	0.190%	0.190%	0.080%	0.750%	0.380%
2	2	1	2	3	0.230%	0.350%	0.195%	0.080%	0.390%	0.160%	0.075%	0.000%	0.230%	0.380%	0.380%	0.090%	0.940%	0.470%
2	2	2	1	1	0.210%	0.210%	0.175%	0.070%	0.350%	0.140%	0.070%	0.000%	0.210%	0.190%	0.190%	0.080%	0.840%	0.420%
2	2	2	1	2	0.280%	0.280%	0.235%	0.090%	0.470%	0.190%	0.095%	0.000%	0.280%	0.280%	0.280%	0.110%	1.130%	0.560%
2	2	2	1	3	0.350%	0.350%	0.290%	0.120%	0.585%	0.230%	0.115%	0.000%	0.350%	0.560%	0.560%	0.140%	1.410%	0.700%
2	2	2	2	1	0.280%	0.280%	0.235%	0.090%	0.470%	0.190%	0.095%	0.000%	0.280%	0.250%	0.250%	0.110%	1.130%	0.560%
2	2	2	2	2	0.380%	0.380%	0.315%	0.130%	0.625%	0.250%	0.125%	0.000%	0.380%	0.380%	0.380%	0.150%	1.500%	0.750%
2	2	2	2	3	0.470%	0.470%	0.390%	0.160%	0.785%	0.310%	0.160%	0.000%	0.470%	0.750%	0.750%	0.190%	1.880%	0.940%
2	2	3	1	1	0.420%	0.420%	0.350%	0.140%	0.700%	0.280%	0.140%	0.000%	0.420%	0.380%	0.380%	0.170%	1.690%	0.840%
2	2	3	1	2	0.560%	0.560%	0.470%	0.190%	0.940%	0.380%	0.190%	0.000%	0.560%	0.560%	0.560%	0.230%	2.250%	1.130%
2	2	3	1	3	0.700%	0.700%	0.585%	0.230%	1.175%	0.470%	0.235%	0.000%	0.700%	1.130%	1.130%	0.280%	2.810%	1.410%
2	2	3	2	1	0.560%	0.560%	0.470%	0.190%	0.940%	0.380%	0.190%	0.000%	0.560%	0.500%	0.500%	0.230%	2.250%	1.130%
2	2	3	2	2	0.750%	0.750%	0.625%	0.250%	1.250%	0.500%	0.250%	0.000%	0.750%	0.750%	0.750%	0.300%	3.000%	1.500%
2	2	3	2	3	0.940%	0.940%	0.785%	0.310%	1.565%	0.630%	0.315%	0.000%	0.940%	1.500%	1.500%	0.380%	3.750%	1.880%
3	1	1	1	1	0.280%	0.210%	0.075%	0.030%	0.160%	0.060%	0.035%	0.560%	0.350%	0.140%	0.140%	0.000%	0.000%	0.000%
3	1	1	1	2	0.380%	0.280%	0.105%	0.040%	0.210%	0.080%	0.040%	0.750%	0.470%	0.190%	0.190%	0.000%	0.000%	0.000%
3	1	1	1	3	0.470%	0.350%	0.130%	0.050%	0.260%	0.100%	0.050%	0.940%	0.590%	0.230%	0.230%	0.000%	0.000%	0.000%
3	1	1	2	1	0.380%	0.280%	0.105%	0.040%	0.210%	0.080%	0.040%	0.750%	0.470%	0.190%	0.190%	0.000%	0.000%	0.000%
3	1	1	2	2	0.500%	0.380%	0.140%	0.060%	0.275%	0.110%	0.055%	1.000%	0.630%	0.250%	0.250%	0.000%	0.000%	0.000%
3	1	1	2	3	0.630%	0.470%	0.175%	0.070%	0.350%	0.140%	0.070%	1.250%	0.780%	0.310%	0.310%	0.000%	0.000%	0.000%
3	1	2	1	1	0.560%	0.280%	0.160%	0.060%	0.315%	0.130%	0.065%	1.130%	0.700%	0.280%	0.280%	0.000%	0.000%	0.000%

Soil[1]	Lu[2]	Prec[3]	pH[4]	Temp[5]	fNemfeNit 1,*	fNemfeUr 2,*	fNemap cattle liquid	cattle solid	pigs liquid	pigs solid	poultry	fNemgr	fNemmi	fNemdep	fNemfix	fNemcrcer cereals fNemcr	fNemcrveg vegetables	fNemcrres others
3	1	2	1	2	0.750%	0.380%	0.210%	0.080%	0.415%	0.170%	0.085%	1.500%	0.940%	0.380%	0.380%	0.000%	0.000%	0.000%
3	1	2	1	3	0.940%	0.470%	0.260%	0.100%	0.525%	0.210%	0.105%	1.880%	1.170%	0.470%	0.470%	0.000%	0.000%	0.000%
3	1	2	2	1	0.750%	0.380%	0.210%	0.080%	0.415%	0.170%	0.085%	1.500%	0.940%	0.380%	0.380%	0.000%	0.000%	0.000%
3	1	2	2	2	1.000%	0.500%	0.275%	0.110%	0.555%	0.220%	0.110%	2.000%	1.250%	0.500%	0.500%	0.000%	0.000%	0.000%
3	1	2	2	3	1.250%	0.630%	0.350%	0.140%	0.695%	0.280%	0.140%	2.500%	1.560%	0.630%	0.630%	0.000%	0.000%	0.000%
3	1	3	1	1	1.130%	0.560%	0.315%	0.130%	0.625%	0.250%	0.125%	2.250%	1.410%	0.560%	0.560%	0.000%	0.000%	0.000%
3	1	3	1	2	1.500%	0.750%	0.415%	0.170%	0.835%	0.330%	0.165%	3.000%	1.880%	0.750%	0.750%	0.000%	0.000%	0.000%
3	1	3	1	3	1.880%	0.940%	0.525%	0.210%	1.040%	0.420%	0.210%	3.750%	2.340%	0.940%	0.940%	0.000%	0.000%	0.000%
3	1	3	2	1	1.500%	0.750%	0.415%	0.170%	0.835%	0.330%	0.165%	3.000%	1.880%	0.750%	0.750%	0.000%	0.000%	0.000%
3	1	3	2	2	2.000%	1.000%	0.555%	0.220%	1.110%	0.440%	0.225%	4.000%	2.500%	1.000%	1.000%	0.000%	0.000%	0.000%
3	1	3	2	3	2.500%	1.250%	0.695%	0.280%	1.390%	0.560%	0.275%	5.000%	3.130%	1.250%	1.250%	0.000%	0.000%	0.000%
3	2	1	1	1	0.140%	0.210%	0.115%	0.050%	0.235%	0.090%	0.050%	0.000%	0.700%	0.130%	0.130%	0.060%	0.560%	0.280%
3	2	1	1	2	0.190%	0.280%	0.160%	0.060%	0.315%	0.130%	0.065%	0.000%	0.940%	0.190%	0.190%	0.080%	0.750%	0.380%
3	2	1	1	3	0.230%	0.350%	0.195%	0.080%	0.390%	0.160%	0.075%	0.000%	1.170%	0.380%	0.380%	0.090%	0.940%	0.470%
3	2	1	2	1	0.190%	0.280%	0.160%	0.060%	0.315%	0.130%	0.065%	0.000%	0.940%	0.170%	0.170%	0.080%	0.750%	0.380%
3	2	1	2	2	0.250%	0.380%	0.210%	0.080%	0.415%	0.170%	0.085%	0.000%	1.250%	0.250%	0.250%	0.100%	1.000%	0.500%
3	2	1	2	3	0.310%	0.470%	0.260%	0.100%	0.525%	0.210%	0.105%	0.000%	1.560%	0.500%	0.500%	0.130%	1.250%	0.630%
3	2	2	1	1	0.280%	0.280%	0.235%	0.090%	0.470%	0.190%	0.095%	0.000%	1.410%	0.250%	0.250%	0.110%	1.130%	0.560%
3	2	2	1	2	0.380%	0.380%	0.315%	0.130%	0.625%	0.250%	0.125%	0.000%	1.880%	0.380%	0.380%	0.150%	1.500%	0.750%
3	2	2	1	3	0.470%	0.470%	0.390%	0.160%	0.785%	0.310%	0.160%	0.000%	2.340%	0.750%	0.750%	0.190%	1.880%	0.940%
3	2	2	2	1	0.380%	0.380%	0.315%	0.130%	0.625%	0.250%	0.125%	0.000%	1.880%	0.330%	0.330%	0.150%	1.500%	0.750%
3	2	2	2	2	0.500%	0.500%	0.415%	0.170%	0.835%	0.330%	0.165%	0.000%	2.500%	0.500%	0.500%	0.200%	2.000%	1.000%
3	2	2	2	3	0.630%	0.630%	0.525%	0.210%	1.040%	0.420%	0.210%	0.000%	3.130%	1.000%	1.000%	0.250%	2.500%	1.250%
3	2	3	1	1	0.560%	0.560%	0.470%	0.190%	0.940%	0.380%	0.190%	0.000%	2.810%	0.500%	0.500%	0.230%	2.250%	1.130%
3	2	3	1	2	0.750%	0.750%	0.625%	0.250%	1.250%	0.500%	0.250%	0.000%	3.750%	0.750%	0.750%	0.300%	3.000%	1.500%
3	2	3	1	3	0.940%	0.940%	0.785%	0.310%	1.565%	0.630%	0.315%	0.000%	4.690%	1.500%	1.500%	0.380%	3.750%	1.880%
3	2	3	2	1	0.750%	0.750%	0.625%	0.250%	1.250%	0.500%	0.250%	0.000%	3.750%	0.670%	0.670%	0.300%	3.000%	1.500%
3	2	3	2	2	1.000%	1.000%	0.835%	0.330%	1.665%	0.670%	0.335%	0.000%	5.000%	1.000%	1.000%	0.400%	4.000%	2.000%
3	2	3	2	3	1.250%	1.250%	1.040%	0.420%	2.085%	0.830%	0.415%	0.000%	6.250%	2.000%	2.000%	0.500%	5.000%	2.500%

1) 1:sand, 2:clay/unknown, 3:peat.
2) 1:grass, 2: arable, 3: nature.
3) 1: <600, 2: 600-900, 3: >900.
4) 1: acid/peat, 2: intermediate, basic, calcareous.
5) 1: <8, 2:8-12, 3:>12.

A1.6 Calculation of nitrogen leaching and runoff

Leaching and runoff in INTEGRATOR is distinguished in (i) N leaching from manure in housing and/or manure storage systems (ii) N surface runoff, (iii) N leaching to surface water or sub-surface runoff and (iv) N leaching to groundwater; as illustrated in Figure 3. N leaching from housing and manure storage systems is calculated as a fraction of N excreted in housing systems (frNle,hs, which is a function of the type of animal, manure and housing system). N leached from housing and storage systems is added to the N surplus in the soil system. The N surplus is divided over leaching below the root zone [fle] and denitrification [1-fle]. N leached below the root zone is further divided between sub-surface runoff to surface water [fro] and leaching to deep groundwater [1-fro]. Surface runoff is calculated as a fraction of N inputs to soil from grazing, manure application and fertiliser [fsr]. Surface runoff and sub-surface runoff are added up to obtain total N runoff to surface water.

Leaching from stored manure

Leaching of N from manure in housing and/or manure storage systems is calculated as a fraction of the amount of N excreted and stored in those systems according to:

$$N_{le,hs} = fNr_{le,hs} * N_{hs} \tag{A1.6.1}$$

Where:

N_{hs} = N excreted and stored in housing and manure storage systems (kg N ha^{-1} yr^{-1})

$frN_{le,hs}$ = Leaching fraction of N excreted and stored in housing and manure storage systems (-)

N leaching fractions for housing and manure storage systems, frNle,hs are based on expert judgement (Velthof et al., 2009). Values are shown in Table A1.6.1.

Table A1.6.1 *Used N leaching fractions for housing and manure storage systems (frNle,hs) and their occurrence in Western and Eastern Europe (after Velthof et al., 2009).*

Manure system	Concrete floor?	Covered storage?	Leaching fraction (% of stored N)	Occurrence (%)	
				Western Europe	Eastern Europe
Liquid/slurry	No	No	10	10	25
	No	Yes	5	0	0
	Yes	No	0	9	7.5
	Yes	Yes	0	81	67.5
Solid manure	No	No	5	47.5	47.5
	No	Yes	2	2.5	2.5
	Yes	No	2	47.5	47.5
	Yes	Yes	0	2.5	2.5

Surface runoff

Surface runoff (N_{sr}) is calculated as:

$$N_{sr} = f_{sr} * \left(N_{fe} + N_{am} + N_{bs}\right) \tag{A1.6.2}$$

Where:

N_{fe} = N input by fertilizer (kg N ha^{-1} yr^{-1})

N_{am} = N input by manure and grazing (kg N ha^{-1} yr^{-1})

N_{bs} = N input by biosolids (kg N ha^{-1} yr^{-1})

f_{sr} = surface runoff fraction in % of the N applied via fertilizer and manure (including grazing)

As with MITERRA-EUROPE, the value of f_{sr} is calculated from a maximal surface runoff and a set of reduction fractions according to (Velthof et al., 2009):

$$f_{sr} = f_{sr.max} * f_{lu} * min(f_p, f_s, f_{rc}) \quad \text{(A1.6.3)}$$

Where

$f_{sr,max}$ = maximum surface runoff fraction for different slope classes

f_{lu} = reduction fraction for land use or crop

f_p = reduction fraction for precipitation surplus

f_s = reduction fraction for soil type

f_{rc} = reduction fraction for depth to rock

The used maximum surface runoff fractions, $f_{sr,max.}$ as a function of slope classes are:

- Level (dominant slope ranging from 0 to 8%): fsr,max = 10%
- Sloping (dominant slope ranging from 8 to 15%): fsr,max = 20%
- Moderately steep (dominant slope ranging from 15 to 25%): fsr,max = 35%
- Steep (dominant slope over 25%): fsr,max = 50%

The reduction fraction for precipitation, f_p, is included as a function of precipitation surplus (PS):

- PS > 300mm: $f_p = 1$
- PS 100–300 mm: $f_p = 0.75$
- PS 50–100 mm: $f_p = 0.50$
- PS < 50 mm: $f_p = 0.25$

The reduction fraction for land use, f_{lu}, is 0.25 for grassland and 1.0 for cropland.

The reduction fraction for soil type, $f_{s,}$ is included as a function of texture:

- Very fine (clay ≥ 60%): fs = 1
- Fine (35% ≤ clay < 60%): fs = 0.90
- Medium (18% ≤ clay < 35%): fs = 0.75
- Coarse (18% < clay): fs = 0.25
- Peat: fs = 0.25

The reduction fraction for depth to rock f_{rc} is included as:

- For a depth of less than 25 cm: $f_{rc} = 1$
- For a depth > 25 cm: $f_{rc} = 0.8$

Soil N surplus, leaching below the root zone and denitrification

The soil N surplus available for subsurface runoff, leaching and denitrification is calculated as:

$$N_{sur} = N_{in} - N_{up} - N_{em} - N_{sr} + N_{mi} + N_{cr} \quad \text{(A1.6.4)}$$

Where:

N_{sur} = N surplus available for subsurface runoff, leaching and denitrification (kg N ha^{-1} yr^{-1})

N_{in} = Total N input via fertilizer, manure application, grazing, biosolids, atmospheric deposition, and biological N fixation (kg N ha^{-1} yr^{-1})

N_{up} = Total N uptake (both harvested crops and crop residues) (kg N ha^{-1} yr^{-1})

N_{em} = Total N (NH_3, N_2O, NO_x) emission from soil applied fertilizer, manure, grazing, atmospheric deposition and biological N fixation (kg N ha^{-1} yr^{-1})

N_{sr} = N in surface runoff (kg N ha^{-1} yr^{-1})

N_{mi} = Net N mineralisation (kg N ha^{-1} yr^{-1})

N_{cr} = N input by crop residues (kg N ha^{-1} yr^{-1})

Subsequently, N leaching below the root zone, including leaching to groundwater (also denoted as leaching) and leaching to surface water (also denoted as subsurface runoff), and denitrification are calculated as:

$$N_{le} = f_{le} * N_{sur} \tag{A1.6.5}$$

$$N_{de} = (1 - f_{le}) * N_{sur} \tag{A1.6.6}$$

Where:

N_{le} = The N leaching below the root zone (kg N ha^{-1} yr^{-1})
N_{de} = The N emission (totally included as N_2 emission) by denitrification (kg N ha^{-1} yr^{-1})
f_{le} = Leaching fraction of N surplus from the rooting zone (-)

As with MITERRA-EUROPE, the value of fr_{le} is calculated from a maximal leaching fraction and a set of reduction fractions according to (Velthof et al., 2009), where the fractions for land use and precipitation surplus have (slightly) been adapted:

$$f_{le} = f_{le.max} * f_{lu} * min(f_p, f_t, f_c) \tag{A1.6.7}$$

$f_{le,max}$ = maximum leaching fraction for different soil types
f_{lu} = reduction fraction for land use
f_p = reduction fraction for precipitation surplus
f_t = reduction fraction for temperature
f_c = reduction fraction for soil organic carbon content

The following soil type dependent maximum leaching fractions $f_{le,max}$ are used:

- sandy soil: $f_{le,max,sand}$ = 1.0
- loamy soil: $f_{le,max,loam}$ = 0.75
- clay soil: $f_{le,max,clay}$ = 0.50
- peat soil: $f_{le,max,peat}$ = 0.20

The reduction fraction for land use, f_{lu}, is 0.85 for grassland and 1.0 for cropland.

Denitrification increases and thus leaching decreases at lower precipitation surplus due to longer residence times allowing enhanced denitrification The reduction fraction for precipitation surplus, fp, is slightly adapted from Velthof et al. (2009) and calculated as a continuous function based on soil type according to:

For sandy and loamy soils:

- PS < 50 mm: f_p = 0.25
- 50 mm ≤ PS < 300 mm: f_p = 1+(PS-300)*0.003
- PS ≥ 300 mm: f_p = 1

For peat and clay soils:

- PS < 50 mm: f_p = 0.25
- 50 mm ≤ PS < 100 mm: f_p = 1+(PS-100)*0.015
- 100 mm ≤ PS < 300 mm: f_p = 1
- 300 mm ≤ PS < 400 mm: f_p = 1-(PS-300)*0.005
- PS ≥ 400 mm: f_p = 0.5

Graphs of the reduction fraction for as a function of the precipitation surplus are given in Figure A1.6.1.

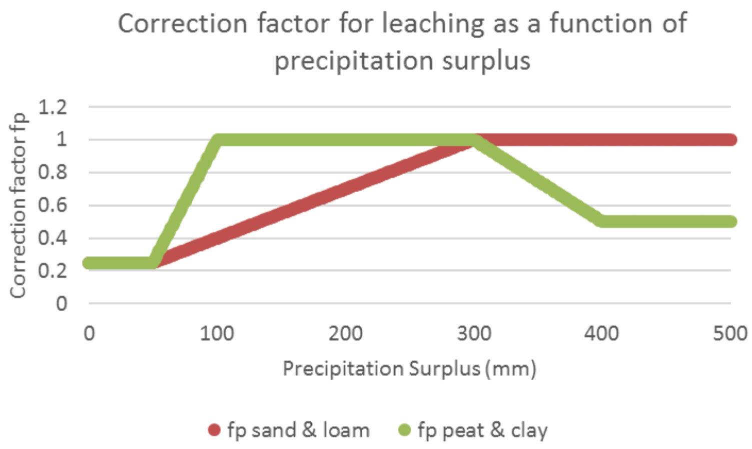

Figure A1.6.1 *Used reduction fractions for the leaching fraction as a function of the precipitation surplus for sandy and loamy (red) and for peat and clay soils (green).*

The function is based on measurements which show that N removal in areas with a low precipitation surplus (such as Spain) are much higher than in areas with a high precipitation surplus (such as France) (Penuelas, pers. comm).

Denitrification increases with increasing temperature and thus leaching decreases. The following reduction fractions for temperature, ft are used (assuming that denitrification at 15 ºC is twice as high as at 5 ºC; a general effect of temperature on microbial activity):

- < 5 ºC: $f_t = 1$
- 5-15 ºC: $f_t = 0.75$
- > 15 ºC: $f_t = 0.50$

Denitrification increases with increasing total soil organic carbon (SOC_ content and thus leaching decreases. The following reduction fractions for SOC content, fc, are used:

- SOC < 1%: $f_c = 1$
- SOC 1-2%: $f_c = 0.90$
- SOC 2-5%: $f_c = 0.75$
- SOC > 5%: $f_c = 0.50$

Division of leaching over ground water and surface water

The division of N leaching below the root zone to leaching to groundwater (also denoted as leaching) and leaching to surface water (also denoted as subsurface runoff) is calculated as:

$$N_{ro} = f_{ro} * N_{le} \quad \text{(A1.6.8)}$$

$$N_{gw} = (1 - f_{ro}) * N_{le} \quad \text{(A1.6.9)}$$

Where

N_{ro} = N subsurface runoff flux towards surface water (kg N ha^{-1} yr^{-1})

N_{gw} = N leaching flux towards ground water (kg N ha^{-1} yr^{-1})

f_{ro} = Subsurface runoff fraction, being the fraction of leached N laterally transported to surface water.

The value of f_{ro} is calculated as function of lithology, area above sea level and the occurrence of natural surface waters, derived from the IMAGE groundwater model, as described in Keuskamp et al. (2012).

The total N influx to surface water is calculated as:

$$N_{sw} = N_{sr} + N_{ro} \tag{A1.6.10}$$

Data on the soil organic carbon (SOC) and clay contents were based on the joint WISE, SPADE 1 and EFSDB databases, which jointly contain approximately 3,600 soil profiles, irregularly distributed over Europe. Data at NCU level were derived with a multivariate regression kriging model accounting for the spatial structure of the soil properties and their dependency on explanatory variables such as soil type and land cover (Heuvelink et al., 2016).

A1.7 Calculation of N concentrations in leaching to groundwater and in runoff to surface water

N concentrations in leaching to groundwater

The NO_3 concentration in the leaching flux to groundwater (to enable comparison with the Nitrate Directive value of 50 mg NO_3 l^{-1}) is calculated as:

$$[NO3]_{gw} = \frac{N_{gw}}{Q_{gw}} * cF_{cNO3} \tag{A1.7.1}$$

Where:

$[NO3]_{gw}$	=	Nitrate concentration in the leaching flux towards groundwater (mg NO_3 l^{-1})
N_{gw}	=	N leaching flux towards groundwater (kg N ha^{-1} yr^{-1})
Q_{gw}	=	Water flux leaching towards groundwater (m^3 ha^{-1} yr^{-1})
cf_{cNO3}	=	Conversion factor from (kg N ha^{-1})/(m^3 ha^{-1}) to mg NO_3 l^{-1}, i.e. (62/14)*1000

Furthermore, the following equations hold:

$$Q_{gw} = Q_{tot} - Q_{sr} - Q_{ro} \tag{A1.7.2}$$

$$Q_{sr} = f_{sr} * Q_{tot} \tag{A1.7.3}$$

$$Q_{ro} = f_{ro} * (Q_{tot} - Q_{sr}) = f_{ro} * (1 - f_{sr}) * Q_{tot} \tag{A1.7.4}$$

Where:

Q_{tot}	=	The total precipitation surplus discharging towards groundwater and surface water (including surface runoff and subsurface runoff) (m^3 ha^{-1} yr^{-1})
Q_{sr}	=	Water flux to surface water via surface runoff (m^3 ha^{-1} yr^{-1})
Q_{ro}	=	Water flux to surface water via sub-surface runoff (m^3 ha^{-1} yr^{-1})
f_{sr}	=	The surface runoff fraction of precipitation surplus, being equal to the value used for nitrogen (see Annex A1.5)
f_{ro}	=	Subsurface runoff fraction of precipitation surplus, being equal to the value used for nitrogen (see Annex A1.5)

Combining the equations A1.7.1-A 1.7.4 leads to:

$$[NO3]_{gw} = \frac{N_{gw}}{(1-f_{sr})*(1-f_{ro})*Q_{tot}} * cF_{cNO3} \tag{A1.7.5}$$

N concentrations in runoff to surface water

The N concentration in the total runoff from agriculture to surface water (including surface runoff and subsurface runoff) is calculated as:

$$[N]_{sw} = \frac{N_{sr}+N_{ro}}{Q_{sr}+Q_{ro}} * cF_{cN} \tag{A1.7.6}$$

Combining the equations A 1.7.3, A 1.7.4 and A 1.7.6 with N_{ro} being equal to f_{ro} x N_{le}, leads to

$$[N]_{sw} = \frac{N_{sr}+f_{ro}*N_{le}}{f_{sr}+f_{ro}*(1-f_{sr})*Q_{tot}} * cF_{cN} \tag{A1.7.7}$$

Where:

$[N]_{sw}$	=	The N concentration in the total runoff flux (surface + subsurface runoff) towards surface water (mg l^{-1})
N_{le}	=	The N leaching flux below the root zone (includes flux to groundwater and sub-surface flux to surface water) (kg N ha^{-1} yr^{-1})
cf_{cN}	=	The conversion factor from kg N ha^{-1} /(m^3 ha^{-1}) to mg N l^{-1}, i.e. 1000

Note that the equation for N runoff from agriculture to surface water does not include the dilution of N from non-agricultural areas as used in the back calculation. This aspect is included when calculating the N concentration in total runoff, according to:

$$[N]_{sw} = \left(1-f_{ag}\right) * 0.5 + f_{ag} * \frac{N_{sr}+f_{ro}*N_{le}}{f_{sr}+f_{ro}*(1-f_{sr})*Q_{tot}} * cF_{cN} \tag{A1.7.8}$$

Annex 2 Details of the calculation of region- and crop-specific yield potentials

A2.1 Testing scaling approaches for wheat, maize and barley

Before deciding on the methodology used to derive yield potentials for all crops and countries in Europe, we tested three different scaling methodologies. The two methodologies other than the one described in the main text (Section 2.3.1) are described below, and results of all three methods are compared. Performance of the three scaling approaches was compared by applying each scaling approach to wheat, maize and barley, and then assessing how close the thus derived estimates come to the actual potential yields presented in GYGA.

'Simple' country-based scaling approach
As discussed in Section 2.3.1, the "country-based scaling approach" estimates potential yields for each crop and country according to:

$$Yw_{crop_n,cz_{ij}} = Ya_{crop_n,cz_{ij}} * YRw_{wheat,cz_{ij}} * \left(\frac{YRm_{crop_n,co_j}}{YRm_{wheat,co_j}}\right) \tag{A2.1.1}$$

If we assume that for cereals the maximum yield ratio YRm_{crop_n,co_j} equals the maximum yield ratio for wheat YRm_{wheat,co_j}, then we can calculate yield potentials for cereals as:

$$Yw_{crop_n,cz_{ij}} = Ya_{crop_n,cz_{ij}} * YRw_{wheat,cz_{ij}} \tag{A2.1.2}$$

Regression-based approach
The country-based approach can only be applied if we have data on yield gaps for at least one crop in the respective countries (e.g. for Europe, wheat and barley). However, if we want to estimate the yield potential for countries where we do not have any data on yield gaps and yield potentials, we need a different approach.

Therefore we checked a procedure to scale crop yield potentials by assuming that the ratio between the country-level yield of a crop in INTEGRATOR [$Ya_{crop_n,cz_{ij}}$] and the highest yield of this crop that is achieved in any of the EU-27 countries from INTEGRATOR [$Y_{max,crop_n,EU}$] is correlated to the ratio between the country-level actual yield of a crop in GYGA [$YaGYGA_{crop_n,cz_{ij}}$] and the potential yield from GYGA [$YwGYGA_{crop_n,cz_{ij}}$]. We can calculate the correlation between those two ratios for wheat, barley and maize. If we find a good correlation, we can use this to infer the potential yields for other crops from the ratio between [$Ya_{crop_n,cz_{ij}}$] and [$Y_{max,crop_n,EU}$] (which we have for all countries and crops).

We can then draw a regression line for Ratio Y ($Y_{max,crop_n,EU}/Ya_{crop_n,cz_{ij}}$ vs Ratio X ($YwGYGA_{crop_n,cz_{ij}}/YaGYGA_{crop_n,cz_{ij}}$) with: Y = a + b*X and assess X = (Y-a)/b and thus we can calculate the potential yield as $Yw_{crop_n,cz_{ij}}$= X * $Ya_{crop_n,cz_{ij}}$.

Comparing results from three scaling approaches

We compared estimated potential yields from all three scaling approaches with data on water-limited yield potentials (Yw) from GYGA for rainfed wheat, rainfed maize and rainfed barley. In order to compare how well each of the scaling approaches predicts GYGA yield potentials, we calculate the Normalized Root Square Mean Error (NRSME) according to:

$$\mathrm{RSME} = \sqrt{\frac{\sum_{t=1}^{n}(\hat{y}-y)^2}{n}} \qquad \text{(A2.1.3)}$$

Where:

$\hat{y}$ = the predicted water-limited yield potential using the scaling approach

y = the water-limited yield potential from GYGA, and

$$\mathrm{NRSME} = \frac{RSME}{\bar{y}} \qquad \text{(A2.1.4)}$$

Where:

$\bar{y}$ = the average water-limited yield potential from GYGA.

Figure A2.1.1 shows yield potentials for rainfed wheat obtained with the country-based scaling approach vs. GYGA yield potentials (left) and yield potentials obtained with the regression based approach vs. GYGA yield potentials (right). For the case of wheat, results from the ‘simple’ scaling approach are identical to the country-based scaling approach. The country-based approach gives a better fit with the GYGA data, with a lower NRSME.

Figure A2.1.2 shows yield potentials for rainfed maize obtained with the country-based scaling approach (left), the ‘simple’ scaling approach (middle) and the regression-based approach (right) plotted against actual GYGA yield potentials. Yield potentials estimated with the different scaling approaches are almost always higher than the potential yields estimated by GYGA. This is to be expected since the ratio YG/YD for wheat, used to correct the maximum crop yield, is generally higher for wheat than for maize. This is because GYGA estimates the yield gaps for wheat and barley to be much higher than for maize (they estimate the ratio Ya/Yw at 59% for wheat, 58% for barley and 72% for maize, when averaged across all European countries). Again, the country-based approach gives the best fit (lowest NRSME).

Figure A2.1.3 shows yield potentials for rainfed barley obtained with the country-based scaling approach (left), the ‘simple’ scaling approach (middle) and the regression-based approach (right) plotted against actual GYGA yield potentials. For barley, all three approaches perform similarly well, with small differences in NSRME. While the country-based approach tends to over-estimate yield potentials, the ‘simple’ approach and the regression-based approach under-estimate yield potentials for most countries.

Overall, the country-based scaling approach obtains the best match with the GYGA estimates.

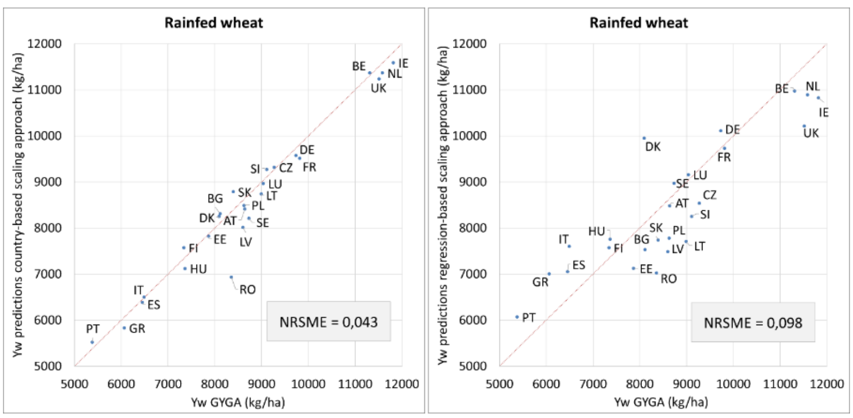

Figure A2.1.1 *Scaling approach equation 1 vs. GYGA (left) and regression-based scaling approach vs. GYGA (right) for rainfed wheat. Red line is 1:1 line.*

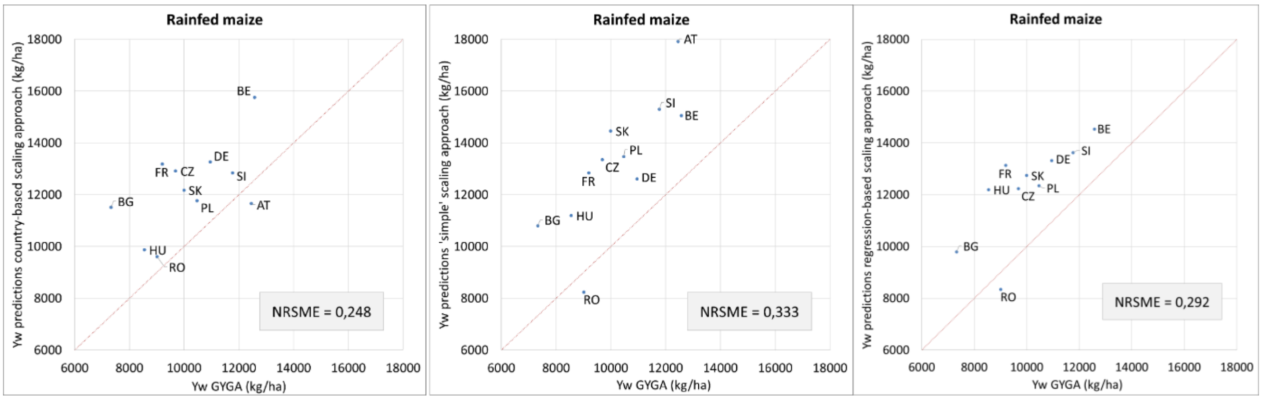

Figure A2.1.2 *Scaling approach equation 1 vs. GYGA (left), scaling approach equation 2 vs. GYGA (middle) and regression-based scaling approach vs. GYGA (right) for rainfed maize. Red line is 1:1 line.*

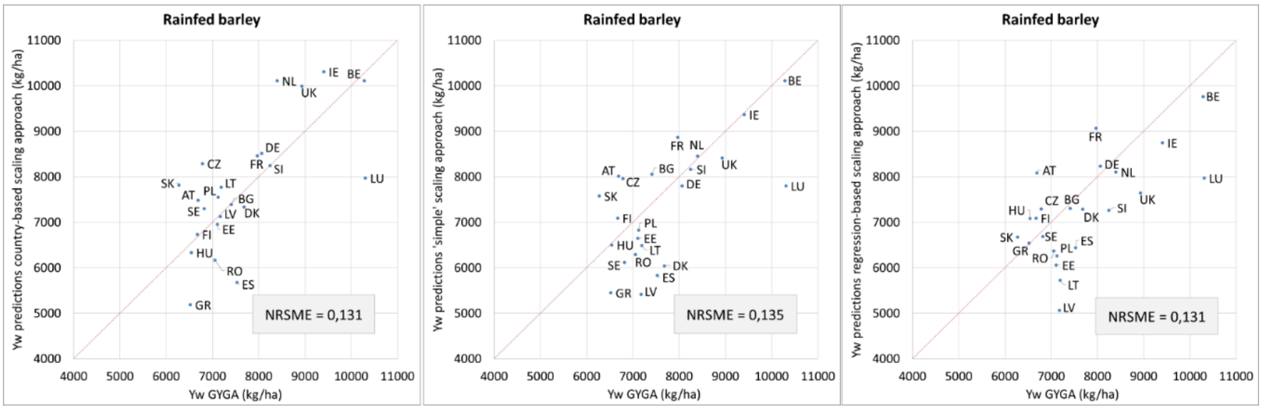

Figure A2.1.3 *Scaling approach equation 1 vs. GYGA (left), scaling approach equation 2 vs. GYGA (middle) and regression-based scaling approach vs. GYGA (right) for rainfed barley. Red line is 1:1 line.*

A2.2 Exceptions to scaling procedure I: crop groups

After applying the basic scaling approach to calculate yield potentials as described in Section 2.3.1 (main text), there were several crop-country combinations where the yield potential was extremely high compared to the actual yield - see Figure A2.3.1 below where we plotted for each crop and country the 'required yield increase to obtain scaled yield potentials' (compared to actual yields from INTEGRATOR/ FAO). Crop-country combinations where the difference between actual yield and scaled yield potential was more than a factor 3 were:

1. Rye: Portugal (325%)
2. Other fresh vegetables: Slovakia (401%)
3. Other fruit: Portugal (391%), Finland (902%), Bulgaria (1262%), Lithuania (923%), Slovakia (440%), Czech Republic (371%)
4. Other crops, permanent industrial crops: Spain (420%), Bulgaria (359%), Poland (410%), Lithuania (368%)

These high values might be due to the fact that groups like 'other fruit' contain several types of fruit with very different yields (e.g. melons and strawberries). We thus decided to apply a different scaling procedure to groups of crops. For these group of crops, yield potentials were calculated as:

$$Yw_{crop_n,cz_{ij}} = Ya_{crop,cz_{ij}} * YRw_{wheat,cz_{ij}} \tag{A2.2.1}$$

Where

$Yw_{crop_n,cz_{ij}}$ = the water-limited yield potential for a certain crop in climate zone i and country j

$Ya_{crop,cz_{ij}}$ = actual crop yield in INTEGRATOR for a certain crop in climate zone i and country j (as derived by downscaling described above)

$YRw_{wheat,cz_{ij}}$ = the potential yield ratio defined as $\left(\frac{Yw_{wheat,cz_{ij}}}{Ya_{wheat,cz_{ij}}}\right)$, with $Yw_{wheat,cz_{ij}}$ = water-limited wheat yield potential for climate zone i in country j from GYGA and $Ya_{wheat,cz_{ij}}$ = actual wheat yield for climate zone i in country j from GYGA.

This applies to the following crop groups:

- Fibre and oleaginous crops; cotton
- Other fresh vegetables
- Fodder other on arable land, temporary grassland
- Other fruit
- Other crops, permanent industrial crops
- Other oil

A2.3 Exceptions to scaling procedure II: climate zones without wheat yield data or locations with no climate zone

Even after re-assigning similar climate zones *with* wheat data to climate zones with missing wheat data, there are still climate zones with no wheat data (either because there was no similar climate zone with wheat data within a country; or because there was no climate zone assigned to a region – see Annex A1.3). For these climate zones, all crop yields are national average crop yields, and scaled yield potentials are calculated as:

$$Yw_{crop_n,nocz,co_j} = Ya_{crop_n,co_j} * YRw_{wheat,nocz,co_j} * \left(\frac{YRm_{crop_n,co_j}}{YRm_{wheat,co_j}}\right) \tag{A2.3.1}$$

Where:

$Yw_{crop_n,nocz,co_j}$ = the water-limited yield potential for crop n in an area with "no climate zone or no wheat-yield climate zone" in country j

Ya_{crop_n,co_j} = the actual country-level crop yield for crop n in country j in INTEGRATOR based on FAO data

$YRw_{wheat,nocz,co_j}$ = the potential yield ratio defined as $\left(\frac{Yw_{wheat,ave,co_j}}{Ya_{wheat,ave,co_j}}\right)$ with Yw_{wheat,ave,co_j} = water-limited wheat yield potential for country j from GYGA and Ya_{wheat,ave,co_j} = actual wheat yield for country j from GYGA.

YRm_{wheat,co_j} and YRm_{crop_n,co_j} are the same as in Eq. (1) in Section 2.3.1.

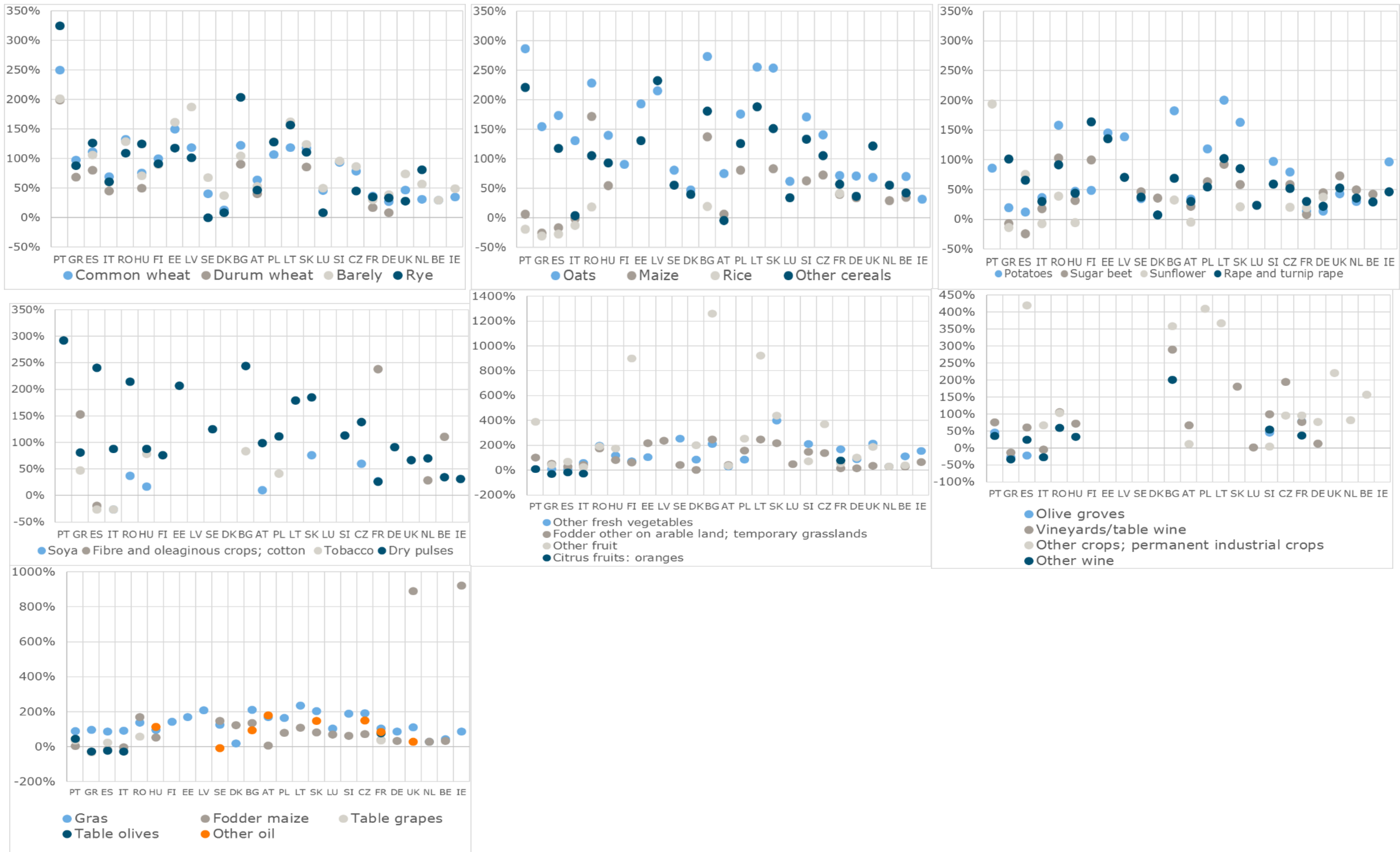

Figure A2.3.1 *Relative difference (in %) between actual yield and scaled yield potential per crop and country.*

A2.4 The yield increase in % that is required to obtain 80% of yield potential (calculated as (0.8 Yw-Ya)/Ya x 100) for crop-country combinations

	Common wheat	Durum wheat	Barley	Rey	Oats	Maize	Rice	Other cereals	Potatoes	Sugar beet	Sunflower	Rape and turnip rape	Soya	Fibre and oleaginous crops;	Tobacco	Dry pulses	Other fresh vegetables	Fodder other on arable land;	Other fruit	Citrus fruits: oranges	Olive groves	Vineyards/table wine	Other crops; permanent	Other wine	Gras	Fodder maize	Table grapes	Table olives	Other oil
AT	31%	12%	23%	18%	41%	-14%	#N/A	-23%	8%	-2%	-23%	4%	-12%	#N/A	#N/A	59%	4%	16%	9%	#N/A	#N/A	34%	-10%	#N/A	117%	-14%	#N/A	#N/A	125%
BE	4%	#N/A	4%	#N/A	36%	8%	#N/A	14%	4%	14%	#N/A	4%	#N/A	69%	#N/A	8%	71%	4%	13%	#N/A	#N/A	#N/A	106%	#N/A	15%	8%	#N/A	#N/A	#N/A
BG	78%	53%	64%	143%	199%	90%	-4%	125%	126%	#N/A	7%	35%	#N/A	#N/A	47%	176%	149%	180%	990%	#N/A	#N/A	212%	267%	141%	149%	90%	#N/A	#N/A	57%
CZ	43%	#N/A	49%	16%	93%	39%	#N/A	65%	44%	27%	-3%	22%	29%	#N/A	#N/A	91%	#N/A	93%	277%	#N/A	#N/A	136%	57%	#N/A	134%	39%	#N/A	#N/A	102%
DE	2%	-13%	11%	7%	37%	7%	#N/A	10%	-9%	16%	10%	-2%	#N/A	#N/A	#N/A	53%	52%	-6%	62%	#N/A	#N/A	-9%	42%	#N/A	50%	7%	#N/A	#N/A	#N/A
DK	-9%	#N/A	10%	-13%	18%	#N/A	#N/A	12%	-14%	9%	#N/A	-14%	#N/A	#N/A	#N/A	#N/A	51%	-17%	142%	#N/A	#N/A	#N/A	#N/A	#N/A	-3%	80%	#N/A	#N/A	#N/A
EE	100%	#N/A	109%	74%	135%	#N/A	#N/A	85%	96%	#N/A	#N/A	89%	#N/A	#N/A	#N/A	146%	64%	156%	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	117%	#N/A	#N/A	#N/A	#N/A
ES	69%	45%	65%	81%	119%	-33%	-42%	75%	-10%	-39%	41%	33%	#N/A	-35%	-40%	173%	-14%	3%	36%	-32%	-37%	30%	316%	0%	51%	-33%	0%	-37%	#N/A
FI	60%	#N/A	52%	53%	53%	#N/A	#N/A	#N/A	19%	60%	#N/A	111%	#N/A	#N/A	#N/A	41%	37%	31%	701%	#N/A	#N/A	#N/A	#N/A	#N/A	95%	#N/A	#N/A	#N/A	#N/A
FR	9%	-6%	4%	8%	38%	12%	13%	26%	-9%	-13%	-4%	5%	2%	171%	#N/A	1%	115%	-5%	26%	45%	43%	42%	57%	10%	64%	12%	10%	43%	49%
GR	58%	35%	51%	51%	104%	-40%	-44%	#N/A	-4%	-25%	-31%	61%	#N/A	102%	18%	45%	-12%	23%	16%	-42%	-41%	-30%	#N/A	-46%	58%	-40%	-46%	-41%	#N/A
HU	40%	20%	37%	80%	92%	24%	#N/A	55%	18%	6%	-24%	15%	-6%	#N/A	43%	50%	76%	46%	122%	#N/A	#N/A	38%	#N/A	7%	59%	24%	#N/A	#N/A	72%
IE	8%	#N/A	19%	#N/A	6%	#N/A	#N/A	#N/A	57%	#N/A	#N/A	18%	#N/A	#N/A	#N/A	6%	105%	34%	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	50%	719%	#N/A	#N/A	#N/A
IT	36%	16%	28%	29%	85%	-21%	-30%	-16%	10%	-6%	-25%	4%	-41%	#N/A	-41%	50%	28%	16%	0%	-41%	-41%	-23%	34%	-41%	54%	-21%	-41%	-41%	#N/A
LT	75%	#N/A	110%	106%	185%	#N/A	#N/A	131%	141%	54%	#N/A	62%	#N/A	#N/A	#N/A	124%	#N/A	179%	719%	#N/A	#N/A	#N/A	274%	#N/A	170%	68%	#N/A	#N/A	#N/A
LU	17%	#N/A	20%	-13%	30%	#N/A	#N/A	8%	#N/A	#N/A	#N/A	-1%	#N/A	#N/A	#N/A	#N/A	#N/A	20%	#N/A	#N/A	#N/A	-18%	#N/A	#N/A	64%	37%	#N/A	#N/A	#N/A
LV	75%	#N/A	130%	62%	152%	#N/A	#N/A	166%	91%	#N/A	#N/A	37%	#N/A	#N/A	#N/A	#N/A	#N/A	171%	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	148%	#N/A	#N/A	#N/A	#N/A
NL	5%	#N/A	26%	45%	#N/A	4%	#N/A	25%	4%	20%	#N/A	9%	#N/A	4%	#N/A	36%	4%	5%	4%	#N/A	#N/A	#N/A	46%	#N/A	4%	4%	#N/A	#N/A	#N/A
PL	66%	#N/A	83%	83%	121%	45%	#N/A	81%	75%	31%	#N/A	24%	#N/A	#N/A	14%	70%	50%	107%	185%	#N/A	#N/A	#N/A	308%	#N/A	113%	45%	#N/A	#N/A	#N/A
PT	180%	140%	141%	240%	209%	-15%	-35%	157%	49%	#N/A	135%	#N/A	#N/A	#N/A	#N/A	214%	-11%	63%	292%	-13%	17%	41%	#N/A	9%	53%	-15%	9%	17%	#N/A
RO	86%	#N/A	83%	67%	163%	118%	-5%	65%	107%	62%	12%	53%	10%	#N/A	#N/A	152%	138%	120%	134%	#N/A	#N/A	65%	63%	28%	92%	118%	28%	#N/A	#N/A
SE	12%	#N/A	34%	-20%	45%	#N/A	#N/A	25%	8%	17%	#N/A	10%	#N/A	#N/A	#N/A	80%	185%	14%	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	81%	99%	#N/A	#N/A	-25%
SI	55%	#N/A	57%	#N/A	117%	30%	#N/A	87%	59%	#N/A	#N/A	27%	#N/A	#N/A	#N/A	71%	149%	101%	40%	#N/A	17%	60%	-16%	24%	133%	30%	#N/A	#N/A	#N/A
SK	74%	49%	80%	69%	183%	47%	#N/A	101%	111%	27%	-3%	49%	41%	#N/A	#N/A	128%	301%	156%	332%	#N/A	#N/A	125%	#N/A	#N/A	144%	47%	#N/A	#N/A	100%
UK	17%	#N/A	39%	2%	35%	#N/A	#N/A	78%	15%	39%	#N/A	22%	#N/A	#N/A	#N/A	34%	151%	10%	130%	#N/A	#N/A	#N/A	158%	#N/A	70%	694%	#N/A	#N/A	3%

Annex 3 Methods used to calculate the spatial variation of critical inputs of nitrogen

A3.1 Calculation of critical ammonia emissions from agriculture from critical N deposition on natural land

In calculating critical N inputs in view of critical N deposition on terrestrial ecosystems, we assumed that the average total N deposition on agricultural land equals the average total N deposition on non-agricultural land (both in kg N ha^{-1}). This assumption holds specifically in areas where the surface roughness of non-agricultural land is comparable to that of arable land, which is true for low vegetation (grasslands, heathlands etc.) but not for forests. Overall, however, the assumption is reasonable, as illustrated by comparing average N deposition on agriculture and N deposition on nature at country level (see Figure A3.1.1).

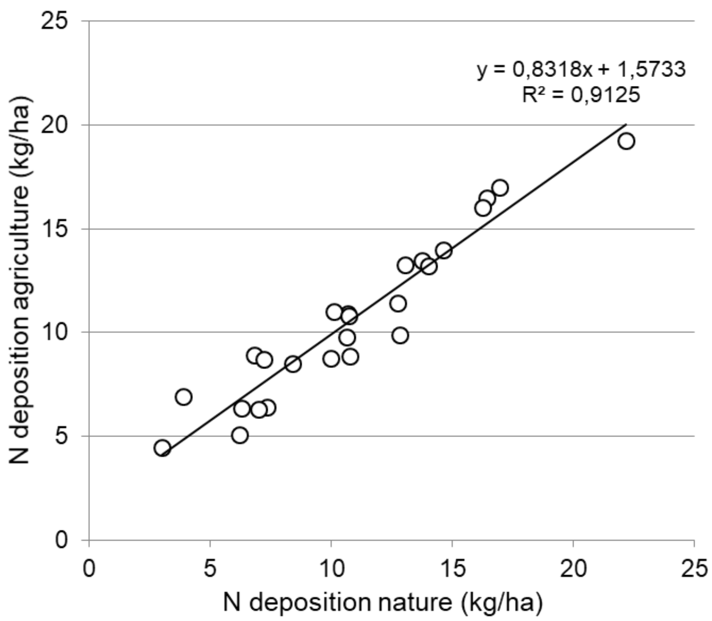

Figure A3.1.1 *The relationship between total N (NH_3-N and NO_x-N) deposition on agricultural land and total N deposition on non-agricultural land for the 27 EU Member States (MSs) for the year 2010. The N deposition data were derived from EMEP.*

In formula:

$$NH_3\text{-}N_{dep}(ag) + NO_x\text{-}N_{dep}(ag) = NH_3\text{-}N_{dep}(non\text{-}ag) + NO_x\text{-}N_{dep}(non\text{-}ag) \qquad (A3.1.1)$$

Within a given region, we also assumed that the amount of NH_3 that is emitted (coming from agriculture) is deposited in the same region, but then on all (agricultural land and non-agricultural) land (both in kg N ha^{-1}). In formula form:

$$NH_3\text{-}N_{dep}(all) = f(ag).\ NH_3\text{-}N_{em}(ag) \qquad (A3.1.2)$$

where all stands for all (agricultural and non-agricultural) land in a region, f(ag) stands for the fraction agricultural land in a region and where NH_3-N_{em} and NH_3-N_{dep} are the average NH_3-N emission and deposition (both in kg N ha^{-1}).

For a given region (NCU, NUTS3 or MS), the following relationships further hold:

$$Ndep_{tot}(all) = NH_3\text{-}N_{dep}(all) + NO_x\text{-}N_{dep}(all) \qquad (A3.1.3)$$

$$NO_x\text{-}N_{dep}(all) = fNO_x \times Ndep_{tot}(all) \qquad (A3.1.4)$$

Where $Ndep_{tot}$ is the average total N deposition in kg N ha^{-1} and fNO_x stands for the fraction NO_x in total (NO_x+NH_3) deposition.

Combining Eq. (3.1.2)-(3.1.4) gives

$$Ntot_{dep}(all) = f(ag)/(1- fNO_x) \times NH_3\text{-}N_{em}(ag) \qquad (A3.1.5)$$

Assuming that total N deposition consists of NO_x deposition and NH_3 deposition, fNO_x equals 1-fNH_3 where fNH_3 stands for the fraction NH_3 in total (NO_x+NH_3) deposition and Eq. (3.1.5) becomes:

$$Ndep_{tot}(all) = f(ag)/fNH_3 \times NH_3\text{-}N_{em}(ag) \text{ or } NH_3\text{-}N_{em}(ag) = Ndep_{tot}(all) \times fNH_3/f(ag) \qquad (A3.1.6)$$

Since we assumed (see Eq. 3.1.1) that $Ndep_{tot}(ag)$ = $Ndep_{tot}$(non-ag), Eq. 3.1.6 can be written as:

$$NH_3\text{-}N_{em}(ag) = Ndep_{tot}(non\text{-}ag) \times fNH_3/f(ag) \qquad (A3.1.7)$$

In this way, a critical N deposition for non-agricultural land, $Ndep_{tot}$(non-ag)(crit), can be used to calculate a critical NH_3 emission from agricultural land, NH_3-N_{em}(ag)(crit), as given in Eq. (23) in the main text.

Maps of spatial variation in fraction agricultural land (fag), in the fraction of NH_3 in total (NH_3+NO_x) deposition (fNH_3Dep), of the critical N load on natural areas ($Ndep_{tot}$(non-ag)(crit) denoted as clN) and of the resulting critical NH_3 emissions as calculated by Eq A 3.1.7 is given in Figure A3.1.2.

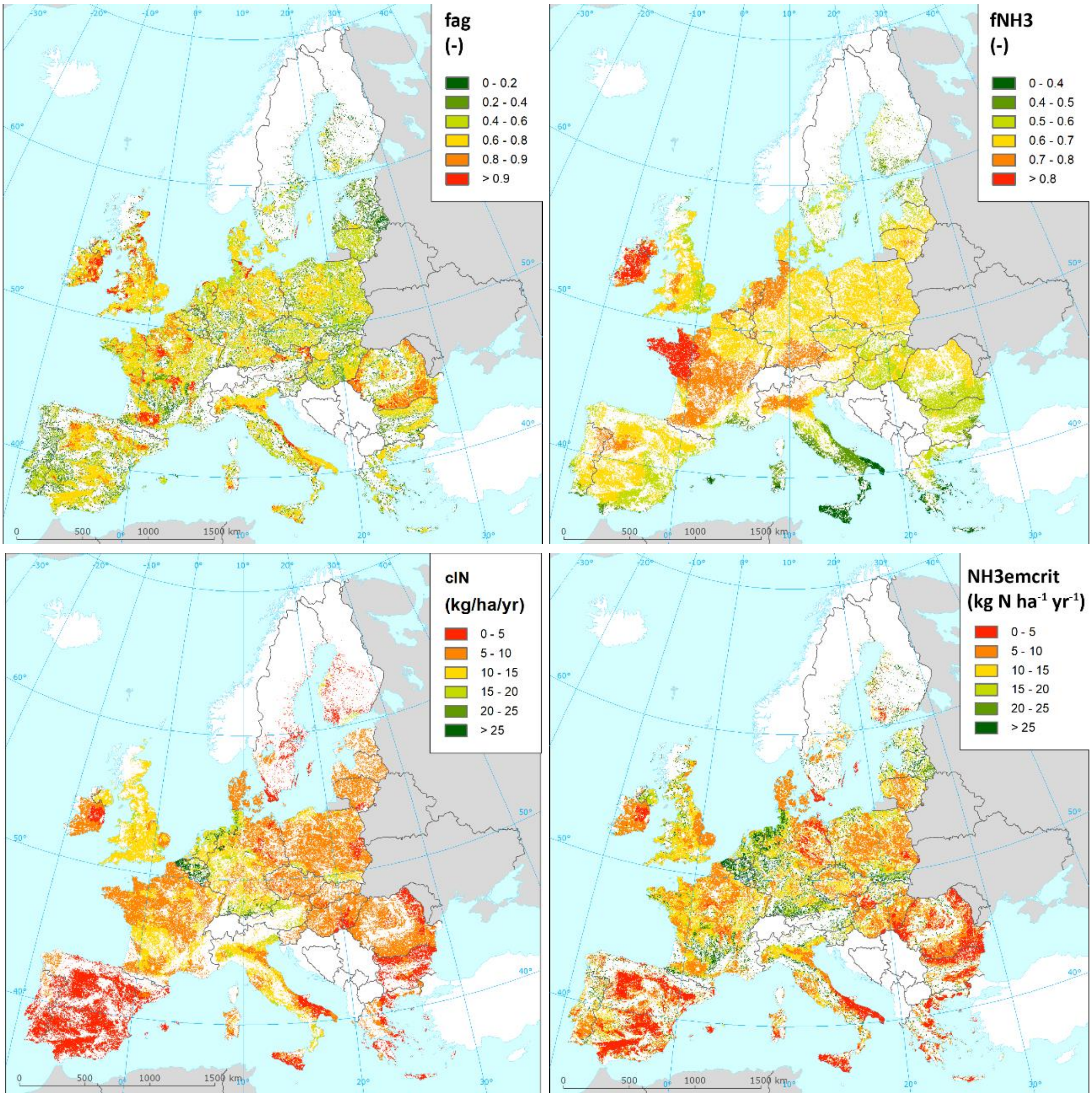

Figure A3.1.2 *Maps of the spatial variation in fraction agricultural land (fag), in the fraction of NH_3 in total (NH_3+NO_x) deposition (fNH3), of the critical N load on natural areas (clN) and of the calculated critical NH_3 emissions (NH3emcrit).*

A3.2 Back-calculation of critical nitrogen inputs

Deviation of formula for critical inputs with respect to critical N concentrations in runoff to surface water

Step 1) Replace "Nsur(crit)" in Eq. (17) with the right-hand side of Eq. (19).

Step 2) Replace "Nle(crit)" in Eq. (20) with the right-hand side of the new Eq. (17).

Step 3) Replace "Nro(crit)" in Eq. (22) with the right-hand side of new Eq. (20), and replace "Nsr(crit)" in Eq. (22) with the right-hand side of Eq. (16).

Step 4) In the new Eq. (22), replace:

- "Noff(crit)" with the right-hand side of Eq. (9),
- "Nem(crit)" with the right-hand side of Eq. (14),
- "Ndep(crit)" with the right-hand side of Eq. (15),
- "Nsr(crit)" with the right-hand side of Eq. (16),

Step 5) In the new Eq. (22), replace:

- "Nem(crit)" with the right-hand side of Eq. (14),
- "Ndep(crit)" with the right-hand side of Eq. (15),
- "Nsr(crit)" with the right-hand side of Eq. (16),

Step 6) In the new Eq. (22), replace:

- "NH3em(crit)" with the right-hand side of Eq. (11)

Step 7) As we know Nsw(crit) from Eq. (30), the resulting equation now includes two unknowns: Nfe+fix(crit) and Nex+bs(crit). Replace "Nfe+fix(crit)" in the new Eq. (22) by the right-hand side of Eq. (24).

Step 8) Solve the formula for Nex+bs(crit).

The resulting equation (A 3.2.1) is:

$$N_{ex+bs(crit,sw)} = \frac{N_{sw(crit)} - N_{min} * f_{le} * f_{ro} * \left(1 - frN_{off}\right)}{\frac{fN_{fe}}{1-fN_{fe}} * \left(f_{sr} + f_{le} * f_{ro} * \left(1 + fNH3_{em,fe} * \frac{f_{ag}}{f_{NH3}} - fN_{em,fe} - f_{sr} + frN_{off} * \left(f_{sr} - 1 - fNH3_{em,fe} * \frac{f_{ag}}{f_{NH3}} + fN_{em,fe}\right)\right)\right) + \left(f_{sr} + f_{le} * f_{ro} * \left(1 + fNH3_{em,ex} * \frac{f_{ag}}{f_{NH3}} - fN_{em,ex} - f_{sr} + frN_{off} * \left(f_{sr} - 1 - fNH3_{em,ex} * \frac{f_{ag}}{f_{NH3}} + fN_{em,ex}\right)\right)\right)}$$

As we assume that the fraction of N fertilizer + fixation compared to the sum of N fertilizer, N fixation, N excretion and N biosolids at critical N inputs is equal to the actual value for each crop and NCU (see Eq. (7)), critical N inputs from fertilizer and fixation can be calculated with Eq. (24).

Deviation of formula for critical inputs with respect to critical N concentrations in runoff to groundwater

Step 1) Replace "Nsur(crit)" in Eq. (17) with the right-hand side of Eq. (19).

Step 2) Replace "Nle(crit)" in Eq. (21) with the right-hand side of the new Eq. (17).

Step 3) In the new Eq. (21), replace:

- "Noff(crit)" with the right-hand side of Eq. (9),
- "Nem(crit)" with the right-hand side of Eq. (14),
- "Ndep(crit)" with the right-hand side of Eq. (15),
- "Nsr(crit)" with the right-hand side of Eq. (16),

Step 4) In the new Eq. (21), replace:

- "Nem(crit)" with the right-hand side of Eq. (14),
- "Ndep(crit)" with the right-hand side of Eq. (15),
- "Nsr(crit)" with the right-hand side of Eq. (16),

Step 5) In the new Eq. (21), replace:

- "NH3em(crit)" with the right-hand side of Eq. (11)

Step 6) As we know $N_{gw(crit)}$ from Eq. (33), the resulting equation now includes two unknowns: $N_{fe+fix(crit)}$ and $N_{ex+bs(crit)}$. Replace "$N_{fe+fix(crit)}$" in the new Eq. (21) by the right-hand side of Eq. (24).

Step 7) Solve the formula for Nex+bs(crit).

The resulting equation (A 3.2.1) is:

$$N_{ex+bs(crit,gw)} = \frac{\frac{N_{gw(crit)}}{f_{le} * (1 - f_{ro})} - N_{min} * \left(1 - frN_{off}\right)}{\frac{fN_{fe}}{1 - fN_{fe}} * \left(1 + fNH3_{em,fe} * \frac{f_{ag}}{f_{NH3}} - fN_{em,fe} - f_{sr} + frN_{off} * \left(f_{sr} - 1 - fNH3_{em,fe} * \frac{f_{ag}}{f_{NH3}} + fN_{em,fe}\right)\right) + \left(1 + fNH3_{em,ex} * \frac{f_{ag}}{f_{NH3}} - fN_{em,ex} - f_{sr} + frN_{off} * \left(f_{sr} - 1 - fNH3_{em,ex} * \frac{f_{ag}}{f_{NH3}} + fN_{em,ex}\right)\right)}$$

A3.3 Differences in the forward and back-calculations of the ammonia emission fraction for excreted manure

In the forward calculations with INTEGRATOR, NH_3 emissions from manure excretion are calculated by first dividing total excreted manure over manure excreted in housing systems and by grazing animals. The amount that is applied to the soil is calculated as excretion in housing systems minus emissions from housing systems. In each step, NH_3 emissions are calculated using differentiated emission fractions per (i) animal category, (ii) housing type, (iii) application technique and (iv) manure type (see Annex A1.4).

In the back-calculations, however, we use a country-averaged NH_3 emission fraction for excreted manure ($fNH3em_{ex}$). We could derive an NCU-averaged NH_3 emission fraction for excreted manure by dividing total NH_3 emissions from housing, grazing and manure application in an NCU by total N excretion in an NCU (similar to the NH_3 emission fraction per NCU for fertilizer). However, in the forward calculations not all manure excreted within housing sytems in an NCU is necessarily applied to agricultural land in the same NCU. If application of manure from housing systems leads to an exceedance of maximum application rates, manure is transported to neighbouring NCUs. For NCUs with either net manure import or export, "N excretion" is thus not an accurate representation of the amount of manure leading to emissions: part of the N excreted might be exported and applied in another NCU, and conversely there might be manure that is applied in an NCU that has not been excreted in that NCU.

To solve this issue, in the back-calculations we can calculate an 'approximated' excretion per NCU, that is equal to total manure application plus grazing in an NCU, plus N emissions from housing systems in that NCU; and this approximated N excretion can be used to calculate $fNH3em_{ex}$ according to:

$$N_{ex(approx)} = N_{am} + Nem_{hous} \quad \text{(A3.3.1)}$$

$$N_{ex(approx)} = N_{am} + N_{trans} \quad \text{(A3.3.2)}$$

$$fNH3em_{ex} = \frac{NH3em_{hous} + NH3em_{am}}{N_{ex(approx)}} \quad \text{(A3.3.3)}$$

Where:

$N_{ex(approx)}$	= approximation of N excretion, accounting for manure (kg N ha^{-1} yr^{-1})
N_{am}	= manure applied to soil + excreted by grazing animals in an NCU (kg N ha^{-1} yr^{-1})
N_{trans}	= net manure transport (negative for export, positive for import) (kg N ha^{-1} yr^{-1})
Nem_{hous}	= N emissions from housing and manure storage systems in an NCU (kg N ha^{-1} yr^{-1})
$NH3em_{hous}$	= NH_3 emissions from housing and manure storage systems (kg N ha^{-1} yr^{-1})
$NH3em_{am}$	= NH_3 emissions from manure application + grazing (kg N ha^{-1} yr^{-1})

$N_{ex(approx)}$ will be lower than the true N excretion in NCUs with net manure export, and higher than the true N excretion in NCUs with net manure import. This implies that if we calculate $fNH3em_{ex}$ per NCU with Equation (A 3.3.3), it will be higher than the true $fNH3em_{ex}$ in NCUs with net manure export, and lower than the true $fNH3em_{ex}$ in NCUs with net manure import. Table A3.3.1 shows the differences between the $fNH3em_{ex}$ calculated at NCU level with Eq. (A 3.3.3) (and then aggregated to country level by taking the area-weighted average), and the actual $fNH3em_{ex}$ used in the back-calculations (calculated as total NH_3 emissions from excretion per country divided by total N excretion per country).

Figure A3.3.1 shows frequency distributions of $fNH3em_{ex}$ calcualted with Eq. (A 3.3.3) for the EU25 and for a selection of countries. The actual $fNH3em_{ex}$ used in the back-calculations is shown in these figures as a red line. Results show that the $fNH3em_{ex}$ calculated at NCU level differs mostly less than 10% from the $fNH3em_{ex}$ used in the back-calculations at country-level (Table A3.3.1), but at NCU level the differences can be up to a factor four (Figure A3.3.1).

Table A3.3.1 *fNH3emex calculated in two different ways, and relative difference between the two fractions.*

Country	$fNH3em_{ex}$ (@ NCU level)	$fNH3em_{ex}$ (@ country level)	Difference
AT	0.33	0.28	-15%
BE	0.28	0.26	-7%
BG	0.32	0.30	-8%
CZ	0.28	0.26	-6%
DE	0.28	0.26	-9%
DK	0.23	0.22	-4%
EE	0.32	0.30	-8%
ES	0.30	0.26	-11%
FI	0.29	0.27	-9%
FR	0.32	0.28	-13%
GR	0.37	0.30	-20%
HU	0.29	0.27	-8%
IE	0.45	0.29	-36%
IT	0.40	0.36	-9%
LT	0.34	0.31	-11%
LU	0.29	0.30	1%
LV	0.30	0.28	-6%
NL	0.30	0.24	-19%
PL	0.31	0.28	-10%
PT	0.30	0.27	-9%
RO	0.33	0.30	-9%
SE	0.28	0.26	-7%
SI	0.37	0.36	-3%
SK	0.31	0.26	-15%
UK	0.39	0.33	-15%

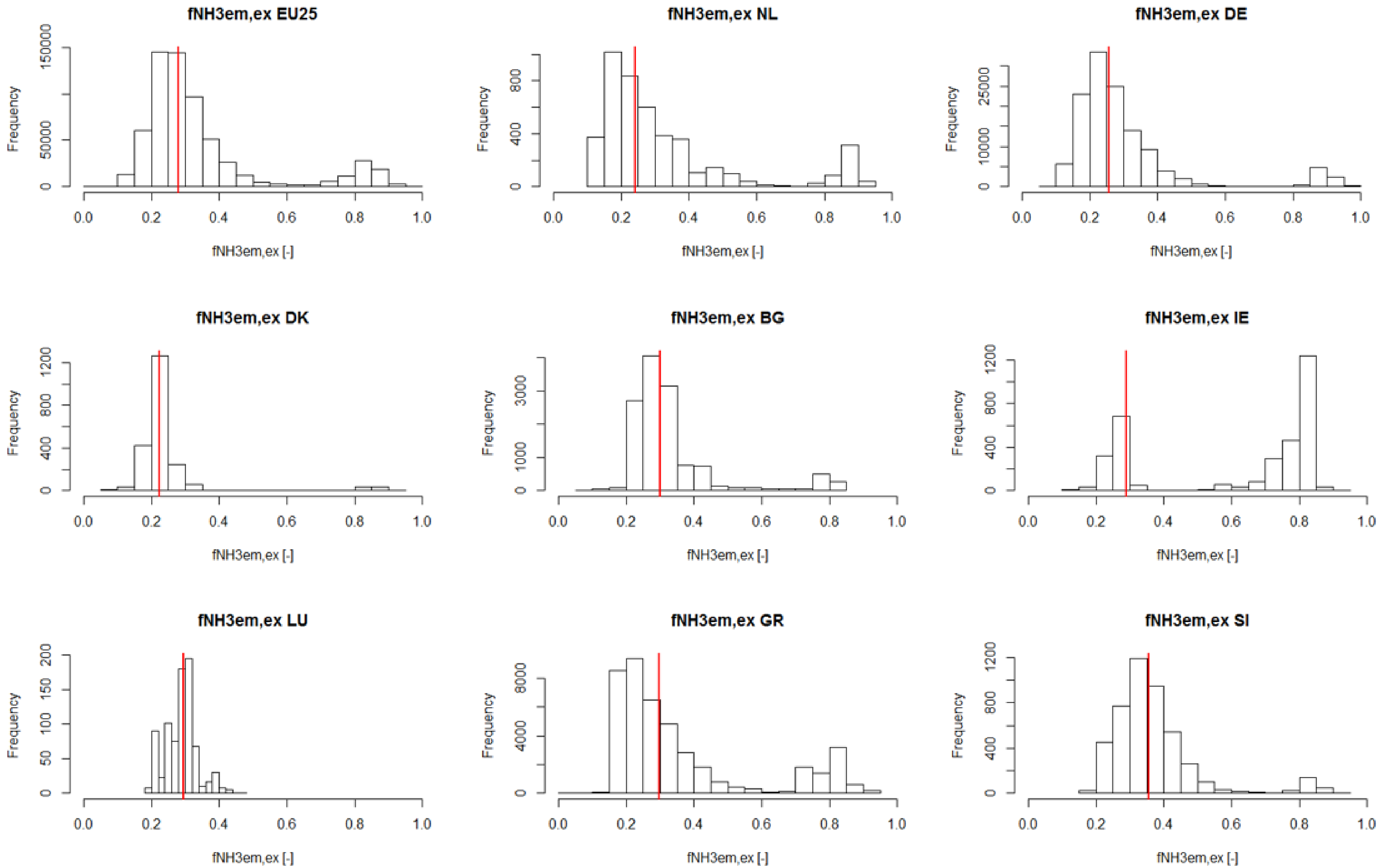

Figure A3.3.1 *Histograms showing frequency distributino of fNH3em$_{ex}$ calculated for each crop/NCU with Eq. (2) for selected countries and EU25. Red line shows country-level fNH3em$_{ex}$ used in the back-calculations.*

Annex 4 Actual, required and critical N inputs for different crop types, N input types and soil types

A4.1 Actual, required and critical N inputs for different crop types at EU level

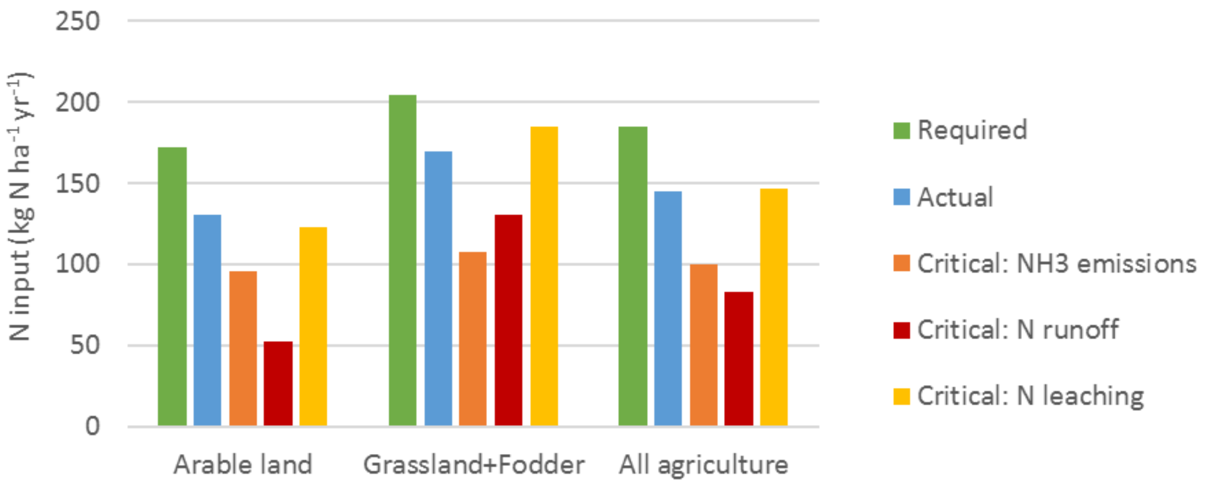

Figure A4.1.1 *Average required, actual and critical N inputs for arable land, grassland + fodder and all agriculture for EU-27.*

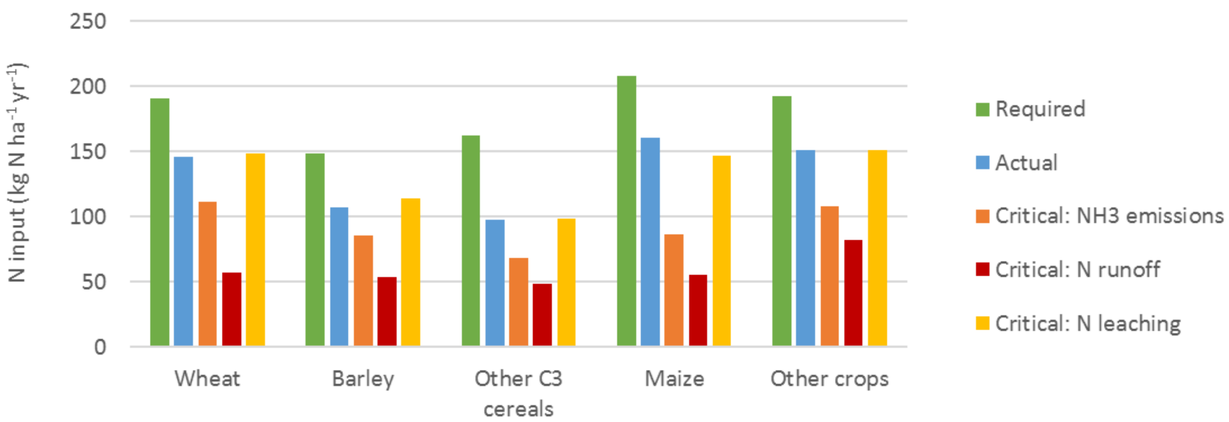

Figure A4.1.2 *Average required, actual and critical N inputs for wheat, barley, other C3 cereals, maize, and other crops for EU-27. Other C3 cereals includes rye, oats, rice and other cereals. Other crops includes all INTEGRATOR crops except the categories mentioned separately, and grassland.*

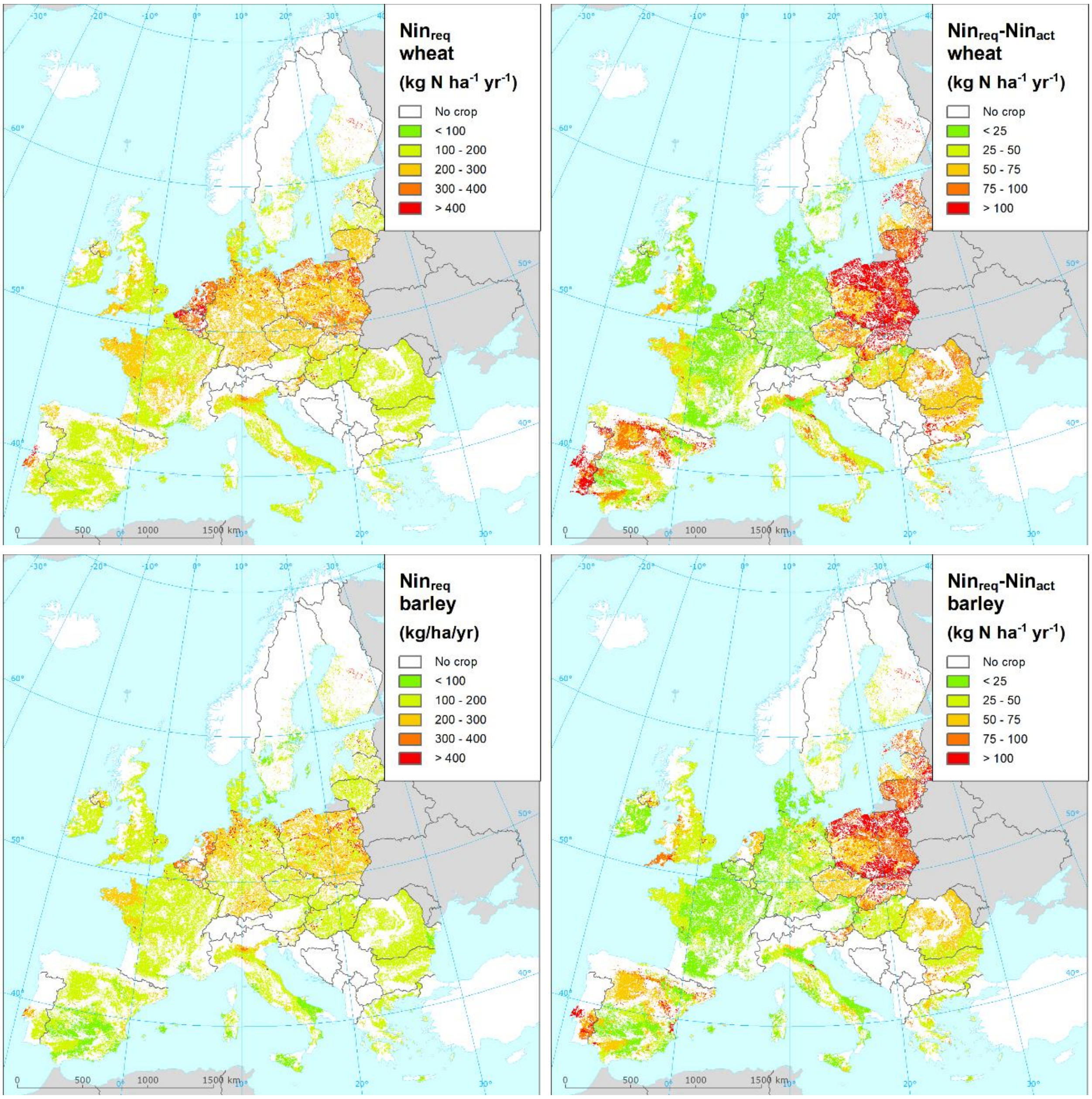

Figure A4.1.3 *Maps of the spatial variation in required N inputs (left) and required increase in N inputs (required N inputs minus actual N inputs, right) for wheat (top) and barley (bottom).*

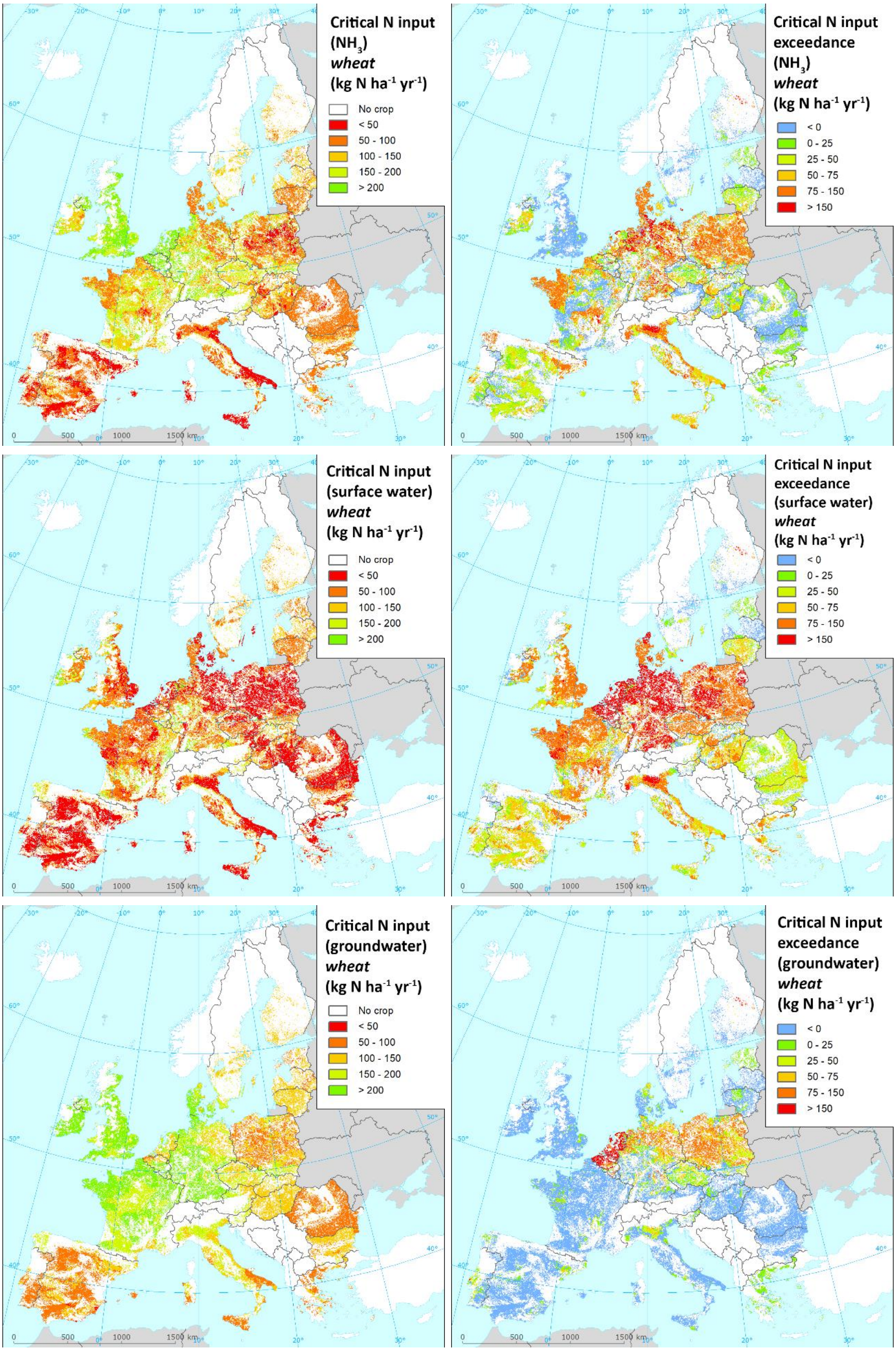

Figure A4.1.4 *Maps of the spatial variation in critical inputs (left) in view of critical NH_3 emissions (top), critical N runoff to surface water (middle) and critical N leaching to groundwater (bottom), and exceedance of actual N inputs by critical N inputs (right) for wheat.*

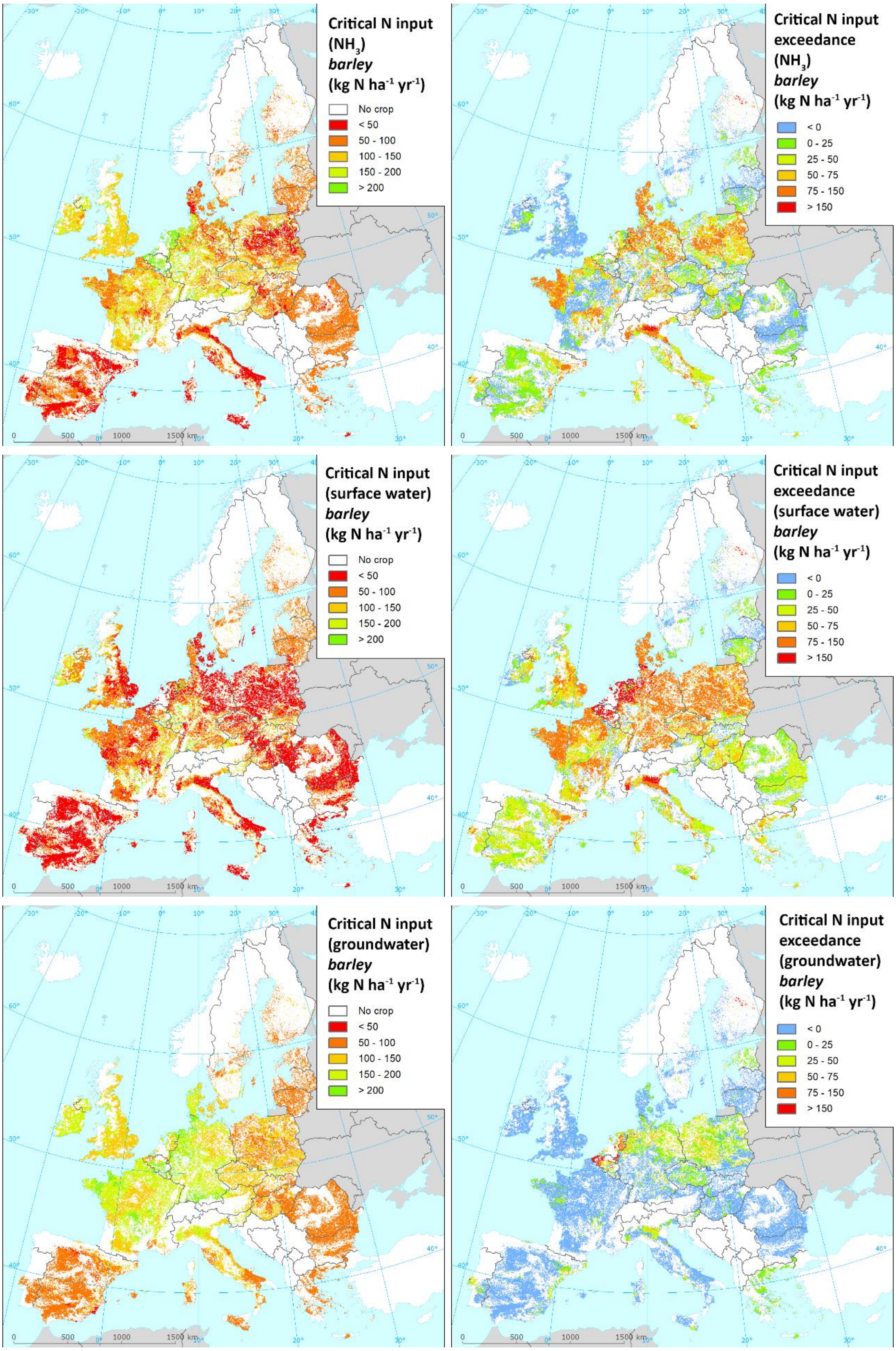

Figure A4.1.5 *Maps of the spatial variation in critical inputs (left) in view of critical NH_3 emissions (top), critical N runoff to surface water (middle) and critical N leaching to groundwater (bottom), and exceedance of actual N inputs by critical N inputs (right) for barley.*

A4.2 Critical N inputs from fertilizer and fixation and from manure and biosolids at NUTS level

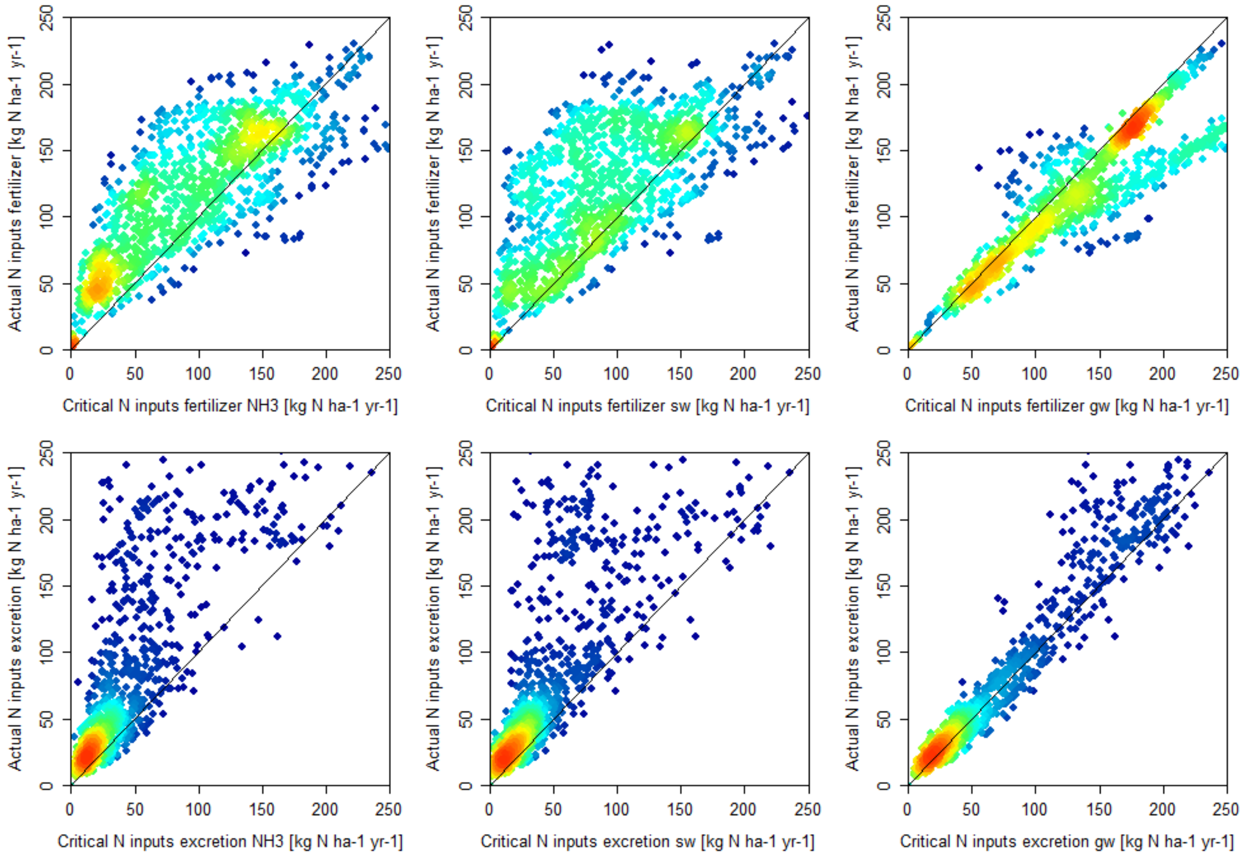

Figure A4.2.1 *Top row: The relationship between actual N inputs and critical N inputs from fertilizer and fixation in view of critical NH_3 emissions (left), critical N runoff to surface water (middle) and critical N leaching to groundwater (right). Bottom row: The relationship between actual N inputs from and critical N inputs from manure and biosolids in view of critical NH_3 emissions (left), critical N runoff to surface water (middle) and critical N leaching to groundwater (right). Colours refer to point density.*

A4.3 Actual and critical N losses and N inputs for different soil types

Soil N losses depend on (i) the fraction of the added N that is taken up by the crop, called the N use efficiency (NUE, defined here as N removal in harvested crops, divided by the sum of N inputs) and (ii) how much of the N surplus goes to air and to water, which is affected by the occurrence of denitrification. Both uptake and denitrification are affected by soils. For example, NUE is generally higher in more fertile soils, such as clay soils and there is also more denitrification (N loss to the atmosphere, mainly as N_2), and thus less nitrate leaching in those soils than in sandy soils, and even more so for peat soils. The importance of soil type on N budgets is illustrated Table A4.3.1.

Table A4.3.1 *Average current (2010) N budgets for sandy soils, clay soils, peat soils and all soils in agricultural land in EU-27.*

Source	**N budget EU-27 (kg N ha^{-1} yr^{-1})**			
	Sandy soils	**Clay soils**	**Peat soils**	**All soils**
Input to land				
Fertilizer +fixation	79.4	78.4	52.9	78.3
Excretion+ biosolids	68.2	52.6	97.9	55.7
N deposition	12.0	10.2	13.2	10.5
N mineralisation	0.0	0.0	92.2	0.9[1]
Total input	**159.6**	**141.2**	**256.2**	***145.4***
Output from land				
Crop N removal	96.7	90.8	140.1	92.3
N surplus	62.9	50.3	116.1	53.1
N emission (NH_3, N_2O, NO_x)	22.5	18.2	29.0	19.2
Denitrification	14.4	17.3	78.1	17.4
Runoff to surface water	5.2	8.4	6.0	7.8
Leaching to groundwater	20.7	6.3	2.9	8.7
Total output	**159.4**	**141.0**	**256.1**	***145.4***
NUE	0.61	0.64	0.55	0.63
N loss fraction	0.16	0.10	0.03	0.11

Average EU-27 current (2010) N budgets for major soil types show that the NUEs decrease going from clay soils (0.64) to sandy soils (0.61) to peat soils (0.55) whereas the denitrification fractions (denitrification/N surplus) increase going from sandy soils (0.23) to clay soils (0.34) to peat soils (0.67). On average the fraction of incoming N that is lost to water ((N runoff + N leaching)/N input) thus decreases from sandy soils (0.16) to clay soils (0.10) to peat soils (0.03). Soil types not only affect the calculated actual NH_3-N emissions, N runoff to surface water and N leaching to groundwater but also the critical N losses and the related N inputs for different soil types below arable land and grassland, as illustrated in Table A4.3.2, Table A4.3.3 and Table A4.3.4, respectively.

Table A4.3.2 *Average actual and critical NH_3-N emissions and average actual N inputs and critical N inputs in relation to critical N deposition for different soil types and land uses in EU-27 as calculated by INTEGRATOR.*

Land use	**Soil type**	**NH_3-N emissions (kg N ha^{-1} yr^{-1})**			**N inputs (kg N ha^{-1} yr^{-1})**		
		Actual	**Critical**	**Exceedance**	**Actual**	**Critical**	**Exceedance**
Arable land	Sand	18.3	9.7	8.6	146.7	95.1	51.6
	Clay	12.7	7.2	5.4	126.6	95.0	31.5
	Peat	14.0	12.8	1.2	203.3	204.0	-0.7
	All	13.6	7.7	5.9	130.2	95.6	34.6
Grassland + fodder	Sand	23.3	12.9	10.5	178.7	111.3	67.4
	Clay	19.0	10.9	8.1	164.9	104.5	60.4
	Peat	24.5	21.7	2.8	279.7	242.4	37.4
	All	19.9	11.4	8.5	169.3	108.0	61.3

Table A4.3.3 *Average actual and critical N runoff to surface water and average actual N inputs and critical N inputs in relation to a critical N concentration in surface water for different soil types and land uses in EU-27 as calculated by INTEGRATOR.*

Land use	Soil type	N runoff to surface water (kg N ha^{-1} yr^{-1})			N inputs (kg N ha^{-1} yr^{-1})		
		Actual	Critical	Exceedance	Actual	Critical	Exceedance
Arable land	Sand	18.3	5.8	12.5	146.7	47.5	99.2
	Clay	12.7	4.8	7.9	126.6	52.9	73.7
	Peat	14.0	11.6	2.4	203.3	160.0	43.3
	All	13.6	5.0	8.6	130.2	52.5	77.7
Grassland + fodder	Sand	23.3	13.3	10.0	178.7	115.1	63.6
	Clay	19.0	14.0	5.0	164.9	131.1	33.7
	Peat	24.5	26.3	-1.9	279.7	269.9	9.8
	All	19.9	14.1	5.7	169.3	130.7	38.6

Table A4.3.4 *Average actual and critical N leaching to groundwater and average actual N inputs and critical N inputs in relation to critical N concentration in groundwater for different soil types and land uses in EU-27 as calculated by INTEGRATOR.*

Land use	Soil type	N leaching to groundwater (kg N ha^{-1} yr^{-1})			N inputs (kg N ha^{-1} yr^{-1})		
		Actual	Critical	Exceedance	Actual	Critical	Exceedance
Arable land	Sand	18.3	13.4	4.8	146.7	111.6	35.1
	Clay	12.7	11.2	1.5	126.6	125.1	1.4
	Peat	14.0	15.2	-1.2	203.3	202.5	-15.0
	All	13.6	11.6	2.0	130.2	123.3	6.9
Grassland + fodder	Sand	23.3	20.7	2.6	178.7	172.9	5.8
	Clay	19.0	19.8	-0.8	164.9	184.6	-19.7
	Peat	24.5	39.6	-15.2	279.7	313.6	-36.6
	All	19.9	20.3	-0.4	169.3	184.7	-15.5

The much lower actual N inputs on peatland are caused by the high N mineralization rate, thus requiring much less external N inputs, while the high critical N inputs reflect the high denitrification rates of those soils. The higher N inputs on sandy soils than clay soils mainly reflect differences in livestock in different regions, whereas the lower critical N inputs for surface water are mainly due to the lower denitrification of sandy soils as compared to clay soils. The extreme differences for peat soils, when using a ground-or surface water limit as criterion, are due to the fact that net N mineralization is included in the assessment of actual N inputs, whereas this is excluded in the critical N load calculation. This implies the need for extra N also considering that these limits allow high N inputs due to high denitrification in peat soils.

Annex 5 Actual, required and critical nitrogen fluxes at country level

A5.1 Actual and required nitrogen inputs

Table A5.1.1 *Comparison of actual and required N inputs, and the required increase in N inputs (required N inputs minus actual N inputs).*

Country	Area (ha)[1]	Actual N inputs (kg N ha^{-1} yr^{-1})	Required N inputs (kg N ha^{-1} yr^{-1})	Required increase in N inputs (kg N ha^{-1} yr^{-1})	Actual N inputs (kton N yr^{-1})	Required N inputs (kton N yr^{-1})	Required increase in N inputs (kton t N yr^{-1})
AT	2,319,087	140.3	161.4	21.0	325	374	49
BE	1,349,440	319.1	416.0	97.0	431	561	131
BG	3,852,681	78.8	122.7	43.8	304	473	169
CZ	3,463,196	134.5	181.0	46.5	466	627	161
DE	15,991,378	214.2	226.6	12.4	3,426	3,623	198
DK	2,548,283	177.9	187.2	9.3	453	477	24
EE	792,093	90.3	162.7	72.4	72	129	57
ES	18,434,892	94.3	131.2	36.9	1,738	2,418	680
FI	2,267,955	104.0	165.1	61.1	236	374	138
FR	25,581,899	168.0	196.5	28.5	4,299	5,028	729
GR	2,985,753	105.9	137.3	31.4	316	410	94
HU	3,882,804	121.2	155.9	34.7	470	605	135
IE	4,130,084	231.2	280.3	49.1	955	1,158	203
IT	11,587,084	131.8	153.8	22.0	1,527	1,782	255
LT	2,651,040	98.5	170.8	72.4	261	453	192
LU	130,828	210.5	243.8	33.3	28	32	4
LV	1,259,661	71.5	124.0	52.5	90	156	66
NL	1,806,706	384.9	404.6	19.7	695	731	36
PL	13,295,103	140.6	227.9	87.3	1,869	3,031	1,161
PT	2,207,999	87.6	179.4	91.8	193	396	203
RO	12,383,567	72.9	119.4	46.5	903	1,478	575
SE	3,020,683	107.8	136.5	28.7	326	412	87
SI	426,808	160.9	274.1	113.3	69	117	48
SK	1,800,394	106.4	165.8	59.4	192	298	107
UK	11,812,888	181.9	220.4	38.5	2,149	2,603	454
EU25	**149,982,307**	**145.3**	**185.0**	**39.7**	**21,791**	**27,747**	**5,956**

A5.2 Actual and critical nitrogen losses, surpluses and inputs

Actual and critical nitrogen losses

Table A5.2.1 *Comparison of actual N losses with critical N losses and the exceedance of critical losses by actual losses for (i) critical NH_3 emissions in view of critical N deposition, (ii) critical N runoff to surface water in view of critical N concentration in surface water, (iii) critical leaching to groundwater in view of a critical N concentration in groundwater.*

Country	Area (ha)[1]	NH_3 emissions[1] (kg N ha^{-1} yr^{-1})			N runoff to surface water[2] (kg N ha^{-1} yr^{-1})			N leaching to groundwater[3] (kg N ha^{-1} yr^{-1})		
		Actual	Critical	Exceedance (%)	Actual	Critical	Exceedance (%)	Actual	Critical	Exceedance (%)
AT	2,319,087	16.0	11.1	30%	8.5	6.3	25%	6.7	6.9	-2%
BE	1,349,440	40.9	26.9	34%	23.0	6.7	71%	30.5	17.0	44%
BG	3,852,681	5.9	4.9	18%	6.9	4.2	39%	2.2	2.4	-6%
CZ	3,463,196	11.2	9.3	17%	10.8	4.6	57%	11.1	9.3	16%
DE	15,991,378	23.1	13.9	40%	10.7	4.5	57%	13.6	10.7	21%
DK	2,548,283	20.4	7.0	66%	6.3	2.1	66%	18.4	17.6	4%
EE	792,093	7.9	8.5	-7%	4.7	4.7	1%	6.8	6.5	4%
ES	18,434,892	10.5	5.6	46%	4.1	2.2	45%	2.7	2.4	13%
FI	2,267,955	8.1	5.6	31%	5.1	4.9	5%	5.2	5.4	-3%
FR	25,581,899	17.2	10.3	40%	9.7	5.0	48%	7.6	7.0	8%
GR	2,985,753	10.4	4.0	61%	7.6	4.1	46%	4.2	3.4	20%
HU	3,882,804	11.7	7.3	38%	9.1	4.3	53%	4.6	4.3	7%
IE	4,130,084	25.2	6.5	74%	5.2	4.2	20%	6.1	6.9	-13%
IT	11,587,084	22.9	8.7	62%	7.5	3.7	50%	10.2	7.3	28%
LT	2,651,040	11.0	9.8	11%	4.8	3.4	30%	8.7	7.9	9%
LU	130,828	24.3	10.8	56%	10.6	7.1	32%	4.8	5.0	-4%
LV	1,259,661	7.7	11.4	-48%	3.0	3.9	-30%	4.5	5.3	-20%
NL	1,806,706	50.7	18.2	64%	16.3	4.0	76%	43.3	22.2	49%
PL	13,295,103	17.3	10.4	40%	10.0	3.3	67%	18.4	12.0	35%
PT	2,207,999	11.8	7.0	41%	4.9	3.9	21%	5.4	4.5	17%
RO	12,383,567	7.5	5.3	30%	5.7	3.3	42%	2.9	2.8	1%
SE	3,020,683	8.5	6.6	22%	4.0	4.6	-13%	3.0	3.6	-19%
SI	426,808	28.1	14.5	48%	8.1	7.2	11%	4.5	4.3	3%
SK	1,800,394	10.4	8.3	21%	8.1	4.9	40%	6.9	6.4	8%
UK	11,812,888	15.8	10.6	33%	6.5	3.8	42%	6.2	6.1	2%
EU25	**149,982,307**	16.0	9.1	43%	7.8	4.0	49%	8.7	7.0	20%

1 NH_3-N emissions that correspond to the area-averaged critical N-load on nature.

2 Critical N surface plus sub-surface runoff based on a critical concentration in runoff to surface water of 2.5 mg N l-1.

3 Critical N leaching to groundwater based on a critical concentration in leached water of 11.6 mg N l-1.

Table A5.2.2 *Total actual NH_3 emissions, critical NH_3 emissions based on critical deposition, exceedance of actual NH_3 emissions by critical NH_3 emissions, critical NH_3 emission after cutoff at Nup,max and exceedance of actual NH_3 emissions by critical NH_3 emissions after cutoff.*

			NH_3 emissions (kton N yr^{-1})		
Country	**Actual**	**Critical (before cut-off at Nup,max)**	**Exceedance (before cut-off at Nup,max)**	**Critical (after cut-off at Nup,max)**	**Exceedance (after cut-off at Nup,max)**
AT	37.1	54.8	-17.6 (-48%)	25.8	11.3 (30%)
BE	55.2	49.1	6.1 (11%)	36.3	18.9 (34%)
BG	22.9	27.0	-4.1 (-18%)	18.7	4.2 (18%)
CZ	38.7	39.8	-1.1 (-3%)	32.2	6.5 (17%)
DE	368.7	259.6	109.1 (30%)	222.3	146.4 (40%)
DK	52.0	18.1	33.9 (65%)	17.9	34.2 (66%)
EE	6.3	19.3	-13.1 (-209%)	6.7	-0.4 (-7%)
ES	192.7	139.5	53.2 (28%)	103.4	89.2 (46%)
FI	18.3	51.8	-33.5 (-183%)	12.6	5.7 (31%)
FR	439.4	329.7	109.7 (25%)	262.7	176.7 (40%)
GR	31.0	26.3	4.7 (15%)	12.1	18.9 (61%)
HU	45.5	33.8	11.6 (26%)	28.3	17.2 (38%)
IE	103.9	30.7	73.2 (70%)	26.9	77 (74%)
IT	265.4	144.9	120.5 (45%)	100.3	165.1 (62%)
LT	29.1	29.3	-0.2 (-1%)	25.9	3.3 (11%)
LU	3.2	1.8	1.4 (43%)	1.4	1.8 (56%)
LV	9.7	27.4	-17.7 (-182%)	14.4	-4.7 (-48%)
NL	91.7	36.5	55.2 (60%)	32.8	58.8 (64%)
PL	230.5	155.7	74.7 (32%)	138.5	92 (40%)
PT	26.1	26.6	-0.4 (-2%)	15.5	10.6 (41%)
RO	92.7	87.0	5.8 (6%)	65.1	27.7 (30%)
SE	25.8	50.1	-24.3 (-94%)	20.1	5.7 (22%)
SI	12.0	10.3	1.7 (14%)	6.2	5.8 (48%)
SK	18.8	21.5	-2.8 (-15%)	14.9	3.9 (21%)
UK	186.4	182.0	4.4 (2%)	124.7	61.7 (33%)
EU25	2402.8	1852.4	550.4 (23%)	1365.6	1037.3 (43%)

Actual and critical nitrogen soil surpluses

Table A5.2.3 *Actual N soil surplus and critical N soil surplus (all agricultural land) in view of critical NH_3 emissions, critical surface + sub-surface runoff to surface water and critical leaching to groundwater, and exceedances of critical N soil surpluses by actual N soil surpluses. A negative exceedance thus indicates that critical surpluses are larger than actual N surpluses. N soil surplus is defined as N inputs minus N offtake, N emissions and N surface runoff.*

Country	Area (ha)[1]	N surplus (kg N ha^{-1} yr^{-1})				Exceedance (kg N ha^{-1} yr^{-1})					
		Actual	Critical - NH_3	Critical – Surface water	Critical – Ground-water	NH_3		Surface water		Groundwater	
AT	2,319,087	29.3	29.8	19.1	29.9	-8.1	(-2%)	10.2	(35%)	-0.5	(-2%)
BE	1,349,440	102.4	86.9	29.4	65.5	-16.6	(15%)	73.0	(71%)	36.8	(36%)
BG	3,852,681	20.9	15.8	11.6	21.1	-1.0	(24%)	9.3	(45%)	-0.3	(-1%)
CZ	3,463,196	38.4	28.6	15.5	32.7	0.3	(25%)	23.0	(60%)	5.7	(15%)
DE	15,991,378	43.3	25.0	16.8	36.7	0.1	(42%)	26.5	(61%)	6.6	(15%)
DK	2,548,283	34.0	13.4	10.2	32.6	7.1	(61%)	23.8	(70%)	1.4	(4%)
EE	792,093	24.0	23.5	22.4	23.4	-5.8	(2%)	1.6	(7%)	0.7	(3%)
ES	18,434,892	21.4	12.4	9.1	18.5	2.2	(42%)	12.2	(57%)	2.8	(13%)
FI	2,267,955	17.1	16.1	15.7	17.8	-6.0	(6%)	1.4	(8%)	-0.7	(-4%)
FR	25,581,899	31.6	21.5	13.8	29.4	3.2	(32%)	17.8	(56%)	2.2	(7%)
GR	2,985,753	30.9	21.8	12.6	24.6	0.6	(30%)	18.3	(59%)	6.4	(21%)
HU	3,882,804	28.1	19.7	11.9	26.6	0.8	(30%)	16.2	(58%)	1.5	(5%)
IE	4,130,084	19.8	7.0	14.4	22.2	0.6	(65%)	5.4	(27%)	-2.4	(-12%)
IT	11,587,084	31.3	16.6	10.9	24.3	2.7	(47%)	20.5	(65%)	7.0	(22%)
LT	2,651,040	22.4	15.4	14.0	20.6	3.2	(31%)	8.4	(38%)	1.8	(8%)
LU	130,828	29.0	16.0	17.4	29.8	5.8	(45%)	11.6	(40%)	-0.8	(-3%)
LV	1,259,661	12.0	13.1	13.3	14.1	-4.9	(-9%)	-1.3	(-11%)	-2.1	(-18%)
NL	1,806,706	110.6	66.4	28.0	69.0	8.3	(40%)	82.6	(75%)	41.6	(38%)
PL	13,295,103	52.8	28.0	15.6	36.8	8.9	(47%)	37.2	(70%)	16.0	(30%)
PT	2,207,999	23.1	15.6	14.2	19.1	-1.0	(33%)	8.9	(39%)	4.0	(17%)
RO	12,383,567	19.1	15.0	9.7	18.6	-0.7	(22%)	9.4	(49%)	0.5	(3%)
SE	3,020,683	10.3	9.8	8.4	12.1	-6.1	(4%)	1.9	(18%)	-1.8	(-18%)
SI	426,808	21.5	13.4	17.4	20.6	-5.5	(38%)	4.1	(19%)	0.9	(4%)
SK	1,800,394	26.1	14.5	12.6	24.0	7.2	(44%)	13.5	(52%)	2.1	(8%)
UK	11,812,888	21.8	21.0	10.3	21.5	-8.3	(3%)	11.4	(53%)	0.3	(1%)
EU25	**149,982,307**	**31.4**	**20.4**	**13.1**	**26.9**	**0.9**	**(35%)**	**18.4**	**(58%)**	**4.6**	**(15%)**

Actual and critical nitrogen inputs

Table A5.2.4 *Actual N inputs and critical N inputs for all agricultural land in view of critical NH_3 emissions, critical runoff to surface water and critical leaching to groundwater, and exceedances of critical N inputs by actual N inputs. A negative exceedance thus indicates that critical inputs are larger than actual N inputs.*

Country	N inputs (kg N ha^{-1} yr^{-1})				Difference critical/actual inputs (in kg N ha^{-1} yr^{-1}, % in brackets shows difference relative to actual inputs)					
	Actual	Critical - NH_3	Critical – Surface water	Critical – Ground water	NH_3		Surface water		Groundwater	
Austria	140	146	110	160	5	(+4%)	-30	(-22%)	20	(+14%)
Belgium	319	272	109	220	-47	(-15%)	-210	(-66%)	-99	(-31%)
Bulgaria	79	69	48	88	-10	(-12%)	-31	(-39%)	10	(+12%)
Czech Republic	135	105	62	122	-29	(-22%)	-73	(-54%)	-12	(-9%)
Germany	214	131	104	197	-83	(-39%)	-110	(-51%)	-18	(-8%)
Denmark	178	73	69	187	-105	(-59%)	-109	(-61%)	9	(+5%)
Estonia	90	91	89	91	1	(+1%)	-2	(-2%)	1	(+1%)
Spain	94	55	51	93	-39	(-42%)	-43	(-46%)	-2	(-2%)
Finland	104	106	108	120	2	(+2%)	4	(+4%)	16	(+15%)
France	168	122	98	190	-47	(-28%)	-70	(-42%)	22	(+13%)
Greece	106	74	43	87	-32	(-31%)	-63	(-60%)	-19	(-18%)
Hungary	121	86	58	121	-35	(-29%)	-63	(-52%)	0	(0%)
Ireland	231	94	210	274	-137	(-59%)	-21	(-9%)	43	(+19%)
Italy	132	65	62	124	-67	(-51%)	-70	(-53%)	-7	(-6%)
Lithuania	98	73	76	102	-25	(-26%)	-22	(-22%)	4	(+4%)
Luxemburg	210	137	162	223	-73	(-35%)	-49	(-23%)	12	(+6%)
Latvia	72	90	91	95	18	(+25%)	20	(+27%)	24	(+33%)
Netherlands	385	209	101	259	-176	(-46%)	-284	(-74%)	-126	(-33%)
Poland	141	77	47	106	-64	(-45%)	-93	(-66%)	-34	(-24%)
Portugal	88	66	61	79	-21	(-24%)	-26	(-30%)	-9	(-10%)
Romania	73	63	43	78	-9	(-13%)	-30	(-41%)	5	(+6%)
Sweden	108	121	121	169	13	(+12%)	13	(+13%)	61	(+57%)
Slovenia	161	118	149	162	-42	(-26%)	-12	(-7%)	1	(+1%)
Slovakia	106	67	61	108	-39	(-37%)	-46	(-43%)	1	(+1%)
United Kingdom	182	177	145	218	-5	(-2%)	-37	(-20%)	36	(+20%)
EU25	145	100	83	147	-45	**(-31%)**	-63	**(-43%)**	2	**(+1%)**

Table A5.2.5 *Total actual N inputs (2010) and critical N inputs in view of thresholds for NH_3 emissions, N runoff to surface water and N leaching to groundwater, per country, for all agricultural land.*

Country	**N inputs (kton N yr^{-1})**			
	Actual	**Critical - NH_3**	**Critical – Surface water**	**Critical – Groundwater**
Austria	325	338	255	371
Belgium	431	366	147	297
Bulgaria	304	267	185	341
Czech Republic	466	365	214	423
Germany	3,426	2,096	1,664	3,143
Denmark	453	185	175	476
Estonia	72	72	70	72
Spain	1,738	1,016	941	1,708
Finland	236	241	246	272
France	4,299	3,109	2,500	4,869
Greece	316	220	128	259
Hungary	470	336	227	471
Ireland	955	389	869	1,132
Italy	1,527	756	715	1,440
Lithuania	261	194	202	271
Luxemburg	28	18	21	29
Latvia	90	113	115	120
Netherlands	695	378	182	467
Poland	1,869	1,023	628	1,415
Portugal	193	146	136	174
Romania	903	786	535	961
Sweden	326	365	366	511
Slovenia	69	51	64	69
Slovakia	192	121	109	194
United Kingdom	2,149	2,096	1,715	2,578
EU25	**21,791**	**15,045**	**12,409**	**22,062**

Annex 6 Additional results on necessary NH_3 emission fractions and nitrogen use efficiencies

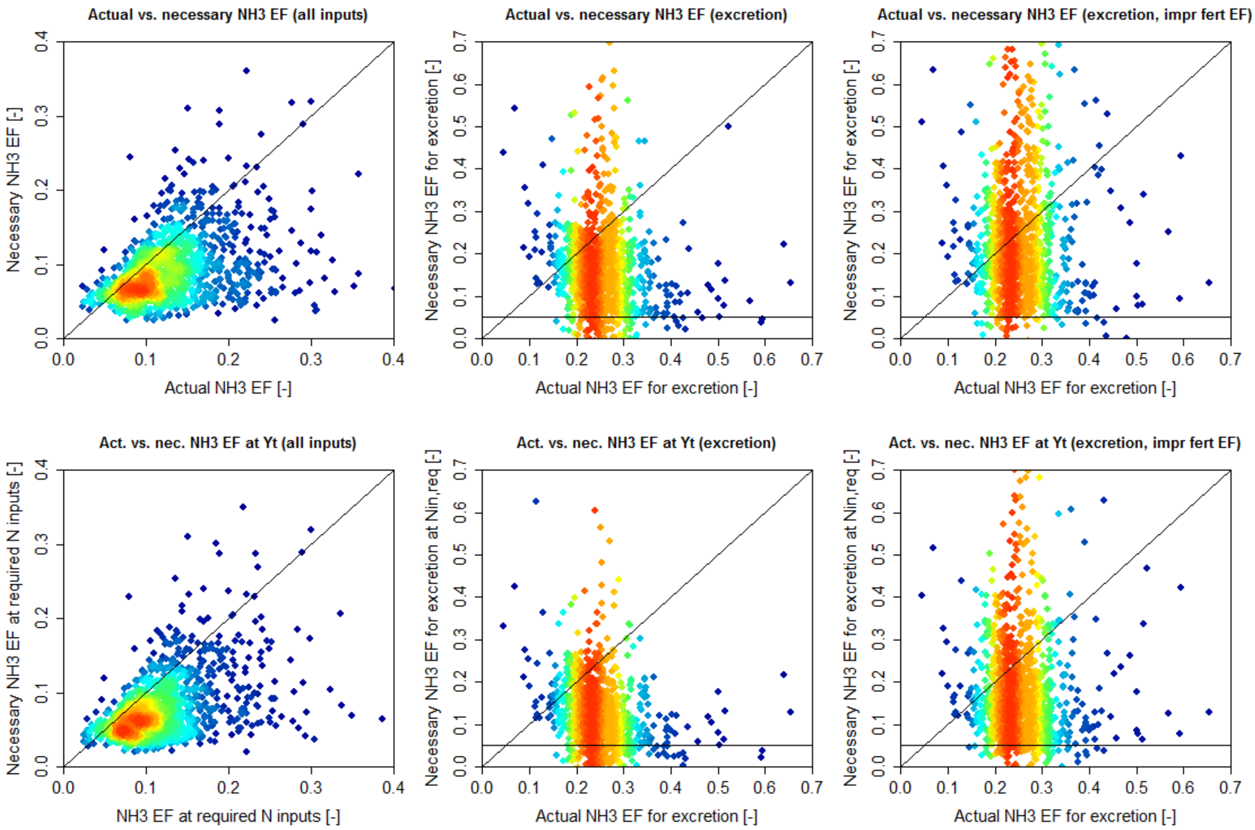

Figure A6.1 *Graphs showing the relationship between actual and necessary NH_3-N emission fractions for all agricultural land at actual crop yields (top) and target crop yield (bottom). Left: overall emission fraction for all N inputs; middle: necessary EF for excretion, assuming a constant EF for fertilizer application; right: necessary EF for excretion, assuming an improved EF for fertilizer application of 0.02. The solid line is the 1:1 line. The horizontal line in the middle and right figures shows the minimum emission fraction for excretion (0.05) that we assumed feasible.*

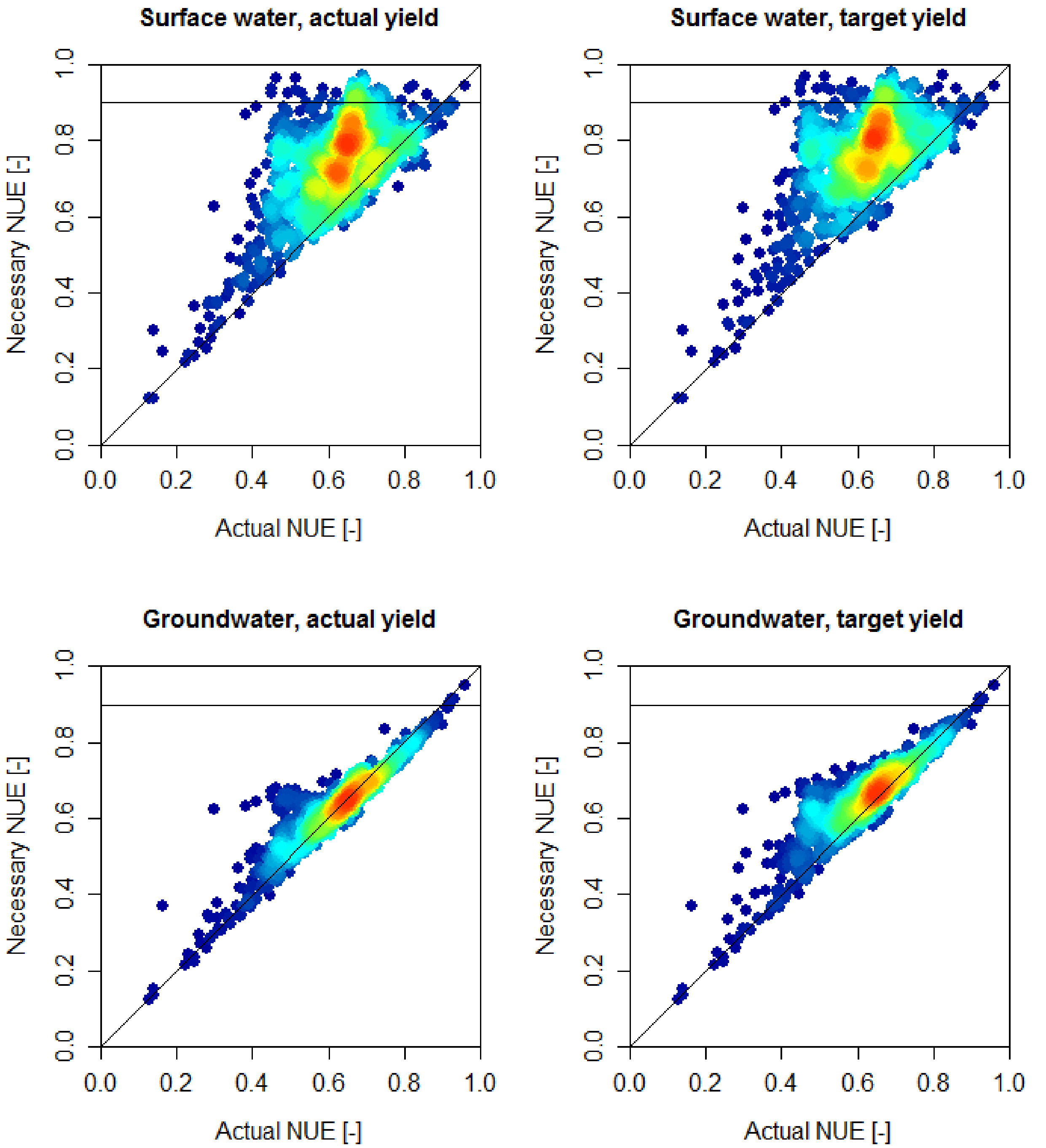

Figure A6.2 *Relationship between actual and necessary nitrogen use efficiencies to obtain actual yields (left) or target yields (right) without exceeding critical N runoff to surface water (top) and critical N leaching to groundwater (bottom). Solid lines indicate the 1:1 line and the maximum plausible value for necessary NUE (0.9).*

Table A6.1 *Share of agricultural land where it is possible to stay below critical N surface runoff / N leaching by increasing the NUE, considering a plausible maximum of 0.9, for (i) actual N input and (ii) required N input and for arable land (excl. fodder), fodder and grassland.*

	Surface water		**Groundwater**	
	Actual input	**Required input**	**Actual input**	**Required input**
ARABLE LAND EXCL FODDER				
Share of agricultural land where it is possible to stay below critical N losses by increasing NUE (max. = 0.85)	82%	72%	100%	100%
Current NUE	0.60	0.59	0.60	0.60
Necessary NUE	0.75	0.78	0.63	0.67
*... for **all** plots (cutting off NUE,nec at 0.9)*				
Current NUE	0.60	0.60	0.60	0.60
Necessary NUE	0.77	0.81	0.63	0.67
FODDER				
Share of agricultural land where it is possible to stay below critical N losses by increasing NUE (max. = 0.85)	61%	49%	88%	86%
Current NUE	0.78	0.76	0.79	0.79
Necessary NUE	0.82	0.84	0.81	0.82
*... for **all** plots (cutting off NUE,nec at 0.9)*				
Current NUE	0.63	0.63	0.63	0.63
Necessary NUE	0.75	0.78	0.65	0.67
GRASS				
Share of agricultural land where it is possible to stay below critical N losses by increasing NUE (max. = 0.85)	98%	97%	98%	98%
Current NUE	0.59	0.59	0.59	0.59
Necessary NUE	0.64	0.64	0.59	0.60
*... for **all** plots (cutting off NUE,nec at 0.9)*				
Current NUE	0.63	0.63	0.63	0.63
Necessary NUE	0.75	0.78	0.65	0.67

Wageningen Environmental Research
P.O. Box 47
6700 AA Wageningen
The Netherlands
T 0317 48 07 00
wur.eu/environmental-research

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Wageningen Environmental Research
P.O. Box 47
6700 AB Wageningen
The Netherlands
T +31 (0) 317 48 07 00
wur.eu/environmental-research

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