From planetary to regional nitrogen boundaries for targeted policy support

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Abstract

Excessive agricultural nitrogen (N) use causes serious environmental problems globally[1], to an extent that scientists have claimed that the safe planetary boundary has been exceeded[2]. Earlier estimates for the planetary N boundary[3,4], however, did not account for spatial variability in both ecosystems' sensitivity to nitrogen pollution and agricultural nitrogen losses. Here we used a spatially explicit model to establish regional boundaries for agricultural nitrogen surplus from thresholds for eutrophication of terrestrial and aquatic ecosystems and nitrate in groundwater. We show that regional boundaries for agricultural nitrogen pollution reveal both overuse and room for intensification. The aggregated global surplus boundary to respect all thresholds is 43 Mt N yr^{-1}, 64% lower than current (2010) nitrogen surplus (119 Mt N yr^{-1}). Allowing nitrogen surplus to increase to close yield gaps in regions where environmental thresholds are not exceeded lifts the planetary nitrogen boundary to 57 Mt N yr^{-1}. Feeding the world without trespassing regional and planetary nitrogen boundaries requires large increases in nitrogen use efficiencies accompanied by mitigation of non-agricultural nitrogen sources such as sewage water. This asks for coordinated action, recognizing the heterogeneity of agricultural systems, non-agricultural nitrogen losses, and environmental vulnerabilities.

Full Text

Nitrogen (N) is at the core of several Sustainable Development Goals related to both food security and a clean environment[5,6]. Food production depends on inputs of reactive N[7]. In order make N available for crop growth, it is 'fixed' from the atmosphere during fertilizer production and through biological fixation by leguminous crops, such as soybean[8]. With inherent inefficiencies in crop and livestock production, however, much of the reactive N inputs to food production are lost to the environment, resulting in multiple pollution threats, such as dead zones in coastal waters[9], harmful algal blooms[10], terrestrial and aquatic biodiversity loss[11–13], nitrate contamination of drinking water[14], air pollution[15], stratospheric ozone depletion, and climate change[16,17]. Therefore, intentional N fixation has been proposed as one of the control variables to monitor transgression of 'planetary boundaries'[3,18,19] for human disturbance of Earth System processes.

A planetary boundary for intentional N fixation (mainly N fixed for synthetic fertilizer production and by leguminous crops) has first been quantified by Rockström et al.[18] and later revised by Steffen et al.[3], who estimated that the safe limit is about half the current rate. This planetary N boundary has served as benchmark for many subsequent studies that assessed options to meet food demands within environmental limits under current conditions and future scenarios[20–26]. However, the usefulness of a planetary N boundary for evaluating regional problems such as N pollution has been questioned, due to the large spatial variation in N losses and related impacts[27–29]. Several studies have inferred N boundaries for countries and regions[30–34], generally by allocating an equal share of the planetary boundary to each global inhabitant. Planetary boundaries were, however, 'not designed to be downscaled or disaggregated'[3], and such approaches ignore regional differences in agricultural systems, soils and ecosystems that affect both N losses and resulting impacts.

Apart from a lack of spatial detail, the current approach to quantify the planetary N boundary[3,4] has several other limitations. First, it defined limits for 'intentional human N fixation', which does not account for regional impacts of N losses from *recycled* N sources, such as animal manure. Second, a boundary for N fixation requires assumptions on the N use efficiency (NUE), as a higher NUE allows for more N inputs while still remaining within environmental thresholds for N pollution. Third, previous boundary estimates only considered the reductions in N inputs required to respect environmental thresholds[4], ignoring possibilities for increases in N inputs where thresholds allow. The latter is crucial as low N inputs constrain yields in large parts of the world[35]. Fourth, the boundary focused on agricultural N fixation and failed to consider N pollution from other sources, such as NO_x emissions from traffic and industry and N discharge in wastewater. Fifth, boundaries were derived for several N-related impacts individually[4], while a safe limit should avoid all N-related problems *simultaneously*. Finally, the approach did not consider differences between crop and grazing systems, which require different approaches to relate N levels, pollution, and productivity.

Here we present a new approach for estimating regional and planetary boundaries for agricultural N surplus and N inputs. Agricultural N surplus (defined as total N input minus crop or grass N removal) is presented as the central indicator to define a planetary boundary, because it represents the total of all N losses from the agricultural system and is thus closely related to adverse impacts of N[36], which is why it is frequently used as an indicator to support policy making[37,38]. Unlike a boundary for N input, it is not sensitive to assumptions on NUE, and therefore several recent publications have identified N surplus as the preferred indicator for a planetary N boundary[2,21,26]. In addition, we also present boundaries for total agricultural N inputs (both 'new' inputs from fertilizer and biological fixation and 'recycled' inputs from manure and deposition) under current regional N use efficiencies.

Regional and planetary boundaries are derived based on spatially explicit environmental thresholds for (i) N deposition rates (to avoid or limit terrestrial biodiversity loss), (ii) N concentrations in surface water (to limit eutrophication) and (iii) N concentrations in groundwater (to meet the WHO drinking water standard). Nitrogen's contribution to climate change and stratospheric ozone depletion through N_2O emissions as well as health impacts of air pollution from NH_3 emissions were not considered (see Methods), but we quantify effects of meeting planetary boundaries for aforementioned thresholds on global N_2O emissions (Supplementary Discussion). We mapped where one or several of these thresholds are transgressed, and where N inputs and associated surplus can safely increase to close yield gaps. To this end, we configured the Integrated Model to Assess the Global Environment (IMAGE) – Global Nutrient Model (GNM)[39] to calculate 'critical' agricultural N inputs and surpluses (levels at which thresholds are reached) at a 0.5°x0.5° resolution for the year 2010.

Non-agricultural N pollution (e.g., NO_x emissions from transport and industry, N load to surface water from wastewater and erosion) was assumed constant. The critical N surplus in each grid cell thus depends on the sensitivity of the ecosystem (acceptable losses) and N loading caused by non-agricultural sources, while the critical N input is also determined by the regional NUE. Critical N surplus and inputs for each grid cell were aggregated to derive regional and planetary N boundaries. We also estimated to what extent regional and global food demand can be met while respecting N boundaries at either current or improved NUE, under varying assumptions regarding non-agricultural N losses and legacy N delivery.

Planetary nitrogen boundary

Reductions in agricultural N surplus required to respect thresholds for deposition, surface water quality and groundwater quality differ strongly (Fig. 1). In line with Steffen et al.[3], we find that surface water quality is the most stringent criterion, requiring the strongest reductions in global N surplus: from 119 to 92 Mt N yr^{-1} (boundary including possibilities for intensification in areas of no threshold exceedance; Fig. 1c). Respecting N surplus boundaries to avoid deposition rates that threaten terrestrial biodiversity requires a global reduction of 15% (to 101 Mt N yr^{-1}, Fig. 1b), whereas the N surplus boundary to avoid exceedance of health-impacting nitrate concentrations in groundwater (117 Mt N yr^{-1}, Fig. 1d) is close to the current surplus. However, whereas Steffen et al.[3] assumed that respecting the most restrictive threshold would also avoid other N impacts, our results show that respecting all thresholds *simultaneously* leads to a much lower boundary of 57 Mt N yr^{-1} (Fig. 1a).

Unlike the earlier estimates[3], our boundary estimates account for possibilities to increase N inputs in regions where thresholds are not transgressed (blue values in Fig. 1, whereas orange values show boundaries *not* accounting for intensification possibilities). In these regions, N inputs and associated surplus were increased up to the level needed to reach yield potentials at the current regional NUE (see Methods). For example, to respect all three N-related thresholds, N surplus needs to decrease by 77% (from 99 to 23 Mt N yr^{-1}) in regions where thresholds are exceeded, but can increase by 70% (from 20 to 34 Mt N yr^{-1}) in regions where thresholds are not exceeded (Fig. 1a). Allowing for intensification in regions with no threshold exceedance increases the global N boundaries by 32–62%, depending on the threshold considered.

At current NUE, the global N surplus boundary for all thresholds corresponds to a total global N input of 134 Mt N yr^{-1} (Fig. 2). Of these inputs, 65 Mt N yr^{-1} come from new N fixation (34 Mt N yr^{-1} from fertilizer and 31 Mt N yr^{-1} from biological fixation, Extended Data Fig. 1). For the surface water criterion, the global boundary for new N fixation is 106 Mt N yr^{-1} (Fig. 2), which is higher than the value of 62–82 Mt N yr^{-1} proposed by Steffen et al.[3] for a global boundary for new N fixation in view of surface water quality. However, if like Steffen et al. we do not account for the possibility to increase N inputs in regions with no threshold exceedance, our estimated global boundary for new N fixation (84 Mt N yr^{-1}, Fig. 2) is close to theirs.

For all thresholds, stronger reductions (in relative terms) are required for N surplus than for total N input (Fig. 2), highlighting that the largest threshold exceedances occur in regions with below-average NUE. Average required reductions for arable land are higher than for grassland for all thresholds (Supplementary Fig. 2), partly due to the higher NUE in grasslands. Respecting boundaries for biodiversity and water quality would reduce global agricultural N_2O emissions by 18–55% (see Supplementary Discussion), highlighting co-benefits for climate mitigation and ozone protection.

Spatial variation in risk areas

Exceedances of critical surplus for all impacts show strong regional variation (Fig. 3a and Extended Data Fig. 2), with a similar spatial distribution in croplands and grasslands (Supplementary Fig. 3). The spatial variation in exceedances results from heterogeneity in both current N losses (Extended Data Fig. 3a–c) and sensitivity of ecosystems to N losses (Extended Data Fig. 3d–f). Exceedances are most severe in north-western Europe (especially Germany + BENELUX), India/Pakistan and eastern China. Smaller regions with high exceedances include the Nile Basin, areas in Saudi Arabia and along the Peruvian Coast. In these regions surplus reductions of > 80 kg N ha^{-1} yr^{-1} are required to comply with all three N thresholds. These widespread required reductions result from combining the spatially distinct transgression patterns for the individual thresholds (Fig. 3b). China, western Europe and the eastern US are primarily affected by transgressions of surface water limits and/or deposition limits, while the midwestern US and central Europe are dominated by transgression of surface- and/or groundwater limits (Fig. 3b). Parts of the eastern US, northern India, northeast China and eastern Europe face transgression of all three thresholds simultaneously (Fig. 3b). In many regions where thresholds for N load to surface water are exceeded, thresholds for N leaching to groundwater are also exceeded, and vice versa (Fig. 3b), while the threshold for N deposition is often transgressed in areas where water-related thresholds are not. Groundwater thresholds are exceeded more frequently on arable land than on grassland (Extended Data Fig. 4). Overall, at least one of the thresholds has been exceeded in 66% of the global agricultural land area (accounting for as much as 83% of current global N surplus). For the surface water threshold, exceedances occur on 50% of agricultural land, whereas this is 38% for the deposition threshold and 39% for the groundwater threshold. For all thresholds, the share of land with exceedances is higher for arable land than for grassland (Extended Data Table 1).

In contrast to the excess regions, thresholds have not yet been exceeded for any of the three N-related impacts in 34% of all agricultural land, situated mostly in Sub-Saharan Africa, Central and South America and South East Asia (Fig. 3b). Nitrogen inputs and associated surplus in these regions could safely increase without exceeding environmental limits (Fig. 3a), potentially allowing for increases in food production.

Option space for agriculture

Reducing agricultural N surplus alone not always suffices to avoid N-related impacts. Previous assessments of planetary N boundaries focused exclusively on the agricultural sector[3,4,21,23], while our approach explicitly accounts for N loss contributions from non-agricultural sources. Half of all agricultural land is located in areas where non-agricultural N losses *alone* exceed at least one of the three thresholds (deposition levels, surface water quality and groundwater quality; Fig. 4a), with similar patterns in croplands and intensively managed grasslands (Extended Data Fig. 5). This phenomenon is especially widespread for the surface water criterion: in 44% of all agricultural land, thresholds for N load to surface water are exceeded by non-agricultural N losses alone (Fig. 4c). The largest contributions come from N discharge from sewage (Extended Data Fig. 6a) and from N runoff from natural land (Extended Data Fig. 6b). Thresholds for deposition in terrestrial ecosystems are exceeded by NO_x emissions from industry and traffic alone in areas containing 9% of all agricultural land, mainly situated in China, eastern US and western Europe (Fig. 4b and Extended Data Fig. 6d). Average deposition in these areas (25 kg N ha^{-1} yr^{-1}) is about four times the global average rate, and NO_x on average accounts for 78% of that deposition. Thresholds for N leaching to groundwater are exceeded at zero agricultural N surplus in 17% of the total agricultural area (Fig. 4d).

Crop production within N boundaries

Feeding a future population of ~10 billion people while remaining within the safe operating space for N is only possible through drastic changes to both food production systems and consumption patterns. Assessments that have attempted to model a world where sufficient food can be supplied within environmental thresholds found that this can only be achieved by combining efficiency improvements, dietary changes, re-distributing N inputs and cropland, reducing food waste and recycling nutrients[21,23,24,26]. We find that increasing NUE gradually allows for more crop production within N boundaries (S1 in Fig. 5). Increasing NUE to ~0.77 could be enough to meet a ‘minimum crop demand’ of the current global population without boundary transgression, where the minimum crop demand was estimated by assuming a balanced diet (one-third animal protein, two-thirds plant protein) and equal distribution of food (no over-consumption; see Methods). However, current global crop production (114 Mt N yr^{-1}) is not compatible with N boundaries, even if NUE is increased to 0.90 (a level that is not feasible under many circumstances[2]). This is partially because NUE improvements have no effect on non-agricultural losses (which alone exceed thresholds in many regions, Fig. 4) and because reductions in field-level N losses only fully translate into reductions in surface water N load after years or decades, depending on the travel time of N through soil and groundwater (legacy effect). Scenarios where either non-agricultural N losses are reduced proportionally with agricultural losses or where the legacy effect is neglected (being more indicative of the long-term effect of NUE improvements on N load) provide more room for crop production within N boundaries (S2+S3 in Fig. 5). If both scenarios are combined (S4 in Fig. 5), global crop demand under a balanced diet could be met while respecting N boundaries at a minimum NUE of ~0.60, and current crop production would be compatible with N boundaries at a minimum NUE of ~0.77.

However, the potential to meet the minimum regional crop demand under a balanced diet within N boundaries varies strongly across regions (Extended Data Fig. 7b): while North and South America and Australia could produce more than twice their estimated minimum regional demand within N boundaries in a balanced diet scenario, many highly populated regions in Africa and Asia cannot meet regional demands within N boundaries, even at drastically improved NUEs. These findings are in line with previous studies that showed that optimizing the distribution of production and N inputs could contribute substantially to producing more crops with less N pollution[23,35], although this may clash with goals of regional and national food self-sufficiency[40]. However, they also show that NUE improvements per se are likely not sufficient to meet future crop demands while avoiding adverse N impacts and need to be complemented by demand-side measures, as pointed out earlier[20,21,26,41]. Additional potential for crop production within N boundaries may be realized by expanding cropland (see e.g. ref [23], not considered in this study), although land conversion may have negative impacts on biodiversity and carbon storage.

From planetary to regional boundaries

Aggregating our spatially explicit N surplus thresholds for protecting air, surface water and groundwater quality results in a global planetary boundary for N surplus in croplands and grasslands. The most important result, however, is the insight in the spatial distribution of acceptable environmental N losses for different N impacts as well as N pollution from non-agricultural sources.

Independent bottom-up estimates of N boundaries for the EU[42] and China[43] are in good agreement with boundaries for these regions derived with our approach (see Supplementary Discussion), showing that our approach is suitable for deriving bottom-up regional N boundaries (Extended Data Fig. 8 and Extended Data Table 2). These can replace current top-down N boundaries based on equal per capita shares that ignore environmental heterogeneity (e.g., ref. [30]).

The N boundaries presented in this paper represent thresholds for the current agricultural system, but the approach allows for a dynamic assessment of N boundaries under changing conditions and practices. For example, using scenarios such as the shared socioeconomic pathways[44] allows quantifying synergies between strategies needed to respect biodiversity- and water quality-related N boundaries one the one hand and mitigating other N-related impacts, such as health impacts from NH_3-induced air pollution and climate impacts from N_2O emissions, on the other.

The Sustainable Development Goals adopted by the UN aim to improve human well-being while protecting ecosystems. Our results highlight the magnitude of this challenge with regards to agricultural N use. Fixation of reactive N will remain vital for sustaining crop production, but the costs to the environment are high, with thresholds for several N-related problems already exceeded on most of the agricultural land. Producing more food with less pollution will require targeted strategies, with increases in efficiency and/or extensification in areas with vulnerable ecosystems and increases in N inputs in areas where additional losses are acceptable from an environmental perspective. Feeding the world without trespassing a planetary N boundary thus requires a coordinated action that recognizes the regional diversity of agricultural systems and multiple environmental impacts.

Declarations

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Author contributions: All authors contributed to the concept and design of the study, L.S. & A.H.W.B. built the model to calculate critical inputs, A.H.W.B. provided input data for the calculations, L.S. performed all analyses and made figures, L.S., A.F.B. & W.d.V. wrote the manuscript.

Competing interests: Authors declare no competing interests.

Data and materials availability: All data are available in the main text or Extended Data. Additional data, as well as a comprehensive mathematical description of the calculations are provided in the Supplementary Material. All model input files as well as global maps of critical surpluses, inputs and their exceedances are provided via an online repository at doi.org/10.5281/zenodo.6395016. Correspondence and requests for additional materials should be addressed to lena.schulteuebbing@gmail.com.

Supplementary Information is available for this paper:

Supplementary Methods

Supplementary Discussion

Supplementary Figures 1 to 6

Supplementary Tables 1 to 6

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Methods

Spatially explicit boundaries for agricultural nitrogen (N) surplus and inputs were derived in four steps (see Extended Data Fig. 9a): Step 1; establish thresholds for N concentrations at which unacceptable impacts occur ('critical concentration'), Step 2; derive N losses at which critical concentrations are reached but not exceeded ('critical losses'), Step 3; calculate agricultural N inputs and N surplus that correspond to critical losses ('critical inputs' and 'critical surplus') and Step 4; for areas with no threshold exceedance, cut-off critical inputs at a maximum, set to the input level required to obtain crop yield potentials.

Thresholds for nitrogen impacts

Boundaries for agricultural N surplus and N inputs are derived for various N impacts, using thresholds for: (i) N deposition in natural ecosystems (related to biodiversity and acidification in terrestrial systems), (ii) N concentrations in surface water (related to eutrophication impacts on aquatic biodiversity) and (iii) N concentrations in groundwater (related to drinking water norms).

Critical N deposition rates to limit terrestrial biodiversity loss were derived for each of the 14 biomes represented in the IMAGE model[45], mainly based on a paper presenting an extensive synthesis of empirical studies[12]. Critical deposition rates vary from 5 to 20 kg N ha^{-1} yr^{-1} for the most and least sensitive biomes, respectively (see Supplementary Table 2 for biome-specific critical deposition rates and Supplementary Fig. 4 for the resulting global distribution in critical deposition rates).

Critical N concentration in surface water to limit eutrophication impacts was set to 2.5 mg N (total dissolved N) per litre, based on (i) an extensive study on the ecological and toxicological effects of inorganic N pollution[46], (ii) an overview of maximum allowable surface water N concentrations in national surface water quality standards[47] and (iii) different European objectives for N compounds. Rather than imposing limits for N concentrations in surface water itself, we used a threshold for N concentration in runoff to surface water. This threshold was set to 5.0 mg N l^{-1}, based on the assumption that on average 50% of N entering surface water is removed through retention and sedimentation (see Supplementary Methods).

(iii) Critical nitrate concentration in groundwater to limit health effects was set to 50 mg NO_3^- l^{-1} (11.3 mg NO_3-N l^{-1}), based on WHO guidelines for drinking water[48]. We imposed this threshold concentration for excess water leached from agricultural land.

Two other impacts of N were not considered: the impact of N_2O emissions on climate warming and stratospheric ozone depletion, and health effects of air pollution by NH_3, either directly or by contributing to particulate matter (PM) formation. These impacts were not considered for several reasons: First, N_2O concentrations only show slight interhemispheric and seasonal variations, making a spatially explicit calculation of critical inputs irrelevant. Second, with regards to climate change, N_2O is only the third most important contributor to climate warming, and thus deriving a critical limit for N_2O emissions thus requires making assumptions on reductions in other greenhouse gases, especially CO_2 and CH_4. Third, the warming effect from anthropogenic N_2O emissions may partly be compensated by the cooling effect of additional carbon sequestration in forests induced by enhanced N deposition[49,50]. One recent study estimating that N-induced carbon sequestration almost fully offsets the warming effect of N-induced N_2O emissions[51], whereas previous studies found much smaller effects[52–54]. Whereas defining a global threshold for N_2O in view of climate change and stratospheric ozone depletion was beyond the scope of this study, we did calculate the impact of respecting other thresholds on global agricultural N_2O emissions (see Supplementary Discussion).

For air pollution impacts of NH_3, critical limits could be derived based on thresholds for PM_{10} and $PM_{2.5}$ and the relative contribution of NH_3 to PM formation. The contribution of NH_3 and NO_x to overall PM concentrations varies considerably between population centres and is estimated to be on average 30% in urban areas and 15% in rural areas for $PM_{2.5}$[55]. However, the impact of reductions in agricultural NH_3 emissions on PM formation strongly depend on chemical and meteorological conditions that vary in time in space. For example, aerosol formation in Europe and North America is generally not primarily limited by NH_3 availability[15], and a reduction in NH_3 emissions thus does not linearly translate into a reduction in PM formation in these regions. Assessing the effects of NH_3 on PM formation would require detailed atmospheric chemistry models that capture these processes.

IMAGE-GNM model

All calculations are performed for the year 2010 at a spatial resolution of 0.5x0.5 degrees, based on output files from the Global Nutrient Model (GNM), a sub-model of the Integrated Model to Assess the Global Environment (IMAGE). IMAGE is a comprehensive integrated modelling framework that allows to analyse interactions between human development and global change[45]. IMAGE–GNM simulates the fate of N and phosphorus (P) in the soil-hydrological system (for a comprehensive description of IMAGE-GNM, see ref. [39]). Total N load to surface water in IMAGE-GNM consists of (also see Extended Data Fig. 9b):

i. N load from point sources that enters surface water directly, including wastewater, aquaculture, allochthonous organic matter and direct deposition to surface water,
ii. N load from soil erosion (both from agricultural and natural land) and
iii. N load from soil N budgets that are susceptible to surface runoff and leaching. Nitrogen leached from the root zone travels through the soil profile and is eventually delivered to surface water via sub-surface runoff. Sub-surface delivery of N to surface water is calculated while accounting for travel times, historical N inflows and N removal through denitrification in soils and riparian zones.

Surface water N concentration is derived from total N load, transport of N from upstream grid cells and in-stream nutrient retention[39]. Uncertainties in the estimation of N inputs and losses in IMAGE, which also affect the calculation of critical inputs, have been discussed extensively in previous publications[39,56–58];

methods to estimate spatial distribution of N inputs by manure and fertilizer are briefly summarized in the Supplementary Methods.

Major assumptions in calculating critical nitrogen losses and inputs

Spatially explicit boundaries were derived for (i) agricultural N surplus, defined as total N input minus crop or grass N uptake; (ii) total N input from fertilizer, manure, biological N fixation and deposition, and (iii) 'intentional N fixation', used as an indicator previous assessments of planetary N boundaries[3].

All calculations were performed with IMAGE-GNM (see Extended Data Fig. 9b) while making several assumptions (see below). All equations used for calculating critical N surplus and critical N inputs, as well as an overview of all gridded IMAGE datafiles used as input in the calculations, can be found in the Supplementary Methods and Supplementary Tables 3 & 4.

Assumption 1: Changes in agricultural N inputs. Total N inputs to agriculture consist of N inputs from mineral fertilizer, manure, biological N fixation and deposition (see Extended Data Fig. 9b). Critical inputs are calculated by varying only those inputs directly managed by farmers, i.e., mineral fertilizer and manure. Inputs from biological N fixation were assumed to be constant, and inputs from deposition were calculated as a linear function of NH_3 and NO_x emissions at critical N inputs. Nitrogen inputs from fertilizer and manure were reduced (or increased) in equal proportions until thresholds are no longer exceeded.

Assumption 2: Constant N losses from other sources. All N losses from non-agricultural sources were assumed constant. This includes NO_x emissions from stationary and mobile combustion, as well as N load to surface water from point sources and erosion (see Extended Data Fig. 9b). Where N loss thresholds are exceeded, agriculture thus has to carry the full burden of reductions. We also tested the impact of alternative assumptions regarding non-agricultural loses on the results.

Assumption 3: Constant properties of the agricultural system. N losses (surplus) and uptake were assumed to change linearly with N inputs. The use of constant uptake and loss fractions implies that we do not consider possibilities to reduce specific losses that would affect loss fractions, such as reducing NH_3 emissions through manure injection or increasing NUE by implementing 4R strategies. Our approach also does not consider end-of-pipe measures such as decreasing surface runoff through buffer strips or increasing denitrification by using woodchips. We assumed no changes in extent and distribution of agricultural land. Land use classes in IMAGE were aggregated to four land-use types: 1. Arable land, 2. Intensively managed grassland, 3. Extensively managed grassland (pastoral land) and 4. Natural land (see Extended Data Fig. 9b). Critical N inputs were calculated only for land-use types 1 and 2, while N inputs to (and N losses from) 3 and 4 were assumed constant (except for inputs from deposition related to NH_3 emissions from manure and fertilizer inputs to 1 and 2).

Assumption 4: N emissions and N deposition. Nitrogen deposition within a grid cell was assumed to be homogenously distributed (i.e., same deposition rates for all land use types within a grid cell). Total N (NH_3+NO_x) emissions were assumed equal to total N deposition within a grid cell, i.e., we assumed no inter-grid transport of N emissions. NO_x emissions were calculated as the difference between N deposition and NH_3 emissions. Spatial distribution of N deposition in IMAGE is derived from the TM5 model[59], corrected for the difference in emission estimate between TM5 and IMAGE at the level of world regions. If NH_3 emissions exceeded N deposition in a grid cell, N deposition was set equal to NH_3 emissions. This increased total global N deposition by ~10% (from 82 to 90 Mt N yr^{-1}), a figure that is well within the uncertainty range for global N deposition estimates[60].

Assumption 5: Legacy N delivery. Depending on the travel time distribution for the lateral flow, a part of N delivered to surface water via groundwater ("N groundwater delivery" in Extended Data Fig. 9b) is caused by N inputs in the past. To reflect this time-lag in our calculations, N groundwater delivery was split into a variable component (assumed to change linearly with N inputs) and a fixed component (assumed constant). The fraction of the variable component was derived as a function of precipitation surplus, and increases linearly from 0 at no precipitation surplus to 0.95 at a precipitation surplus of 2000 mm yr^{-1} and higher.

Cut-off value for critical N surpluses and N inputs

In areas where N losses are (far) below environmental thresholds, critical N surpluses and inputs need to be constrained by a maximum value in order to avoid unrealistically high N values (step 4 in Extended Data Figure 9a). Such a maximum value should reflect that farmers will not apply more N than required for crop production, but also that current N inputs constrain yields in many regions[61]. We thus set the maximum level for critical N inputs in each grid cell, $Nin_{(crit,max)}$, to the input required to obtain crop yield potentials at current nitrogen use efficiency (NUE):

$$Nin_{(crit,max)} = Nup_{(Yp)} / NUE_{(act)} \quad \text{(Eq. 1)}$$

$$Nup_{(Yp)} = Nup_{(act)} * YG \quad \text{(Eq. 2)}$$

Where YG is the yield gap, calculated as yield potential (Yp) for arable land or intensively managed grassland divided by the current yield (Ya), $Nup_{(Yp)}$ is the N uptake at crop yield potential, and $NUE_{(act)}$ is the current regional NUE for arable cropping systems, calculated for each grid cell as N uptake divided by total N inputs. As high NUEs occur in regions where N is mined from the soil, we capped the NUE for the calculation of maximum N input at 0.8.

Regional yield potentials for arable land were derived based on attainable yields for 17 crops and 155 countries presented in ref. [35], and yield potentials for intensively managed grassland were derived based on maximum livestock densities and feed requirements from ref. [62], see Supplementary Methods for details. While our analysis highlights regions where N inputs can be increased to close yield gaps without exceeding environmental thresholds for N losses, in some regions closing yield gaps will require alleviating other yield-limiting factors in addition to N, such as phosphorus or water availability.

Aggregation to regional and planetary boundaries

Regional and planetary boundaries for agricultural N surplus (inputs) were calculated as the sum of critical N surpluses (inputs) for all grid cells within a region. Boundaries were calculated for each of the three thresholds individually, and for all thresholds simultaneously (based on the minimum of the individual boundaries in each grid cell). Where N losses from non-agricultural sources alone exceeded thresholds, critical N inputs from fertilizer and manure were set to zero.

Potential for crop production within N boundaries under various scenarios

In areas where N loss thresholds are exceeded, respecting thresholds without crop yield losses is only possible at a higher nitrogen use efficiency (NUE). We tested the impact of gradually increasing NUE on the amount of crop production that can be obtained while respecting N boundaries ('safe' crop production) under varying assumptions regarding non-agricultural N losses and the legacy effect (Fig. 5):

Non-agricultural N losses contribute substantially to the exceedance of critical thresholds (see Fig. 3 and Extended Data Fig. 6). In the standard calculation of critical N inputs, these losses were assumed constant (year 2010 values, see Assumption 2). In an alternative scenario, we reduced all other anthropogenic N losses proportionally with agricultural N losses. For the deposition threshold, NO_x emissions were set to change proportionally with agricultural NH_3 emissions while for the surface water threshold, N load from wastewater, aquaculture, direct deposition, and erosion was set to change proportionally with agricultural N load from surface runoff and groundwater delivery. These scenarios serve to illustrate the sensitivity of our boundaries to alternative modelling assumptions.

The '**legacy effect**' describes the lag time between the implementation of measures to reduce N inputs and effects on water quality due to the travel time of N through soil and groundwater. This effect is captured in our modelling approach by assuming that a certain fraction of groundwater N delivery to surface water is not instantly influenced by changes in agricultural N inputs, and is thus kept constant in the calculations (see Assumption 5). This 'legacy fraction' varies regionally between 0.05 and 1, with a global average of 0.85. While this approach is adequate to capture short-term effects of reductions in N inputs on surface water N load, on the long term, reductions in N inputs will eventually translate into reduced groundwater N loads. This long-term effect is modelled by setting the legacy fraction to zero (thereby implying that total groundwater N delivery changes linearly with N inputs).

Global and regional minimum crop N demand under a balanced diet

The required minimum crop production (in Tg N yr^{-1}) for global and regional food self-sufficiency was calculated as:

$$Nup,req_{(i)} = (pop_{(i)} * N_{demand} * (fN_{veg} / NUE,chain_{veg} + fN_{ani} / NUE,chain_{ani})) \quad \text{(Eq. 3)}$$

Where:

- $Nup,req_{(i)}$ = Crop N production (uptake) required to produce enough protein to be food self-sufficient for region i [kg N yr^{-1}]
- $pop_{(i)}$ = population for region i for the year 2020 [# persons], obtained from ref. [63]
- N_{demand} = per capita N intake requirement [kg N $person^{-1}$ $year^{-1}$]; set to 3 kg N $person^{-1}$ yr^{-1} based on ref. [64]
- fN_{veg} = average share of vegetal protein in total protein intake [-], set to 2/3 based on ref. [64]
- fN_{ani} = average share of animal protein in total protein intake [-], set to 1/3 based on ref. [64]
- $NUE,chain_{veg}$ = average food chain NUE for vegetal protein, i.e., the share of N in harvested crops that is ingested by humans [-]; estimated at 45% based on ref. [65]
- $NUE,chain_{ani}$ = average food chain NUE for animal protein, i.e., the share of N in harvested crops that is converted into animal protein and ingested by humans [-]; estimated at 13%, based on ref. [65]

We intentionally used uniform values for per capita N intake requirement, the share of vegetal and animal protein in diets and food chain NUE instead of regionally differentiated values, in order to relate the potential crop production within N boundaries (which could be seen as a measure of a region's 'carrying capacity' for agricultural N pollution) to a 'standardized' crop demand that is only affected by the size of a region's population.

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Figures

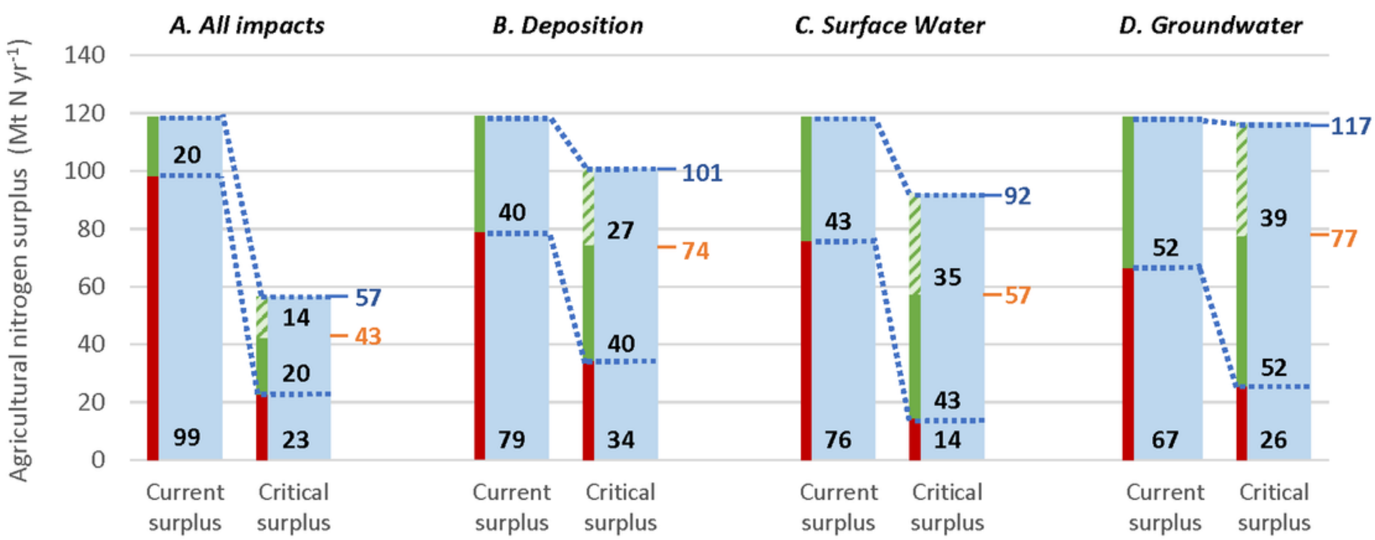

Figure 1

Current (2010) and critical agricultural nitrogen (N) surplus. Critical surpluses in view of **a**, all thresholds, **b**, critical N deposition to limit terrestrial biodiversity loss, **c**, critical N load to surface water to limit eutrophication and **d**, critical N leaching to groundwater to meet drinking water standards. For each threshold, left-hand bars show current surplus split up into surplus on land where threshold is exceeded (red edges) / not exceeded (green edges), and right-hand bars show corresponding critical surplus. Striped green bars show allowable increase in N surplus on land where threshold is not exceeded. Numbers right of critical surplus bars indicate global N boundaries with (blue) and without (orange) allowing N surplus to increase where possible within thresholds. Values are in Mt N yr^{-1}. Corresponding results for critical N input are shown in Supplementary Figure 1.

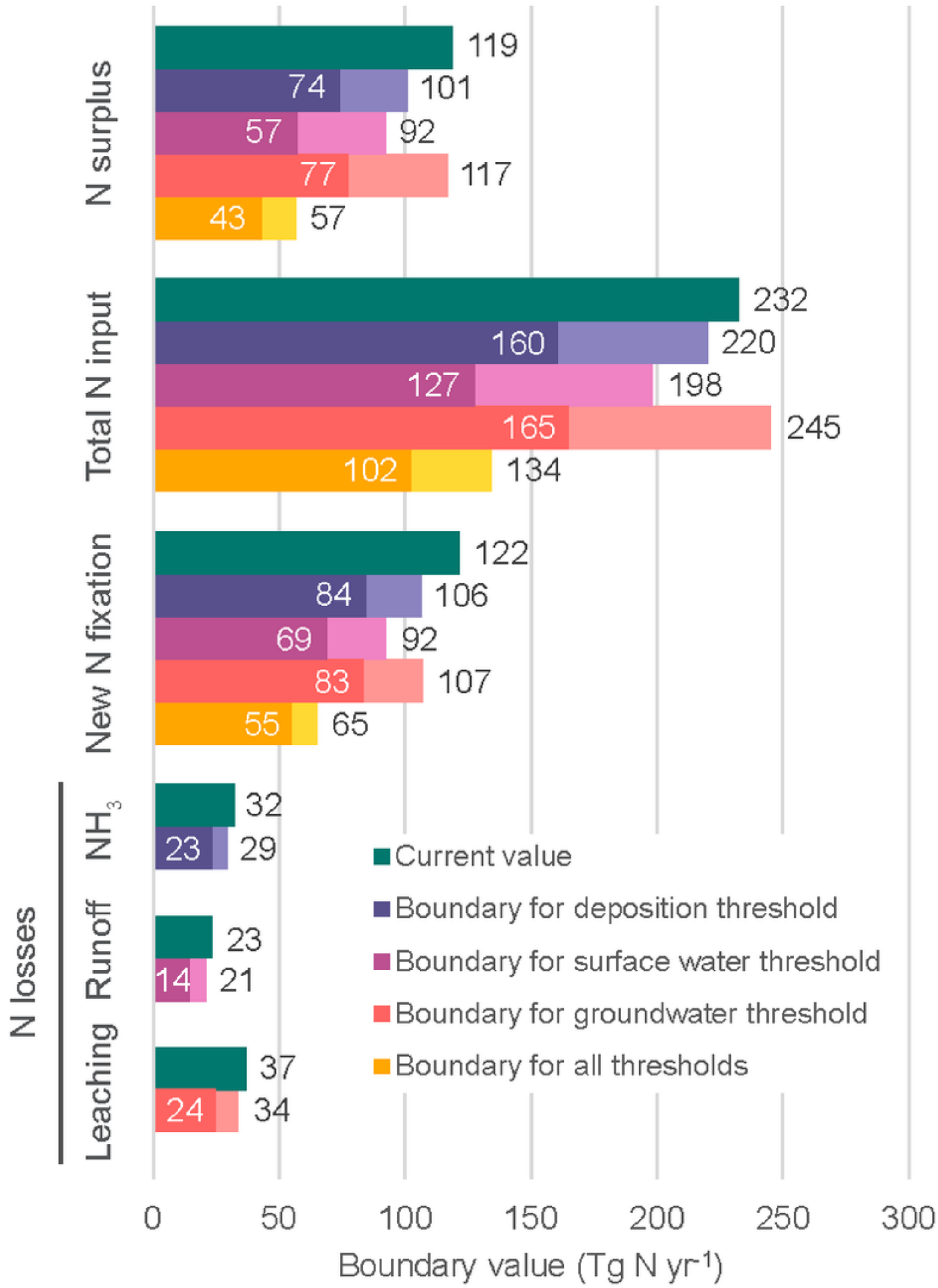

Figure 2

Estimated global boundaries for various N indicators. Darker-shade bars (white numbers) represent boundaries without accounting for possibilities to increase N inputs and associated N surplus and N losses in regions where thresholds are not exceeded, lighter shade bars indicate possibilities for expansion, black numbers show total boundary including expansion. All values are in Tg N yr^{-1}.

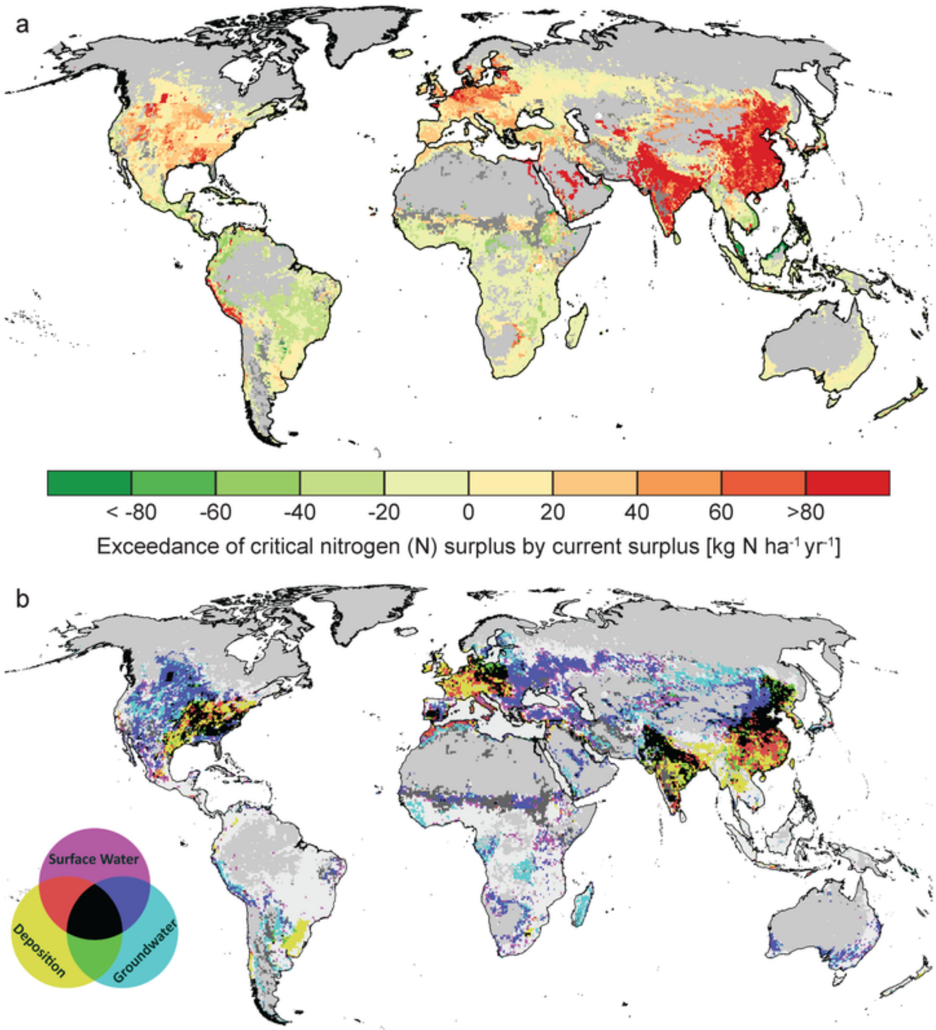

Figure 3

Spatial variation in global exceedance of N thresholds. a, Reductions of agricultural N surplus required to respect all three environmental thresholds simultaneously. Positive values (red) indicate needed reductions, negative values (green) indicate possible increases within thresholds. Required reductions to respect individual thresholds are shown in Extended Data Figure 2b–d. **b**, Type of N-related threshold (critical N deposition, critical N load to surface water and critical N leaching to groundwater) that has been exceeded. Colors indicate exceedance of none (white), one, two or all three thresholds (see legend). Areas with no agricultural land are light gray, areas where critical inputs could not be calculated are dark gray.

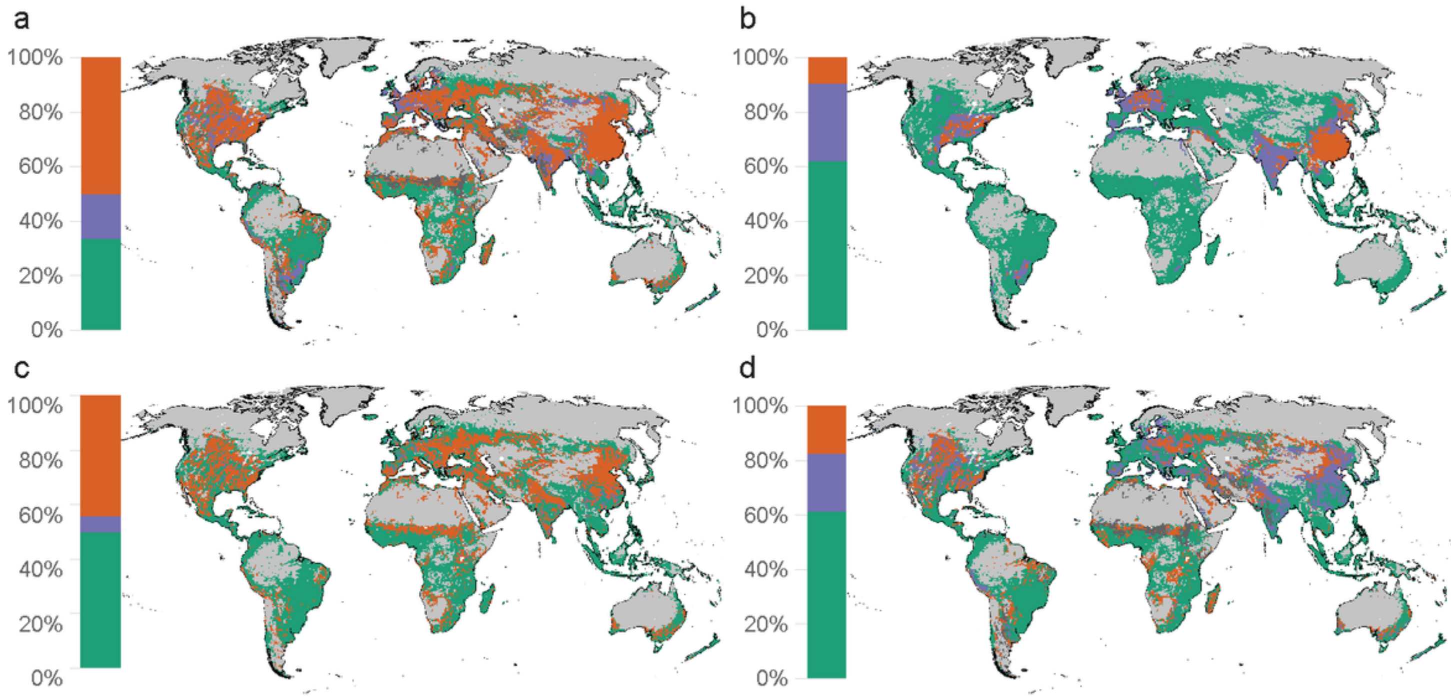

Figure 4

Possibilities for respecting environmental thresholds by reducing agricultural N losses alone. for **a**, all thresholds combined, **b**, critical N deposition to limit terrestrial biodiversity loss, **c**, critical N load to surface water to limit eutrophication and **d**, critical N leaching to groundwater to meet drinking water standards. Green = regions where threshold is not exceeded (reducing N losses not necessary), purple = regions where threshold is exceeded and reducing agricultural N losses is sufficient to respect threshold, orange = regions where threshold is exceeded and reducing agricultural N losses alone is not sufficient to respect threshold (threshold exceeded by non-agricultural N losses alone). Bars show the share of global agricultural land within each category. Areas with no agricultural land are shown in gray.

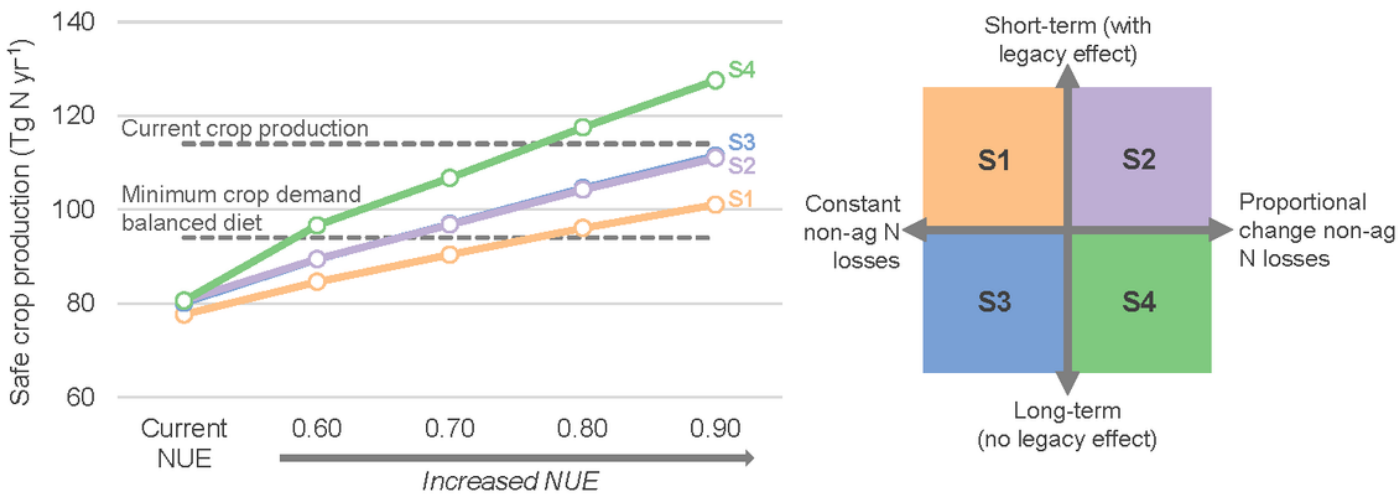

Figure 5

Possibilities for crop production within the safe operating space for nitrogen. Maximum safe crop production within boundaries for nitrogen (N) losses that respect all thresholds at current and gradually improved N use efficiency (NUE), and under four scenarios with varying assumptions on non-agricultural N losses and legacy N delivery to surface water (see Methods for more details on scenarios). Dashed lines show current (year 2010) global crop production and minimum crop requirement to meet global demand under a balanced diet (see Eq. 3 in Methods) for reference. Regional variation in possibilities for crop production within N boundaries is shown in Extended Data Fig. 7.

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