From planetary to regional boundaries for agricultural nitrogen pollution

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Excessive agricultural nitrogen use causes environmental problems globally[1], to an extent that it has been suggested that a safe planetary boundary has been exceeded[2]. Earlier estimates for the planetary nitrogen boundary[3,4], however, did not account for the spatial variability in both ecosystems' sensitivity to nitrogen pollution and agricultural nitrogen losses. Here we use 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 estimate regional boundaries for agricultural nitrogen pollution and find both overuse and room for intensification of agricultural nitrogen. The aggregated global surplus boundary with respect to all thresholds is 43 megatonnes of nitrogen per year, which is 64 per cent lower than the current (2010) nitrogen surplus (119 megatonnes of nitrogen per year). Allowing the nitrogen surplus to increase to close yield gaps in regions where environmental thresholds are not exceeded lifts the planetary nitrogen boundary to 57 megatonnes of nitrogen per year. 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 that recognizes the heterogeneity of agricultural systems, non-agricultural nitrogen losses and environmental vulnerabilities.

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]. To 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) was first quantified by ref. [18] and later revised by ref. [3], which estimated that the safe limit is about half the current rate. This planetary N boundary has served as benchmark for many subsequent studies that have assessed the 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, owing 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 considered only 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 nitrogen oxide (NO_x) emissions from traffic and industry and N discharge in wastewater. Fifth, boundaries were derived for several N-related impacts individually[4], whereas 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.

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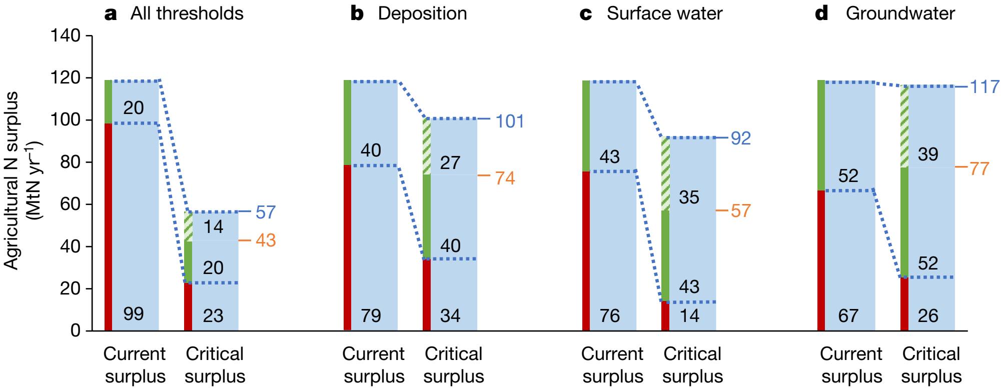

Fig. 1 | Current (2010) and critical agricultural nitrogen surplus. **a**–**d**, Critical N surplus in view of all thresholds (**a**), critical N deposition to limit terrestrial biodiversity loss (**b**), critical N load to surface water to limit eutrophication (**c**) and critical N leaching to groundwater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

Here we present an 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 policymaking[37,38]. Unlike a boundary for intentional N fixation or total 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 corresponding boundaries for total agricultural N inputs (both 'new' inputs from fertilizer and biological fixation and 'recycled' inputs from manure and deposition) under current regional NUEs.

Regional and planetary boundaries are derived based on spatially explicit environmental thresholds for (1) N deposition rates (to avoid or limit terrestrial biodiversity loss), (2) N concentrations in surface water (to limit eutrophication) and (3) N concentrations in groundwater (to meet the World Health Organization (WHO) drinking water standard). Nitrogen's contribution to climate change and stratospheric ozone depletion through nitrous oxide (N_2O) emissions as well as health impacts of air pollution from ammonia (NH_3) emissions were not considered (Methods), but we quantify effects of meeting planetary boundaries for the 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° × 0.5° resolution for the year 2010.

Non-agricultural N pollution (for example, NO_x emissions from transport and industry and 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, whereas 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. Modelling assumptions, their implications and major uncertainties are discussed in Methods and Supplementary Information.

Planetary nitrogen boundary

The reductions in agricultural N surplus required to respect thresholds for deposition, surface water quality and groundwater quality differ strongly (Fig. 1b–d). In line with previous findings[3], we find that surface water quality is the most stringent criterion, requiring the strongest reductions in global N surplus: from 119 MtN yr^{-1} to 92 MtN 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 MtN yr^{-1}) (Fig. 1b), whereas the N surplus boundary to avoid exceedance of health-impacting nitrate concentrations in groundwater (117 MtN yr^{-1}) (Fig. 1d) is close to the current surplus. However, whereas the previous research[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 global boundary of 57 MtN 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 (Methods). For example, to respect all three N-related thresholds, the N surplus needs to decrease by 77% (from 99 MtN yr^{-1} to 23 MtN yr^{-1}) in regions where at least one threshold is exceeded, but can increase by 70% (from 20 MtN yr^{-1} to 34 MtN yr^{-1}) in regions where no threshold is 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 the current NUE, the global N surplus boundary for all thresholds corresponds to a total global N input of 134 MtN yr^{-1} (Fig. 2). Of these inputs, 65 MtN yr^{-1} come from new N fixation (34 MtN yr^{-1} from fertilizer and 31 MtN yr^{-1} from biological fixation; Extended Data Fig. 1). For the surface water criterion, the global boundary for new N fixation is 92 MtN yr^{-1} (Fig. 2), which is higher than the value of 62–82 MtN yr^{-1} proposed by ref. [3] for a global boundary for new N fixation in view of surface water quality. However, if like ref. [3] 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 (69 MtN yr^{-1}; Fig. 2) falls within their range.

For all thresholds, stronger reductions (in relative terms) are required for N surplus than for total N input (Fig. 2), highlighting that the largest

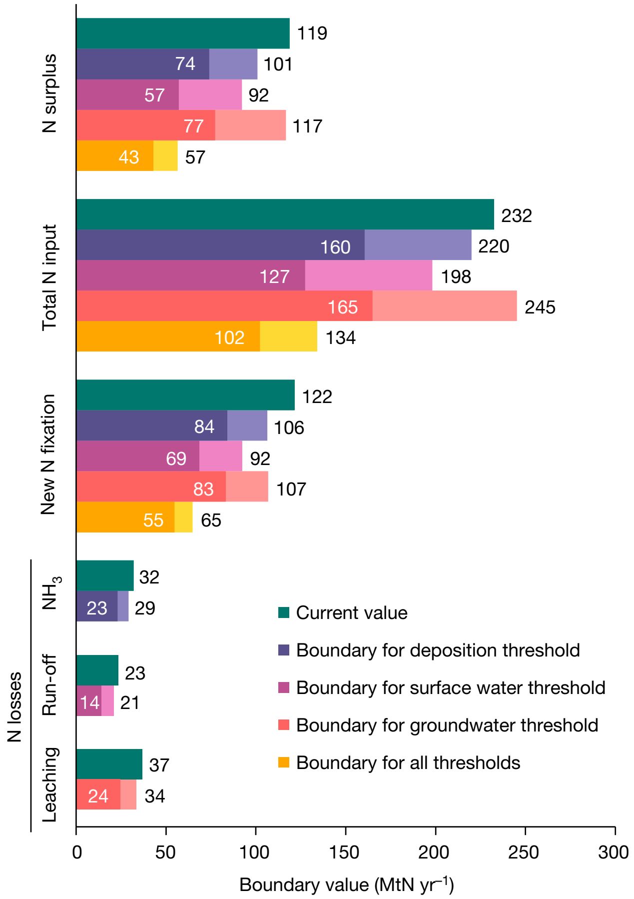

Fig. 2 | Estimated global boundaries for various nitrogen indicators. The darker-shade bars (white numbers) represent boundaries without accounting for possibilities to increase N inputs and associated N surplus and N losses in regions where thresholds are not exceeded. The lighter shade bars indicate possibilities for expansion and the black numbers show the total boundary including expansion. All values are in MtN yr^{-1}.

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 owing to the higher NUE in grasslands. Respecting boundaries for biodiversity and water quality would reduce global agricultural N_2O emissions by 18–55% (Supplementary Discussion), highlighting co-benefits for climate mitigation and ozone protection.

Spatial variation in risk areas

Exceedances of the critical N surplus for all thresholds 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 the sensitivity of ecosystems to N losses (Extended Data Fig. 3d–f). Exceedances are most severe in northwestern 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 more than 80 kgN 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 USA are primarily affected by transgressions of surface water limits and/or deposition limits, whereas the midwestern USA and central Europe are dominated by transgression of surface water and/or groundwater limits (Fig. 3b). Parts of the eastern USA, northern India, northeast China and eastern Europe face transgression of all three thresholds simultaneously (Fig. 3b). In many regions where the threshold for N load to surface water is exceeded, the threshold for N leaching to groundwater is also exceeded, and vice versa, whereas the threshold for N deposition is often transgressed in areas where water-related thresholds are not (Fig. 3b). 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 the 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 southeast 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 the agricultural N surplus alone does not always suffice to avoid N-related impacts. Previous assessments of planetary N boundaries focused exclusively on the agricultural sector[3,4,21,23], whereas 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: 44% of all agricultural land is located in areas where 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 run-off 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 USA and western Europe (Fig. 4b and Extended Data Fig. 6d). The average deposition in these areas (25 kgN 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 input in 17% of the total agricultural area (Fig. 4d).

Crop production within N boundaries

Feeding a future population of about 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 (scenario S1 in Fig. 5). Increasing NUE to about 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 and two-thirds plant protein) and equal distribution of food (no over-consumption; Methods). However, current global crop production (114 MtN yr^{-1}) is not compatible with N

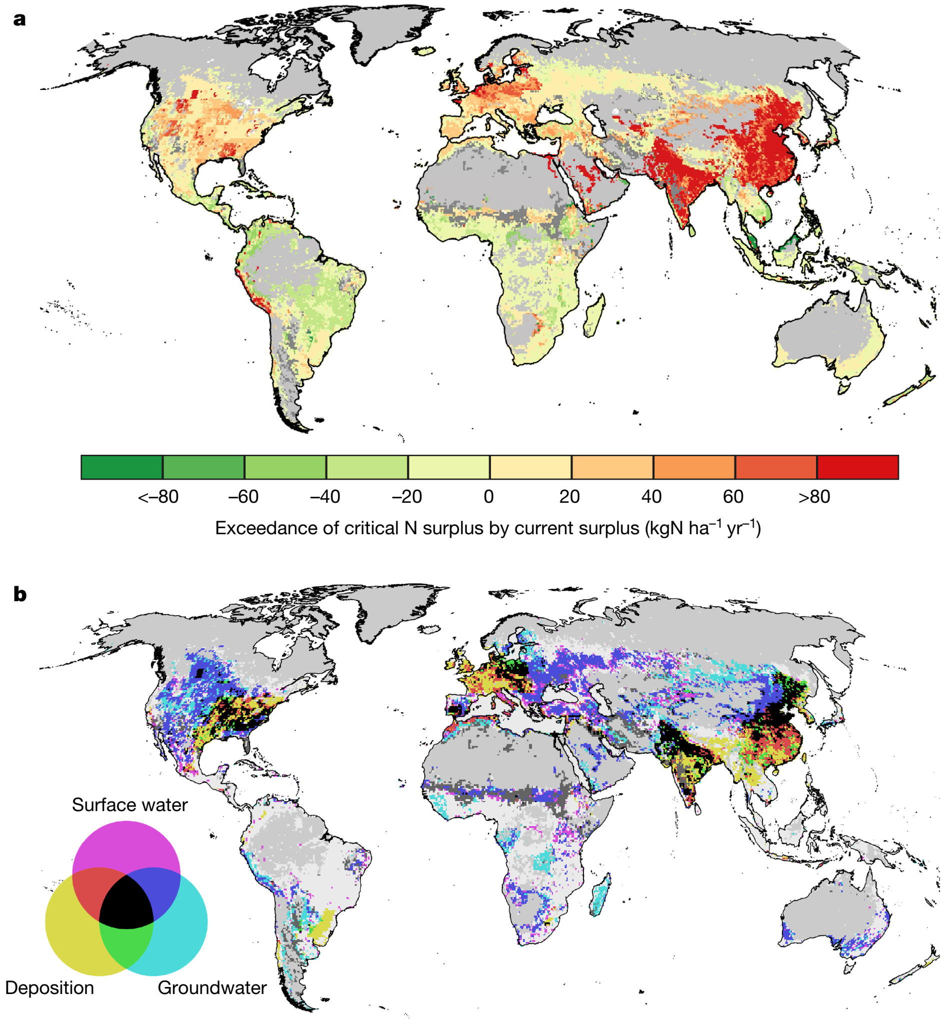

Fig. 3 | Spatial variation in global exceedance of nitrogen thresholds. **a**, Reductions of agricultural N surplus required to respect all three environmental thresholds simultaneously. Positive values (red) indicate needed reductions and negative values (green) indicate possible increases within thresholds. Required reductions to respect individual thresholds are shown in Extended Data Fig. 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. The colours indicate exceedance of none (white), one, two or all three thresholds (see legend). Areas with no agricultural land are light grey and areas where critical surplus could not be calculated are dark grey.

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 (scenarios S2 and S3 in Fig. 5). If both scenarios are combined (scenario S4 in Fig. 5), global crop demand under a balanced diet could be met while respecting N boundaries at a minimum NUE of about 0.60, and current crop production would be compatible with N boundaries at a minimum NUE of about 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): whereas North America, 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 crop production and N inputs could contribute substantially to producing more crops with less N pollution[23,35], although this may clash with regional and national food self-sufficiency goals[40]. However, they also show that NUE improvements per se are probably 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, for example, 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 on the spatial distribution of acceptable environmental N losses for different N impacts as well as N pollution from non-agricultural sources.

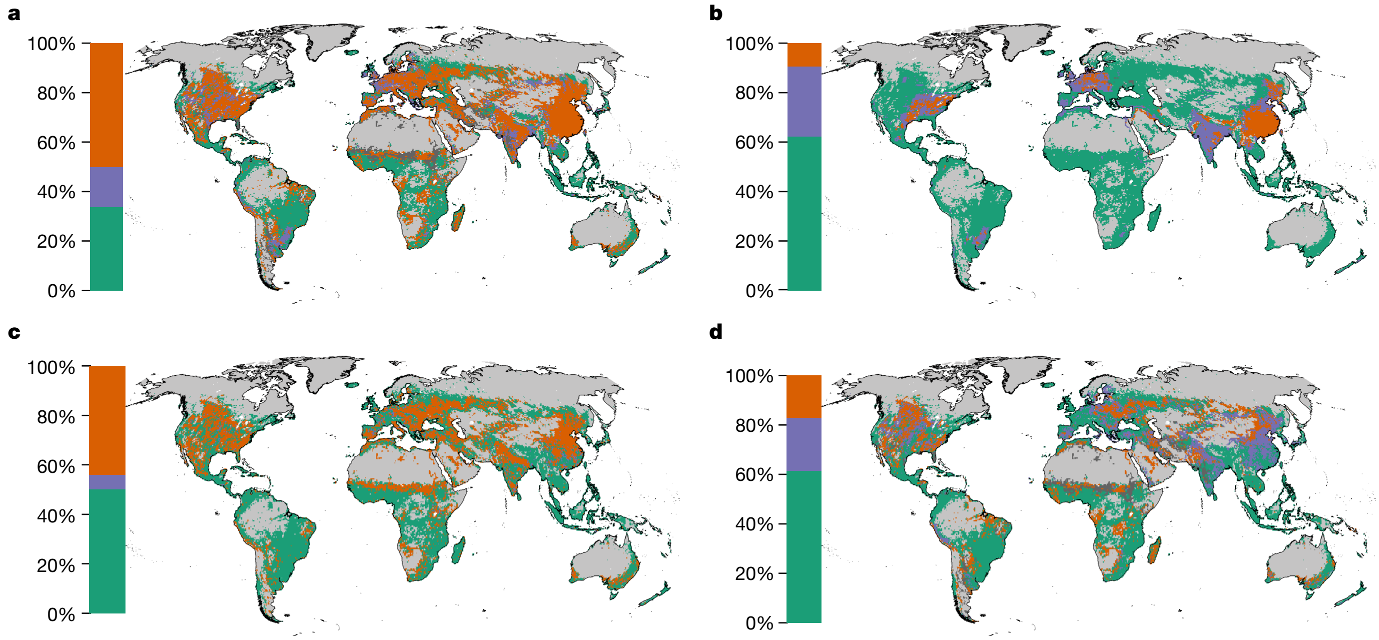

Fig. 4 | Possibilities for respecting environmental thresholds by reducing agricultural nitrogen losses alone. a–d, For all thresholds combined (**a**), critical N deposition to limit terrestrial biodiversity loss (**b**), critical N load to surface water to limit eutrophication (**c**) and critical N leaching to groundwater to meet drinking water standards (**d**). 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). The bars show the share of global agricultural land within each category. Areas with no agricultural land are shown in grey.

Independent bottom-up estimates of N boundaries for the European Union[42] and China[43] are in good agreement with boundaries for these regions derived with our approach (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 (for example, 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 quantification of the synergies between strategies needed to respect biodiversity-related and water-quality-related N boundaries on 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 hand.

The Sustainable Development Goals adopted by the United Nations 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.

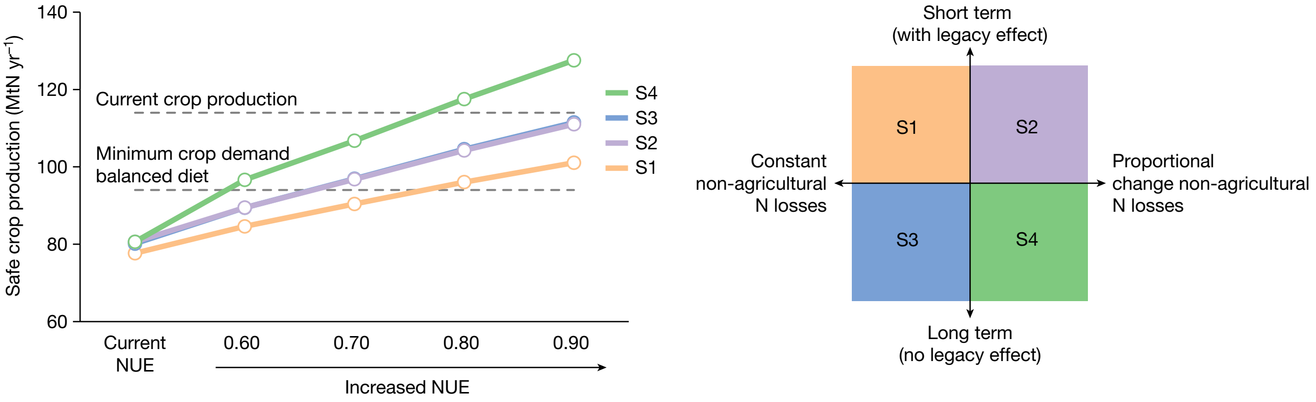

Fig. 5 | Possibilities for crop production within the safe operating space for nitrogen. Maximum safe crop production within boundaries for N losses that respect all thresholds at current and gradually improved NUE, and under four scenarios with varying assumptions on non-agricultural N losses and legacy N delivery to surface water (see Methods for more details on the scenarios). The dashed lines show current (year 2010) global crop production and minimum crop requirement to meet global demand under a balanced diet (see equation (3) in Methods) for reference. Regional variation in possibilities for crop production within N boundaries is shown in Extended Data Fig. 7.

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.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-022-05158-2.

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Methods

Spatially explicit boundaries for agricultural N surplus and inputs were derived in four steps (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'). Step 4: for areas with no threshold exceedance, cut off critical inputs and surplus at a maximum value, set to the input level required to obtain crop yield potentials.

Thresholds for N impacts

Boundaries for agricultural N surplus and N inputs are derived for various N impacts, using thresholds for: (1) N deposition in natural ecosystems (related to eutrophication and acidification and associated biodiversity loss in terrestrial systems); (2) N concentrations in surface water (related to eutrophication impacts on aquatic biodiversity); and (3) 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 kgN ha^{-1} yr^{-1} to 20 kgN 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).

The critical N concentration in surface water to limit eutrophication impacts was set to 2.5 mgN (total dissolved N) per litre, based on (1) an extensive study on the ecological and toxicological effects of inorganic N pollution[46], (2) an overview of maximum allowable surface water N concentrations in national surface water quality standards[47] and (3) different European objectives for N compounds[48]. Rather than imposing limits for N concentrations in surface water itself, we used a threshold for N concentration in run-off to surface water. This threshold was set to 5.0 mgN l^{-1}, based on the assumption that on average 50% of N entering surface water is removed through retention and sedimentation (Supplementary Information).

The critical nitrate (NO_3^-) concentration in groundwater to limit health effects was set to 50 mg NO_3^- per litre (11.3 mg NO_3-N per litre), based on the WHO guideline for drinking water[49]. 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 the health effects of air pollution by NH_3, either directly (NH_3 is toxic at high concentrations) or indirectly by contributing to particulate matter (PM) formation. These impacts were not considered for several reasons. First, N_2O concentrations show only 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 deriving a critical limit for N_2O emissions in view of a target to limit warming to 1.5 or 2 °C thus requires making assumptions on reductions in other greenhouse gases, especially carbon dioxide and methane. 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[50,51]. One recent study estimating that N-induced carbon sequestration almost fully offsets the warming effect of N-induced N_2O emissions[52], whereas previous studies found much smaller effects[53,54,55]. Although 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 (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 $PM_{2.5}$ (ref. [56]). However, the impact of reductions in agricultural NH_3 emissions on PM formation strongly depends 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 translate into a proportional 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 0.5° ×0.5°, based on output files from the GNM, a submodel of IMAGE. IMAGE is a comprehensive integrated modelling framework that allows the analysis of interactions between human development and global change[45]. IMAGE-GNM simulates the fate of N and phosphorus in the soil-hydrological system (for a comprehensive description of IMAGE-GNM, see ref. [39]). The total N load to surface water in IMAGE-GNM consists of (see Extended Data Fig. 9b): (1)N load from point sources that enters surface water directly, including wastewater, aquaculture, allochthonous organic matter and direct deposition to surface water; (2) N load from soil erosion (both from agricultural and natural land); and (3)N load from soil N budgets that are susceptible to surface run-off and leaching. Nitrogen leached from the root zone travels through the soil profile and is eventually delivered to surface water via subsurface run-off. Subsurface 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[39,57–59]; methods to estimate spatial distribution of N inputs by manure and fertilizer are briefly summarized in Supplementary Methods.

Major assumptions in calculating critical N losses and inputs

Spatially explicit boundaries were derived for (1) agricultural N surplus, defined as total N input minus crop or grass N uptake; (2) total N input from fertilizer, manure, biological N fixation and deposition, and (3) 'intentional N fixation', used as an indicator previous assessments of the planetary N boundary[3].

All calculations were performed with IMAGE-GNM (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 Supplementary Methods and Supplementary Tables 3 and 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 (Extended Data Fig. 9b). Critical inputs are calculated by varying only those inputs directly managed by farmers, that is, 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 in equal proportions until thresholds were no longer exceeded (or increased in equal proportions until the cut-off value for N inputs was reached).

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

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. Our approach also does not consider end-of-pipe measures such as decreasing surface run-off 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: type 1, arable land; type 2, intensively managed grassland; type 3, extensively managed grassland (pastoral land); type 4, natural land (Extended Data Fig. 9b). Critical N inputs were calculated only for land-use types 1 and 2, whereas N inputs to (and N losses from) land-use types 3 and 4 were assumed constant (except for inputs from deposition related to NH_3 emissions from manure and fertilizer inputs to land-use types 1 and 2).

Assumption 4: N emissions and N deposition. Nitrogen deposition within a grid cell was assumed to be homogenously distributed (that is, the same deposition rates for all land-use types within a grid cell). Total N ($NH_3 + NO_x$) emissions were assumed to be equal to total N deposition within a grid cell, that is, we assumed no net intergrid transport of N emissions. NO_x emissions were calculated as the difference between total N deposition and NH_3 emissions. The spatial distribution of N deposition in IMAGE is derived from the TM5 model[60], corrected for the difference in emission estimates 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 about 10% (from 82 MtN yr^{-1} to 90 MtN yr^{-1}), a figure that is well within the uncertainty range for global N deposition estimates[61].

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 2,000 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 to avoid unrealistically high N values (step 4 in Extended Data Fig. 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[62]. We thus set the maximum level for critical N inputs in each grid cell, $\mathrm{Nin}_{(\mathrm{crit,max})}$, to the input required to obtain crop yield potentials at current NUE:

$$\mathrm{Nin}_{(\mathrm{crit,max})} = \mathrm{Nup}_{(\mathrm{Yp})}/\mathrm{NUE}_{(\mathrm{act})} \quad (1)$$

$$\mathrm{Nup}_{(\mathrm{Yp})} = \mathrm{Nup}_{(\mathrm{act})} \times R_{\mathrm{YG}} \quad (2)$$

where R_{YG} is the yield gap ratio, calculated as yield potential (Yp) for arable land or intensively managed grassland divided by the current yield (Ya), $\mathrm{Nup}_{(\mathrm{Yp})}$ is the N uptake at crop yield potential, and $\mathrm{NUE}_{(\mathrm{act})}$ is the current regional NUE, calculated for each grid cell as (crop or grass) 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. [63] (see Supplementary Methods for details). Although 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 surplus (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 NUE. We tested the impact of gradually increasing NUE on the amount of crop production that can be obtained while respecting N boundaries (termed 'safe' crop production) under varying assumptions regarding non-agricultural N losses and the legacy effect (Fig. 5). These scenarios serve to illustrate the sensitivity of our boundaries to alternative modelling assumptions.

Non-agricultural N losses contribute substantially to the exceedance of critical thresholds (Fig. 3 and Extended Data Fig. 6). In the standard calculation of critical N inputs (scenario S1), these losses were assumed constant (year 2010 values; see assumption 2). In an alternative scenario (dcenario S2), 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 whereas 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 run-off and groundwater delivery.

The 'legacy effect' describes the lag time between the implementation of measures to reduce N losses and effects on water quality owing 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 surplus, 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. Although this approach is adequate to capture short-term effects of reductions in N inputs on surface water N load, in the long term, reductions in N inputs will eventually translate into reduced groundwater N loads. In an alternative scenario (scenario S3), we modelled this long-term effect by setting the legacy fraction to zero (thereby implying that total groundwater N delivery changes linearly with N inputs). In scenario S4, we combined proportional reduction in non-agricultural losses with a legacy fraction of zero.

Global and regional minimum crop N demand under a balanced diet

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

$$\mathrm{Nup,\,req}_{(i)} = (\mathrm{pop}_{(i)} \times \mathrm{N}_{\mathrm{demand}} \times (\mathrm{fN}_{\mathrm{veg}}/\mathrm{NUE,\,chain}_{\mathrm{veg}} + \mathrm{fN}_{\mathrm{ani}}/\mathrm{NUE,\,chain}_{\mathrm{ani}})) \quad (3)$$

where, $\mathrm{Nup,req}_{(i)}$ is the crop N production (uptake) required to produce enough protein to be food self-sufficient for region i (kgN yr^{-1}); $\mathrm{pop}_{(i)}$ is the population for region i for the year 2020 (number of persons), obtained from ref. [64]; N_{demand} is the per capita N intake requirement (kgN per person per year), set to 3 kgN per person per year based on ref. [65]; fN_{veg} is the average share of vegetal protein in total protein intake (unitless), set to 2/3 based on ref. [65]; fN_{ani} is the average share of animal protein in total protein intake (unitless), set to 1/3 based on ref. [65]; $\mathrm{NUE,chain}_{\mathrm{veg}}$ is the average food chain NUE for vegetal protein, that is, the share of N in harvested crops that is ingested by humans (unitless), estimated at 45% based on ref. [66]; and $\mathrm{NUE,chain}_{\mathrm{ani}}$ is the average food chain NUE for animal protein, that is, the share of N in harvested crops that is converted into animal protein and ingested by humans (unitless); estimated at 13%, based on ref. [66]. 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, 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.

Data 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 Supplementary Information. All model input files as well as global maps of critical nitrogen surpluses, nitrogen inputs and their exceedances are provided via an online repository at https://doi.org/10.5281/zenodo.6395016. Source data are provided with this paper.

Code availability

The Python modelling code and additional materials are available from the corresponding author upon request.

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

Competing interests The authors declare no competing interests.

Additional information

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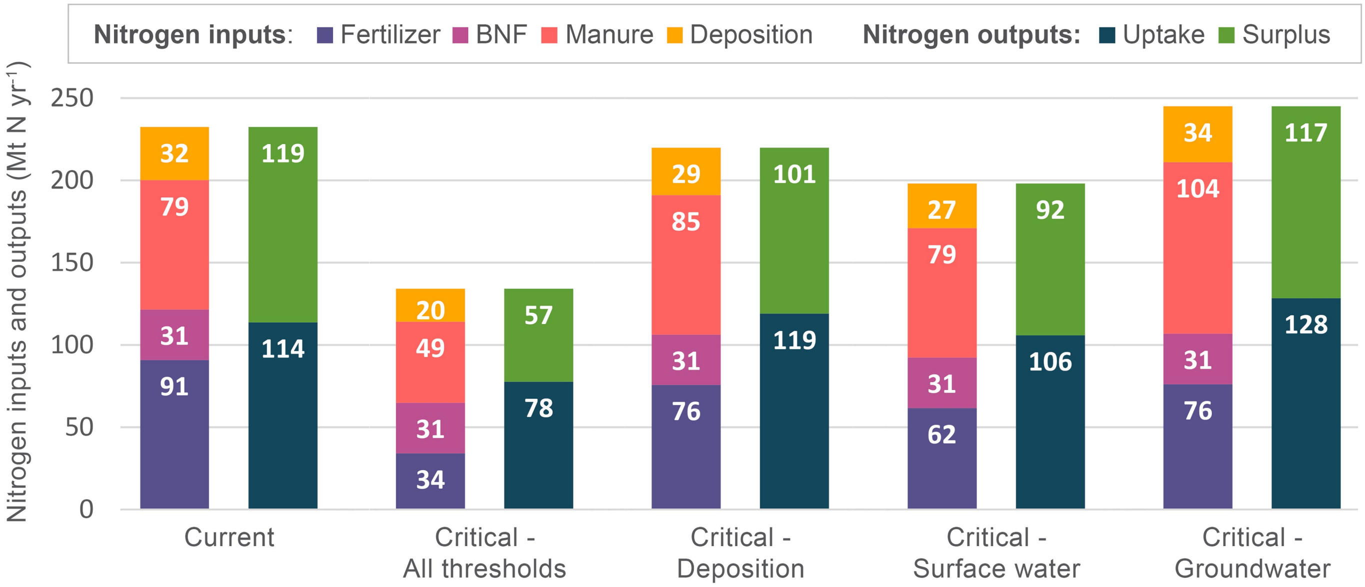
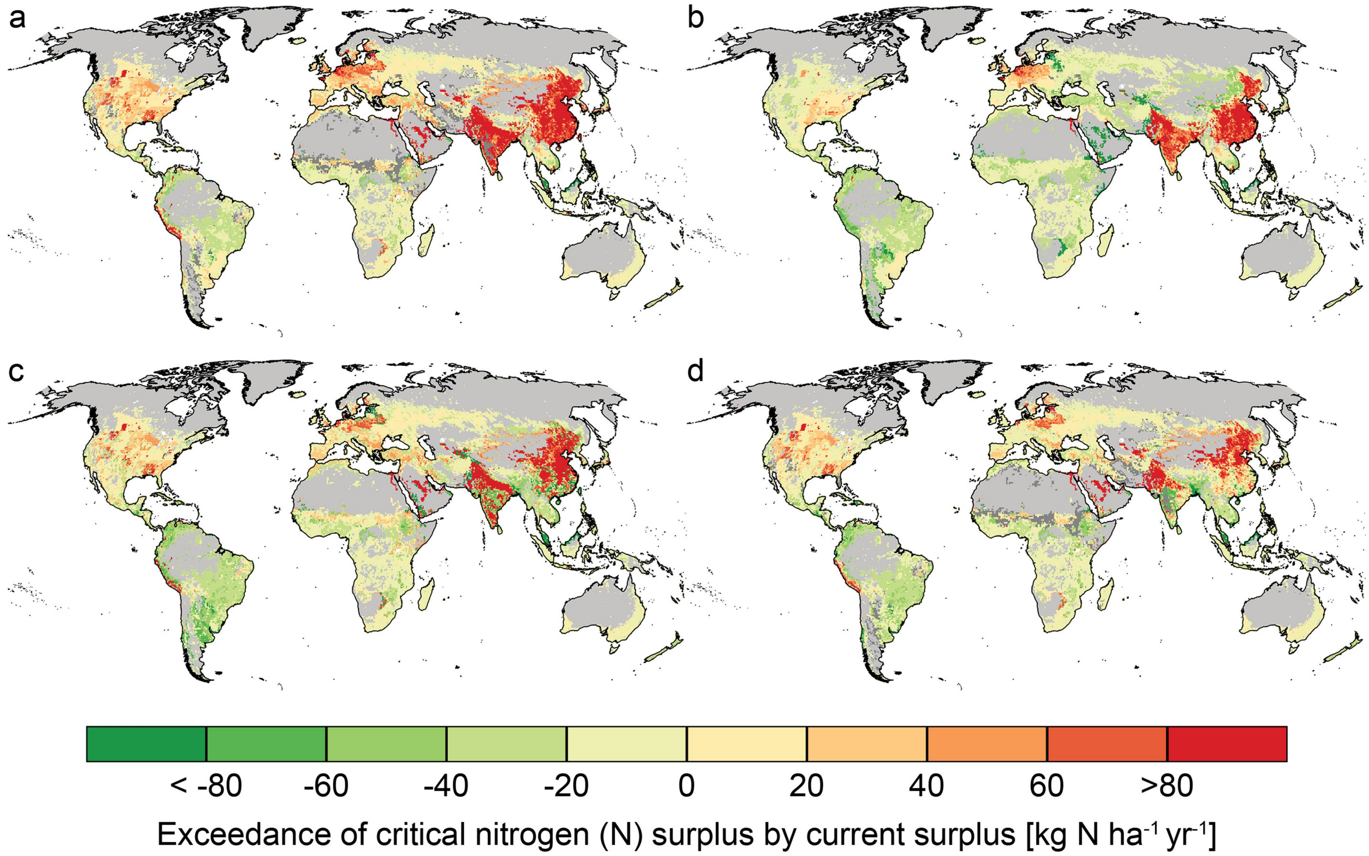
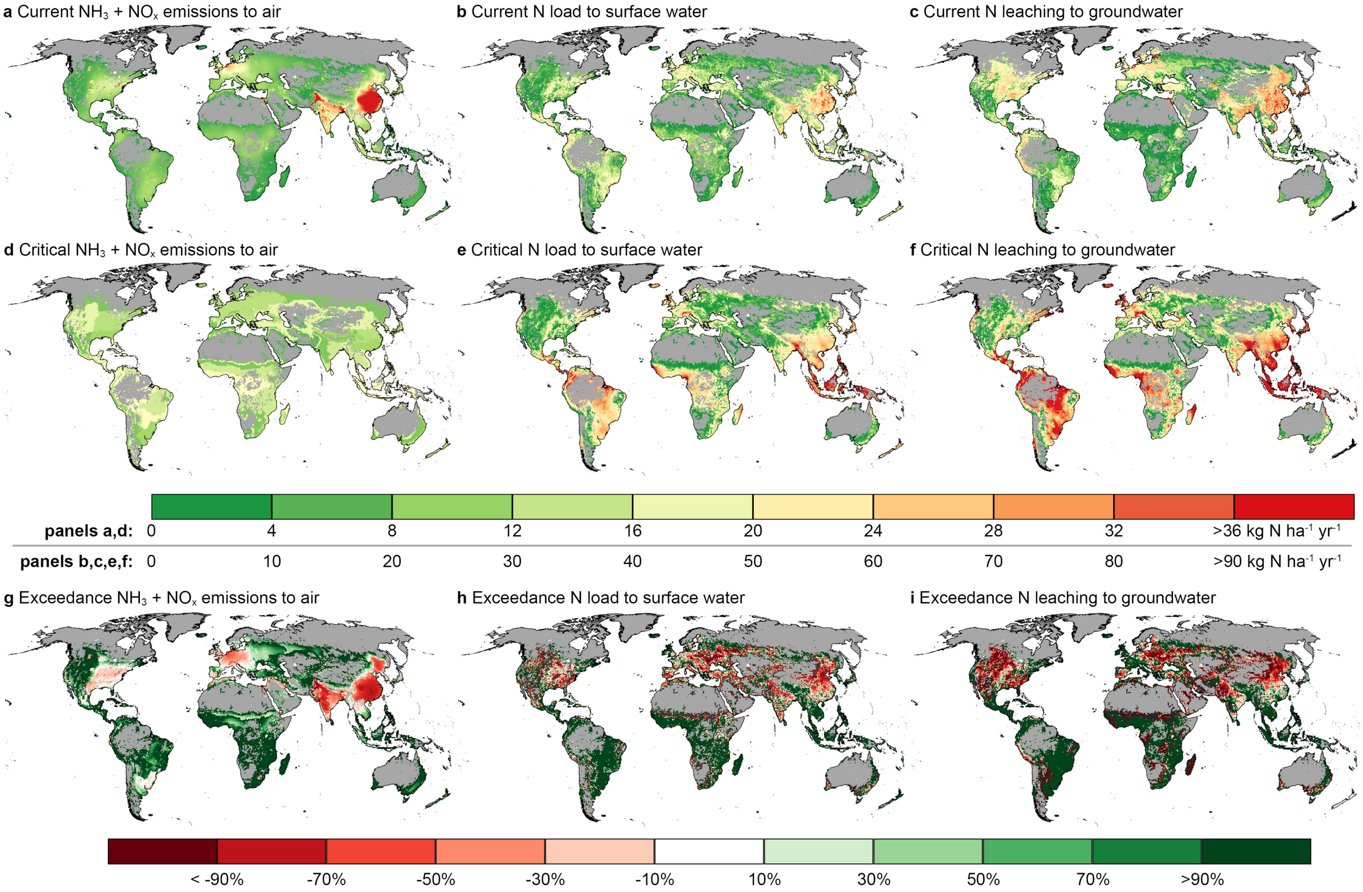


Extended Data Fig. 1 | Current and critical N inputs and outputs. Global current (year 2010) nitrogen (N) inputs (subdivided into fertilizer, BNF, manure and deposition) and N outputs (subdivided into N uptake and N surplus) and critical N inputs and outputs related to three thresholds (N deposition to limit terrestrial biodiversity loss, N load to surface water to limit eutrophication, and N leaching to groundwater to meet drinking water standards), and for all thresholds combined. To convert inputs and outputs in MtN yr^{-1} to average rates in kgN ha^{-1} yr^{-1}, divide by 2.3. Results split into arable land and intensively managed grassland are shown in Supplementary Fig. 2.

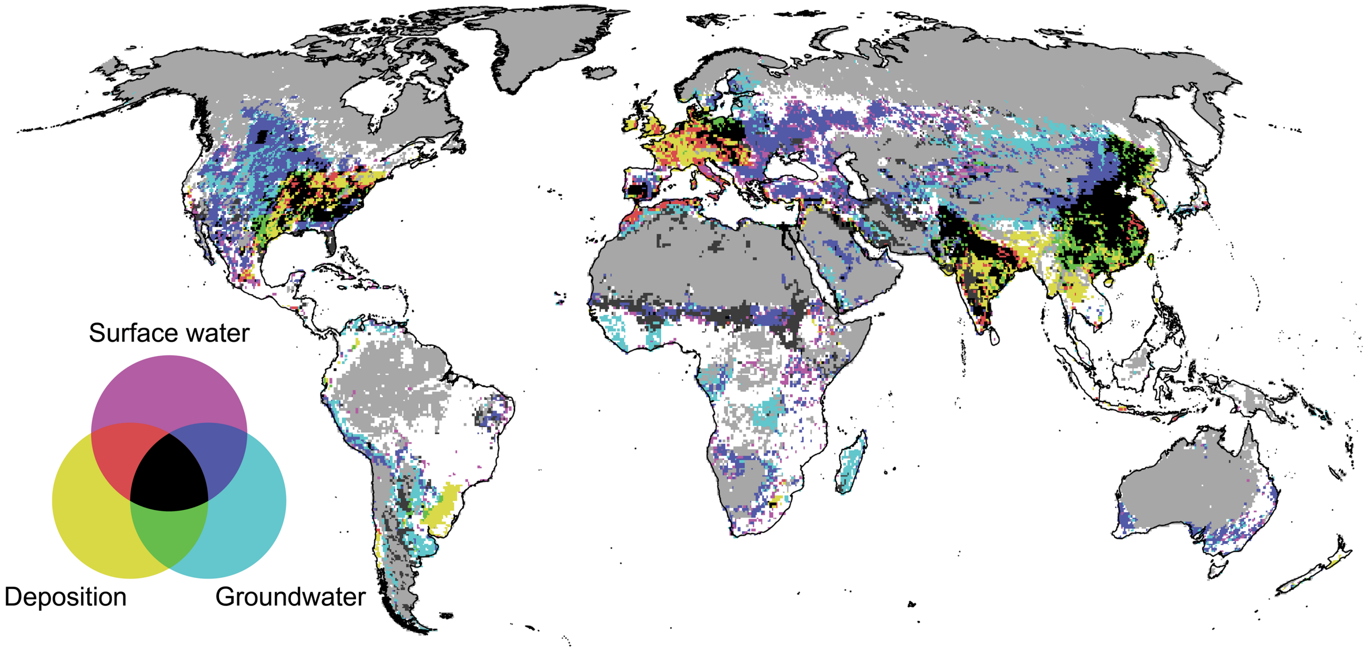


Extended Data Fig. 2 | Exceedance of critical nitrogen surplus per impact. Spatial variation in the exceedance of critical nitrogen (N) surplus in agricultural land by current surplus related to **a**, all thresholds combined (corresponds to Fig. 3a in main text), **b**, critical deposition to limit 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. Positive values indicate by how much agricultural N surplus needs to decrease in order to avoid exceeding environmental thresholds. Negative values indicate by how much agricultural N surplus can increase to allow additional N inputs to close yield gaps without exceeding environmental thresholds. Grid cells with no agricultural land are shown in grey. Separate results for arable land and intensively managed grassland are shown in Supplementary Fig. 3.

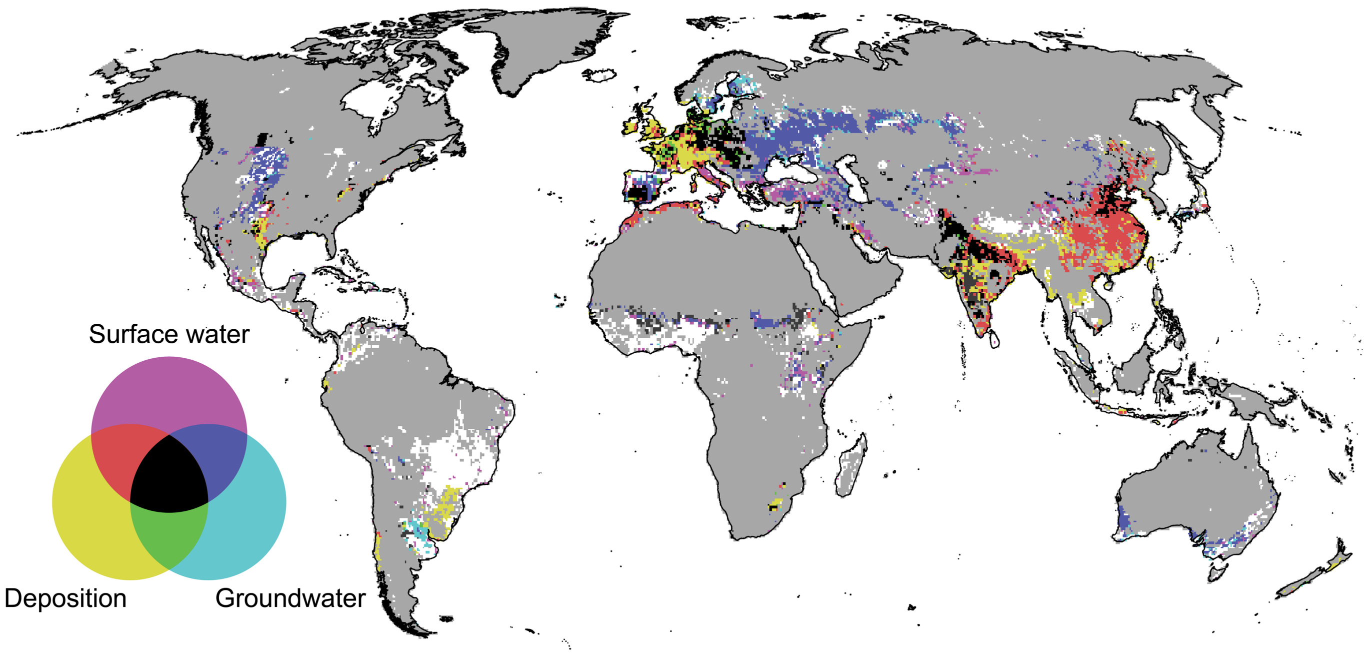


Extended Data Fig. 3 | Current and critical nitrogen losses and exceedances. Spatial variation in **a**–**c**, current nitrogen (N) losses to air and water, **d**–**f**, critical N losses to air and water and **g**–**i**, exceedance of current by critical N losses. **a**, Current total N (NO_x + NH_3) emissions, **b**, critical N emissions to limit terrestrial biodiversity loss, and **c**, exceedance of current by critical N emissions. **d**, Current total N load to surface water from all sources (both agricultural and other sources), **e**, critical N load to surface water related to eutrophication impacts, and **f**, exceedance of current by critical N load to surface water. **g**, Current total N leaching to groundwater, **h**, critical N leaching to groundwater to meet drinking water standards, and **i**, exceedance of current by critical N leaching to groundwater. Grid cells with no agricultural land are shown in grey.

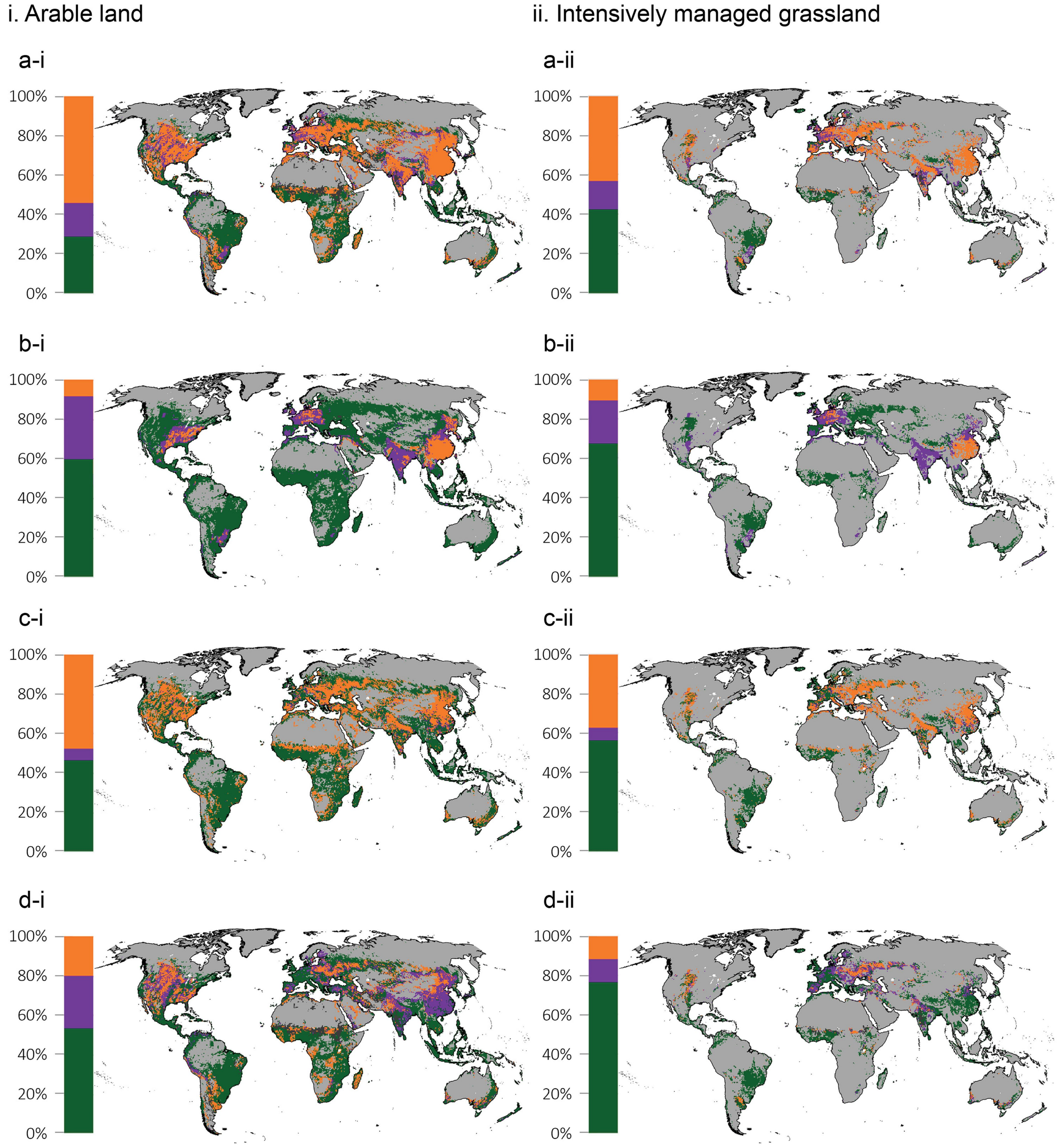
a. Arable land



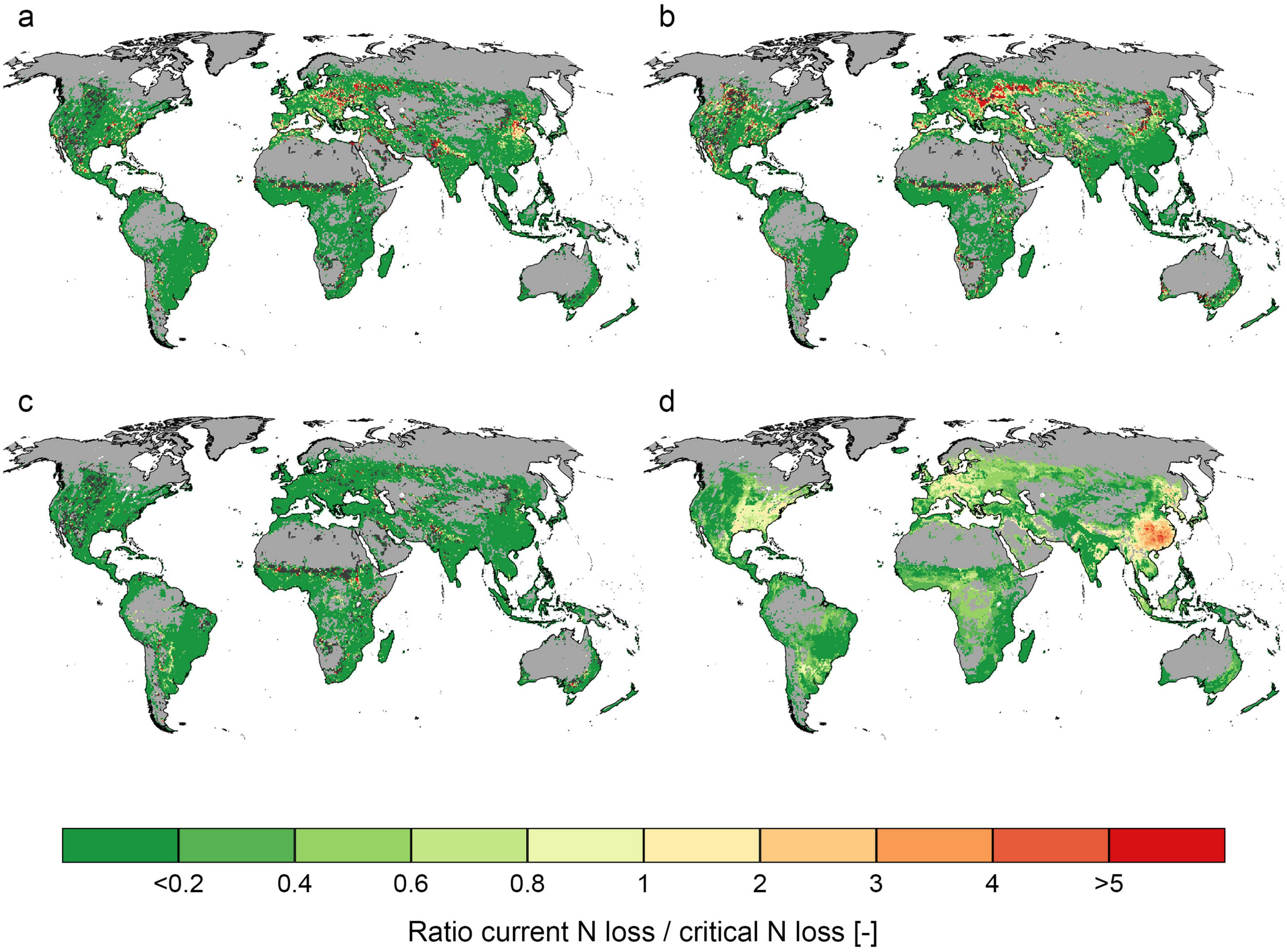
b. Intensively managed grassland



Extended Data Fig. 4 | Threshold exceedance per impact type. Exceedance of thresholds for three nitrogen (N)-related environmental impacts (critical deposition to limit terrestrial biodiversity loss, critical N load to surface water to limit eutrophication, and critical N leaching to groundwater to meet drinking water standards) for **a**, arable land and **b**, intensively managed grassland. Colours indicate how many and which of the thresholds are exceeded: none (white), one threshold (magenta, cyan, yellow), two thresholds (red, blue, green) or all three thresholds (black); see legend for impact type per colour. Grey = areas with no arable land / intensively managed grassland.

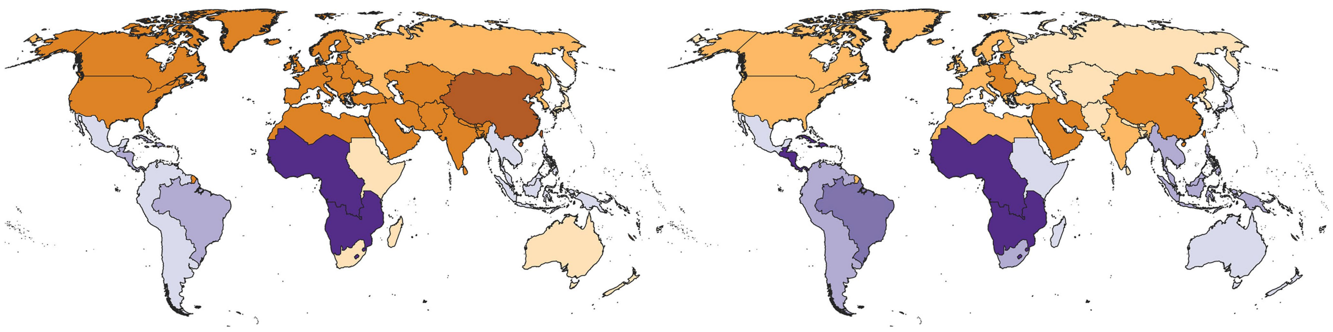


Extended Data Fig. 5 | Option space for agricultural N loss reductions. Possibilities for respecting environmental thresholds by reducing agricultural nitrogen (N) losses alone on (**i**), arable land and (**ii**), intensively managed grassland for **a**, all thresholds combined, **b**, critical deposition 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 total fraction of agricultural land within each category. Grey = no arable land / intensively managed grassland.



Extended Data Fig. 6 | Critical versus current N losses from different sources. Ratio between current (year 2010) N losses from non-agricultural sources and total critical N losses. **a**, Ratio between current N load from wastewater and critical N load to surface water (to avoid eutrophication impacts). **b**, Ratio between current N load from erosion (both from agricultural land and natural land) and critical N load to surface water. **c**, Ratio between current N load from allochthonous organic matter and total critical N load to surface water. **d**, Ratio between current NO_x emissions and total critical N emissions to limit deposition in terrestrial ecosystems and resulting biodiversity loss. A ratio > 1 indicates that N losses from an individual source alone exceed thresholds, and thus that thresholds for surface water N concentrations or N deposition are exceeded even at zero inputs to agriculture. Grey = no agricultural land.

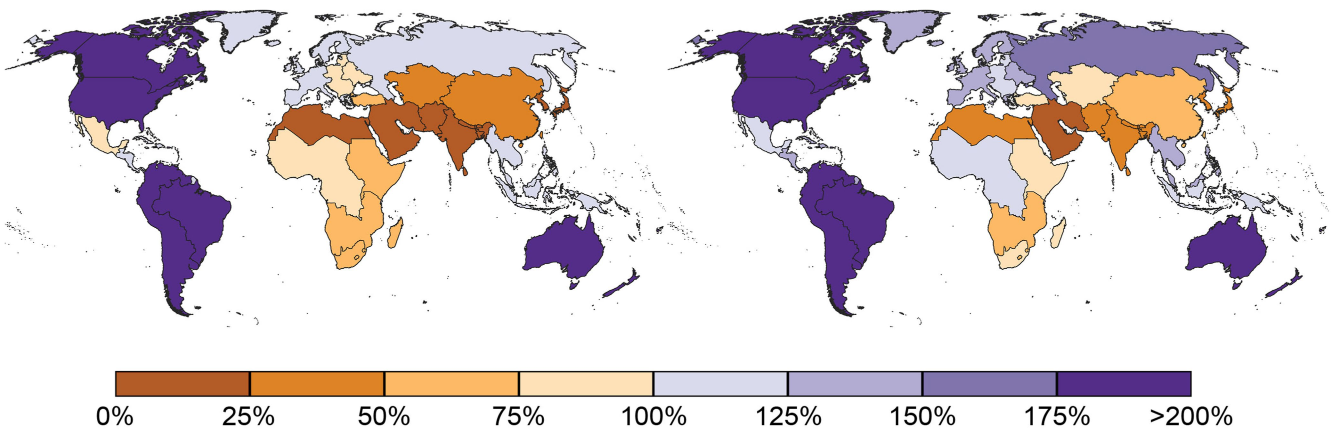
a. Possible crop production within N boundaries as share of current regional crop production



a-i. At current NUE

a-ii. At NUE = 0.90

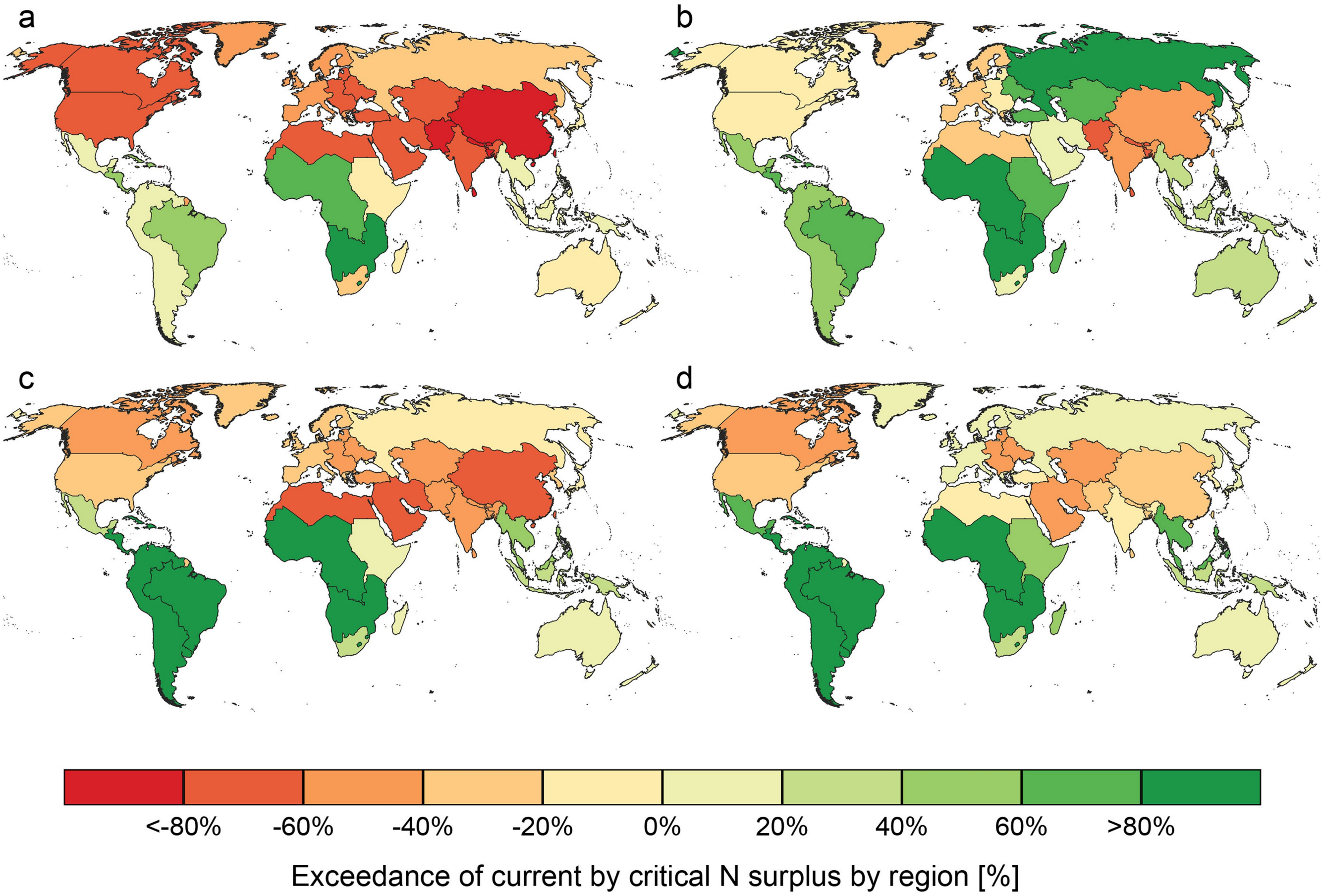
b. Possible crop production within N boundaries as share of estimated regional crop demand (balanced diet)



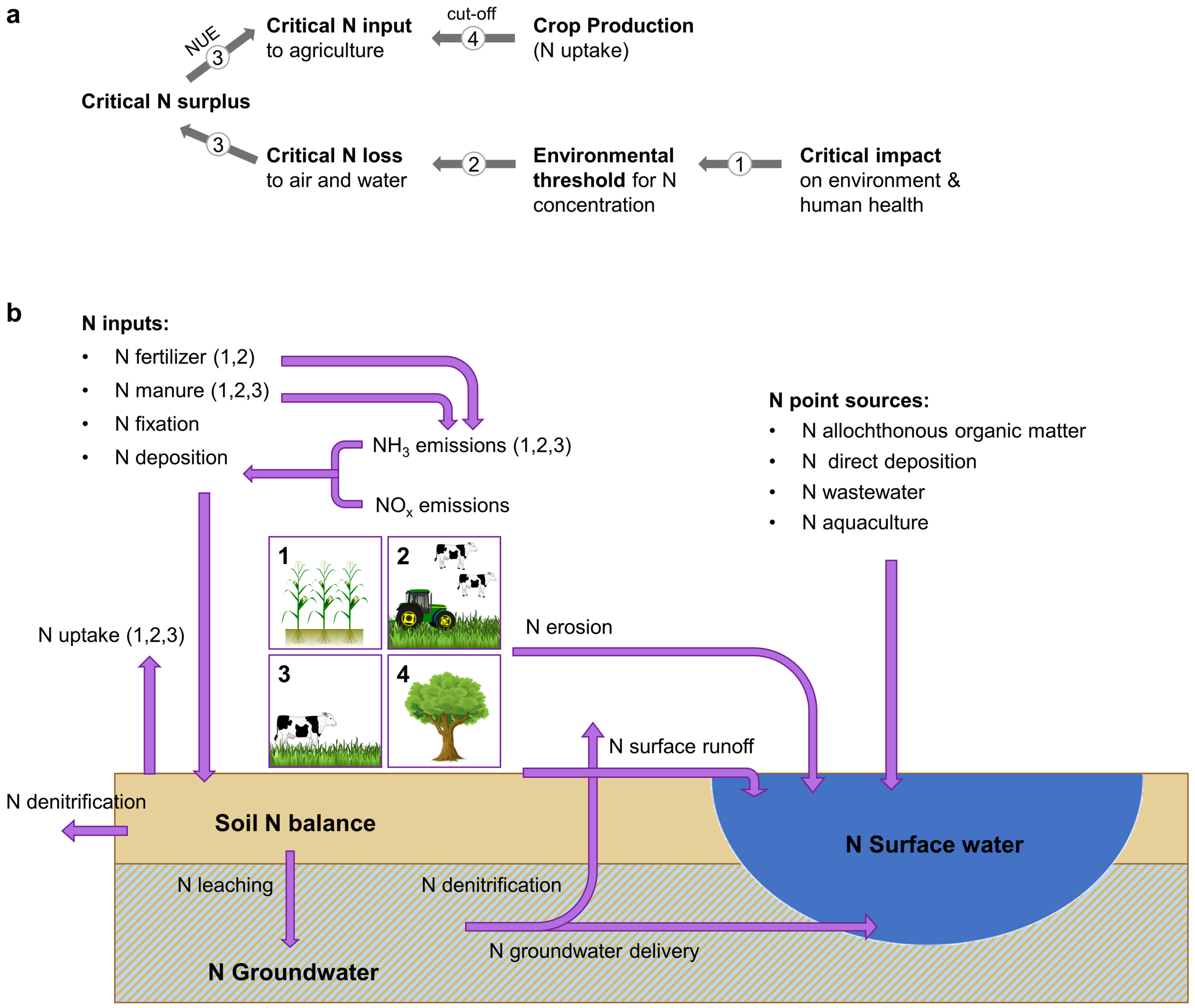
b-i. At current NUE

b-ii. At NUE = 0.90

Extended Data Fig. 7 | Potential for regional crop production within N boundaries. Crop production that can be obtained while respecting boundaries for all three N-related thresholds simultaneously, expressed as a share of **a**, current regional crop production and **b**, minimum regional crop demand under a balanced diet as estimated with Eq. 3 (see Methods), and (i) at current N use efficiency (NUE) and (ii) if NUE is increased to 0.90 everywhere. Results shown are for the assumption of constant non-agricultural N losses and a legacy effect (Scenario S1, see Fig. 5).



Extended Data Fig. 8 | Exceedance of current by critical N surplus by region. Exceedance of current (year 2010) N surplus by critical N surplus, for all agricultural land, aggregated to the level of 26 world regions represented in the IMAGE model. Percentages indicate by how much, on average, current surplus needs to decrease (red) in order to respect environmental thresholds or may increase (green) to allow for additional N inputs to close yield gaps while still respecting thresholds for **a**, all thresholds combined, **b**, critical 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. Current and critical N surpluses for each world region are shown in Extended Data Table 2.



Extended Data Fig. 9 | Schematic illustrations of the modelling approach. **a**, Schematic representation of the steps for back-calculating critical N surplus and critical N input from critical impacts. **b**, Simplified schematic representation of the calculations of N losses in the IMAGE-GNM model used in the back-calculation of critical agricultural N surplus and N input. Boxes represent different land-use types (1 = arable land, = intensively managed grassland, 3 = extensively managed grassland, 4 = natural land).

Extended Data Table 1 | Share of agricultural land where thresholds are exceeded

	Deposition	Surface water	Groundwater	All thresholds
All agricultural land	38%	50%	39%	66%
Arable land	40%	53%	47%	71%
Intensively managed grassland	33%	44%	23%	57%

Share of exceedance for individual thresholds and all thresholds combined (i.e., share of land where at least one of the three individual thresholds is exceeded), for all agricultural land combined and separately for arable land and intensively managed grassland.

Extended Data Table 2 | Current (year 2010) and critical N surplus (all agricultural land) in view of thresholds for three environmental impacts, and for all impacts combined

	Agricultural N surplus (all agricultural land; kg N ha^{-1} yr^{-1})								
IMAGE region	Current N surplus	Critical N surplus: Deposition		Critical N surplus: Surface Water		Critical N surplus: Groundwater		Critical N surplus: All impacts	
Canada	35	34	(-1%)	16	(-54%)	17	(-51%)	14	(-61%)
USA	40	36	(-10%)	25	(-38%)	27	(-33%)	15	(-63%)
Mexico	34	51	(+49%)	43	(+25%)	57	(+67%)	36	(+6%)
Central America	45	76	(+68%)	82	(+82%)	93	(+105%)	66	(+45%)
Brazil	30	50	(+67%)	65	(+114%)	67	(+121%)	48	(+59%)
Rest of South Am.	31	47	(+52%)	75	(+140%)	66	(+112%)	34	(+10%)
Northern Africa	49	32	(-34%)	19	(-60%)	46	(-6%)	11	(-77%)
Western Africa	13	31	(+139%)	31	(+142%)	31	(+143%)	23	(+78%)
Eastern Africa	27	46	(+68%)	30	(+11%)	42	(+54%)	25	(-10%)
South Africa	34	35	(+3%)	41	(+21%)	47	(+39%)	26	(-23%)
Western Europe	50	33	(-34%)	37	(-25%)	50	(+1%)	21	(-58%)
Central Europe	48	40	(-16%)	21	(-56%)	27	(-42%)	12	(-74%)
Turkey	42	69	(+65%)	17	(-58%)	37	(-11%)	15	(-64%)
Ukraine region	27	46	(+70%)	12	(-56%)	12	(-56%)	8	(-72%)
Central Asia	32	56	(+72%)	15	(-53%)	15	(-53%)	8	(-76%)
Russia region	14	30	(+120%)	12	(-12%)	14	(+3%)	9	(-31%)
Middle East	47	53	(+14%)	15	(-67%)	27	(-43%)	10	(-79%)
India	114	59	(-48%)	67	(-41%)	106	(-7%)	31	(-73%)
Korea region	84	62	(-27%)	58	(-31%)	83	(-2%)	43	(-49%)
China region	93	41	(-56%)	35	(-63%)	61	(-35%)	16	(-83%)
Southeastern Asia	56	67	(+20%)	83	(+49%)	94	(+69%)	60	(+7%)
Indonesia region	49	60	(+22%)	64	(+29%)	66	(+35%)	59	(+19%)
Japan	157	165	(+5%)	151	(-4%)	168	(+6%)	135	(-14%)
Oceania	20	27	(+33%)	21	(+4%)	21	(+5%)	17	(-15%)
Rest of South Asia	186	60	(-68%)	99	(-47%)	129	(-31%)	36	(-81%)
Rest of Southern Afr.	12	32	(+165%)	28	(+131%)	26	(+117%)	23	(+97%)
World	**51**	**44**	**(-15%)**	**40**	**(-22%)**	**50**	**(-2%)**	**24**	**(-52%)**

Both current and critical N surpluses are given as rates (kgN ha^{-1} yr^{-1}) rather than totals, for easier comparison between regions with different agricultural areas. Percentages in brackets show relative difference between critical and current N surplus. Corresponding current and critical N inputs are shown in Supplementary Table 1. Note that regional differences in critical N surpluses are caused by differences in both (i) the acceptable N surplus from an environmental perspective and (ii) the cut-off value (maximum critical N surplus) in regions where the environmentally acceptable N surplus is higher than the cut-off value. The former is determined by properties of the agricultural system, sensitivity of the ecosystem, and N loading from non-agricultural sources; the latter is calculated as the current regional N surplus times the regional yield gap (see Methods and Supplementary Discussion for further details).