# Reconciling regional nitrogen boundaries with global food security

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## Abstract

While nitrogen inputs are crucial to agricultural production, excess nitrogen contributes to serious ecosystem damage and water pollution. Here, we investigate this trade-off using an integrated modelling framework. We quantify how different nitrogen mitigation options contribute to reconciling food security and compliance with regional nitrogen surplus boundaries. We find that even when respecting regional nitrogen surplus boundaries, hunger could still be significantly alleviated by 590 million less people at risk of hunger from 2010 to 2050, if all nitrogen mitigation options were mobilized simultaneously. Our scenario experiments indicate that when introducing regional N targets, supply-side measures such as the nitrogen use efficiency improvement are more important than demand-side efforts for food security. International trade plays a key role in sustaining global food security under nitrogen boundary constraints if only a limited set of mitigation options is deployed. Policies that respect regional nitrogen surplus boundaries would yield a substantial reduction in non-$CO_2$ GHG emissions of 2.3 Gt $CO_2$e yr$^{-1}$ in 2050, which indicates a necessity for policy coordination.

## Main text

### Introduction

Sufficiency of food production largely depends on the availability of reactive N (Nr). Mineral N fertilizers play a key role in ensuring food security[1] (UN Sustainable Development Goal (SDG) 2 "Zero hunger"). N surpluses, defined as the N input into agricultural systems minus the N removal in agricultural products (crops, grass forage and animal products) are released to the environment. Excess N contributes to atmospheric pollution[2,3] ($NH_3$ and $NO_x$; hindering progress on SDG3 "Good health and well-being"), vegetation degradation and biodiversity losses[4] ($NO_x$; SDG15 "Life on land"), and to climate change through $N_2O$ emissions[5] (SDG13 "Climate action"). N excess also causes ground and surface water degradation[6-8] mainly through $NO_3^-$ surface runoff and leaching, and impacts freshwater (lakes) and marine ecosystems through river transport[9], critical to SDG6 ("Clean water and sanitation") and SDG14 ("Life below water"). Thus, N cycle management is an essential part of the wider sustainable development agenda.

The planetary nitrogen boundary[10] has been substantially transgressed[11]. In absence of nitrogen mitigation actions, this environmental pressure will likely increase[12]. Despite the fact that this concept is debated[13], we consider the global planetary nitrogen boundary as a good aggregate proxy of the severity of the problem. However, regional heterogeneity needs to be considered in the boundary definition[14,15]. For example, in Sub-Saharan Africa (except South Africa) the limited access to, and affordability of, synthetic N fertilizer currently keeps the N level in water in the "safe" zone. On the contrary, severe nitrogen-related water pollution has occurred in Europe[16] and China[17] due to high levels of mineral N fertilizer use (Europe and China), increased household wastes (China), and low nitrogen use efficiency (China). Such regional risks call for translating the boundary framework to the regional level accounting for their climatic, environmental, and socioeconomic circumstances.

Policies targeting mitigation of N pollutions have been successfully implemented in many regions and countries[18]. The role of Nr in future food supply has been investigated at regional[19,20] and global levels[19,21-23]. However, the implications for food security of reaching environmental targets (e.g., avoiding water pollution) have received less attention. Limiting N inputs without improving nitrogen use efficiency (NUE) may reduce food production, increase food prices, and finally lead to hunger. Ref[14] derived a global estimate of Nr inputs that respects food security and a N boundary to protect biodiversity, while calling for a detailed approach including representation of the full N cycle. Ref[24] and ref[25] recently quantified the theoretical biophysical potential of providing sufficient food calories for human population at current level[24] or for 10 billion people[25] within multiple environmental boundaries, but without considering aspects of regional production, market effects and food security. Ref[25] suggests the use of integrated assessment modelling as the next step.

Here, we provide an integrated global assessment of food security and regional N surplus boundaries accounting for a comprehensive set of food system drivers. We have newly developed a detailed representation of the N cycle (Fig. 1; see Methods) in the global land-use model GLOBIOM (Global Biosphere Management Model[26]). In our approach, we assimilate the regional N surplus boundary with a critical N concentration in runoff (through surface runoff and leaching N flow) to surface waters from agricultural land of 2.5 mg N $l^{-1}$ following refs[27,28] (see Methods). Four indicators informing on two dimensions of food security are used: two indicators for food availability, the mean dietary energy availability and the mean dietary protein availability, and two indicators for food access, the population at risk of hunger and the food price[29]. A set of scenarios was developed to help understand the trade-offs between environmental and food security targets: 1) a business-as-usual (BAU) scenario following the middle-of-the-road shared socio-economic pathway (SSP2[30]) as a baseline; 2) a set of water quality protection scenarios where N surplus is constrained within regional N surplus boundaries (NrRB), differentiated by the assumptions about N mitigation strategies in place, following the socio-economic drivers assumptions of the BAU scenario (Table 1). To account for climate uncertainty, we ran a series of sensitivity simulations. Our scenarios do not explicitly address disruptors such as COVID19. It remains unclear to what extent such events could have long-lasting impacts on agricultural markets[31].

## Results

### *Regional N surplus boundaries*

We derived regional N surplus boundaries which, at the global scale, aggregate to 248 Tg N $yr^{-1}$ based on a calculated critical N runoff (hereafter, N runoff stands for surface runoff and leaching N flow) to surface water, using a critical N load in runoff of 2.5 mg N $l^{-1}$ (see Methods; Fig. 2 and Supplementary Table 5). We find that the regional critical N surplus has been far exceeded already in dry climate zones (Middle East, North Africa, and southern Europe), and in both high N input regions (India, China, and western Europe) and in low NUE regions (India and China). Large reductions in N surplus (relative to the 2010 value) would be needed in these regions to stay within the regional N surplus boundary (Fig. 2). Agricultural expansion and intensification (e.g., enhanced N inputs to improve crop yield) would be possible, without exceeding the critical regional N concentration in runoff, in Oceania, Southeast Asia, Latin America and the Caribbean, and Sub-Saharan Africa (except South Africa). Such an expansion might however lead to undesirable impacts on soil and vegetation carbon stocks and biodiversity.

### *Food security implications without and with N constraints*

Under BAU global crop production and livestock production are projected to increase by 69% and 74% by 2050 compared to 2010 (Fig. 3a). International trade of crop products is projected to increase by 121%, while trade of animal products would increase by 90% by 2050, compared to 2010 (Fig. 3b). From 2010 to 2050, the largest increase in net crop import is projected in Eastern Asia, followed by South Asia, and Middle East and North Africa, while Latin America and North America are the largest and second largest exporting regions (Supplementary Figure 1). Europe is projected to turn from a net importer in 2010 to a net exporter by 2050. For animal products, increase in net import from 2010 to 2050 is mainly by South Asia and Sub-Saharan Africa, while Europe and Latin America would become major exporters (Supplementary Figure 2). We calculated an increase in the global mean dietary energy availability of 14% (from ca. 2800 to 3200 kcal per person per day; Fig. 4a), an increase in the global mean dietary protein availability of 14% (from 78 to 89 g protein per person per day; Fig. 4b), and a decrease in the population at risk of hunger from 824 million to 288 million from 2010 to 2050 (a reduction of 536 million; Fig. 4d). Food prices are projected to decrease in Eastern Asia (-16%) and developed regions (-1% to -14%; Supplementary Figure 3), slightly increase in other developing regions (7% to 12%), and decrease by 4% globally between 2010 and 2050 as improved productivity compensates for the food demand increase.

In the NrRB-BAU scenario, limiting regional N surplus below a critical boundary is projected to lead to a 13% lower crop production and a 13% lower livestock production by 2050, compared with the BAU scenario (Fig. 3a). These values would result in food availability of 2900 kcal per capita per day and 80 g protein per capita per day globally by 2050, food prices increased by 26% compared to 2010, and a population of 741 million at risk of hunger (8.1% of the 9.1 billion total population by 2050 under BAU, only 82 million less compared to 2010; Fig. 4a-d).

Agricultural production strongly decreases compared to the BAU scenario, and food supply largely relies on agricultural imports mainly in South Asia, Eastern Asia, and the Middle East and North Africa (Supplementary Figure 1 and 2). In absence of dedicated N-surplus mitigation strategies, international trade act as the main adjustment mechanism. International trade in crop and animal products compared to the BAU scenario is projected to increase by 36% and 117%, respectively (Fig. 3b), in spite of the lower global production (Fig. 3a). Food prices are projected to rise very unevenly across regions reflecting the different levels of the critical regional N surplus (Supplementary Figure 1). South Asia sees a strong decrease in dietary energy and protein availability leading to a large population at risk of hunger (495 million) by 2050 under the NrRB-BAU scenario (Fig. 5). Strongest decrease in dietary energy (by -19%) and protein (by -20%) availability compared to the BAU scenario is projected in Eastern Asia by 2050 under the NrRB-BAU scenario (Supplementary Figure 4-5). Eastern Asia and the Middle East and North Africa are projected to have populations at risk of hunger of 94 million and 13 million, respectively, by 2050 under the NrRB-BAU scenario, which are lower values than those in 2010, but still 9.4 times and 2.1 times those projected under the BAU scenario, respectively.

In Southeast Asia, Sub-Saharan Africa, and Latin America and the Caribbean, the regional critical N surplus is much higher than the current level in respect of N runoff to surface water (Fig. 2), therefore allowing further increases in agricultural production through expansion and/or intensification. However, this does not prevent a larger population being projected to be at risk of hunger in Southeast Asia (53 million under the NrRB-BAU scenario compared to 23 million under the BAU scenario), and Sub-Saharan Africa (76 million under the NrRB-BAU scenario, compared to 60 million under the BAU scenario). In these two regions, we projected a lower dietary energy and protein intake under the NrRB-BAU scenario than that under the BAU scenario (Supplementary Figure 4-5), in spite of similar or even higher agricultural production (Supplementary Figure 1 and 2). Similar dynamics are projected for Latin America and the Caribbean, albeit with a smaller impact on hunger.

For the Former Soviet Union region, the number of people at risk of hunger remains small. Zero hunger in Europe, North America and Oceania is due to model assumptions which follow the FAO approach (see Methods). The level of crop and animal production in North America, and Oceania is projected to be even higher under the NrRB-BAU scenario than that under the BAU scenario (Supplementary Figure 1 and 2), and is explained by two factors: i) the potential for additional production within regional N boundaries (i.e., environmental capacity to produce more; $RI_{Nsurplus\ ,r} > 1$), ii) the demand for food imports by regions with stringent N constraints.

### *The effects of N mitigation strategies*

Combining all mitigation strategies considered in this study (the NrRB-Combined scenario) can entirely eliminate the negative impacts on food security from constraining regional N surplus. The combination reduces the population at risk of hunger to 234 million by 2050, which is 590 million lower than that of 2010, even 54 million lower compared to the BAU scenario, and 507 million lower than under the NrRB-BAU scenario. By 2050, food prices would be 19% lower compared to 2010 (i.e., 14% below their 2050 levels under the BAU scenario). The global N surplus would be reduced to 65 Tg N $yr^{-1}$ by 2050, which is 58% of the value in 2010 (155 Tg N $yr^{-1}$). The regional N surplus would still hit the regional boundary in the Middle East and North Africa (i.e., food production is still limited by the critical N surplus; Supplementary Figure 6). The global N fertilizer demand would be reduced to 35 Tg N $yr^{-1}$ by 2050 (35% of the N fertilizer use of 100 Tg N $yr^{-1}$ in 2010). In addition, combining all strategies to reach regional N boundaries would provide a large contribution to achieving the goals of the Paris Agreement. While in 2050 the expected reduction of agricultural non-$CO_2$ ($CH_4$+$N_2O$) emissions in 1.5 °C target mitigation pathways lies in the range of 2.9-4.9 Gt$CO_2$e $yr^{-1}$ [32], the NrRB-Combined scenario reaches in the same year a non-$CO_2$ GHG emissions reduction of 2.3 Gt $CO_2$e $yr^{-1}$ from non-$CO_2$ GHG emissions in comparison to the BAU scenario. From this 2.3 Gt $CO_2$e $yr^{-1}$, 1.0 Gt $CO_2$e $yr^{-1}$ of $CH_4$ reductions from decreased livestock numbers and 1.3 Gt $CO_2$e $yr^{-1}$ of $N_2O$ reductions due to less mineral fertilizer, less manure managed and applied, and a higher NUE (i.e., less losses; Fig. 4f). Under the NrRB-Combined scenario, results on food security indicators, N surplus, N fertilizer demand, and agricultural non-$CO_2$ emissions are almost the same as those under the BAU-Combined scenario without constraining the regional N surplus. The only differences came from the Middle East and North Africa, where food security was still slightly limited by the low critical N surplus (Fig. 5b).

Under N constraints, most individual N mitigation options considered here can improve global food security by 2050, compared to the NrRB-BAU scenario, by reducing the population at risk of hunger (67 to 420 million less undernourished) and food prices (by 7% to 26%; Fig. 4c-d). All of these scenarios alleviate global environmental pressure by different magnitudes through decreasing N surplus (by 0 to 45 Tg N $yr^{-1}$; Fig. 4f), although the effects on agricultural non-

$CO_2$ GHG emissions can be different in sign depending on the scenario (from +0.2 Gt $CO_2$e $yr^{-1}$ increase to -0.7 Gt $CO_2$e $yr^{-1}$ reduction; Fig. 4g). The individual efforts reduce global N fertilizer use by 4 to 45 Tg N $yr^{-1}$ by 2050, compared to that under the NrRB-BAU scenario. The impacts of these strategies are even more disparate at the regional level (Supplementary Figures 1-8).

Reaching targeted high NUE (the NrRB-NUE scenario) is the most effective option considered here to reduce the population at risk of hunger (-420 million), N surplus (-45 Tg N $yr^{-1}$), and N fertilizer demand (-45 Tg N $yr^{-1}$). The scenario significantly increases food production in regions with low limits of N surplus compared to the NrRB-BAU scenario (i.e., Middle East and North Africa, South Asia, Eastern Asia; Fig. 2) and effectively reduces their population at risk of hunger (Fig. 5).

Improving manure recycling (the NrRB-Manure scenario) directly reduces N surplus from manure management, thus allowing more N surplus in cropland and pasture systems given the total regional N surplus is constrained, particularly in regions that are already close to or above the critical N surplus. Compared to the NrRB-BAU scenario, it reduces the population at risk of hunger by 67 million (mainly in China and India.

Improving sewage treatment and recycling (the NrRB-Sewage scenario) does not greatly affect the food security indicators as it does not change N surplus over agricultural land. However, it reduces the direct discharge of N into surface water (point loads). The recycling of removed N from wastewater treatment plants has a small effect on reducing fertilizer demand (-4 Tg N $yr^{-1}$).

Reducing harvest loss increases the supply without using any additional land and fertilizer. Reducing food waste throughout the supply chain effectively reduces the agricultural production needed to satisfy the human food demand. Therefore, more people can be fed with less food production reducing the population at risk of hunger by 224 million compared to the NrRB-BAU scenario. The scenario reduces undernourishment in all regions (Fig. 5).

Changing diets towards less animal products (the NrRB-DietShift scenario) reduces the population at risk of hunger by 208 million compared to the NrRB-BAU scenario. This large reduction is driven by the fact that a plant based diet make a meal more affordable as the total system costs of food production are reduced. Given the fact that animal products have low N efficiency and high GHG emission intensity compared to crop production, less meat and milk consumption can also reduce GHG emissions to 4.2 Gt $CO_2$e $yr^{-1}$ (Fig. 4g). A decrease in global

N fertilizer demand (-5 Tg N yr$^{-1}$) is projected by 2050, compared to that under the NrRB-BAU scenario, as a result of two contrasting effects: (1) feed demand reduction from crop-based products; (2) increased mineral N fertilizer demand due to reduced availability of manure (caused by lower livestock numbers).

### *The effects of climate change*

Compared to baseline simulation (BAU) without accounting for climate change impacts, price changes in the RCP8.5 scenario (+4%) lead to reductions in global dietary energy (-2%) and protein (-1%) availability by 2050, and an additional 63 million people are projected to become undernourished. Limiting regional N surplus below a critical boundary is projected to amplify the negative impacts of climate change. Compared to the NrRB-BAU scenario, +6% price increase and an additional 117 million people undernourished are projected in the RCP8.5 scenario (Fig. 4d). However, such additional negative impacts from climate change can be alleviated when individual N mitigation strategies is implemented. When combining all mitigation strategies, climate change only caused an additional 32 million people undernourished in the RCP8.5 compared to that under the NrRB-Combined scenario without climate change (Fig. 4d).

The climate impacts on food security differ among regions. Under the RCP8.5 climate scenario, crop dry matter production is projected to be significantly lower than those without climate change in North America, Southeast Asia, South Asia and Sub-Saharan Africa, while Oceania, the Former Soviet Union region, Latin America and Europe is projected to benefit from climate change with higher crop production (Supplementary Figure 1). Through adjustment in trade, supply and demand, high global warming level under the RCP8.5 climate scenario lead to 1) higher global food price 2) lower dietary energy and protein availability in North America, Southeast Asia, South Asia, and Sub-Saharan Africa, and 3) additional people become undernourished in South Asia (+50 million), and Sub-Saharan Africa (+10 million), and Southeast Asia (+3 million; Fig. 5 and Supplementary Figure 3-5). Climate change impacts on food security are less pronounced under intermediate climate change (i.e., RCP4.5 and RCP6.0 scenario), and are marginal under the low global warming level (RCP2.6 scenario; Fig. 4a-d).

## Discussion

Although our study represents the state of the art in this area, there are some additional aspects of water quality, food security and even additional sustainability dimensions that could be considered. For example, the critical N surplus, and the associated constraints, applied in the model are still highly aggregated (37 regions are represented in the model), not allowing for a spatially-explicit representation of water pollution. The critical N concentration may still be exceeded in parts of a region (hotspots of water N pollution; e.g., the northeastern United States and the Mississippi river basin[33]). We applied a time-fixed coefficient of variation of the food distribution of dietary energy consumption within countries[34]. In fact, pursuing a more equitable food distribution by reallocating food deficits and excesses (e.g., through reducing over-consumption), is another effective way of reducing food insecurity and environmental impacts[35]. Production and related land expansion in the regions well within the N boundary could lead to biodiversity loss and carbon emissions from land conversion. These additional trade-offs, which are not explicitly considered here, reinforce the importance of integrated strategies for a more sustainable and equitable development. Despite these potential extensions, our study provides robust assessment on the trade-offs between nitrogen required for ensuring food security and the risk of nitrogen losses to cause environmental pollutions, and quantify how different N mitigation strategies contribute to reconcile the trade-offs.

Our analysis indicates that environmental targets of limiting N surplus require large scale deployment of dedicated N mitigation strategies in order to avoid a strong increase in the risk of food insecurity. Without these measures, the global per capita dietary energy availability would be largely reduced with high levels of food prices and the undernourished population. This tension between respecting regional nitrogen surplus boundaries and food security would be even larger than the one between food security and stringent climate mitigation targets where population at risk of hunger was projected to reach 280-500 million and 310-540 million in 2050 under the 2°C and 1.5°C climate mitigation scenarios, respectively[36].

Our results further suggest that if efforts to reduce N surplus in middle-income developing regions such as South Asia, Middle East and North Africa or Eastern Asia, were based on reduced domestic supply rather than improving NUE, this could have severe spillover effects on food security in least developed regions such as Sub-Saharan Africa and Southeast Asia (i.e., these two regions have similar or even higher agricultural production, but lower food consumption and more undernourished under the NrRB-BAU scenarios than under the BAU scenario; Fig. 5 and Supplementary Figure 1-5). Increased production leads to higher marginal cost of production due to the higher land prices caused by an increased demand for land and less productive land is being brought into production. An increased marginal cost of production then translates into higher domestic food prices leading to reduced food consumption. The magnitude of the effect will depend in the sensitivity of the domestic demand to food prices, expressed through the price elasticity of the demand. The latter typically decreasing with the level of the income (as shown in the meta-analysis of ref[37]).

Our results further highlight that policies promoting the mobilization of a comprehensive set of nitrogen mitigation options would allow compliance with the proposed nitrogen sustainability boundary without worsening food security across all world regions. This reconciliation is achieved through domestic efforts on both increasing nitrogen use efficiency in agriculture (improving NUE and manure recycling) and decreasing demand (shifting towards diets with less animal products, and reducing harvest loss and food waste), combined with adjustments in international trade of agricultural products, the latter being particularly important if not all mitigation options are deployed (Fig. 3b). The latter underlines the important role of trade in global food security, while the environmental impacts transmitted via markets should also be considered. Furthermore, the N mitigation strategies not only reduce food insecurity, but also have other environmental and economic co-benefits beyond the impacts of N pollution such as reducing agricultural GHG emissions, N fertilizer use, and the associated energy consumption of the fertilizer industry[38,39].

According to our results, increasing NUE is the most effective strategy to reduce undernourishment while respecting the N-boundaries in regions such as China or India. This supply-side effort plays a more important role on alleviating food insecurity than demand-side efforts of diet shift and reduced waste when introducing regional N targets. Policies facilitating and encouraging multiple N mitigation options need to be implemented simultaneously to deal with N pollution[18], but face substantial institutional and technical challenges[40] (see Supplementary Notes 1 for detail discussion).

## Methods

### *Overall methodology*

We used the global dynamic land-use model GLOBIOM to assess the risk of food insecurity when meeting N boundaries, and to investigate the effects of various sustainability options. Initially, we improved GLOBIOM by adding extended representations of the N cycle in global agricultural systems. The model was then applied under the constraint of meeting the regionally derived N boundaries given by an acceptable N surplus based on a critical N limit in surface water. Our indicators of food security are represented by the dietary energy availability and the dietary protein availability (indicators for food availability), and the number of people at risk of hunger and food prices (indicators for food access).

### *GLOBIOM description*

GLOBIOM (Global Biosphere Management Model) is a global partial equilibrium model allocating land-based activities, i.e. management of cropland, livestock systems and forestry, under land availability constraints, to maximize the sum of producer and consumer surpluses[26]. The model relies on a geographically explicit representation of land-based activities at a 0.5°× 0.5° grid cell resolution. Agricultural production is represented for 18 crops (barley, dry beans, cassava, chick peas, corn, cotton, groundnut, millet, oil palm, potatoes, rapeseed, rice, soybeans, sorghum, sugar cane, sunflower, sweet potatoes, wheat) and seven types of livestock (dairy and other bovines - comprising cattle and buffalos, dairy and other sheep and goats, laying hens and broilers, and pigs), the outputs of which are processed to supply the food, feed, and bioenergy markets. Each of the activities is described at grid cell level through technological parameters provided by a specific biophysical model: EPIC[41] for crops, EPIC and CENTURY[42] for grassland, RUMINANT[43] for livestock, and G4M[44] for forestry. For detail description of the model including the biophysical models, the representations of land use competition and trade, exogenous scenario drivers and their assumptions, and endogenous model behaviour, see Supplementary Notes 2. Our socio-economic narrative is parameterized following the middle-of-the-road shared socio-economic pathway (SSP2[30]). It includes quantified assumptions of economic and population developments, energy intensity improvements, energy resources, bioenergy resources and use, technology cost developments, and land-use developments (see Table 1 of ref[30] for detail). The detailed quantifications and assumptions in SSP2 on the development of crop yields and input intensity, livestock feed conversion efficiency and productivity growth, as well as food demand and losses and wastes (including their differences to other SSPs) can be found in section 2.7 and 4.2, and Table 1 of ref[30]. The SSP2 implementation compares to the other SSPs (and how GLOBIOM differs from IAMs) for demand and yields has been extensively discussed in refs[45-48]. The model is run in a dynamic, recursive setting with ten-year steps over the 2000–2050 period with outputs like market variables (including demand, supply, trade, and prices), and environmental variables such as land and water use, GHG emissions and sinks, and nitrogen balance. All the agricultural and forestry products and their trade are expressed as biomass flows (in kg fresh/dry matter).

Extensive information about the model can be found in earlier studies[26,43,49] and on www.globiom.org.

Here, we implemented the N cycle in global agricultural systems, including cropland, pasture and livestock systems, and in related human food systems in GLOBIOM (Supplementary Notes 3). We transformed all relevant biomass flows represented in GLOBIOM into N flows, and further accounted for additional N flows, including crop residues, biological nitrogen fixation (BNF), manure and fertilizer application, atmospheric deposition and N losses through leaching and gaseous of $NH_3$, NO, $N_2O$, and $N_2$. Figure 1 illustrates the N flows implemented. Detailed descriptions of the N flows, with an overview of the mass-balance equations, are presented in the Supplementary Notes 3, while the data sources are given in the Supplementary Tables 1-4. For future projections, the model is capable of simulating the food, feed, and livestock production, demand, and associated land use (i.e., cropland and pasture area). Since land-use models like GLOBIOM do not include a process-based representation of the soil N cycle, we assumed a long-term balance between soil input and output, where mineralised N was taken up by plants and fully returned to the soil through plant residues, and no net accumulation or loss of soil N pool for cropland and pasture in the projections. This is also justifiable from the perspective of a sustainable use of agricultural land. All N flows, other than fertilizer use, can also be simulated. To project the future fertilizer use by cropland and pasture, the regional N use efficiencies for the year 2010 are used as an exogenous scenario parameter, and their future development ($NUE_{r,t}$; where $t$ indicates the future period) depends on the scenario storyline. The future N removal and input flows other than mineral fertilizer application are simulated by the model (e.g., yields, BNF, deposition after volatilization, manure recycling), and then mineral fertilizer application is adjusted for cropland and pasture to match the exogenous regional NUE assumptions (i.e., $NUE_{r,t}$ for region $r$ in period $t$; see Supplementary Note 3 for detail).

The historical agricultural N flows from GLOBIOM for the year 2000 and 2010 were checked against those from previous studies and statistics (Supplementary Note 4; Supplementary Table 7-9). The global N flows, including mineral N fertilizer, manure N application/manure N recycling rates, BNF, atmospheric N deposition, crop removal and residues, N surplus, N excretion, N gaseous emissions and losses by leaching and runoff, and NUE are comparable with the previous global estimates over cropland[50-54], agricultural land[22] and livestock systems[55]. Great progress has occurred over the past few years in terrestrial nitrogen cycle modelling but important uncertainties prevail especially with respect to manure (production, management, application and deposition; Supplementary Note 4).

In this study, we account for all major agricultural $CH_4$ and $N_2O$ emissions including $CH_4$ from enteric fermentation, manure management and rice cultivation, and $N_2O$ from cropland, pasture and manure management. For detail description of the method used for each emission component, see Supplementary Note 5.

Even though GLOBIOM is run for 37 regions, we aggregated our results to 10 broad regions for aiding clarity based on their geographical closeness and the similarity in economic development within each broad region: Eastern Asia (EAS), Europe (EUR), Former Soviet Union (FSU), Latin America and the Caribbean (LAC), the Middle East and North Africa (MNA), North America (NAM), Oceania (OCE), South Asia (SAS), Southeast Asia (SEA), and Sub-Saharan Africa (SSA). List of region used in the analysis and country mapping is shown in Supplementary Table 10.

### ***Uncertainties analysis***

To account for the uncertainties due to climate change impacts on crop and grass yields, we ran a series of sensitivity simulations with GLOBIOM. Our choice of climate change scenarios was determined by the ISI-MIP Fast Track Protocol used by crop modellers to calculate crop and grass yield impacts[56]. We used all four RCPs that reflect increasing levels of radiative forcing by 2100 (the 2.6 W $m^{-2}$, 4.5 W $m^{-2}$, 6 W $m^{-2}$ and 8.5 W $m^{-2}$ scenarios)[57] as projected by the HadGEM2–ES GCM[58]. RCP 2.6 represents climate stabilization at 2 °C and RCP 8.5 a temperature range of 2.6–4.8 °C (ref[59]). Yield impacts are based on simulations from the crop model EPIC[60]. Each RCP × GCM combination was modelled including $CO_2$ fertilization effects.

Climate change impact simulations are conducted for three management systems – subsistence (used also for the low-input commercial system), high-input and irrigated[61]. The dates of operations such as sowing are adapted to the climate[61]. For Oil palm, an average value is used – calculated from the climate change impacts on groundnuts, rice, soybeans and wheat – following the protocol of ref[62]. Climate change impact on grasslands is captured through shifts in relative productivity calculated for managed grasslands by EPIC. It should be noted that the mean values of climate impact on crop yield are used, while climate variability including extreme events could have more severe impacts, which unfortunately cannot be captured in GLOBIOM and similar models.

The climate impacts on agricultural production and food availability are determined by the biophysical impacts on crop and grass yield and the subsequent adaptations through various mechanisms[63]. Marginal adaptation to climate change, in terms of input level or adjustments of operation dates is implicit in the crop model results. GLOBIOM models additional mechanisms which can mitigate the effects of climate change on the agricultural sector. In addition to relocating production activities within or across the various regions (i.e., through production relocation and international trade) to exploit new comparative advantages between locations and individual production activities, a major adaptation mechanism represented in GLOBIOM is switching between different production systems[61]. In the crop sector, this can take the form of shifting some of the production from the rainfed system to the irrigated system in response to increased droughts. In the livestock sector, it generally involves shifting ruminants from grazing systems to mixed crop-livestock systems or vice versa, changes which can play an important role in the future livestock sector development[49].

***Building regional N surplus boundaries***

Until now boundaries for N are generally based on the inputs, such as the N planetary boundary, being the global critical N input to agriculture, that has been derived on the basis of critical N $NH_3$ emissions to air (use of a critical limit of 1-3 μg $m^{-3}$ in air) and critical N losses by runoff (through surface runoff and leaching) to surface water (use of a critical limit of 1-2.5 mg N $l^{-1}$ in runoff) in view of biodiversity impacts on terrestrial and aquatic ecosystems, respectively[14]. In this study, however, regional N boundaries were derived on the basis of a critical N concentration in runoff (through surface runoff and leaching N flow) from agricultural land only. In all regions, this is the most limiting condition – i.e., not transgressing it likely leads to acceptable nitrate leaching rates to ground water and ammonia emissions to air as shown by ref[14]. The same result was also found in a spatially explicit calculation for the European Union[64]. Complying with a critical N concentration in runoff to surface water has also been used in N planetary boundary assessment[11] and in a regional boundary assessment[25]. Unlike the previous studies, however, we calculated a critical N surplus instead of a critical N input. The reason is that this is a near constant value, as it is based on a critical limit in water multiplied by a water flow which might only slightly change with climate change, and a runoff fraction, linking the N surplus to N runoff (see below). A critical N input, however, is also affected by the N use efficiency, which may strongly change in time by improved fertilizer management[12,64]. Therefore we used a critical N surplus based on a critical N limit in surface water only as the boundary. In this study, N surplus is defined as the difference between N input and N removal of the agricultural land including cropland, pasture and livestock systems. Nitrogen input into the cropland and pasture consist of mineral fertilizer application, biological N fixation, atmospheric N deposition, recycled human sewage and manure. For livestock systems, N input is feed, while N removal include livestock productions and manure deposited/applied on agricultural land. Nitrogen losses to air and water, i.e. leaching and runoff, and gaseous N emission, including $NH_3$, $N_2O$, denitrification ($N_2$ and NO) emissions are determined by this surplus (see Supplementary Notes 3 for detail).

The range of a critical limit of 1-2.5 mg N l$^{-1}$ in runoff is based on i) a literature review on the ecological and toxicological effects of inorganic N pollution[65], leading to 1 mg N l$^{-1}$; but ii) an overview of maximum allowable surface water N concentrations in national surface water quality standards[66] and iii) different European objectives for N compounds lead to a limit near 2.5 mg N l$^{-1}$.We used the latter one, considering that even under the upper limit of 2.5 mg N l$^{-1}$, the regional critical N surplus has been far exceeded already in many regions. The projected population at risk of hunger showed in this study is still conservative. Taking a lower limit of 1 mg N l$^{-1}$ would make the trade-off even more pronounced and we considered this too stringent and not really needed.

In line with De Vries et al.[14] a risk indicator (*RI*) for the N surplus in region *r* for the 37 regions ($RI_{N_{surplus,r}}$) was calculated as:

$$RI_{N_{surplus,r}} = N_{surplus,crit,r}/N_{surplus,present,r} \tag{1}$$

We calculated regional RIs for the N surplus based on a critical N runoff (where N runoff stands for surface runoff and leaching N flow) to surface water in each region *r* ($RI_{Nrunoff,r}$), assuming that a fixed fraction ($fN_{runoff}$) of agricultural N surplus (as N input minus N removal; Supplementary Notes 3) is lost as N runoff to surface water. In formula

$$RI_{N_{surplus,r}} = RI_{Nrunoff,r} \tag{2}$$

with

$$RI_{N_{runoff,r}} = N_{runoff,crit,r}/N_{runoff,present,r} \tag{3}$$

$$N_{runoff,crit,r} = N_{surplus,crit,r} \times fN_{runoff} \tag{4}$$

$$N_{runoff,present,r} = N_{surplus,present,r} \times fN_{runoff} \tag{5}$$

where $N_{runoff,present,r}$ (unit: Tg N yr$^{-1}$) includes regional N losses through surface runoff from cropland ($N_{surface\,runoff-crop}$) and pasture ($N_{surface\,runoff-pasture}$) and leaching from cropland ($N_{leaching-crop}$) and pasture ($N_{leaching-pasture}$), runoff and leaching during manure management ($N_{leach-MMS}$). Regional values of the critical N runoff to the surface water in region *r* ($N_{runoff,crit,r}$) were calculated as:

$$N_{runoff,crit,r} = W_{runoff,present,r} \times [N]_{runoff,crit,r} \qquad (6)$$

where $W_{runoff,present,r}$ (unit: 1000 km$^3$) is the regional runoff to the surface water in region *r,* and $[N]_{runoff,crit,r}$ is the critical N concentration in surface water (2.5 mg N l$^{-1}$). In this study, present year refers to year 2000 given the data availability on $W_{runoff,present,r}$ (see below).

*RI* values below 1 imply that the agricultural N surplus and related N runoff in those regions should decrease to protect water quality, whereas values above 1, imply that the agricultural N surplus in those regions could increase (in view of crop N demand) without affecting water quality. The regional N surplus boundaries ($N_{surplus,crit,r}$) were derived by GLOBIOM by multiplying the present regional N surplus of agricultural systems (including surpluses over cropland, pasture, and livestock systems; $N_{surplus,present,r}$) in 2000 (see Eq. 1 and 2):

$$N_{surplus,crit,r} = N_{surplus,present,r} \times RI_{Nrunoff,r} \qquad (7)$$

Given the fact that we used 2010 as the base year, the risk indicator used refers to 2010 (as shown in Fig. 2):

$$RI_{Nsurplus,2010,r} = N_{surplus,crit,r} / N_{surplus\,,2010,r} \qquad (8)$$

The above components of regional N losses through surface runoff and leaching ($N_{runoff,present,r}$) were estimated by GLOBIOM. $N_{leach-MMS}$ was calculated using an emission factor gathered from the RUMINANT model (see the supporting information Sect. 7 and Table S17-S21 of ref [67]). $N_{surface\,runoff-crop}$, $N_{surface\,runoff-pasture}$, $N_{leaching-crop}$, and $N_{leaching-pasture}$ were calculated using a spatially explicit fraction following the INTEGRATOR-MITERRA approach[27,28], which is adapted from MITERRA-EUROPE [68]. Details on the methods used are presented in Section 3.6 of Supplementary Notes 3. We used the regional precipitation surplus in region *r* ($PS_{present,r}$) as a proxy for $W_{runoff,present,r}$, based on the fact that long-term changes in terrestrial water storage (e.g., −108 ± 64 km$^3$ yr$^{-1}$ over the 2003–2013 decade [69]) are marginal compared to total river discharge (e.g., a climatology value of 37288 ± 662 km$^3$ yr$^{-1}$ using data from various periods between 1961-1999 [70]). PS was defined as precipitation (*P*) minus evapotranspiration (*E*), taken from the CRU-JRA v1.1 data set[71] and the LandFlux-EVAL data set[72], respectively. We calculated both $N_{runoff,present,r}$ and $PS_{present,r}$

for a period around 2000 (1996-2005), as the evapotranspiration data we used were not available after 2005 (see below).

Remote areas were not accounted for as they are either unsuitable for agricultural use (e.g., high-latitude boreal forest and tundra regions) or not desirable for agriculture expansion in view of ecosystem and biodiversity protection issues (e.g., tropical forests in Amazon and Africa). Therefore, grid cells at 1° resolution with agricultural land (cropland, pasture and rangeland) making up less than 1% of the grid cell area were excluded in the calculation of $PS$. Cropland, pasture and rangeland fractions were derived from the HYDE3.2 data set[73] for the year 2000. In addition, grid cells with $PS \leq 0$ (i.e., $E \geq P$) were also excluded, to avoid overestimating $N_{runoff,present,r}$. As a result, we derived $N_{runoff,present,r}$ and $RI_{Nrunoff,r}$ as shown in Supplementary Table 5.

The regional critical N surplus defined in this way reflects the boundary in view of critical N concentrations in runoff from agricultural land to surface water. It should be kept in mind that use of a limit value for runoff from agriculture is only a surrogate in terms of the surface water quality[64]. As explained in ref[64], higher values can be acceptable due to denitrification or N retention in surface water, while lower values may be needed because of mixing of runoff water with point loads of N into surface water. Here, these effects were assumed to compensate for each other, as in ref[64]. In addition, the regional critical N surplus is defined at the scale of the whole region and does not reflect the critical N boundary in individual river basins.

### *Constraining N surplus and the impact chain on food security*

The regional constraint of a critical N surplus was included in GLOBIOM by the following function:

$$N_{surplus-crop,r} + N_{surplus-pasture,r} + N_{surplus-live,r} \leq N_{surplus,crit,r} \qquad (5)$$

where $N_{surplus\text{-}crop,r}$, $N_{surplus\text{-}pasture,r}$, and $N_{surplus\text{-}live,r}$ are N surplus over cropland, pasture and livestock systems in economic region $r$, respectively. Regional N surplus constraints were applied in the model from 2030 to 2050, with linear reduction from the modelled regional N surplus of 2020 under the BAU scenario to $N_{surplus,crit,r}$ by 2050. For North Africa, the N surplus from other crops (crops other than the 18 crops modelled explicitly by GLOBIOM) in 2050 (1.1 Tg N $yr^{-1}$) is higher than the $N_{surplus,crit,r}$ of 0.75 Tg N $yr^{-1}$ (Supplementary Table 5). Since other crops production is considered constant, and the Nitrogen use thus cannot be endogenously reduced to comply with the constraint, in order to avoid model infeasibility caused by the total N surplus constraint, a value for $N_{surplus,crit,r}$ of 1.1 Tg N yr$^{-1}$ was used in this region.

In all NrRB scenarios, the regional N surplus boundaries are used as an additional constraint when solving the model, preventing an over-use of N in production. Within a region, we assume the same NUE for a given crop and pasture independent of its location and management system, leading to a linear relationship between nitrogen application to a specific crop and its production at the regional level. Hence, for regions where total agricultural N surplus exceeds the defined regional boundaries and without the dedicated N mitigation strategies considered in the corresponding NrRB scenarios, reduction of N input to a crop will lead to proportional decrease in its production, which in turn will lead to increasing food prices. The increase in prices will however also trigger several endogenous adjustment mechanisms to adapt to the regional N constraint: i) switch between livestock systems if that allows to reduce total surplus from cropland, pasture and livestock, ii) supplement the missing domestic supply by imports from regions where the regional N surplus constraint is not binding, iii) modify consumption patterns, and overall food and feed demand (i.e., reduced mean dietary energy availability). Indeed, the livestock sector represented in several alternative production systems, can contribute by adapting the feed ratios as well as the manure management systems and thus the overall N efficiency. In regions where total agricultural N surplus is below the defined regional critical boundaries, production can potentially be increased for exports to satisfy the import demand in the N constrained-regions. Increasing production will also in these regions lead to increasing marginal production cost, which will lead to food price increases and food consumption reduction also in these regions, although these are not locally constrained by their regional N boundary.

The above-mentioned endogenous model adjustments to the N surplus constraints will vary based on additional scenario assumptions. For example, with the implementation of one or multiple sustainability effort(s) the N surplus per unit of production can be reduced, allowing for a higher domestic production within the defined N boundaries. Conversely, the reduced demand through dietary changes and reduced food waste will facilitate compliance with the N boundaries and will reduce the pressure on the food system. Lower demand for N-intensive commodities in regions with excessive consumption and higher domestic supply will both lead to reduction in food prices, which in turn will allow for increased consumption and reduction of food insecurity in food deficient regions.

### *Estimation of the number of people at risk of hunger*

The narrow definition of undernourishment, or hunger, is a state of energy (calorie) deprivation lasting for more than one year; this does not include the short-term effects of temporary crises [74]. The method used to estimate the number of people at risk of hunger is based on the FAO approach[75]. The approach has been implemented in agricultural economic models [76,77], and has recently been applied in eight global agricultural economic models (including GLOBIOM) to assess the risk of food insecurity[34]. In principle, the risk of hunger is calculated by referring to the mean dietary energy availability projected by GLOBIOM (scenario- and time horizon-specific). The population at risk of hunger is a multiple of the prevalence of the undernourishment (PoU) and the total population. According to FAO[75], the PoU is calculated from three key factors: the mean dietary energy availability (kcal per person per day), the mean minimum dietary energy requirement (MDER, time-fixed in this study), and the coefficient of variation (CV) of the domestic distribution of dietary energy consumption in a country. The food distribution within a country is assumed to obey a lognormal distribution which is determined by the mean dietary energy availability (mean) and the equity of the food distribution (variance)[34]. The proportion of the population under the MDER is then defined as the PoU. The calorie-based food consumption (kcal per person per day) output from GLOBIOM was used as the mean dietary energy availability. The future mean MDER is calculated for each year and country using the mean MDER in the base year at the country level[29], and an adjustment coefficient for the MDER in different age and sex groups[78] and the future population demographics[79] to reflect differences in the MDER across age and sex. The future equality of food distribution was estimated by applying the historical trend of income growth and the improved CV of the food distribution to the future, so that equity is improved along with income growth in the future at an historical rate up to the present best value (0.2). Here, we took into account the increased food availability for intake, in the case where food waste is reduced (as in the NrRB-FoodWaste scenario), by introducing an extra parameter for domestic food waste to be applied to dietary energy availability. Currently, according to the FAO approach, there is assumed to be no PoU in Europe, North America and Oceania, and so the PoU measure is not applicable in these three regions (see ref[76] for more information).

### *Code Availability*

Code used for the statistical analysis of the scenario data is available from the corresponding author on request.

### *Data Availability*

The main data which support the findings of this study are available at the public Data Repository of the International Institute of Applied Systems Analysis (IIASA DARE; https://dare.iiasa.ac.at/125/; DOI: 10.22022/IBF/07-2021.125).

## Acknowledgement

J.C. and M.O. were supported by European Research Council Synergy grant ERC-2013-SynG-610028 Imbalance-P. Support received from the Global Environment Facility (GEF) of the United Nations Environment Program (UNEP) through the project 'Towards an International Nitrogen Management System' (INMS) for organization of workshops proved essential to the success of this work.

## Author contributions

J.C. and P.H. designed the study; J.C. carried out GLOBIOM modelling with help from P.H., D.L., H.V., and A.D.; W.V. provided the methodology in estimating regional N surplus boundaries. J.C. performed the analysis and wrote an initial draft; all authors contributed significantly to the final revisions of the manuscript.

## Competing Interests statement

The authors declare no competing interests.

**Table 1. Scenario assumptions, sustainability options, and their direct effects on the food system and related N cycles.**

| Scenarios and sustainability options | Scenario assumptions | Direct effects of the sustainability options on the food system and related N cycles | Source |
|---|---|---|---|
| *Baseline* (BAU) | Constant manure recycling as in 2000; a constant fraction of population connected to wastewater treatment systems (D) and N removal rate ($N^R$), no recycling of N from human wastewater treatment' business-as-usual diet change following GDP development; business-as-usual changes in NUE*. | | |
| NrRB-BAU | Constrained by regional N surplus boundaries without dedicated N surplus mitigation strategies (i.e., with N assumptions the same as the BAU scenario). | | |
| NrRB-NUE (Achieving target nitrogen use efficiency*)* | Constrained by regional N surplus boundaries with the regional NUE of cropland will reach the target NUEs of ref[50] by 2050 with a linear progression towards that target starting in 2010. For regions where the baseline NUE (for the year 2010) calculated by the model is higher than the target NUEs of ref[50], no NUE changes are applied. | Positive: reducing N air and water pollutions (high NUE indicates less N losses per unit of production); decrease N fertilizer demand. | Zhang et al., 2015[50] |
| NrRB-Manure (Improving manure recycling*)* | Constrained by regional N surplus boundaries with a minimum 90% of the manure excretion out of grazed grassland is collected and managed by 2050 # and a 50% reduction in N loss | Positive: directly reduces N surplus from livestock systems; effectively reducing direct manure discharge to water bodies; technologies reducing N loss during | Adapted from UNEP, 2013; Kanter et al., 2020[80,81] |

|  |  |  |  |
|---|---|---|---|
|  | during manure management†, with a linear progression towards that target starting in 2010. | manure storage, processing and application could improve local air and water quality, and reduce mineral N fertilizer demand for food and feed production.<br>Negative: might increase soil $N_2O$ emissions during manure application to soils. |  |
| NrRB-Sewage *(*Improving sewage treatment and recycling*)* | Constrained by regional N surplus boundaries with the gap between the fraction of the total population that is connected to public sewerage systems (D) in 2010 and 100% WTTPs connection for urban population is closed by 25%, 50%, 62.5%, and 75% in 2020, 2030, 2040 and 2050, respectively§; regional changes in $N^R$ derived from ref[82] §; a 50% of the N removed by WTTPs is recycled as fertilizer to cropland by 2050 with a linear progression towards that target starting in 2030. | Positive: less direct N discharge to water bodies; N removed by WTTPs can be recycled to substitute N fertilizers. | Van Drecht et al., 2009[82] |
| NrRB-FoodWaste (Less harvest loss and food waste) | Constrained by regional N surplus boundaries with a 17%, 33% and 50% reduction of the harvest loss and food waste in 2030, 2040, and 2050, respectively, compared to the harvest loss and food waste under the BAU scenario in the corresponding years 2030, 2040 and 2050¶. | Positive: less total demand (actual food consumption plus food waste) and effective supply (production minus losses in field, during processing and during transportation) can effectively satisfy human food intake with less agriculture | United Nations 2015;<br>Springmann et al., 2018[12,83] |

| | | | |
|---|---|---|---|
| | | production; potential reduce in N fertilizer demand, N surplus and agricultural GHG emissions for food production. | |
| NrRB-DietShift (Less animal products in diet) | Constrained by regional N surplus boundaries with a reduction of meat and dairy consumption in regions with above average consumption by 17%, 33% and 50% in 2030, 2040, and 2050, respectively, compared to the diet composition under the BAU scenario in the corresponding years 2030, 2040 and 2050. | Positive: improve health of people with over-consumption of meat and dairy products; effectively reducing GHG emissions from livestock and feed production. | Bodirsky et al., 2014; Frank et al., 2019[23,32] |
| NrRB-Combined | Constrained by regional N surplus boundaries with simultaneously implementation of all above mitigation measures. | | |
| BAU-Combined | Simultaneously implementation of all above mitigation measures without N surplus constraints. | | |

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* The business-as-usual changes in NUE are based on the finding that cropland NUE first decreases and then increases with economic growth (i.e., an Environmental Kuznets Curve)[50,84]. We assume that 1) the cropland and pasture NUE of OECD countries will reach the target NUEs of ref[50] by 2050, 2) the cropland and pasture NUE of non-OECD countries will converge to a lower target. The low target NUEs by 2050 are set to 0.5, 0.4 and 0.4 for non-OECD countries in Latin America, Sub-Saharan Africa, and Asia respectively, which indicate an increasing NUE for countries such as India and China, a decreasing NUE for countries like Malawi, and a constant NUE for countries like Brazil. For regions where the baseline NUE (for the year 2010) calculated by the model is higher than the target NUEs of ref[50], no NUE changes will be applied.

# In the model, the share of collected manure (i.e., excluding those left on pasture by grazing livestock) allocated to other uses is capped to 10% by 2050 (adapted from refs[80,81]) with a linear progression towards that target starting in 2010.

† The fraction of N loss during manure management ($Frac_{LossMS}$) is assumed to be reduced by 50% by 2050 through technological improvement of manure management, with a linear progression towards that target starting in 2010.

§ The sewage treatment improvement is adapted from the Global Orchestration scenario[82] in the Millennium Assessment Scenarios. The scenario assumes 50% of the gap between $D$ in 2000 and full connection to WTTPs for the urban population (i.e., 100% improved sanitation) is closed in the period 2000-2030, and a further 50% of the remaining gap is closed in the period 2030-2050. The $N^R$ increase follows the regional improvement shown in Table 4 of ref[82].

¶ This is a projection in line with pledges made as part of the Sustainable Development Goals[12,83]. GLOBIOM integrates information on the rate of losses and waste based on FAO past work[85]. It is possible in the model to distinguish domestic food consumption (including waste) from food intake per capita (net excluding waste). Reducing waste therefore allows to decrease the demand for food and the pressure on land use and the environment without affecting food intake. The model represents such scenarios as “what if?” assumptions, simply changing the parameter values without any assumption on the underlying cost of such policies.

## Figure legends

**Figure 1. Illustration of modelled N flows and their magnitudes in 2010 (blue numbers in Tg N yr$^{-1}$).** Total livestock intake not only include crops (30 Tg N yr$^{-1}$), grasses (49 Tg N yr$^{-1}$), and crop residues (stover; 2 Tg N yr$^{-1}$), but also occasional feed (9 Tg N yr$^{-1}$) and other feed and additives (18 Tg N yr$^{-1}$) that are assumed not come from agricultural land. Crop related N flow estimates are for food (32 Tg N yr$^{-1}$), feed (30 Tg N yr$^{-1}$) and other uses such as fiber products and bioenergy (9 Tg N yr$^{-1}$). Manure management losses include leaching (3 Tg N yr$^{-1}$), gaseous losses ($NH_3$, NO, $N_2O$ and $N_2$; 14 Tg N yr$^{-1}$), and other use (10 Tg N yr$^{-1}$). Losses of untreated household waste and sewage sludge consist of direct discharge of untreated sewage (13 Tg N yr$^{-1}$), gaseous emissions from untreated sewage (4 Tg N yr$^{-1}$), recycling to agricultural land (3 Tg N yr$^{-1}$) and other losses such as landfill (10 Tg N yr$^{-1}$).

**Figure 2. Spatial variation in a regional N risk indicator ($RI_{Nsurplus,2010,r}$) for the year 2010.** *RI*, the ratio of the critical N surplus over the current N surplus, measures the degree of exceedance of the estimated surface runoff and leaching N flow in surface water relative to the critical N concentration of 2.5 mg N l$^{-1}$. $RI_{Nsurplus,2010,r} < 1$ indicates that regional N runoff to surface water has transgressed the critical regional boundary by 2010. Regional values of $RI_{Nsurplus,2010,r}$ are listed in Supplementary Table 5.

**Figure 3. Projections of relative changes in global agricultural production (a) and international trade (b) for crop (in dry matter) and animal products (in protein).** Projections are presented as relative changes compared to the year 2010 under a business-as-usual scenario (BAU), and scenarios constrained by regional N boundaries (NrRB) in combination with a BAU and dedicated N mitigation strategies and a combination of all N mitigation strategies. Bars indicated results without assuming climate change impacts and symbols indicate the range associated with climate change induced crop and grass impacts in line with 2.6, 4.5, 6, and 8.5 W m$^{-2}$ RCP scenarios. The narratives of the scenarios and the details about the underlying assumptions and data can be found in Table 1.

**Figure 4. Projections of dietary energy availability (a), dietary protein availability (b), agricultural commodity price index (c), population at risk of hunger (d), mineral N fertilizer use/demand (e), N surplus (f), and agricultural non-$CO_2$ GHG emissions (g).** Values are presented for the year 2010, a business-as-usual scenario (BAU), and scenarios constrained by regional N boundaries (NrRB) in combination with a BAU and dedicated N mitigation strategies and a combination of all N mitigation strategies. Value for 2010 in (d)

refers to mineral N fertilizer use from data, while values for 2050 under different scenarios refer to mineral N fertilizer demand projected by the model. Bars indicated results without assuming climate change impacts and symbols indicate the range associated with climate change induced crop and grass impacts in line with 2.6, 4.5, 6, and 8.5 W $m^{-2}$ RCP scenarios. The narratives of the scenarios and the details about the underlying assumptions and data can be found in Table 1.

**Figure 5. Population at risk of hunger by 2050 by selected world regions under different N management and climate scenarios.** For developed countries in North America, Europe, and Oceania, the population at risk of hunger measure is not applicable because, in accordance with the FAO's approach, it was assumed that there was no prevalence of undernourishment (PoU) in these regions[75]. The horizontal-scale of the regional population at risk of hunger has been adjusted so that the effects can be easily seen. Figure legend is consistent with Figures 3 and 4.

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