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Review

Revisiting safe and just planetary boundaries for nitrogen and phosphorus

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Over the past 15 years, the planetary boundaries (PB) framework has advanced as a scientific approach to define limits for Earth's system processes, including boundaries for nitrogen (N) and phosphorus (P). These boundaries have been conceptualized and quantified using various approaches, leading to varying estimates and interpretations. In this paper, we review existing control variables and methods used to define and quantify 'safe' N and P boundaries for environmental impacts and 'just' N and P boundaries for food production. Based on our analysis, we propose that 'N losses' (N delivery to surface water, N leaching to groundwater, and NH_3 emissions to air) and 'P delivery to surface water' are the most suitable control variables for defining 'safe' boundaries for biogeochemical flows of these elements. We present quantitative estimates for both 'safe' planetary N and P boundaries, for N based on previous studies and for P based on new calculations. We then assess the contribution of the food system (including agricultural production, aquaculture, and human wastewater streams) to N and P losses. We propose to define 'just' boundaries for N and P based on the required input of these nutrients to meet the dietary needs of the population. We indicate possible values for such 'just' N and P boundaries and provide options to attain those boundaries while staying with 'safe' N and P boundaries.

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Introduction

Planetary boundaries (PBs) for nitrogen (N) and phosphorus (P) are defined by their adverse impacts on ecosystems and humans due to the loss of N compounds (ammonia, nitrogen oxides, and nitrous oxides) to air and both N and P compounds (dissolved inorganic, organic, and particulate N and P) to water (see supplementary text S1). Since their introduction in 2009 [1], various control variables and methods have been proposed to set these boundaries, reflecting advances in understanding how disruption to biogeochemical cycles poses risks to the Earth system. These approaches continue to evolve as methods improve. Recently, a distinction has been made between 'safe' N and P boundaries, which protect ecosystems, and 'just' N and P boundaries, which address human impacts [2,3]. The food system is the main cause of N and P losses to air and water, and most PBs derived, thus, focus on agricultural N and P inputs (see supplementary text S2 for an overview of estimated safe PBs for N and P since 2009).

In this opinion paper, we first present a critical review of '**safe**' N and P boundaries by (i) giving an overview of impacts of N and P on the environment based on multiple pollution pathways, (ii) describing the derivation of safe N and P boundaries at both regional and global scales within PB frameworks to date, and then (iii) discuss the most suitable control variables for deriving such boundaries. We then present an approach to derive critical N and P losses to air and water with a focus on the 'delivery to surface water', which we consider the most suitable control variables for assessing safe N and P boundaries. We do so by presenting critical N and P concentrations, that is, the concentration at which certain environmental impacts occur, and approaches to use those concentrations to derive the safe planetary N and P loss boundaries. In addition, we indicate how safe boundaries for N losses can be used to assess safe boundaries for 'N surplus' and 'N inputs' of agricultural land.

The second part of this opinion paper is a critical review of currently derived '**just**' N and P boundaries. As with safe boundaries, 'just' boundaries are currently also based on adverse impacts on the environment, but then in relation to the degree to which environmental impacts cause significant harm to human wellbeing [2,3]. However, we argue that such boundaries should be derived in view of the critical role of these nutrients in ensuring the required global food production. Although acknowledged in both papers by the use of 'minimum access levels' for N and P [2,3], this is limited to the N and P consumption by humans, and the required N and P use is not linked to it. We suggest new threshold values for these just boundaries and indicate options to reconcile the just N and P boundaries needed for food production with the safe N and P boundaries to protect the environment.

Control variables and methods to define and quantify safe nitrogen and phosphorus boundaries

Regional versus planetary safe nitrogen and phosphorus boundaries

In the original PB paper, Rockström and colleagues [1] noted that 'setting a PB for human modification of the nitrogen cycle is not straightforward.' Unlike greenhouse gas emissions, whose effects on climate occur globally, the impacts of N and P losses are primarily regional. Inputs, losses, and impacts of N and P are highly unevenly distributed across the world. In many developed and rapidly growing economies, fertilizer and manure inputs remain too low to close yield gaps, with crop yields often being only one-half to one-quarter of their potential under optimal nutrient management [4]. In such deficit regions, additional N or P input can increase crop yields without causing environmental harm [5]. In contrast, in many developed nations, N and P are applied at rates far exceeding what is needed to obtain current yields, leading to environmental degradation.

Because impacts of N and P are region-specific, boundaries should first be derived at the regional scale, taking into account differences in agricultural systems, soils, and ecosystems that influence both nutrient losses and their effects (e.g. [6,7]). For example, the risk of surface water eutrophication increases when N and/or P concentrations exceed a critical threshold. The concentration is affected by the quantity of N and P and the water flux entering aquatic systems, the latter being influenced by precipitation, evapotranspiration, and the use of irrigation. Furthermore, the fraction of the N surplus that is lost to water is affected by site conditions affecting denitrification, including land use, climate, texture, and soil organic carbon content [8], and nitrate adsorption, which plays a role in highly weathered tropical soils. These regional boundaries can then be aggregated to continental or global scales (e.g. [5,7,9]). Note that when aggregating regional boundaries to a global PB, it is implicitly assumed that N and P inputs are optimally allocated across regions.

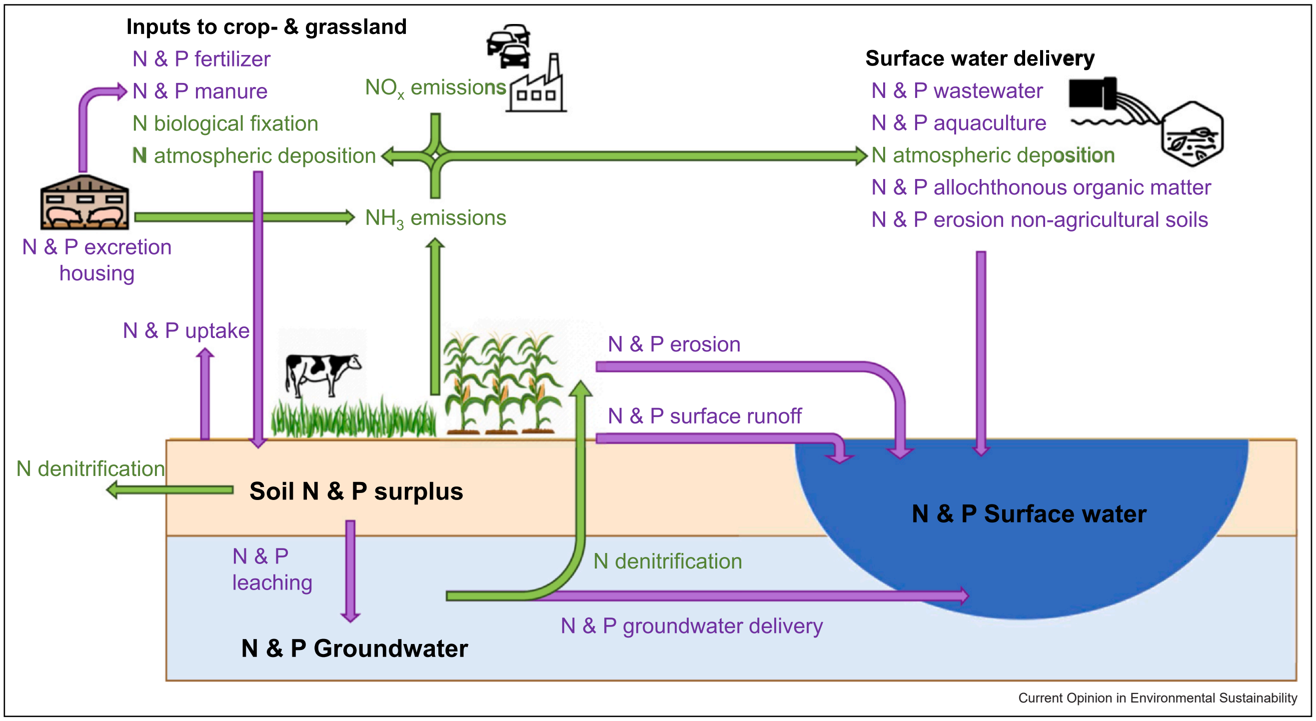
Suitable control variables for impacts of nitrogen and phosphorus

As outlined above, different control variables have been used in PB assessments to define N and P boundaries. Early assessments focused on external nutrient inputs to agricultural systems, whereas recent assessments have focused on agricultural nutrient surpluses (Table S1). Irrespective of the selected control variable, environmental impacts are ultimately driven by N and P losses to water and by N losses to air. The relationships between agricultural inputs or surpluses and subsequent losses (Figure 1) are complex and highly context dependent. Estimating critical N and P inputs or surpluses from critical N and P loss thresholds, therefore, requires several assumptions. Table 1 summarizes the main advantages and disadvantages of control variables that have been used to operationalize safe and just PBs for N and P. In general, the advantages relate to the practical use of a control variable, being either the N and P input or surplus, whereas the disadvantages mostly relate to the assumptions that need to be made to derive those control variables (see supplementary text S3).

The best indicator for N and P impacts on eutrophication is the total delivery (loads) to surface water. This consists of erosion and runoff, both from agricultural and natural systems, next to inputs from point sources such as sewage systems and aquaculture (Figure 1). In case of N, however, there are also other N losses that need to be considered, including NO_3^- leaching to groundwater for groundwater pollution and NH_3 + NO_x emissions for N deposition and associated loss of terrestrial biodiversity.

The disadvantage is that this means that three separate boundaries are derived for N, which is more complex to communicate. To address this, Schulte-Uebbing et al. [13] used the agricultural N surplus boundary (defined as total N input minus N removal through crop harvest) as an overarching boundary, as it integrates these three N-related environmental concerns into a single, more practical indicator. To avoid dependence on nitrogen use

Figure 1



Schematic diagram showing the relations between N & P inputs, surpluses, losses, and environmental concentrations. Purple = flow of N & P, green = flow of N only.

efficiency (NUE), Schulte-Uebbing et al. [13] used the N surplus for defining a safe N boundary instead of N input. Safe limits for N surplus represent the threshold above which harmful losses occur. Deriving a boundary for agricultural N losses (rather than total N losses) and agricultural N surplus, however, requires making assumptions on nonagricultural losses that contribute to environmental N load (see Figure 1).

Below, we describe the approach to derive safe boundaries for the N and P delivery to surface water with the results. We then give a state-of-the-art description of derived safe N surplus and safe N input boundaries based on critical N losses, with their implicit assumptions, since such boundaries are more practical to use in managing N and P flows. Then, the assessment of a safe P input boundary is discussed in connection with a just P input boundary, since both are highly correlated.

Safe nitrogen and phosphorus loss boundaries

Safe boundary for nitrogen and phosphorus delivery to surface water

For both N and P, the delivery (loads) to surface water is the sum of N and P in effluent from agriculture, aquaculture, wastewater, and natural land. N and P losses from agricultural soils to surface waters are due to runoff and erosion. In the case of P, erosion is the dominant source [10], and thus, particulate P is the largest source of P input to surface water [11]. Erosion is determined by (i) the soil erosion rate, and (ii) the soil P content (soil P pool), which in turn is affected by the natural soil P content and the legacy of accumulated P inputs over time [12]. The critical P delivery to surface water in a region can be derived by multiplying a critical P concentration with water fluxes, while accounting for river P retention. Using an estimated global water discharge of 38 000 km^3 yr^{-1} [13] a critical P concentration of 75 mg. m^{-3} (see supplementary text S4, Table S2) and a global average river P retention fraction of 53% [14], this leads to a critical global P delivery to surface water of 6.1 Tg P yr^{-1}, being ca 37% lower than the current (2015) P delivery to surface water, which has been estimated at 9.7 Tg P yr^{-1} [14]. For N, a similar calculation can be made using a critical N concentration of 1–2.5 mg N l^{-1} (See supplementary text S4, Table S2) and a global average river N retention fraction of 50% [5], leading to a critical global N delivery to surface water of 76–190 Tg N yr^{-1}. The latter value is extremely high as it allows filling up all waters up to a value of 1–2.5 mg N L^{-1}, while all regions outside (intensive) agriculture stay below this value. Considering agricultural regions, only Schulte-Uebbing et al. [5] calculated a safe boundary for nitrogen delivery to surface water of 21 Tg N yr^{-1} only (see also Table 3).

Table 1

Advantages and drawbacks of control variables used to present safe and just planetary boundaries for N and P.

Nitrogen			Phosphorus		
Control variable	Advantage	Disadvantage	Control variable	Advantage	Disadvantage
N input by industrial and intentional biological fixation	Presents external N input to earth by N_2 fixation from the atmosphere	Depends on NUE in food chain	P fertilizer input to agriculture	Presents external P input to agriculture being (nearly) equal to mining of P rocks	Depend on soil P status, organic P recycling, erosion rates, and non-agricultural P losses
Total N inputs to agriculture	It presents the manageable N input to agriculture	Depends on NUE soil-crop-animals and assumptions of non-agricultural N losses	Total P inputs to agriculture	It presents the manageable P input to agriculture	Depend on soil P status, erosion rates, and non-agricultural P losses
N surplus from agriculture	It links to major N losses and does not depend on NUE	Depends on assumptions of non-agricultural N losses	P surplus from agriculture	Presents the unused P, accumulated in soil or lost to water	Impractical as just boundary; safe boundary depends on soil P status
N losses to air and water	Links directly to effects	Impractical as just boundary; N losses poorly manageable by farmers	P delivery to freshwater systems	Links directly to effects	Impractical as just boundary; P delivery not manageable by farmers

NUE, nitrogen use efficiency.

Contribution of the current food system to observed N and P losses

To identify the present-day contribution of the food system in exceeding the PB of N and P, it is crucial to know the contribution (share in %) of the food system to the estimated N losses to air and N and P delivery to water, both regionally and globally. The contribution of food production is related to agricultural production, human waste, and aquaculture, excluding losses from natural sources. The contribution of agriculture, together with inputs from nonagricultural soils, aquaculture, and wastewater point sources to the N and P river delivery has been estimated for 1980, 2015, and 2050 for various scenarios [14,15]. Using the year 2015 as a base year, approximately 75% of the total N and P losses (71 Tg N yr^{-1} and 9.7 Tg P yr^{-1}) are due to the food system (Table 2).

The contribution of the food system to NH_3 emissions (second part of the N boundary) can be derived from the deposition ratio NH_3/NH_3+NO_x on terrestrial ecosystems, assuming that all NH_3 comes from agriculture (although a small part comes from nonagricultural sources) and all NOx from nonagricultural sources (although a small part comes from agricultural sources). Note that using the ratio 'NH_3+NO_x emission agriculture/ NH_3+NO_x emission total' does not lead to a better estimate, since the behavior of NO_x and NH_3 is different in the atmosphere, with a larger proportion of NO_x being deposited on marine systems compared to NH_3. Using global NH_3 and NO_x deposition data on forest, that is, 11.9 Tg N yr^{-1} and 11.1 Tg N yr^{-1} [16], respectively, implies a contribution by the food system just above 50%. The contribution of agricultural sources to N leaching (third part of the N boundary) can be calculated as the ratio N leaching from agricultural land divided by N leaching from all land, that is, 45 Tg N yr^{-1} and 56 Tg N yr^{-1} [5], leading to 81% due to agricultural N sources.

Safe nitrogen and phosphorus input boundaries

Approach to derive safe loss, surplus, and input boundaries of nitrogen

The approach to derive critical losses, surpluses, and inputs of nitrogen from critical N concentrations is schematized in Figure 2. Impacts of nitrogen, such as biodiversity loss of terrestrial ecosystems, eutrophication of aquatic ecosystems, and effects on drinking water quality, can be linked to critical N deposition levels on terrestrial ecosystems, critical N concentrations in surface water, and critical NO_3 concentrations in drinking water/groundwater, respectively. These concentrations can, in turn, be used to derive critical N (NH_3 and NO_x) emissions to air, N (NO_3) leaching to groundwater, and N runoff to surface water (step not shown in figure). Based on assumptions on nonagricultural N losses, critical values for agricultural NH_3 emissions can be

Table 2

The contribution of the food system to N and P loads (deliveries) to surface water based on data for the year 2015 (data from Ref. [14]; similar data come from results for 2015 presented by [15]).

Sources	Current N load into surface water ($Tg\ N\ yr^{-1}$)	Current P load into surface water ($Tg\ P\ yr^{-1}$)
Agriculture	37[a]	5.3
Aquaculture	1.8	0.2
Waste water	12	1.7
Nature	20[a]	2.5
Total	71	9.7
Share food system	**71%**	**74%**

[a] The current load of N from agriculture and nature also includes the flow of groundwater to surface water below agriculture and nature, respectively, being near 14 $Tg\ N\ yr^{-1}$ in both systems.

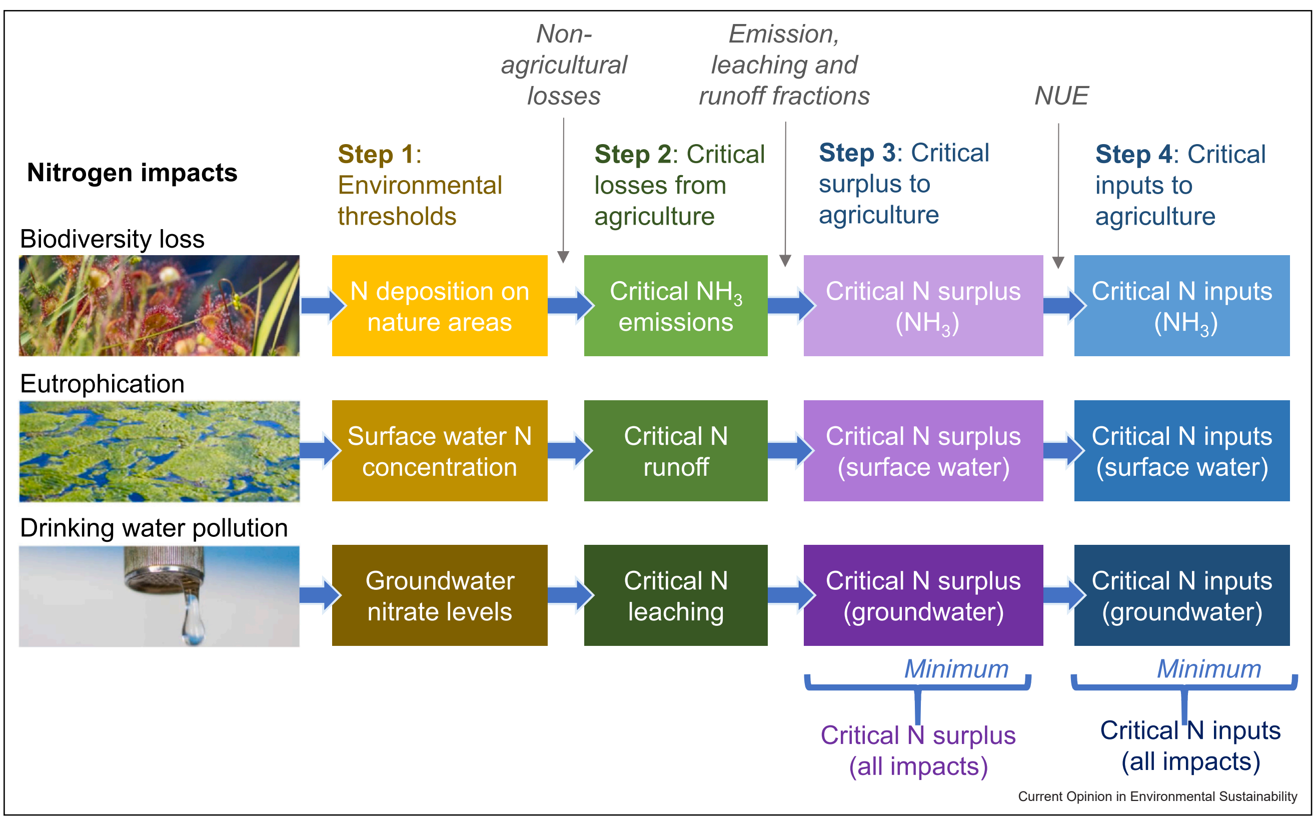
derived from critical N deposition values of surrounding terrestrial ecosystems and the fraction agriculture in a region, while critical N losses to groundwater and surface water can be derived by multiplying critical total N concentrations in either groundwater or runoff to surface water by the net precipitation or water delivery, which are all varying at regional scale [5,7]. These losses in turn can be related to N surplus, amongst others, by accounting for the effect of denitrification and ultimately to N inputs accounting for the N use efficiency ([5,7]). Note that both N surplus and N inputs integrate the three N-related environmental concerns into a single practical indicator (Figure 2).

In PB assessments for nitrogen to date, impacts of NO_x (air pollution) and N_2O (climate change and ozone depletion) were not included. For NO_x, this is because emissions from agriculture are minor. Agriculture does contribute substantially to global N_2O emissions, but the warming effect from anthropogenic N_2O emissions is largely compensated by the cooling effect of additional carbon sequestration in forests induced by enhanced N deposition [21]. In addition, N_2O is only one of several contributors to climate warming, and deriving a critical limit for N_2O emissions requires arbitrary assumptions on reductions in other greenhouse gases, especially CO_2 and CH_4 [13].

Safe nitrogen loss, surplus, and input boundaries

N surplus boundaries, aggregated to a planetary value, have been proposed and derived by Schulte-Uebbing et al. [5] and Chang et al. [5,9]. Schulte-Uebbing et al. [5] derived this boundary according to the methodology presented in Figure 2, explicitly accounting for N loss

Figure 2



Schematic overview of the approach to derive safe losses, surpluses and inputs of nitrogen from critical nitrogen concentrations.

contributions from nonagricultural sources, including sewage, and N runoff from natural land, which can sometimes exceed agricultural N sources (see extended data from Schulte-Uebbing et al. [5]). More specifically, they derived regional N surplus boundaries based on: (i) eutrophication and acidification of terrestrial ecosystems by NH_3 emissions based on critical N deposition levels avoiding adverse impacts on biodiversity; (ii) eutrophication of aquatic ecosystems by N runoff, based on critical N concentrations in surface water; and (iii) groundwater contamination by NO_3 leaching, based on critical NO_3 concentrations used by the WHO (see Figure 2). In most regions, surface water quality emerged as the most constraining threshold for the N surplus boundary, even when considering that Schulte-Uebbing et al. [5] used a critical N concentration in surface water of 2.5 mgL^{-1}. That seems appropriate for rivers, although it is too lenient for lakes, where an ecologically relevant threshold is closer to 1.0 mg L^{-1}.

Despite the dominating N limitation due to water quality impacts, the other two criteria also played an important role in the derivation of the effect of the planetary N surplus boundary. More specifically, this boundary was estimated to be 92 Tg N yr^{-1} in view of N delivery to surface water, 101 Tg N yr^{-1} in view of NH_3-N emissions to air and 117 Tg N yr^{-1} in view of NO_3-N leaching to groundwater while the minimum in view of all three impacts was estimated at 57 Mt N yr^{-1} [5], being half of the estimated current (year 2010) N surplus of 119 Mt N yr^{-1} (See Table 3). The uncertainty of this estimate is likely in a range of 50%.

It is important to consider that the proposed N surplus boundary for agriculture assumes that all N losses from nonagricultural sources, including N loads to surface water from sewage water and nature, stay constant. If N inputs from sewage decrease, the critical agricultural N surplus thus increases, and vice versa. Each year, out of the 35 Tg N yr^{-1} from human excreta and about 3 Tg N yr^{-1} from industry effluents, around 12 Tg N yr^{-1} flows to the surface water [14]. For P, 3.5 Tg P yr^{-1} is from human excreta and 0.4 Tg P yr^{-1}, of which 1.7 Tg P yr^{-1} flows into the surface water [28]. It is therefore critical that N and P inputs to surface water by wastewater sources are reduced.

Safe phosphorus input boundary

Unlike N, the safe total P input (fertilizer and manure) boundary to agriculture is hardly related to the safe P loss boundary, since P losses are mainly related to soil P content and not to P inputs. The safe total P input can be derived as the required P uptake to feed the global population in an efficient way (just P input) plus the acceptable P losses to surface water from agriculture. We estimated the just P input at 18 Tg P yr^{-1} (see section below) while the acceptable P loss from agriculture varies from 1.7 to 3.6 Tg P yr^{-1}. The maximum can be derived from a total acceptable P loss of 6.1 Tg P yr^{-1} and a nonmanageable loss of 2.5 Tg P yr^{-1} from nature, assuming that losses from aquaculture and wastewater are zero, while the minimum is calculated when te the latter losses stay equal to their current values (Table 2). A safe total P input, including fertilizer and manure, would then approximate ca 20 Tg P yr^{-1}, with the current P input being near 40 Tg P yr^{-1}. The key challenge for P is to avoid enhanced future P losses by overuse in soils with an optimal P status, while limiting current P losses to surface water by erosion control, soil conservation, and buffer zones.

Just N and P boundaries in view of food production, and options to reconcile just and safe N and P boundaries

Just N and P input boundaries

A grand challenge for humanity is to balance the maximum allowed N and P loading into the biosphere to

Table 3

Summary of derived global boundaries for N losses, N surplus, total N inputs, and external N inputs by Schulte-Uebbing et al [5].

N indicator	Current global value (Tg N yr^{-1})	Critical global value (Tg N yr^{-1})			
		Terrestrial ecosystems (NH_3 emissions)	Surface water quality (nitrogen runoff)	Drinking water quality (nitrate leaching)	all systems
N losses[1]	Current value in brackets	29 (32)	21 (23)	34 (37)	Not applicable
N surplus[2]	119	101	92	117	**57**
Total N input[3]	232	220	198	245	**134**
External N inputs[4]	122	106	92	107	65

Values in bold are used PBs.
[1] Refers to total N losses to air (NH_3-N), groundwater (NO_3-N), or surface water (total N) from both agricultural and non-agricultural sources.
[2] Refers to agricultural N surplus being the sum of inputs (fertilizer, manure, and N fixation and N deposition) minus N crop offtake.
[3] Refers to total agricultural N inputs (sum of inputs from fertilizer, manure, N fixation, and N deposition).
[4] Refers to new N inputs from atmospherically fixed N, being the sum of N fertilizer and biological N fixation.

maintain a stable Earth system, with the necessary amounts of N and P required to feed humanity. The food system is the dominant driver of N and P delivery (Table 2) and therefore a crucial lever for returning nutrient cycles to within PBs. Estimates of 'human needs' show that feeding nearly 10 billion people by 2050 on current cropland at current NUE would require N applications that exceed regional N surplus boundaries in many parts of the world [5,9]. Conversely, reducing total N inputs to stay within regional N surplus boundaries at current NUE would imply a strong reduction in food production, thereby violating 'just' N boundaries.

Recent PB assessments have defined 'just' N and P boundaries in terms of preventing human harm resulting from N and P cycle disruption [2,3]. These harms include eutrophication leading to fishery collapse and toxic algal blooms, health impacts of air pollution from ammonia-derived aerosols, and exposure to drinking water with nitrate concentrations exceeding safe thresholds (< 50 mg NO_3 L^{-1}). We argue that such impacts should all be part of the **safe** boundaries, whereas a **just** boundary should relate to the essential role of N and P in food production (see also Ref. [6]). The key challenge is to reconcile the just N boundary in view of the need for food production with the safe boundary for environmental losses [5,7,17]. Although both Rockström et al. [2] and Gupta et al. [3] refer to the need to meet human nutritional requirements, using a 'minimum access' concept, this dimension is not elaborated in Rockström et al. [2], whereas the quantitative approach by Gupta et al. [3] seems flawed. Specifically, they estimate just boundaries of 30.1 Mton N and 4.9 Mton P for 2050, assuming a global population of 9.7 billion. These values imply per capita N and P requirements of 3.1 kg and 0.5 kg per year, respectively. These numbers, however, assume 100% efficiency of N and P use in the whole food chain, with no losses during fertilizer application, livestock conversion, food processing, and human consumption, which is unrealistic.

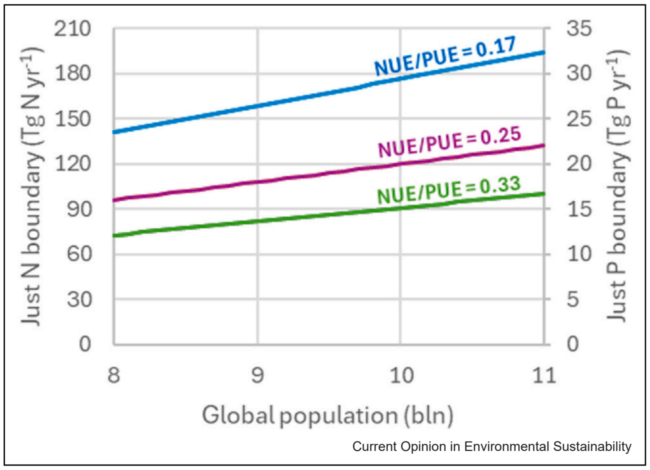
A just PB for total N inputs by fertilizers, manure, N fixation, and N deposition can be derived from human nutritional requirements. This boundary can be estimated by multiplying the global population by the recommended per capita dietary N intake and dividing the value by the NUE of the entire food chain, thereby accounting for losses during crop production, animal production, processing, and human consumption (food waste). This approach assumes that all people consume at the recommended level, thus avoiding both overconsumption and malnutrition. De Vries et al. [6] estimated that total annual N inputs of 163 Tg N yr^{-1} would be required to feed 9 billion people with the recommended N intake of 3 kg $capita^{-1}$ yr^{-1}, using the 'current' global food chain NUE of approximately 17%. This estimate closely matches the median cropland N input of 161 Tg N yr^{-1} for 2010 reported across 13 global nitrogen budget datasets [18]. However, when including grassland, an estimated additional total N input of 103 Tg N yr^{-1} is calculated [19], leading to a total input of 264 Tg N yr^{-1} in 2010. This discrepancy is largely explained by the higher average N intake in 2010, estimated at 4.5 kg $capita^{-1}$ [19], being 50% above the recommended N intake of 3 kg $capita^{-1}$. This illustrates the problem of dietary overconsumption and related obesity in large parts of the world. Reducing overconsumption would substantially reduce the required N input. Moreover, increasing food-chain NUE to 25% would reduce the required input to 108 Tg N yr^{-1}, which is lower than the estimated critical global total N input of 134 Tg N yr^{-1} by Schulte-Uebbing et al. [5] (See Table 3). Feeding the global population without trespassing regional and PBs thus seems possible, but requires dietary changes in combination with large increases in NUE, alongside mitigation of non-agricultural nitrogen sources such as sewage water. Multiple studies demonstrate that such improvements are technically achievable through a combination of improved fertilizer management practices, improved manure recycling, dietary shifts, and reductions in food loss and waste [9,15,20,21].

A similar reasoning can be applied to phosphorus. A just PB for total P inputs from fertilizers and manure can be derived by multiplying the global population by the recommended per capita dietary P intake and dividing by P use efficiency (PUE) in the entire food chain. Assuming a global population of 9 billion, a recommended P intake of 0.5 kg $capita^{-1}$ yr^{-1}, and a PUE of 25% (like N) yields a just boundary of 18 Tg P yr^{-1}. However, the potential to increase in PUE is likely larger than for NUE due to the different behavior of N and P in soils. Unlike N, P accumulates in soils, and fertilizer inputs only need to exceed crop uptake when soil P contents are below agronomic target levels, above which crop yields no longer respond to additional P inputs [22]. Currently, global soil P contents (stocks) are deficient in some areas, such as large parts of Africa, and above optimum in other areas, especially in areas with a history of high agricultural P fertilization, such as large parts of Western Europe and China. This spatial imbalance implies significant opportunities for improved P management through redistribution, legacy P utilization, and more precise targeting of fertilizer inputs.

Options to reconcile just and safe N and P input boundaries

Sustainable P management for crop production can be based on the 'Build-up or mining and Maintenance' approach. Depending on soil P availability, as determined by soil P tests, P inputs (fertilizer plus manure) should exceed, fall below, or match crop P removal when soil P status is low, high, or optimal, respectively [23].

Figure 3



Derived just planetary boundaries for N and P depending on global population and nutrient use efficiency, based on per-capita N and P demands of 3 kg yr^{-1} and 0.5 kg yr^{-1}, respectively.

The objective is to move from soil P deficiency (very low P-status) or soil P oversupply (very high P-status), toward an optimum soil P level above which additional P inputs no longer increase crop yields. To increase crop yields while protecting water quality, global soil P stocks should be increased in regions with P-deficient soils (building up P reserves in soils with low P-status) or decreased in regions with excessive P accumulation (mining P reserves in soils with a high P-status). Once the optimum level is achieved, P application should maintain soil P stocks by replacing the P removed through harvest. Under such management, the field-level PUE, defined as the ratio of crop P uptake to P inputs, can approach 100%. The food chain PUE is then mainly determined by losses occurring during harvest, processing, and consumption. Given that a PUE of 100% for field application is unattainable, and the substantial losses occur elsewhere in the food system, a maximum food-chain PUE of 33% seems realistic. The dependency of just PBs for N and P on global population and nutrient use efficiency is illustrated in Figure 3. The current total N and P input in agriculture, being near 265 Tg N and 40 Tg P, exceeds the calculated just N and P input even at a current NUE and PUE near 0.17 due to overconsumption. Combining dietary change with an increase in NUE and PUE would strongly reduce the required N and P input up to safe levels.

McDowell et al. [22] calculated that an initial capital application of 57 Tg P would be required to raise soil Olsen P concentrations globally to their agronomic optimal (optimum P-status). Thereafter, an annual P input of 17.5 Tg would be sufficient to maintain these levels in cropland to resupply P removed by harvest. This maintenance requirement is comparable to the 18 Tg P yr^{-1} calculated above at a PUE of 25%. Note, however, that this number is affected by the current recycling of manure, compost, and sludge. Increased recycling of organic P would reduce the required mineral P fertilizer use. This specifically holds for China, where manure recycling is limited. It has been estimated that P input by mineral and organic fertilizers according to the 'Build-up or mining and Maintenance' approach would reduce the overuse of P fertilizer (P input in excess of P crop removal) in China, consuming ca. 25% of the global P fertilizers, by ca. 75% [24].

In this study, we argue that safe boundaries can best be operationalized in terms of N and P losses to the environment, while just boundaries should be defined by manageable N and P inputs, as schematically illustrated in Figure 2. Comparing these boundaries requires translating safe loss thresholds into corresponding N and P input limits, which in turn depend on assumptions regarding NUE and PUE. Reconciling just and safe N and P boundaries, therefore, necessitates reducing N and P inputs by appropriate application and recycling, thereby increasing the NUE and PUE. In addition, N and P losses from sewage water should be reduced by implementing better wastewater management. Furthermore, N and especially P delivery to surface water should be reduced by improved land management (e.g. erosion control). Finally, dietary changes can enhance the reconciliation between just and safe N and P boundaries. Model scenario experiments with transformation towards low-meat diets, presented in Ref. [15], suggest that a sustainable world (SSP1) is not sufficient to improve global water quality with respect to N and P concentrations. Significant reductions in N and P delivery to surface waters are achieved through a transformation to low-meat diets and improvement of the agricultural efficiencies, as well as wastewater reduction, wastewater treatment, and soil conservation.

Conclusions

The control variables and related PBs for N and P, as presented in comprehensive PB assessments since 2009, focused until 2023 on the external N and P inputs due to chemical (N fertilizer) and biological N fixation and P fertilizer, sourced from mines. Since 2023, several studies have presented boundaries for N and P surplus, being the external inputs plus the recycled inputs of N and P by manure, other organic sources, and deposition on land minus crop N and P removal. While N surplus is a better indicator for impacts than external N inputs, this does not hold for P, where P delivery to surface water is more appropriate. We estimate a critical global P delivery to surface water of 6.1 Tg P yr^{-1}, being ca 37% lower than the current (2015) river P delivery to surface water, which has been estimated at 9.7 Tg P yr^{-1}. The contribution of the food system to N and P loads (deliveries) to surface water is 70%–75%, while it is near 50% for the N load on terrestrial ecosystems, due to ammonia emission, and near 80% for the nitrate load of groundwater. Just boundaries of N and P should, in our view, be related to their need for food production, which makes the needed input on agricultural land a suitable indicator. We estimate that if food-chain NUE and PUE are increased to 0.25, the just boundaries for N and P at a population level of 9 billion are 108 Tg N yr^{-1} and 18 Tg P yr^{-1}, respectively, with current N and P inputs being nearly double. While these numbers are associated with large uncertainties, they indicate that enhancing the NUE and PUE combined with erosion control is required to reconcile food production with environmental protection.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cosust.2026.101685.

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