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Taking planetary nutrient boundaries seriously: Can we feed the people?

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ABSTRACT

Recent research suggests that anthropogenic nutrient flows may have transgressed the regulatory capacity of the earth. Agrifood systems account for most of the flows, and the food supply is limited more by reducing the excessive flows than by phosphorus (P) reserves or population growth. The food supply is limited primarily by the P flow tolerated by freshwater ecosystems and next by the needed reduction in the conversion of nitrogen (N) to reactive form in fertilizer manufacture, legume cultivation and fossil fuel combustion. The required reduction in P and N flows would reduce the food supply to 250 and 710 kcal capita^{-1} d^{-1}, respectively, in the current agrifood systems. Dietary changes, waste prevention and nutrient recycling are parts of the necessary transformation.

1. Introduction

Nutrient flows in the earth system are instrumental to food security. Increase in the flows of nutrients is linked with climate change and the loss of biodiversity, those being the three human-induced shifts that have led to overstepping the ‘planetary boundaries’ (Rockström et al., 2009a, 2009b) or ‘the upper tolerable limits’ (Carpenter and Bennett, 2011) of the regulatory capacity of the earth system. We cannot afford to risk the vital processes of the earth, but can we feed the world population within these boundaries?

The global demand for food is rapidly increasing. The world's population has been projected to plateau at nearly ten billion people by the middle of this century and to peak at eleven billion by the end of the century (UN, 2011). Simultaneously, there is increasing competition for critical resources such as land, biomass, energy and phosphorus (P) reserves. The challenge of feeding the people is even more striking because it must be met when the critical biophysical boundaries for several earth system processes that determine elementary ecosystem services have been transgressed or are on the verge of becoming transgressed (Rockström et al., 2009a, 2009b). Flows of reactive nitrogen (N) and P represent one such process; excessive nutrient flows cause eutrophication and exacerbate biodiversity loss and N flow exacerbates climate change.

The planetary boundaries represent critical thresholds for shifts in the major earth system processes beyond which non-linear, abrupt environmental change may occur on a continental or planetary scale (Rockström et al., 2009a, 2009b). Criticism has been voiced against efforts to quantify the planetary boundaries (e.g., Schlesinger, 2009), the deficit of excluding the social dimension (Schmidt, 2013), the specific criteria (e.g., Samper, 2009) and the boundaries proposed (e.g., Carpenter and Bennett, 2011). However, ‘the first guess’ (Rockström et al., 2009a) to quantify the planetary boundaries is an important step towards operationalizing the ‘limits to growth’ (Meadows et al., 1972) and quantifying the critical ‘thresholds’ of the earth system (Scheffer et al., 2001). The planetary boundaries could be used to quantify the approximate extent of the required transition towards sustainability. For N, the first estimate of the extent of the conversion of N_2 to the reactive form (N_r), which the earth system can accommodate with no major disturbance, is one quarter of the present conversion rate (Rockström et al., 2009a, 2009b). For P, the boundary was determined at ten times the natural background flow to avoid an extensive anoxia at the near-bottom layers of oceans for the next 1000 years. Carpenter and Bennett (2011) showed that the planetary boundary could be one-tenth of the previously presented boundary for P when the carrying capacity of the freshwater systems is taken into account. They used the criterion of 24 mg P m^{-3} of water, which represents the interface between mesotrophy and eutrophy, a typical target to limit the eutrophication of lakes and reservoirs. The major threats are represented by

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an irreversible loss of biodiversity and life (cf. fish kills) in water ecosystems as a consequence of eutrophication, and climate change induced by nitrous oxide.

The food supply for humans depends on N and P because, with water, they represent a universal limiting factor for biomass production and are at the core of agricultural management. Food and nutrient security is a critical social complement to the ecological boundaries. Previous assessments of planetary boundaries for N only include the conversion of atmospheric N_2 to the reactive form (N_r) in fertilizer manufacture (Haber–Bosch process). The previous assessments thus exclude from the calculations the contribution made by the use of fossil energy and by cultivation-induced biological N_2 fixation to the flows of N_r, even though these processes are conceptually included in the framework (Rockström et al., 2009a, 2009b). An aspect not conceptually included in the framework of planetary boundaries (Rockström et al., 2009a, 2009b; Carpenter and Bennett, 2011), that is potentially important regarding nutrients is resource scarcity (Ragnarsdottir et al., 2011). Resource scarcity is a factor affecting the availability of N, even though N_2 is the major component of the atmosphere; 65% of the conversion of N_2 to the reactive form vital for life relies on fossil energy resources (Galloway et al., 2008), the 'peak oil' claimed to be reached already (Murray and King, 2012). In contrast to the P reserves, the use of fossil energy can be substituted for by renewable energy and in fertilizer manufacture by biological N_2 fixation, and does not represent a potential critical boundary in terms of resource scarcity. Regarding P, even though it is abundant in the earth's crust, the quality and accessibility of the reserves are decreasing and the extraction costs increasing (Gilbert, 2009; Sverdrup and Ragnarsdottir, 2011; Cordell and White, 2011; Dawson and Hilton, 2011).

In this study, we complement the assessments of planetary boundaries with the conversion of N_2 to N_r in fossil fuel combustion and biological fixation through the cultivation of legumes and by the critical P reserves. We quantify the consequences of returning to a level within the safe nutrient boundaries on the food supply. Exploring the significance of these issues for nutrient boundaries, we have coupled the debates on the 'safe operating space for humanity' (Rockström et al., 2009a, 2009b; Carpenter and Bennett, 2011), on P as 'the disappearing nutrient' (Cordell et al., 2009; Gilbert, 2009) and on food security (Beddington, 2010; Godfray et al., 2010; Foley et al., 2011; IAASTD, 2009; Tilman et al., 2002), all recently raised on the world agenda. We pose the question as to what returning to within the critical limits set by the regulatory capacity of the earth system in terms of nutrients would mean in quantitative terms, especially regarding food security. Can we feed the people while ensuring the vital processes of the earth? Specifically, these questions are raised:

1. What is the significance of the following complements to the assessment of the planetary nutrient boundaries: fossil fuel combustion, cultivation-induced biological N_2 fixation and scarcity of P reserves?
2. How much would the food supply be reduced by keeping within the safe nutrient boundaries, and how would the reduction depend on the population growth and on potential shifts in the agrifood systems?

2. Material and methods

The prior assessments of the planetary nutrient boundaries (Carpenter and Bennett, 2011; Rockström et al., 2009a, 2009b) served as a starting point for our study. Our stepwise assessment (Table 1) proceeded starting with the complementation of the estimates for the current flows and planetary N boundary presented by Rockström et al. (2009a, 2009b) with cultivation-induced biological N_2 fixation and fossil fuel combustion. We applied the assessment of Carpenter and Bennett (2011) of the lower carrying capacity of the freshwater systems for the planetary P boundary. We estimated whether the P resource scarcity sets an additional constraint to P use. The food supply within the nutrient boundaries was assessed based on the share of the agrifood systems of the nutrient flows, and the additional effect of the shifts in the agrifood systems and of the projected population growth was estimated. The resultant N and P flows, the nutrient boundaries and the excess flows were divided by the global population figure for 2010, thus assuming an equal distribution across the world's population (7.0 billion) (UN, 2011).

Table 1
The stepwise assessment of the needed reduction in current nutrient flows to return to within the planetary nutrient boundaries (Mt a^{-1}, kg $capita^{-1}$ a^{-1}). PB = planetary nutrient boundaries.

	Current flows		PB		Excess	
	Mt a^{-1}	kg $capita^{-1}$ a^{-1} [a]	Mt a^{-1}	kg $capita^{-1}$ a^{-1} [a]	Mt a^{-1}	kg $capita^{-1}$ a^{-1} [a]
Nitrogen (N)—N_2 conversion to reactive N (N_r)						
Rockström et al. (2009a, 2009b)[b]	121	17	35	5.0	86	12
Complemented: BNF, fossil fuels[c]	187	27	47	6.7	140	20
Agrifood systems[d]	139	20	35	5.0	104	15
Population growth[e]				3.2		
Phosphorus (P)—P flow to water systems						
Rockström et al. (2009a, 2009b)[f]	10	1.5	11	1.6	−0.7	−0.1
Freshwater systems[g]	9–32	1.3–4.6	1.2	0.2	7.8–31	1.1–4.4
Agrifood systems[h]	7–26	1.0–3.7	1.0	0.1	6.2–25	0.9–3.5
Population growth[e]				0.1		

[a] The current flows, planetary boundaries and excess flows were divided by the global population in 2010 (UN, 2011).
[b] Including the Haber–Bosch process only (Galloway et al., 2003, 2008).
[c] Including Haber–Bosch, other fossil fuel combustion and cultivation-induced biological N_2 fixation (Galloway et al., 2003, 2008).
[d] The complemented planetary boundary allocated to agrifood systems (Galloway et al., 2003, 2004, 2008; Pimentel et al., 2008).
[e] Planetary boundary of agrifood systems divided by the global population in 2100 (UN, 2011).
[f] Taking only the marine ecosystems into account.
[g] Taking the vulnerability of the freshwater ecosystems into account (Carpenter and Bennett, 2011). The range of the estimates of current flows: Bennett et al. (2001), Howarth et al. (1996), Seitzinger et al. (2010), Smil (2000).
[h] The complemented planetary boundary allocated to agrifood systems (Seitzinger et al., 2010).

2.1. Complements to the assessment of the planetary nutrient boundaries

The assessment of the N_r flow (121 Mt a^{-1} by Rockström et al., 2009a, 2009b) which includes fossil fuel combustion because of fertilizer manufacture and production of chemicals (i.e., the Haber–Bosch process chemistry) only, was complemented with the estimates of the N_r flow of cultivation-induced biological N_2 fixation (40 Mt a^{-1}) and fossil fuel combustion (25 Mt a^{-1}) (Galloway et al., 2003, 2008). The complemented planetary boundary was determined to be 25% of the complemented current conversion to N_r according to the criterion of Rockström et al. (2009a, 2009b).

The P boundary was complemented by a new conceptual element, the effect of the scarcity of the P reserves. The potential additional limitation resulting from the P reserves was assessed assuming the current global average use (2.4 kg capita^{-1} a^{-1}) (Cordell et al., 2009) and the P recovery of 13% for P rock (Cordell and White, 2011), yielding 7920 Mt P from the total technically and economically available global P reserve (Dawson and Hilton, 2011; Van Kauwenbergh, 2010) distributed equally across the growing population until 2100. It was expected that a population of 9.7 billion would be reached in 2050, rising to the peak population of 10.9 billion by 2100 (UN, 2011).

2.2. Food supply within the planetary nutrient boundaries

The agrifood systems' share of the nutrient flows was assessed based on the shares managed in the agrifood systems of the total complemented (see Section 2.1) global N_r flow (74%) (Galloway et al., 2003, 2004, 2008; Pimentel et al., 2008) and of the total global P flow (80%) (Seitzinger et al., 2010).

The quantity of food available within the planetary nutrient boundaries was assessed based on the share of the agrifood system of the current nutrient flows and the complemented boundaries. The available food supply was calculated using the current average food supply (2831 kcal capita^{-1} d^{-1} in 2009) (FAO, 2013) and the proportion of the nutrient boundaries of the current flows. The effect of population growth on the food supply within the planetary nutrient boundaries until 2100 (UN, 2011) was estimated. The nutrient boundaries of the agrifood system in current diet were divided by the projected peak population of 10.9 billion in 2100 (UN, 2011).

The effect of the shifts in the agrifood systems was explored using the example of a shift in consumption to a vegetarian diet, and another example of a shift to total prevention of food waste. The effect of a shift to a vegetarian diet was assessed based on the omitted consumption of nutrients for production of animal proteins in the current food supply (FAO, 2012) replaced by the production of plant proteins. The effect was calculated using the nutrient use efficiency values of various diets for N (Galloway and Cowling, 2002; Leach et al., 2012) and P (Metson et al., 2012; Reijnders and Soret, 2003). The effect of food waste prevention on the food supply in terms of the nutritional value was estimated (Kummu et al., 2012) relative to the current food supply.

3. Results

3.1. Complements to the assessment of the planetary nutrient boundaries

The global requirement to reduce nutrient flows for returning to within the planetary N boundary is 47 Mt a^{-1}. Appropximately one-third of the boundary and the excess to be avoided is because of the complements with conversion of N_2 to N_r through fossil fuel combustion, and biological N_2 fixation in agrifood systems, and two thirds arise from Haber–Bosch process (Table 1).

If the technically and economically available global P reserve, according to current knowledge, is equally divided among the growing population, assuming the current use rate capita^{-1} a^{-1}, the extent of the P reserves will not limit use until 2100. With a medium rate of projected population growth scenario, 74% of the current exploitable reserves would remain untapped. Consequently, the reserve would not restrict P use more than does the flow-based planetary boundary (Fig. 1).

3.2. Food supply within the planetary nutrient boundaries

Agrifood systems are responsible for the major part of the global N conversion and P flow. The critical boundary set by the eutrophication of fragile freshwater systems for P, rather than the boundary set by N conversion, determines food security (Fig. 1).

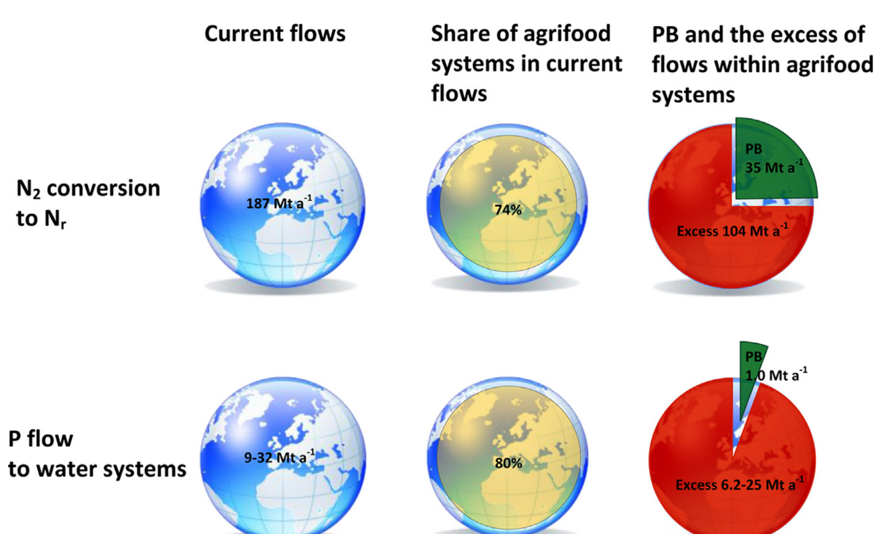

Fig. 1. The share of the agrifood systems (yellow) in the needed reduction (red) of the current nutrient flows to return to within the planetary boundaries (green). PB = planetary nutrient boundaries, N_r = reactive nitrogen, P = phosphorus.

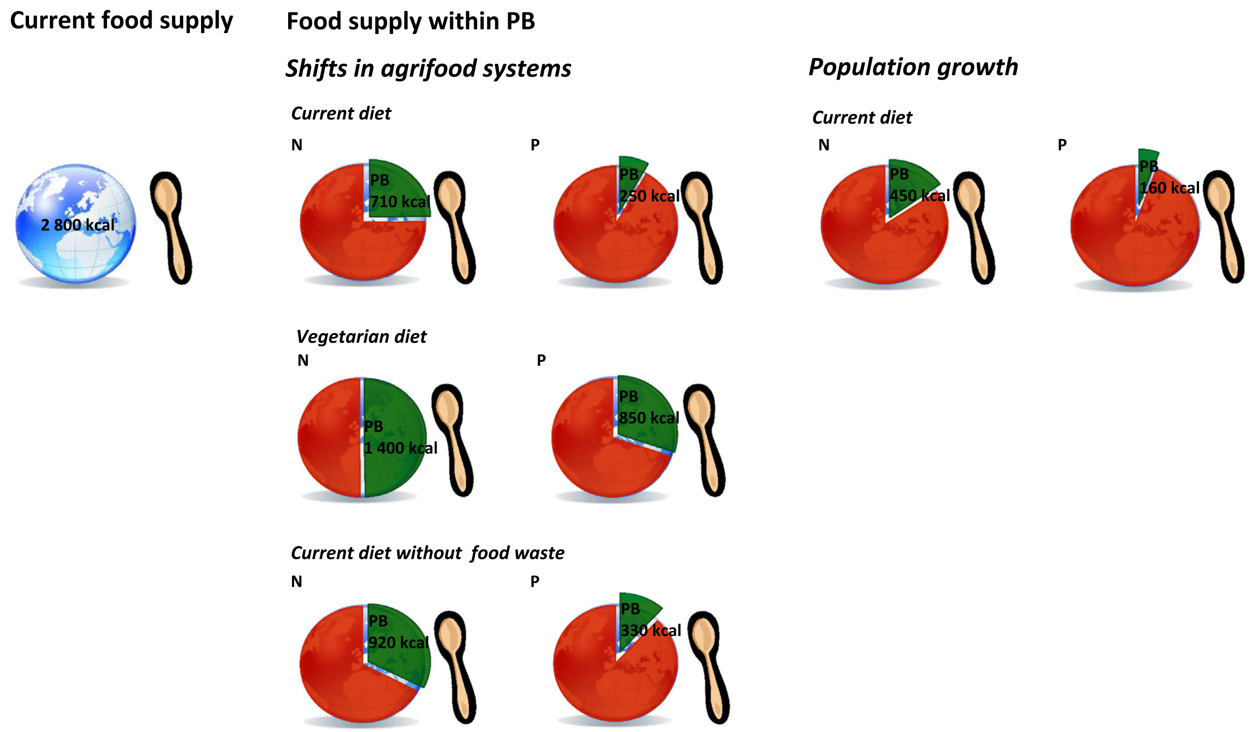

Fig. 2. The food supply within the planetary nutrient boundaries (green) affected by the projected population growth and shifts in the agrifood systems (kcal capita^{-1} d^{-1}). The deficit in comparison with the current food supply is shown in red. PB=Planetary nutrient boundaries.

Returning to within the critical boundaries would require the daily food supply to drop below a tenth of the present supply per capita, with current agricultural practices and diets (Fig. 2). At the expected global peak population in 2100, a further drop of 40% in comparison with the current population would occur within the planetary nutrient boundaries.

Single major shifts in the food supply and demand chain or in the diet would make a difference. The combined effect of the avoidance of food waste and a vegetarian diet, for example, would multiply the available calories of the P-limited diet by nearly four. Consequently, 930 kcal capita^{-1} d^{-1} would be available if the freshwater ecosystems are maintained at the mesotrophy–eutrophy interface according to the commonly applied target. If the N boundary were taken as the limiting factor, even 1610 kcal capita^{-1} d^{-1} could be supplied through the elimination of food waste and a shift to a vegetarian diet, with no other changes in the agrifood systems.

4. Discussion

4.1. Complements to the assessment of the planetary boundaries

The planetary boundary framework represents an ecosystems approach to the sustainability of human activities, a functional approach recognizing humans as an integral component in the ecosystems (UN, 2002). It represents a system integrity approach that is different from the dominant discourse on the sustainable use of resources (Thompson, 2007) or on eco-efficiency (Korhonen and Seager, 2008). The planetary boundary framework, if used for further elaboration and empirical testing, offers a quantitative measure of sustainability. Adopting such quantitative targets enables a focus on the means to enhance sustainability and avoids the dead-ends of paradigmatic conflict reflected in never-ending debates on normative interpretations of sustainability. Further, this resilience oriented systems integrity approach seems to – at least in some cases – reveal more critical limits for the humanity than the resource-oriented eco-efficiency approach alone does, such as here shown for the major plant nutrients N and P.

N conversion in fossil fuel use and the cultivation-induced biological N_2 fixation were added to the estimate that previously included fertilizer manufacture and other chemical production using the Haber–Bosch process only (Rockström et al., 2009a, 2009b). This complement had a marked effect on the estimate of the critical planetary boundary notably increasing the estimate of the needed reduction in the N flow. Involving eutrophication of freshwaters within the boundary for P flows crucially increases the challenge to achieve food security. The question of whether this involvement is justified by a risk of continent- or planet-wide irreversible change (Rockström et al., 2009a, 2009b) through, for example, biodiversity loss or the effect on the oceans, deserves further elaboration.

The functional approach of the planetary boundary framework appears to reveal the tolerable upper limits for P because the P reserves did not further restrict P use in comparison with the carrying capacity of the aquatic ecosystems. The 'peak P' (Cordell and White, 2011), questioned also by the dynamic character of the P reserves (e.g., Van Kauwenbergh, 2010), will not be met if the P load to waterways is to be returned to within the tolerable limits. The reduction in P flow necessary to save the freshwater systems will require a transition of the nutrient economy to reduce and completely recycle the P flows, including reuse of the sparingly available P reserves in field soils (e.g., Kahiluoto, 2000; Sattari et al., 2012) before P scarcity begins to restrict use.

4.2. Food supply within the planetary nutrient boundaries

The perspective of planetary boundaries highlights the critical role of the agrifood systems in the functioning of the earth system. The high share of the nutrient flows managed by the agrifood systems emphasizes the pivotal effect on food security of maintaining tolerable limits of the ecosystems. The limiting factor for food security, if irreversible changes in freshwater systems and fragile seas are to be avoided, is P and not N, because of the relatively wider gap to be bridged for P to return to the tolerable limits. If we were not able to hinder continuous freshwater eutrophication – which would also affect the planetary boundary of freshwater use – the next limit for the safe food supply would be set by N conversion. The complemented estimate for the planetary boundary of N conversion would limit the food supply more than the planetary boundary of the P flows to the oceans. As shown by the translation of the nutrient boundaries into food security in this study, an immediate return to within the planetary nutrient boundaries would lead to widespread starvation and a decrease in the current human population. The additional challenge represented by the expected population growth, to the plateau population of 9.7 billion in 2050 or 10.9 billion in 2100 (UN, 2011), is of relatively minor significance.

Land resources are declining, and land is needed for biodiversity and carbon reservoirs to mitigate biodiversity loss and climate change. Narrowing the yield gap (Mueller et al., 2012; Lobell et al., 2009) and increasing efficiency in livestock production (Wirsenius et al., 2010), while not compromising the planetary nutrient boundaries (Tilman et al., 2011), is important, however, it has its limits. Even minor reductions in waste and the consumption of animal products outweigh the land-use effect of feasible efficiency increases in livestock production (Wirsenius et al., 2010). If the nutrient planetary boundaries are to be taken seriously, a radical transformation of agrifood systems using a broad range of means is imperative (see also Ragnarsdottir et al., 2011; Wirsenius et al., 2010). A complete avoidance of food waste would hardly bridge the gap (cf. e.g., Foley et al., 2011), whereas global transition to a vegetarian diet could be of greater consequence. Only a combination of many shifts in various parts of the agrifood systems could render the required transformation. Increasing global nutrient use efficiency (Cassman et al., 2002), implementing precision and comparative advantage, and recycling residues are obvious mainstays. Reconsideration of the human diet with a higher diversity of crops and crop mixtures, algae, coarse fish, insects and cultured meat as well as food from the wilderness could make an important contribution to nutritional security. If these efforts were to fail, the freshwater ecosystems and fragile estuaries and seas, and the ecosystem services they support, would suffer most. Recycling of the aquatic biomass from the eutrophic freshwaters to agricultural fields could be used to target the management of the aquatic food web to retard the deterioration of aquatic ecosystems.

The current sufficiency of the global food supply for the entire population, if equally distributed, with 12% of the entire population being simultaneously chronically undernourished (FAO, 2013), underlines the importance of equity in the distribution of food and nutrients. When returning to within the planetary boundaries, to reduce the risk of disastrous consequences for humankind, there will be less opportunity for variation among regions and individuals. Policy and market frameworks are needed to implement the return while ensuring intergenerational and global equity in access to nutrients and food. An invaluable opportunity to initiate such a global policy and market framework is offered by the on-going work for the next Sustainable Development Goals, i.e., the 'Post-2015' dialogue, which flags the poorest and strives for synergy among the goals (UN, 2013; Griggs et al., 2013). The proposed improvement in 'full chain N use efficiency' of 20% by 2020 (Sutton et al., 2013) is a valuable step. Many more quick steps, however, have to be taken such as revealed here by the planetary nutrient boundary framework (cf. Erisman et al., 2008) to return to within the safe limits; the implications of the present beyond-the-critical-thresholds-state are not known. Acknowledging the safe limits to human-induced changes in the earth system while striving to eradicate poverty and hunger, means that the mistakes of the past (IAASTD, 2009) will not be repeated and demands new means to make progress. One model is offered by the global carbon trading framework, presuming that the lessons learned from, e.g., transition costs and price formation are used when defining the policy instruments to reduce and redistribute nutrient use.

5. Conclusions

The planetary boundary framework enables quantification of the sustainability target for nutrients in order to create a solid foundation to prioritize and develop the means. The extent of the change required to return to within the safe boundaries in nutrient use is striking, and the agrifood systems are instrumental in the change. Within the critical boundaries, securing access to food – even with equal distribution for the present population – is impossible without a radical transformation of the agrifood systems. The additional challenge represented by the expected population growth is relatively minor. Not increase in productivity alone but many simultaneous shifts in the agrifood systems could render the required transformation. Dietary changes, reduction of losses across the food supply chain and efficient recycling can make a substantial contribution. Because of the wide gap that must be bridged, implementing the transformation through global cross-sector policies and enabling market frameworks such as global trading of nutrient quota could be a pivotal factor in achieving food security while maintaining the vital processes of the earth.

Assessment of planetary boundaries has operationalized the discourse on limits to growth. A simplified assessment is justified for feasibility, but only if no crucial biases appear: We conclude that inclusion of freshwater eutrophication, as well as cultivation-induced biological N_2 fixation and combustion of fossil fuels is decisive for assessing the planetary nutrient boundaries for the food supply, whereas the inclusion of the finite P reserves is not a critical factor. Further critical defining of the quantifications is, however, of utmost importance. For the planetary nutrient boundaries to be taken seriously in setting the targets for action to ensure a 'safe space for humanity', an interlinked social dimension of food security – and the underlying precondition of equity – should be added to the critical boundaries of the framework.

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