Global Food Security 3 (2014) 16–21

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

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

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ARTICLE INFO

Article history:
Received 11 June 2013
Accepted 8 November 2013

Keywords:
Nitrogen
Phosphorus
Reactive flows
Phosphorus reserves
Food security
Agrifood system

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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http://dx.doi.org/10.1016/j.gfs.2013.11.002

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).