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Can our global food system meet food demand within planetary boundaries?

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ABSTRACT

Global food demand is expected to increase, affecting required land, nitrogen (N) and phosphorus (P) inputs along with unintended emissions of greenhouse gasses (GHG) and losses of N and P. To quantify these input requirements and associated emissions/losses as a function of food demand, we built a comprehensive model of the food system and investigated the effects of multiple interventions in the food system on multiple environmental goals. Model outcomes are compared to planetary boundaries for land system change, climate change and the global N and P cycles to identify interventions that direct us towards a safe operating space for humanity. Results show a transgression of most boundaries already for 2010 and a drastic deterioration in the reference scenario for 2050 in which no improvements relative to 2010 were implemented. We defined the following improvements for 2050: reduction of waste, less consumption of animal products, higher feed conversion efficiency, higher crop and grassland yields, reduction of N and P losses from agricultural land and reduction of ammonia (NH_3) volatilization. The effects of these measures were quantified individually and in combination. Significant trade-offs and synergies in our results underline the importance of a comprehensive analysis with respect to the entire food system, including multiple measures and environmental goals. The combination of all measures was able to partly prevent transgression of the boundaries for: agricultural area requirement, GHG emission and P flow into the ocean. However, global mineral N and P fertilizer inputs and total N loss to air and water still exceeded their boundaries in our study. The planetary boundary concept is discussed in relation to the selected variables and boundary values, including the additional necessity of eliminating the dependency of our food production on finite P reserves. We argue that total N loss is a better indicator of the environmental impacts of the global N cycle than fertilizer N input. Most measures studied in this paper are also on the agenda of the United Nations for Sustainable Development, which gives added support to their implementation.

1. Introduction

Food production relies on the availability of resources, such as land, fresh water, fossil energy and nutrients. Current consumption or degradation of these resources exceed their global regeneration rate (e.g. Molden, 2007; Bindraban et al., 2012; Van Vuuren et al., 2010). Furthermore, food production is associated with emissions that deteriorate earth's environmental quality (e.g. Rockstrom et al., 2009), like nutrient leaching that causes eutrophication of natural ecosystems, and greenhouse gas (GHG) emissions that contribute to global warming (IPCC, 2014).

To guide human activities, Rockstrom et al. (2009) and Steffen et al. (2015) selected control variables for nine critical earth system processes and assigned environmentally safe planetary boundaries to these variables. These boundaries refer, inter alia, to the following control variables which are closely related to the use of resources in agriculture and subsequent effects of their use: (i) the area of forested land, (ii) the energy imbalance (or total radiative forcing), (iii) industrial and intended biological nitrogen (N) fixation, (iv) the flow of phosphorus (P) from fertilizers to erodible soils and (v) the flow of P from freshwater systems into the ocean (Table 1). Forested land (i) was selected because of its assumed stronger role in land-climate interactions compared to other biomes. For example, evapotranspiration from the land surface may change when tropical forests are cleared, and boreal forests influence the albedo of the land surface. The energy imbalance (ii) integrates factors that affect the earth's energy balance such as the atmospheric concentrations of greenhouse gasses, and is closely linked to global warming. Industrial N fixation refers mainly to the production of N fertilizers for agricultural use, whereas intended biological N fixation is linked to the cultivation of leguminous crops (iii). Together, they have dominated the recent increase of reactive N input on earth during the last decades. P fertilizer flow to erodible soils (iv) causes eutrophication of watersheds according to Steffen et al. (2015). They assumed that all cropland soils are in principle erodible, and that P

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Table 1
The earth system processes, their control variables and proposed planetary boundaries (from Steffen et al., 2015), closely linked to the global food system.

Earth system process	Control variable(s)	Planetary Boundary
Land system change	Area of forested land as % of original forest cover	75%
Climate change	Energy imbalance at top-of atmosphere (radiative forcing)	$+1.0\ \mathrm{W\ m^{-2}}$
Biogeochemical flows		
N cycle:	Industrial and intended biological fixation of N	$62\ \mathrm{Mt\ N\ y^{-1}}$
P cycle:	P flow from fertilizers to erodible soils	$6.2\ \mathrm{Mt\ P\ y^{-1}}$
	P flow from freshwater systems into the ocean	$11\ \mathrm{Mt\ P\ y^{-1}}$

addition to watersheds is primarily linked to P fertilizer application. P flow from rivers into the ocean (v) was selected to prevent large-scale ocean anoxic events with detrimental effects on biodiversity.

Steffen et al. (2015) provides detailed information on above variables including their motivation for the planetary boundaries as given in Table 1. According to Steffen et al. (2015), the current states of above five control variables are already transgressing their safe zones, i.e. pushing the earth from its relatively stable state of the Holocene into the Anthropocene with unforeseen consequences. The expected growth in world population and increase of the animal protein share in the human diet will probably cause further pressure on agricultural resources and the environment, and may lead to further exceedance of related boundaries.

Several research groups modelled (parts of) the global food system in relation to resource use and emissions to gain insight into feasible options of producing sufficient food within the safe operating space of our planet. For example: land requirement by Erb et al. (2016); GHG emissions by Wollenberg et al. (2016); cropland N cycle by Zhang et al. (2015), Billen et al. (2015) and Liu et al. (2010); whole N cycle by Bodirsky et al. (2014); cropland P cycle by MacDonald et al. (2011) and Sattari et al. (2016); whole P cycle by Van Vuuren et al. (2010); whole N and P cycles by Bouwman et al. (2013) and Sutton et al. (2013). These publications describe only one or two resources or a part of the entire food system, and their results are not always based on a quantitative model where inputs and outputs are linked. However, we need a quantitative description of the main inputs and outputs of the food system and their interdependencies to understand the effects of our food system on multiple earth system processes as in Table 1. We hypothesize that such an integral system description will offer new insights because of unforeseen trade-offs and synergistic processes, especially if multiple measures are applied to achieve multiple environmental goals.

The objectives of our study are 1) to quantify agricultural land use, N and P fertilizer requirements, GHG emissions and losses of N and P for a number of food system scenarios within the context of planetary boundaries and 2) to contribute to the global debate on whether and how our food system can function within planetary boundaries. To our knowledge, such a quantitative analysis has not yet been published, linking current and future food demand to required input levels of land, N and P fertilizers and to associated emissions of GHG, N and P. Therefore, we developed a comprehensive model by integrating all major food and resource flows from the actual food intake by the human population, via food processing, livestock production, up to the N and P balance of cropland and permanent grassland soils. Feedback processes are included in the model to obtain a more realistic calculation.

This paper presents the methodology and the results of a study that explores the consequences of food demand as well as the mitigating effects of potential improvements in agricultural production methods and food chain adjustments. Our analysis is as yet limited to the global food system of 2010 and a projected food demand for 2050. However, the methodology can easily be updated with other data (both spatial and temporal) to explore, for instance, differences among regions or recent developments in food systems.

2. Methodology

2.1. Model description

2.1.1. Overview

We developed the model BIOSPACS (*Balancing Inputs and Outputs for the Sustainable Production of Agricultural CommoditieS*) to quantify N and P flows between five interacting components in the food system and those across the system's boundary as a function of food demand (Fig. 1). Related agricultural land requirements and GHG emissions from agricultural production are also calculated. The five components are: (1) human *Population* consuming food items, (2) the *Food balance* supplying (non-)food items, (3) *Livestock* producing animal-based food products, (4) *Organic fertilizer* consisting mainly of excreted manure from livestock and (5) *Agriculturall and* comprising arable land and permanent grassland for the production of food crops and feed for livestock.

The N and P inputs for the entire system are on the left-hand side of Fig. 1, the wastes and other uses (with unknown final destination) on the right-hand side and the losses from agriculture at the bottom. N and P stock changes are determined for agricultural land, the food balance and the population. Their values indicate either accumulation (inside the boxes) or depletion (outside the boxes).

Non-agricultural land areas, aquatic systems and the atmosphere are not described in BIOSPACS, except for those flows that cross the food system boundary. Requirements for non-food demands such as non-food crops like cotton, and non-feed use of residues like straw for bedding, are not taken into account. Extra food crop demand due to other use of food crops such as for biofuels, is included. However, we did not analyse the effects of changes of this other use in our study and used the value of 2010 also for future scenarios.

Statistical data from FAOSTAT and additional information from other sources are used in our approach to derive quantitative input–output relations of each component in the food system. These relations are described in this paper, while details on the used data and parameterization can be found in Appendix A. We selected 2010 as the reference year to describe the current state of the food system, and for the evaluation of future food systems, we used the population size and diet as projected for 2050 by the population division of the UN (www.un.org/en/development/desa/population/) and Alexandratos and Bruinsma (2012), respectively.

2.1.2. Population

BIOSPACS starts with the calculation of the total amount of consumed food as a function of population size and the amount of food consumed per capita. Here, food consumption is defined as food intake, whereas food supply equals the sum of consumption and waste in households. Both consumption and supply are expressed in fresh weight units of primary production equivalents per year (e.g. wheat). The total food consumption is partitioned into the 20 food groups, as defined by the FAO in their "Food Balance Sheets" (FBS): ten crop groups, three plant-based food groups directly derived from crops (i.e. sugar, vegetable oils and alcoholic beverages), five animal-based food groups and two aquatic food groups. Subsequently, food waste in households is added to the consumption of each food group (based on Gustavsson et al., 2011) in order to calculate the required food supply per food group. These food supplies are used as input for the *Food Balance* component.

Food protein equivalents of supply, consumption and waste are calculated by using the ratio of per capita protein supply and per capita