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Virtual Fertilizer Research Center

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Abstract

Fertilizers affect plant growth fundamentally and are essential to feed the world population. Yet, fertilizer use also causes eutrophication and greenhouse gas emissions. Overuse will aggravate these side effects, but underuse leads to agro-ecosystem's degradation, poverty and hunger.

The use of nitrogen and phosphorus fertilizers has been identified as one of driving forces that push the Earth from its stable geological era of the Holocene into the Anthropocene with unknown implications for life on Earth. Curtailing nutrient losses will therefore have far reaching implications on the Earth's ecosystem functioning and human health and well-being.

This reports describes a methodology to quantitatively link global N and P cycles to four other drivers of global change, being land-system change, freshwater use, climate change and stratospheric ozone depletion. This will allow the assessment of the impact of fertilizer interventions on these drivers revealing synergies and trade-offs with respect to food security and the environment.

1 Overview of planetary boundaries

1.1 Planetary boundaries

Planetary boundaries for nine essential Earth system processes have been proposed by Rockström et al. (2009) to determine a safe operating space for humanity on Earth. The boundaries are set to prevent reaching 'tipping points' where continental or planetary scale systems change into a new state, causing negative or catastrophic environmental change. The proposed boundaries refer to climate change, ocean acidification, stratospheric ozone depletion, global P and N cycles, atmospheric aerosol loading, freshwater use, land system change, biodiversity loss and chemical pollution (Appendix I). In their proposal, Rockström et al. (2009) gave quantifications of seven planetary boundaries, excluding atmospheric aerosol loading and chemical pollution, for which they have not yet identified safe boundary values. In their assessments, three planetary boundaries have already been transgressed, i.e. for the rate of biodiversity loss, climate change and the global N cycle.

Rockström et al. (2009) indicate in their paper that quantification is 'a preliminary, first attempt', and that much uncertainty still exist. They also indicate that interactions among planetary boundaries may occur, mutually affecting the safe boundary levels. These interactions have, however, not been analyzed and the boundaries have been quantified under the assumption that no other boundaries have been transgressed.

The concept of planetary boundaries has been criticized as it may be interpreted as if no action is required as long as the threshold has not been passed (Lewis, 2012). Moreover, many problems play a role at local or regional scale, like nitrogen pollution or P accumulation (Carpenter & Bennett, 2011; Lewis, 2012) and are not captured by the planetary boundary concept. Presenting just one aggregate planetary boundary may reduce action in regions where the problems occur (Lewis, 2012). An argument for using a planetary boundary is that thresholds are intertwined at regional and global scales, and that nitrogen pollution is driven by global trade (Galaz et al., 2012). For phosphorus (P), a critical threshold has been set for the P inflow to the oceans as this is the key driver behind global-scale ocean anoxic events (Rockström et al., 2009). Lewis (2009) suggests to better focus on the finiteness of the fossil P reserves as this is not a threshold but a depletion limit. De Vries et al. (2013) state that planetary boundaries should include 'both adverse impacts and human needs' and calculated that the boundary level of 35 Tg N yr-1 as proposed by Rockström et al. (2009) is too low in view of required N fixation for feeding the global population. They also argue that a value of 60-100 Tg N yr-1 is more appropriate in view of most environmental impacts. This statement is not fully underpinned with scientific data with respect to the safe operating space for humanity, but also the proposed boundary level of 35 Tg N yr-1 by Rockström et al. (2009) is 'a first guess only'.

Further elaboration and scientific underpinning of the boundary levels for the global N and P cycles is required but will not be investigated in this study. Comparing human needs, adverse impacts and planetary boundaries is necessary to identify where action may be required, but in our opinion inclusion of human needs in setting the boundaries makes the entire concept of using planetary boundaries for exploring the safe operating space for humanity obsolete. From the comparison, it may also be concluded that current or future global population is too high and its needs cannot be met by Earth systems. Yet, these outcomes ought to be the consequences that may result from a comprehensive analysis, rather than a presumption. The analysis would allow exploring fertilizer nitrogen and phosphorus interventions to arrive at minimal or optimal amounts required to meet food demand which can then be evaluated against a pre-set boundary value.

1.2 Interactions

Rockström et al. (2009) did not analyze the interactions among planetary boundaries, but indicated that planetary boundaries are interdependent, as transgressing one boundary may change values of other boundaries or cause them to become transgressed. Most of the interactions have a negative impact on the planetary boundaries according to Rockström and colleagues (2009) and further reduce the safe operation space for humanity.

In our research we focus on N and P fertilizer interventions and therefore look at interactions between global N and P cycles and the other Earth system processes. The planetary boundary for N is described as the amount of N_2 removed from atmosphere for human use (Rockström et al., 2009). N_2 conversion into reactive forms can be *intended*, like biological and chemical N fixation mainly for use in agriculture, or *unintended*, like emission of nitrogen oxides (NOx) from industry (De Vries et al., 2013). We focus on the intended N fixation for use in agriculture. The boundary for P is described as the inflow of phosphorus to oceans, expressed as the increase compared with natural background weathering (Rockström et al., 2009). We focus on P use in agriculture aimed at recycling, minimizing losses and minimizing depletion of fossil P reserves.

Main interactions between the global P and N cycles and other Earth system processes are:

1. **Climate change**: Energy use for fertilizer production, especially N fixation contributes to CO_2 emission. The fertilizer industry uses about 1.2% of the global energy consumption and contributes for about 1.2% of the global greenhouse gas emissions (Bernstein et al., 2007).
2. N partly emits as nitrous oxide (N_2O), a potent greenhouse gas, and food production is responsible for the majority of the anthropogenic N_2O emissions (Syakila and Kroeze, 2011). N_2O in total is estimated to contribute for 6 percent to the human induced global warming potential (Forster et al., 2007).
3. **Ocean acidification**: Ocean acidification is mainly caused by rising atmospheric CO_2 concentrations and consequently increased uptake of CO_2 from the atmosphere (Caldeira and Wickett, 2003; Doney et al., 2009). At a global scale, anthropogenic nitrogen (by emissions of NOx and NH_3) and sulfur deposition contribute a few percent to the acidification, with larger impacts in coastal waters (Doney et al., 2007).

4. **Stratospheric ozone depletion**: N_2O emission currently is the single most important ozone-depleting emission and is expected to remain the largest throughout the 21st century (Ravishankara et al., 2009)
5. **Atmospheric aerosol loading**: NH_3 contributes to the formation of secondary aerosols, and its relative importance is growing (Reis et al., 2009). However, due to large uncertainties no quantification is given yet by Rockström et al. (2009) of its boundary value nor its current status.
6. **Freshwater use**: N and P use are closely linked to freshwater use as irrigation generally takes place in well fertilized cropping systems. Irrigation may increase the use efficiency of N (and of P), but it also may decrease it when large amounts of N are leached due to excessive irrigation or rainfall events on moist soil. Vice versa, fertilizer application can substantially increase the use efficiency of water and with that reduce the demand of water per unit product.
7. **Land-system change**: N and P use are closely linked to land use: an increase in global land use for agriculture will increase global use of N and P. Efficient use of N and P may increase yields on the existing agricultural area and limit pressure for taking new land into production.
8. **Biodiversity loss**: the rate of biodiversity loss can be increased by the use of N and P fertilizers through acidification of terrestrial ecosystems and eutrophication of coastal and freshwater systems (Rockström et al., 2009). Yet, favorable feedbacks also occur when less natural lands are cultivated for agriculture due to higher yields on existing agricultural area.
9. **Chemical pollution**: Impurities, in particular Cadmium (Cd), in phosphate rock and derived fertilizers (Smit et al., 2009) may accumulate in soils when P fertilizers with high Cd contents are used (Grant, 2011). The impurities in phosphate rock vary between reservoirs, but reservoirs with relatively low Cd concentrations are prone to be exhausted (Smit et al., 2009). The planetary boundary for chemical pollution of air, water and soil covers much more than these pollutions from fertilizers. Due to the complexity and amount of pollutants and the large local variability, no boundary value is given yet by Rockström et al. (2009).

Feedback mechanisms may reduce the rate of change of different boundaries. Higher CO_2 concentrations increase primary production that captures part of the CO_2 which slows down the increase of CO_2 concentrations. Emissions of nitrate/ammonia and transfer into other ecosystems increase net plant productivity, and as a result also increase carbon sequestration. The net impact of N use on the climate may therefore be small, as increased global warming potential by emission of N_2O is then compensated by the absorption of CO_2 from the atmosphere by plants (De Vries et al., 2013). Increased carbon sequestration will occur both on land and in oceans where elevated CO_2 concentrations may enhance growth of phytoplankton and interact with nutrient cycling (Doney et al., 2009; Hutchings et al., 2009). The net effect of reactive N is estimated to be a reduction of radiative forcing at the global scale, whereby the effect of N_2O emission is offset by increased carbon sequestration in terrestrial systems and oceans, and NOx and NH_3 emissions also reduce global warming potential through increased aerosol density in the atmosphere (Erisman et al., 2011).

1.3 Research objective

The interactions presented in section 1.2 clarify that global P and N cycles relate to all other Earth system processes, but to a varying extent. Within cropping systems, land use, freshwater use and N & P fertilizer use are inherently linked. Fertilizer N use has a substantial impact on stratospheric ozone depletion and climate change. Therefore, in view of the purpose of this research topic ("*impact of fertilizer strategies on planetary boundaries*") we selected the following five Earth system processes in our assessment methodology: global N and P cycles, land-system change, freshwater use, climate change and stratospheric ozone depletion.

The objective of this report is to present a comprehensive methodology that allows analyzing the impact of nitrogen and phosphorus interventions on food production and associated control variables (see Appendix I) for a number of Earth System processes, including climate change, stratospheric ozone depletion, N and P cycles, freshwater use and land-system change.

2 Outline of the methodology

2.1 Purpose and need

To assess the impact of N & P fertilizer interventions on the planetary boundaries, a quantitative description of the key interactions (see 1.2) is needed. Cropland use, green and blue water use and N & P fertilizer use, all closely connected to the nine Earth system processes identified by Rockström et al. (2009), are intimately linked in our human food production system with various synergies and trade-offs. They should therefore be jointly introduced in one quantitative algorithm or model, including the emissions of N & P which are linked to the planetary boundaries for the global N & P cycles through their impact on the resilience of marine, freshwater and terrestrial ecosystems. The emission of P is also an important control variable in relation to the finiteness of soil P reserves from which P fertilizers are mined (Lewis, 2012). Basically, N and P emissions are a function of N and P application rates, their use efficiencies in producing food N and P and the fractions that accumulate in agricultural soils:

N Emission = N Application rate * (1 – N Use efficiency) * (1 – N Soil accumulation fraction) [Eq. 1a]

P Emission = P Application rate * (1 – P Use efficiency) * (1 – P Soil accumulation fraction) [Eq. 1b]

where *Emission* (or loss, in Tg N or P per year) includes emissions of N to the atmosphere and leaching of N and P towards surface and ground waters; *Application rate* (Tg N or P per year) refers to amount of N or P applied to soils; *Use efficiency* (-) is defined as the share of the application that is recovered in food and the *Soil accumulation fraction* (-) gives the share of non-recovered N or P that accumulates in the soil (e.g., in soil organic matter or adsorbed to soil particles).

N and P emissions are thus also related to the total amount of N and P in food products required to feed the population.

N Application rate = Population * N Diet (per capita) / N Use efficiency [Eq 2a]

P Application rate = Population * P Diet (per capita) / P Use efficiency [Eq 2b]

where *Population* (capita) is the total number of persons and *Diet* (Tg N or P per capita per year) refers to the amount of N or P in the diet of the population. Above equations clearly illustrate the interactions of the emissions of N and P with population size, dietary preferences, use efficiencies and accumulation fractions (see also Figure 1).

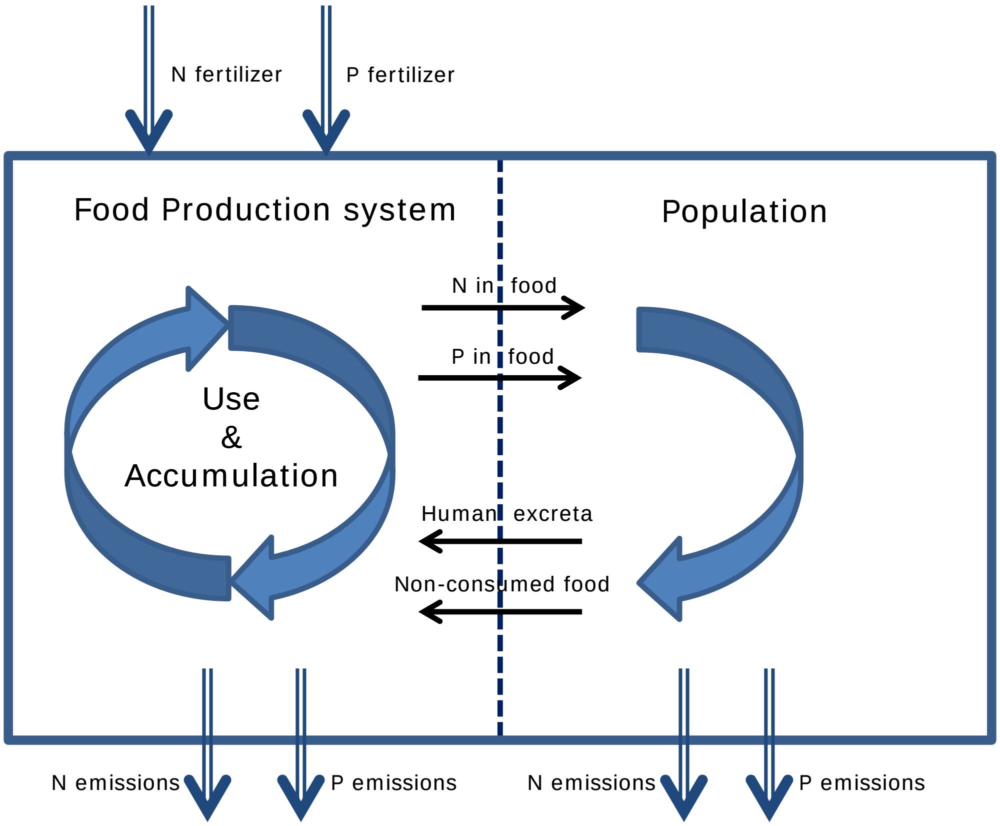

Figure 1. *Illustration of the linkages between fertilizers, food production and emissions (see also eqn. 1a,b – 2a,b).*

To describe the interactions adequately, agricultural land, water and fertilizer use should be linked to food production. After all, N & P fertilizers are applied in agriculture to increase yields for food production and without these fertilizers current human population on Earth could not be sustained (Smil, 1991). It should be made explicit whether planetary boundaries for cropland, blue water and N fertilizer use, e.g., as proposed by Rockström et al. (2009), are adequate to feed the current or future human population and vice versa, the required amount of cropland, blue water and N & P fertilizers should be estimated as function of population size and dietary preferences. Fertilizer interventions, such as measures to improve nutrient use efficiencies, will directly affect the global N and P cycles, and, through the interactions, they may also indirectly impact land-system change and global freshwater use.

The global food system with both plant-based and animal food items is very complex. Part of the produced crops is used as animal feed and part of the manure excreted by animals is used to fertilize cropland. The use of grasslands, although not included in land-system change of the planetary boundary concept, should be taken into account as it contributes to the human diet and indirectly affects cropland use. Production capabilities of cropland and grasslands differ among regions and may also change in time, as they are strongly affected by climate and soil characteristics. Large differences exists in the amount of agricultural land per capita per region and transport/trade are important to feed regional populations. High-input land management (e.g., high application levels of N and P fertilizers and irrigation) may cause high emissions per ha (locally), but also low emission per food product and high land use efficiency. Due to this complexity a concise approach is aimed for ("a summary model"), of which the outline is described in section 2.2. To our knowledge, no such model currently exists in which all four aspects (land, water, N and P) are described interdependently and in the context of the planetary boundary concept. Models incorporating two or three components have been developed already (see 2.3). The approach described in 2.2 is only used for quantifying land-based food production systems which means that any fisheries or sea-based food crops are not included. Also other land use activities (such as growing bioenergy crops) are not taken into account.

Climate change and stratospheric ozone depletion are two other Earth system processes in Rockström et al. (2009) that are directly affected by the use of N & P fertilizers (see 1.3). The effect of N & P fertilizer use on the control variables of these Earth system processes (i.e. energy imbalance and stratospheric ozone concentrations) will be calculated based on the output of the summary model without considering feedback interactions (e.g., effect of climate change on nutrient use efficiencies).

2.2 Outline

To develop a summary model of the global food production system a so-called "big farm" approach is adopted in which all relevant components are described with their interactions and input/output flows over the system's boundaries. The name "big farm" is chosen because the components and activities could in principle occur at one physical farm but usually they are spread over more than one specialized farm. Moreover, the big farm does not have a-priori defined spatial scale: depending on the source of input data it can have the size of an actual farm but it can also be as large as the whole globe when describing the Earth's food production system as one (farm) system. This approach gives flexibility to choose the most suitable spatial scale depending on the availability of data and the purpose of use.

The big farm is delineated by its total land availability divided in a number of land use classes: forest area, cropland (incl. temporary fallow land), grassland (two categories: meadows and pastures used by grazing livestock and grasslands predominantly used by wildlife species) and other land (following FAOSTAT land resources database). By supplying the acreage of each land use class, the total amount of available land and therefore the size of the big farm is defined. The number of inhabitants and numbers of livestock (both ruminants and non-ruminants) are other key characteristics which define the size of the big farm. Only components and flows of the big farm directly related to the food production system will be described, which means that flows associated with land not used for this purpose will not be analyzed. A number of flows are defined as *external*:

N and P: N and P fertilizer input, biological N_2 fixation, emissions of various N forms to non-agricultural ecosystems, import and export of N and P in food items, animal feed and manure-derived products across the boundary of the big farm.

Water: Precipitation, evapotranspiration, irrigation and water flows to non-agricultural ecosystems.

Biological N_2 fixation is an external flow because the atmosphere from where N_2 is captured by leguminous plant species is not defined as part of the farm. Therefore, N_2 fixation for artificial N fertilizer and biological N_2 fixation are both considered inputs (compare Rockström et al. [2009] who proposed a boundary for the total atmospheric N_2 fixation). Obviously, if the big farm encompasses the whole globe and is described as one system, import and export flows are zero by definition. However, import and export need to be quantified when pursuing a global analysis, and multiple big farms (e.g., one for each continent) have been defined to describe the Earth's food system.

The following components and *internal* flows "carrying N and P" within the boundaries of the big farm will be distinguished and quantified:

Table 1. *Components and internal flows/linkages between the components in the big farm model.*

		Inputs/outputs	From/to
1.	Humans	IN Food items OUT Human excreta Food wastes (compost) Food processing residues	FROM Crops and livestock (2, 4, 5) TO Crops and grass (2, 3) Crops and grass (2, 3) Livestock (4, 5)
2.	Crops	IN Human excreta Food wastes (compost) Animal manure OUT Vegetal food items Animal feed, incl. crop by-products	FROM Humans (1) Humans (1) Livestock (4, 5) TO Humans (1) Livestock (4, 5)
3.	Grass	IN Animal manure OUT Animal feed	FROM Livestock (4, 5) TO Livestock (4)
4.	Land-based livestock (ruminants)	IN Grass Crops (feed and by-products) Food processing residues OUT Animal products Animal manure	FROM Grass (3) Crops (2) Humans (1) TO Humans (1) Crops and grass (2, 3)
5.	Landless livestock (non-ruminants)	IN Crops (feed and by-products) Food processing residues OUT Animal products Animal manure	FROM Crops (2) Humans (1) TO Humans (1) Crops and grass (2, 3)

Notes: food waste is used here for the non-consumed food that is converted into compost and can be used to fertilize land; food processing residues is the non-consumed food converted into or used as animal feed. Crop by-products that are used as animal feed is included in feed crop. The amounts of cropland and grassland are not fixed, but are "naturally" limited by the total land availability in the big farm.

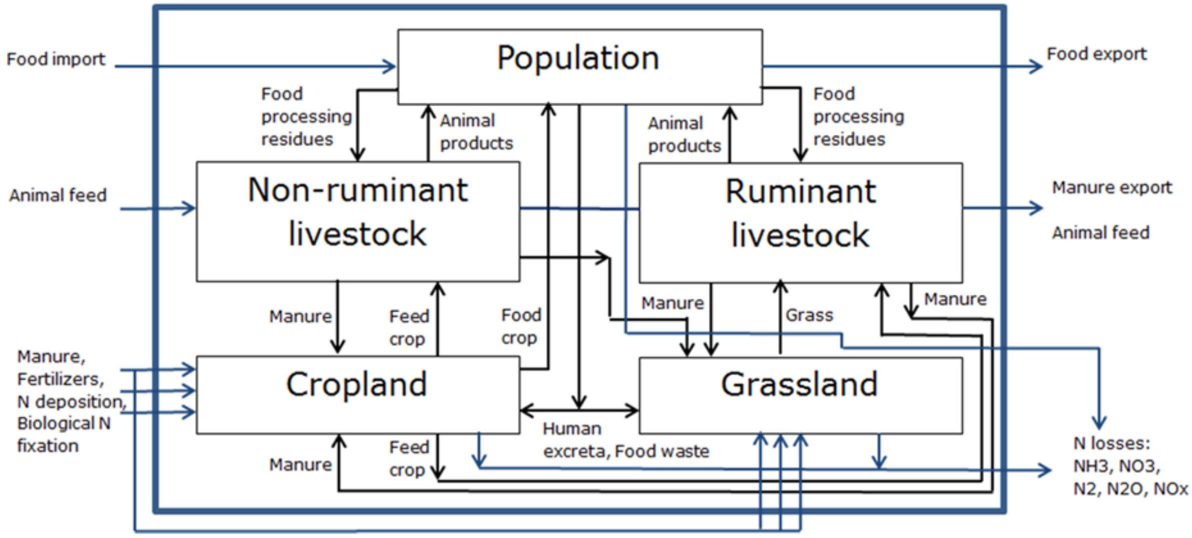

Figure 2. *Flow diagram of the big farm model. Blue arrows are external flows, black arrows are internal flows (see also Table 1).*

The Crop component will be subdivided into different Crop categories, such as cereals, root, oil and sugar crops and pulses, which supply essential food items to both humans and livestock and also leguminous crops specifically grown for soil N fertilization. This subdivision is needed for the calculation of the land, freshwater, N and P use as function of the amount of N and P in the diet. Each material flow (see column inputs/outputs in Table 1) consists of a number of "sub-flows", i.e. total mass (including moisture content), dry mass, energy content, N and P content, which will be described in the model.

We intend to set up the methodology by starting with a total food requirement (energy, protein and P), then calculating the requirements of land, water and nutrients as function of yield levels and use efficiencies and the emissions of N and P as associated consequences. N and P losses will be calculated by summing losses occurring from the soils of cropland and grassland and losses that occur when handling or processing each flow. N and P use efficiencies (defined as output/input) will be used/determined for each component of the big farm.

Special attention will be given to crop and grass response curves as function of water, N and P supply and their possible interactions. Higher yields indicate a higher land use efficiency (more crop/grass produced per unit of land) and can be achieved by lifting one of the three resources up to a higher input level, which may simultaneously improve the use efficiencies of the other two (see example in Figure 3, where the grain yield as function of N application rate depends on P availability). A yield target (e.g., following from food demand) can thus be realized with different combinations of input levels of land, water, N and P, having different effects on associated Earth system processes. On the other hand, fertilizer strategies, like improving nutrient use efficiencies, can affect land and (irrigation) water requirements.

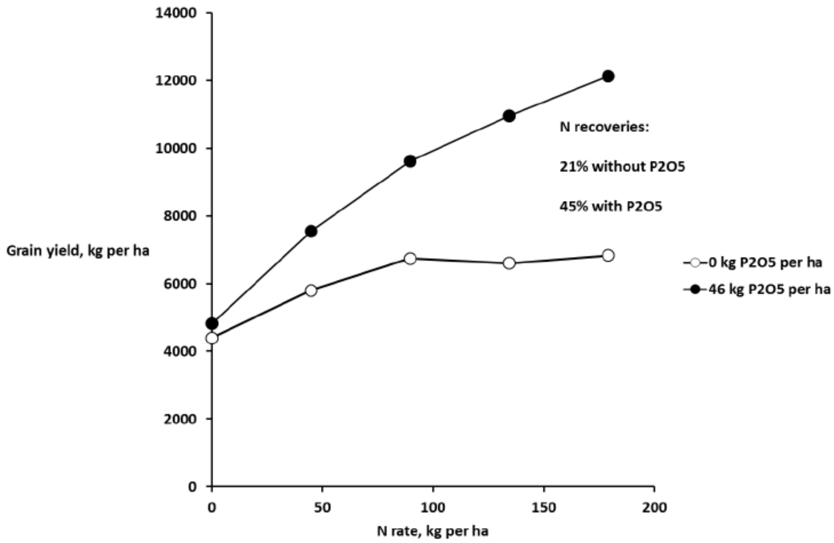

Figure 3. *An example of the interaction between N and P application rates in irrigated continuous corn production in the Great Plains (Schlegel and Havlin, 1995)*

Similar response curves, compared to those of Figure 3, may also exist at higher aggregation levels as was illustrated by Bindraban et al. (2008) who regressed national cereal yield against the national fertilizer consumption rate. This provides confidence that interactions occurring at field level (Figure 3) can be scaled-up to higher levels (national or even continental) which are used in the methodology.

We will estimate the amount of water lost by soil evaporation and plant transpiration during the growing season(s) as function of crop and grass yields in combination with average climatic conditions, e.g., by compiling data of water use efficiencies (e.g., Zwart & Bastiaanssen, 2004). Irrigation will be estimated by taking the difference between the calculated evapotranspiration and the total precipitation within the growing season corrected for the soil moisture reserve at the beginning of the growing season (only for agricultural areas). Information on the irrigation water use efficiency (extra yield per unit irrigated water supply) will be gathered and added to estimate the effects of irrigation on yield levels (only for areas with irrigation equipment).

2.3 Available databases

Several inputs are needed for the big farm model to assess the impact of fertilizer strategies on planetary boundaries. Much of the data can be found at the websites of FAOSTAT (http://faostat.fao.org/) and the UN (http://esa.un.org/wpp/) such as data on population density, food supply, trade, available resources land, water and fertilizers and livestock production. These data refer to country-level statistics and can easily be used for aggregation towards larger geographical units like continents or the whole globe. Another important source of data are found in the numerous spatially explicit databases on weather, soils, land use, livestock density, crop and manure production, and soil management (New et al. [1999], FAO [1996], Erb et al. [2007], Ramankutty et al. [2008], Monfreda et al. [2008], Potter et al. [2010], Conijn et al. [2011]). Overlaying these maps and aggregating the high resolution data to the regional scale and the globe will supply additional information about geographic-specific prevalence of climatic and edaphic conditions for agriculture.

In recent years a number of initiatives and projects has compiled valuable information and data for the methodology. Most of them have focused on only one or two resources required for (global) agriculture, such as a farm N budget model (e.g., Schröder & Sörensen, 2011), a (global) P flow analysis (Smit et al., 2009, Schröder et al., 2011), the relation between land use and food production (Wirsenius et al. 2010, Ramankutty et al., 2008), and worldwide water requirements for food production (e.g., Biemans, 2012). In the Netherlands a project started in 2013 to link C, N and P flows at dairy farms (ANCA: '*Annual Nutrient Cycling Assessment*'). Currently a number of research projects started to supply information and data to a benchmark atlas of agricultural production (www.wageningenur.nl/en/basis). The projects on water and nutrient use efficiencies, manure management and on-farm post-harvest losses are valuable in supplying background information on agricultural use efficiencies. All of these will be used -where possible- in the development of the big farm model and for the estimation of input data.

2.4 Approach other interactions

Fertilizer strategy effects on the planetary boundaries for the global N and P cycles, land-system change and freshwater use can be explored with the big farm model. Additionally (see 1.3), in our assessment the following linkages between fertilizer strategies and climate change and stratospheric ozone depletion will be elaborated. CO_2 emission due to fossil energy used for the production of N and P fertilizers and N_2O emission from the production of N fertilizers and from the soil due to N fertilizer application and N_2 fixation of leguminous crops will be quantified (e.g., following Crutzen et al., 2007). Changes in soil carbon pools linked to fertilizer strategies (e.g., associated with land use change or higher input of organic material following higher yields) will also be estimated (using IPCC tier one assessment methodologies). The relative contribution of these emissions to the atmospheric CO_2 concentration and the energy imbalance at the Earth's surface (being the two control variables for climate change as proposed by Rockström et al., 2009) will be determined to assess the effects of fertilizer strategies on both control variables for climate change. We intend to calculate the amount of stratospheric ozone depletion due to fertilizer strategies in a rather straightforward manner as function of the N_2O emission (see above) according to Ravishankara et al. (2009).

3 Verification

We will compare our assessment with the International Nitrogen Initiative (INI) that has initiated several regional nitrogen assessments, such as the European Nitrogen Assessment (Sutton et al., 2011). For phosphorus, links are already established through our membership of the Global Phosphorus Research Initiative (http://phosphorusfutures.net) and the Global Phosphorus Network (http://globalpnetwork.net). We will build on the current state of knowledge that has been integrated into a global assessment for both nitrogen and phosphorus – Our Nutrient World (Sutton et al., 2013). Data of these and other assessments will be used for some (partial) comparisons with the results of an assessment using the "big farm" methodology, described in this report, to check general validity.

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5 Appendix I

Appendix Table 1. *Proposed planetary boundaries (as published in Rockström et al., 2009).*

Earth System Process	Control Variable	Threshold Avoided or Influenced by Slow Variable	Planetary Boundary (Zone of Uncertainty)	State of Knowledge*
Climate change	• Atmospheric CO_2 concentration, ppm. • Energy imbalance at Earth's surface, W m^{-2}.	• Loss of polar ice sheets. • Regional climate disruptions. • Loss of glacial freshwater supplies. • Weakening of carbon sinks.	• Atmospheric CO_2 concentration: 350 ppm (350–550 ppm). • Energy imbalance: +1 W m^{-2} (+1.0–+1.5 W m^{-2}).	1. Ample scientific evidence. 2. Multiple sub-system thresholds. 3. Debate on position of boundary.
Ocean acidification	• Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag}).	• Conversion of coral reefs to algal-dominated systems. Regional elimination of some aragonite- and high-magnesium calcite-forming marine biota. • Slow variable affecting marine carbon sink.	• Sustain ≥80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80%–≥70%).	1. Geophysical processes well known. 2. Threshold likely. 3. Boundary position uncertain due to unclear ecosystem response.
Stratospheric ozone depletion	• Stratospheric O_3 concentration, DU.	• Severe and irreversible UV-B radiation effects on human health and ecosystems.	• <5% reduction from pre-industrial level of 290 DU (5%–10%).	1. Ample scientific evidence. 2. Threshold well established. 3. Boundary position implicitly agreed and respected.
Atmospheric aerosol loading	• Overall particulate concentration in the atmosphere, on a regional basis.	• Disruption of monsoon systems. • Human-health effects. • Interacts with climate change and freshwater boundaries.	• To be determined.	1. Ample scientific evidence. 2. Global threshold behavior unknown. 3. Unable to suggest boundary yet.

Earth System Process	Control Variable	Threshold Avoided or Influenced by Slow Variable	Planetary Boundary (Zone of Uncertainty)	State of Knowledge*
Biogeo-chemical flows: interference with P and N cycles	• P: inflow of phosphorus to ocean, increase compared with natural background weathering. • N: amount of N_2 removed from atmosphere for human use, Mt N yr^{-1}.	• P: avoid a major oceanic anoxic event (including regional), with impacts on marine ecosystems. • N: slow variable affecting overall resilience of ecosystems via acidification of terrestrial ecosystems and eutrophication of coastal and freshwater systems.	• P: < 10× (10× - 100×). • N: Limit industrial and agricultural fixation of N_2 to 35 Mt N yr^{-1}, which is ~ 25% of the total amount of N_2 fixed per annum naturally by terrestrial ecosystems (25%–35%).	P: 1. Limited knowledge on ecosystem responses. 2. High probability of threshold but timing is very uncertain. 3. Boundary position highly uncertain. N: 1. Some ecosystem responses known. 2. Acts as a slow variable, existence of global thresholds unknown. 3. Boundary position highly uncertain.
Global freshwater use	• Consumptive blue water use, km^3 yr^{-1}.	• Could affect regional climate patterns (e.g., monsoon behavior). • Primarily slow variable affecting moisture feedback, biomass production, carbon uptake by terrestrial systems and reducing biodiversity.	• <4000 km^3 yr^{-1} (4000–6000 km^3 yr^{-1}).	1. Scientific evidence of ecosystem response but incomplete and fragmented. 2. Slow variable, regional or subsystem thresholds exist. 3. Proposed boundary value is a global aggregate, spatial distribution determines regional thresholds.
Land-system change	• Percentage of global land cover converted to cropland.	• Trigger of irreversible and widespread conversion of biomes to undesired states. • Primarily acts as a slow variable affecting carbon storage and resilience via changes in biodiversity and landscape heterogeneity.	• ≤15% of global ice-free land surface converted to cropland (15%–20%).	1. Ample scientific evidence of impacts of land-cover change on ecosystems, largely local and regional. 2. Slow variable, global threshold unlikely but regional thresholds likely. 3. Boundary is a global aggregate with high uncertainty, regional distribution of land-system change is critical.

Earth System Process	Control Variable	Threshold Avoided or Influenced by Slow Variable	Planetary Boundary (Zone of Uncertainty)	State of Knowledge*
Rate of biodiversity loss	• Extinction rate, extinctions per million species per year (E/MSY).	• Slow variable affecting ecosystem functioning at continental and ocean basin scales. • Impact on many other boundaries – C storage, freshwater, N and P cycles, land systems. • Massive loss of biodiversity unacceptable for ethical reasons.	• <10 E/MSY (10–100 E/MSY).	1. Incomplete knowledge on the role of biodiversity for ecosystem functioning across scales. 2. Thresholds likely at local and regional scales. 3. Boundary position highly uncertain.
Chemical pollution	• For example, emissions, concentrations, or effects on ecosystem and Earth System functioning of persistent organic pollutants (POPs), plastics, endocrine disruptors, heavy metals, and nuclear wastes.	• Thresholds leading to unacceptable impacts on human health and ecosystem functioning possible but largely unknown. • May act as a slow variable undermining resilience and increase risk of crossing other thresholds.	• To be determined.	1. Ample scientific evidence on individual chemicals but lacks an aggregate, global-level analysis. 2. Slow variable, large-scale thresholds unknown. 3. Unable to suggest boundary yet.

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