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2011 Environ. Res. Lett. 6 014009

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Reconsideration of the planetary boundary for phosphorus

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Received 9 November 2010

Accepted for publication 25 January 2011

Published 14 February 2011

Online at stacks.iop.org/ERL/6/014009

Abstract

Phosphorus (P) is a critical factor for food production, yet surface freshwaters and some coastal waters are highly sensitive to eutrophication by excess P. A planetary boundary, or upper tolerable limit, for P discharge to the oceans is thought to be ten times the pre-industrial rate, or more than three times the current rate. However this boundary does not take account of freshwater eutrophication. We analyzed the global P cycle to estimate planetary boundaries for freshwater eutrophication. Planetary boundaries were computed for the input of P to freshwaters, the input of P to terrestrial soil, and the mass of P in soil. Each boundary was computed for two water quality targets, 24 mg P m⁻³, a typical target for lakes and reservoirs, and 160 mg m⁻³, the approximate pre-industrial P concentration in the world's rivers. Planetary boundaries were also computed using three published estimates of current P flow to the sea. Current conditions exceed all planetary boundaries for P. Substantial differences between current conditions and planetary boundaries demonstrate the contrast between large amounts of P needed for food production and the high sensitivity of freshwaters to pollution by P runoff. At the same time, some regions of the world are P-deficient, and there are some indications that a global P shortage is possible in coming decades. More efficient recycling and retention of P within agricultural ecosystems could maintain or increase food production while reducing P pollution and improving water quality. Spatial heterogeneity in the global P cycle suggests that recycling of P in regions of excess and transfer of P to regions of deficiency could mitigate eutrophication, increase agricultural yield, and delay or avoid global P shortage.

Keywords: eutrophication, freshwater, peak phosphorus, phosphorus, planetary boundaries, water quality

1. Introduction

As humans exert an ever-growing influence on earth system processes, scientific effort to estimate and categorize that influence has increased. Some researchers suggest that we have entered a new geologic era, the anthropocene, in which human actions are a principal driver of change in earth system processes (Crutzen 2002, Steffen *et al* 2007). The global influence of human action raises questions about the amount of change in global processes that can be accommodated while maintaining or improving human well-being.

Rockström *et al* (2009a, 2009b) introduce the concept of planetary boundaries to define a safe operating space for humanity on Earth. They define a planetary boundary as a human-determined acceptable level of a key global variable. For example, the planetary boundary for stratospheric ozone was defined as a decrease of <5% relative to 1964–80 levels (Rockström *et al* 2009a), and current global policies are likely to maintain ozone levels within this boundary. Rockström *et al* (2009a, 2009b) identified nine global boundaries that, if crossed, would change the earth system with unacceptable consequences for humanity. One of those boundaries pertained

to cycling of phosphorus (P). The P boundary was based on oceanic conditions and proposed to be ten times the pre-industrial flow to oceans (Rockström *et al* 2009a, 2009b).

The current flow to oceans is about three times the pre-industrial flow (Bennett *et al* 2001), yet even this input is associated with extensive eutrophication of freshwaters. Eutrophication makes water non-potable, causes blooms of cyanobacteria that are toxic to humans and livestock, depletes oxygen and causes fish kills, and is expensive to mitigate (Smith *et al* 2006, Schindler 2006). Along with the problem of too much P in some locations, we simultaneously face the potential of having not enough P to support agricultural production and meet growing demand for food. There are indications that the world may be approaching ‘Peak P’, an era when demand for P exceeds available global supply (Cordell *et al* 2009). However, peaks in mineral resources are difficult to forecast and others have disputed the claim that Peak P could be reached in a few decades (van Kauwenbergh 2010). Nonetheless, Peak P is worthy of careful consideration because declines in P availability could significantly decrease agricultural yields.

Widespread eutrophication of freshwaters and coastal oceans, combined with potential P shortages in coming decades, suggest that humanity may have already crossed planetary boundaries for P. Thus the planetary boundary for P warrants a closer look. Here, we reconsider the planetary boundary for P taking effects on freshwater systems into account. We consider human mobilization of P, through soil amendments, as the driver. We consider freshwater eutrophication as the adverse outcome to be avoided. We consider spatial heterogeneity of the global P cycle, as well as implications of eutrophication and Peak P for the planetary boundary.

2. Background

The P concentration of surface freshwaters depends on the inflow of P from surrounding lands, the flow of water that dilutes the P, the rate of storage of P in freshwater sediments, and the export of P to the sea (figure 1). Many of the global stocks and flows needed to determine the planetary boundary for P are previously published and are reviewed in this section of the paper.

2.1. Global phosphorus pools and flows

The flows of P from the continents through terrestrial and freshwater ecosystems to the sea are described in figure 1. The terrestrial pool of P consists mainly of P in terrestrial soil. Surface freshwater ecosystem P includes P dissolved and suspended in water and in surface sediments that exchange actively with the water. Inputs of P to continental ecosystems are mining, human-induced weathering (by land surface disturbance), and natural weathering. Outputs of P from the continents are dust flux from land to oceans, river transport from freshwaters to oceans, and long-term burial in freshwater sediment. Agricultural fertilizer is a major input of P to erodible soil and soil erosion is the principal source of P to

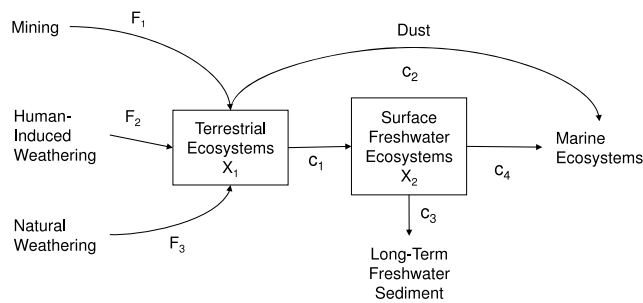


Figure 1. Pools and flows of phosphorus considered in this paper. P in surface freshwater ecosystems includes P in water as well as rapidly exchanging sediments. See text and equations (1) for definitions of symbols.

surface freshwaters. Transport of P from soil to freshwater ecosystems occurs in the form of P sorbed to eroded sediment particles and dissolved forms of P. Once P enters lakes and rivers it can be added to sediments or transported downstream. Freshwater P can be removed from circulation when it enters permanent sediments that are no longer recycled to surface waters on ecological time scales (years to decades).

We evaluated the P system using a linear, donor-controlled mass balance model:

$$\begin{aligned} \frac{dX_1}{dt} &= F_1 + F_2 + F_3 - c_1X_1 - c_2X_1 \\ \frac{dX_2}{dt} &= c_1X_1 - c_3X_2 - c_4X_2. \end{aligned} \quad (1)$$

Terms of equations (1) correspond to the pools and flows depicted in figure 1. X_1 and X_2 are P (Tg) in terrestrial soil and freshwaters (water plus actively exchanging sediments), respectively. F_1 , F_2 , and F_3 are inputs (Tg y^{-1}) from mining, human-induced weathering, and natural weathering, respectively. The rate coefficients (y^{-1}) c_1 , c_2 , c_3 , and c_4 refer, respectively, to transport rates from terrestrial to freshwater ecosystems, terrestrial to marine ecosystems as dust, freshwater ecosystems to permanent sediments, and freshwater ecosystems to the sea.

2.2. P pools and flows: published estimates

Estimates are known for several important global fluxes or pools of P pertinent to equations (1) (table 1).

According to the International Fertilizer Association (IFA 2009), 23.5 Tg P was mined in 2008. Of this mined P, approximately 4% is used for industrial products (Cordell *et al* 2009) and is unlikely to enter terrestrial ecosystems. The remainder, 22.6 Tg y^{-1} , is used principally for fertilizer and a smaller amount is fed to livestock in feed supplements. Nearly all this P is added to terrestrial soil.

Current mass of P in erodible soil is estimated by Smil (2000) to be 50 000 Tg based on an assumption of an average of 0.05% of total P in the top 50 cm of soil (Stevenson and Cole 1999). Weathering is split into human-induced weathering and natural weathering. Assuming a mean lithospheric content of 0.1% P and average global denudation rate of 750 kg ha^{-1} , Smil (2000) estimates that 10 Tg P is released annually from

Table 1. Global phosphorus fluxes (Tg y^{-1}) and pools (Tg) used in analyses reported here.

Flux or pool	Estimate	Source
Total mining of P	23.5	IFA (2009), Van Vuuren <i>et al</i> (2010)
Mined P added annually to soil (F_1)	22.6	IFA (2009), Van Vuuren <i>et al</i> (2010), Cordell <i>et al</i> (2009)
Pre-industrial weathering (F_3)	10–15	Bennett <i>et al</i> (2001), Froelich <i>et al</i> (1982), Judson and Ritter (1964), Smil (2000)
Current weathering ($F_2 + F_3$)	15–20	Bennett <i>et al</i> (2001), Lerman <i>et al</i> (1975)
Current mass of P in erodible soils X_1	50 000	Smil (2000)
Current annual increment of P in erodible soils	10	Bennett <i>et al</i> (1999, 2001)
Dust transport from land to sea ($c_2 X_1$)	1	Duce <i>et al</i> (1991)
Transport from surface freshwaters to the sea ($c_4 X_2$)	22	Bennett <i>et al</i> (2001), Smil (2000), Howarth <i>et al</i> (1996)

P-bearing rocks. Global release of P to surface soil due to weathering ranges between 15 and 20 Tg y^{-1} (Bennett *et al* 2001). By combining the mechanical and chemical denudation rates (20 000 Tg y^{-1}) (Garrels and Mackenzie 1971) with the mean P content of the Earth's crust (0.1%) (Taylor 1964), Lerman *et al* (1975) calculated current P weathering to be 20 Tg y^{-1} . Current P weathering rates are not likely to be lower than 15 Tg y^{-1} , the average of current and pre-industrial weathering rates (Bennett *et al* 2001, Gregor 1970, Judson and Ritter 1964).

The annual increment of P in erodible soil is a small change in a large number. This increment can be calculated two ways. Based on global P budgets, the annual global increment of P in agricultural soils was about 10 Tg y^{-1} from 1975 to 1995 (Bennett *et al* 2001). A second calculation corroborates this estimate. The annual increment of P to soil of an intensively farmed watershed in Wisconsin was about a third of annual inputs, based on two independent measurements (Bennett *et al* 1999). This percentage applied to inputs of mined P to soil suggests that the annual increment of soil P is roughly 7 Tg y^{-1} . Sensitivity analyses presented below suggest that uncertainty in the annual P increment of terrestrial soils is not an important source of error in planetary boundary estimates.

Dust transport from land to sea was based on work by Graham and Duce (1979) who found that 3.2 Tg y^{-1} of P moves from the atmosphere to land and 4.2 Tg y^{-1} from the land to the atmosphere. The excess P (1 Tg y^{-1}) entering the atmosphere from the land is eventually deposited in the ocean (Duce *et al* 1991).

Published estimates of P transport from freshwaters to the sea vary more than three fold. Bennett *et al* (2001) report a published range of 17–32 Tg y^{-1} . A value of 22 Tg y^{-1} has been adopted as the most plausible estimate by several authors (Bennett *et al* 2001, Howarth *et al* 1996, Smil 2000). The most recent estimate based on the global model NEWS is 8.6 Tg y^{-1} (Seitzinger *et al* 2010). These authors state 'Our estimates for PN (particulate nitrogen) and PP (particulate phosphorus) (12 Tg N and 6 Tg P) are considerably lower than Meybeck's (21 Tg N and 20 Tg P) which were based on a POC (particulate organic carbon) budget and assuming fixed N:C:P ratios. NEWS calculates PN and PP as a function of TSS (total suspended solids) in rivers, which we consider a more appropriate approach'. Calculations presented below employ

three values for annual P flux to the sea: the low value of 9 Tg P from Seitzinger *et al* a medium value of 22 Tg P (Howarth *et al* 1996, Bennett *et al* 2001, Smil 2000), and an upper limit of 32 Tg P (GESAMP 1987 cited in Bennett *et al* (2001)).

2.3. Global surface freshwater volume and replacement rate

Calculations of the planetary boundary for P (presented below) require an estimate of the global volume and replacement rate of global surface freshwater. The volume of the world's surface freshwater is $175 \times 10^3 \text{ km}^3$ for lakes and $2 \times 10^3 \text{ km}^3$ for rivers (Oki and Kanae 2006), a total of $177 \times 10^3 \text{ km}^3$.

To estimate replacement rate, we first estimate inflow to the world's surface freshwaters. Then we divide inflow by volume to compute replacement rate. Flow from rivers to the sea is $45.5 \times 10^3 \text{ km}^3 \text{ y}^{-1}$ and human withdrawals of freshwaters are $3.8 \times 10^3 \text{ km}^3 \text{ y}^{-1}$ (Oki and Kanae 2006). Input of water into rivers is at least as large as outflow plus withdrawals. Global precipitation minus evaporation on water body surfaces is positive, so these net inputs are accounted for in the outputs. Thus total inflow of water to lakes and rivers is approximately $49.3 \times 10^3 \text{ km}^3 \text{ y}^{-1}$ (the sum of outflows and human withdrawals of freshwater). This flow indicates a residence time of $177 \times 10^3 \text{ km}^3 / 49.3 \times 10^3 \text{ km}^3 \text{ y}^{-1} = 3.59 \text{ y}$. The inverse of residence time is the replacement rate, 0.278 y^{-1} .

3. Methods

We used the background information described above to calculate planetary boundaries for global freshwater eutrophication. At least three terms of the global P system (figure 1) could serve as planetary boundaries. Managers often seek to control P flux to freshwaters ($c_1 X_1$), and it is reasonable to compute a planetary boundary for this flux. However the flux to freshwaters often depends closely on the input rate of P to erodible soil ($F_1 + F_2 + F_3$) and mass of P (X_1) in erodible soil. Therefore we computed boundaries for these terms as well.

Our calculations followed three steps. (1) From available information, we estimated the rate of sedimentation for the earth's surface freshwaters as a whole, and the global rate of transport of P from land to freshwaters. (2) Using target P concentrations for freshwater quality, we estimated the planetary boundary for P flux that would achieve this

water quality standard for all of earth's surface waters. We estimated this planetary boundary for three terms of the global phosphorus cycle: (i) the annual P flux to surface freshwaters, (ii) the annual input of P in fertilizer and manure to erodible soils, and (iii) the mass of P in terrestrial soils. (3) Finally, we computed a sensitivity analysis to evaluate how our estimates of planetary boundaries might be affected by errors in our assumptions or observed values. This section of the paper describes these steps. All computations were performed in R using programs written by the first author.

3.1. Freshwater sedimentation and transport from land to freshwater

To estimate P flows from land to freshwater and to sediments, we used a well-established model from limnology introduced by Vollenweider (1976). The Vollenweider (1976) model is

$$\frac{dP_L}{dt}V = M - P_L Q - \sigma P_L V, \quad (2)$$

where P_L is mean P concentration in the water body, mass vol^{-1} ; V is the water body volume, vol; M is annual mass load of P to the water body, mass time^{-1} ; Q is water discharge at the outlet of the water body, vol time^{-1} ; σ is the sedimentation coefficient, time^{-1} .

Sedimentation was estimated from the empirical relationship of Canfield and Bachman (Canfield and Bachmann 1981, Ahlgren *et al* 1988)

$$\sigma \approx 0.129 \left(\frac{M}{Q} \rho_w \right)^{0.549}, \quad (3)$$

where ρ_w is water replacement rate Q/V . The Vollenweider model (equation (2)) is interchangeable with the equation for X_2 dynamics in expression (1) under the following identities:

$$\begin{aligned} M &= c_1 X_1 & P_L Q &= \left(\frac{Q}{V} \right) (P_L V) = c_4 X_2; \\ c_4 &= \frac{Q}{V}; & X_2 &= P_L V & \sigma P_L V &= c_3 X_2; \\ c_3 &= \sigma. \end{aligned} \quad (4)$$

Although internal recycling can be important in determining the water quality of individual lakes and rivers (Søndergaard *et al* 2003), recycling depends heavily on local conditions. The global extent of internal P recycling in freshwaters is beyond the scope of this paper.

3.2. Planetary boundaries

Excess biomass of phytoplankton is the most obvious sign of impaired water quality to users of freshwater. Phytoplankton biomass is closely correlated with concentration of total phosphorus in freshwaters, and the latter is often used as an index of eutrophication (Vollenweider 1976, Carlson 1977). Carlson's index (1977) connects several metrics of water quality, including phosphorus concentration, to phytoplankton biomass. Based on Carlson's index, we used 24 mg m^{-3} total

P as a boundary between mesotrophy and eutrophy. As an alternative target, we used the approximate pre-industrial P concentration in global rivers of 160 mg m^{-3} . This estimate was computed from pre-industrial P flows to the sea of 8 Tg y^{-1} (Bennett *et al* 2001) using equations (1)–(4).

To compute the planetary boundary in terms of P flux to freshwaters ($c_1 X_1$) we solved equations (1) and (3) simultaneously (using identities in (4)) to calculate the value of the flux that would yield a steady-state average concentration of P in the world's freshwaters equal to the target P concentrations.

To compute the planetary boundary in terms of P input to erodible soils and P mass in soils, we estimated the parameters of the first expression in (1) using data in table 1, and then calculated the values of P input to soil and P mass in soil that would yield a steady-state average concentration of P in the world's freshwaters equal to the target P concentrations.

Specifically, the equation for dynamics of P mass in soil from expression (1) can be written

$$\frac{dX_1}{dt} = F - c_1 X_1 - c_2 X_1 = F - C X_1, \quad (5)$$

where now F stands for total inputs to terrestrial ecosystems (weathering plus fertilizer) and C is defined as $c_1 + c_2$.

If we know F , X_1 , and the change in X_1 for some time interval then we can solve for C :

$$C = \frac{1}{X_1} \left[F - \frac{\Delta X_1}{\Delta t} \right]. \quad (6)$$

If for the same time interval we know the dust flux rate A (for airborne, mass time^{-1}) and the flux rate from land to freshwater W (for waterborne, mass time^{-1}) then

$$c_1 = C - \frac{A}{X_1} \quad c_2 = C - \frac{W}{X_1}. \quad (7)$$

Next we compute the influx to erodible soils \hat{F} and the P mass in erodible soils \hat{X}_1 that will cause the flux from land to freshwater to equal the desired target T at steady state. By equation (5) at steady state

$$0 = \hat{F} - c_2 \hat{X}_1 - T \quad 0 = \hat{F} - C \hat{X}_1, \quad (8)$$

where C is estimated from equation (6) and c_2 is estimated from equations (7). The planetary boundaries are the values of \hat{F} and \hat{X}_1 that solve equations (8).

3.3. Sensitivity analysis

In the calculations described above, the planetary boundaries for P depend on six imperfectly known quantities: (i) P flow from surface freshwaters to the sea $c_4 X_2$; (ii) water flow into or out of surface freshwaters Q ; (iii) volume of surface freshwaters V ; (iv) flow of P in fertilizers and manure to erodible soil $\text{Sum}(F)$; (v) current annual change in P mass of erodible soil dX_1/dt ; and (vi) sedimentation rate coefficient of P in surface freshwaters c_3 . All other quantities needed to compute the planetary boundaries are derived from these six

Table 2. Calculated global phosphorus pools, coefficients or fluxes based on three estimates of P flow to the sea, c_4X_2 .

Pool, coefficient or flux	Value if $c_4X_2 = 9 \text{ Tg y}^{-1}$	Value if $c_4X_2 = 22 \text{ Tg y}^{-1}$	Value if $c_4X_2 = 32 \text{ Tg y}^{-1}$
Storage in freshwater systems, X_2 (Tg)	32.3	79.0	114.9
Storage in freshwater systems per unit water volume, X_2 , (mg m^{-3})	183	446	649
Sedimentation coefficient, c_3 (y^{-1})	0.026	0.045	0.056
Sedimentation flux, c_3X_2 (Tg y^{-1})	0.85	3.52	6.41
Flow of P from terrestrial ecosystems to freshwater, c_1X_1 (Tg y^{-1})	9.9	25.9	38.4

empirical values. How sensitive are the calculated planetary boundaries to these estimated quantities?

We computed a sensitivity analysis by systematically perturbing each of the six uncertain terms to 95% and 105% of the nominal value in a 2^6 factorial design. Results were analyzed by Yates' algorithm (Box *et al* 1978) to compute main effects and all factor interactions for each of the three planetary boundaries.

4. Results

Global P pools and fluxes are presented for three published estimates of P flux to the sea. The three planetary boundaries are presented for each of the two P concentration targets using the three different estimates of P flux to the sea.

4.1. Phosphorus mass in global surface freshwaters

P mass in surface freshwaters ranges roughly between 32 and 115 Tg and, as a ratio of mass to water volume, between 180 and 665 mg m^{-3} (table 2). Some (perhaps most) of the P in freshwaters is in the form of suspended particles. Most of the P moving to the sea in the world's freshwaters is suspended in river water. Rivers have rather high P concentrations (Howarth *et al* 1996, Seitzinger *et al* 2010), while the water stored in lakes like has lower P concentrations (Vollenweider 1976, Carlson 1977, Canfield and Bachmann 1981). The planetary boundaries are based on a flow-weighted average of the world's lakes and rivers.

4.2. Sedimentation and transport from land to water

Sedimentation coefficients and fluxes (c_3X_2) calculated from the model of Canfield and Bachmann (1981) indicate that less than 10% of the P mass in global freshwaters is retained in sediment (table 2). This fraction is reasonable for rivers, which account for most of the flow. However, lakes in general retain a larger fraction of their P mass in sediments (Ahlgren *et al* 1988).

Calculated fluxes of P from land to surface freshwaters (c_1X_1) are larger than the estimated flows from freshwaters to the sea (table 2), because some P is stored in freshwater sediments. Flows to freshwaters are substantially smaller than the global P pool in soils and the annual inputs of P to soils (table 1). In an intensive study of a single watershed, the flow

from land to freshwater was also much smaller than the annual inputs of P to erodible soils (Bennett *et al* 1999).

4.3. Planetary boundaries for phosphorus

For all three estimates of P flow from freshwaters to the sea, the calculated planetary boundaries are smaller than current conditions (figure 2). Numerical values of the planetary boundaries are tabulated in the appendix.

For the medium estimate of P flow from freshwaters to the sea (22 Tg y^{-1}), the current flow rate is about 20 times the planetary boundary for the lower target concentration (24 mg m^{-3}) and almost three times the planetary boundary for the higher target concentration for P in freshwaters (160 mg m^{-3}).

Current conditions are closest to the planetary boundary for the low estimate of P flow from freshwaters to the sea (9 Tg y^{-1}) and the high target concentration. Nonetheless, even under these conditions the current conditions exceed the planetary boundary.

4.4. Sensitivity analysis of planetary boundary estimates

Sensitivity of the calculated planetary boundaries to each factor acting alone are presented in figure 3 for the medium estimate of P flow from freshwaters to the sea (22 Tg y^{-1}) and high target concentration for P in freshwaters (160 mg m^{-3}). Patterns of sensitivity are similar for all scenarios we considered. Results for the medium estimate of P flow from freshwaters to the sea (22 Tg y^{-1}) and low target concentration for P in freshwaters (24 mg m^{-3}) are presented in the appendix. Also, all interactions among factors are tabulated in the appendix.

The calculated planetary boundary for P inputs to freshwater is most sensitive to estimates of Q , water input or output to freshwaters. An error of +10% in Q leads to an error of about +10% in the planetary boundary. This planetary boundary is also somewhat sensitive to the sedimentation rate coefficient, c_3 .

The calculated planetary boundaries for P inputs to soil and for P mass in soil are most sensitive to estimates of P flow from surface freshwaters to the sea (c_4X_2) and water flow into or out of surface freshwaters (Q), but in opposite directions. An increase of 10% in P flow from freshwater to the sea decreases the calculated planetary boundaries by about 10%. An increase in Q of 10% increases the calculated planetary

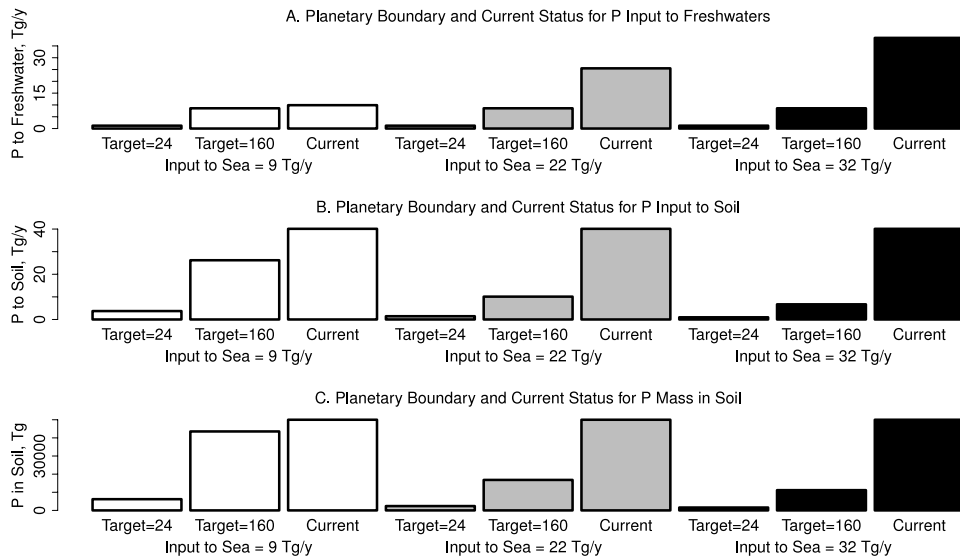


Figure 2. Planetary boundaries and current status of the P cycle. (A) Planetary boundary and current status for P input to freshwaters from terrestrial ecosystems, $Tg\ y^{-1}$. (B) Planetary boundary and current status for P input to terrestrial soils, $Tg\ y^{-1}$. (C) Planetary boundary and current status for P mass in terrestrial soils, Tg. In each bar plot, white bars are results if P flow to the sea is $9\ Tg\ y^{-1}$, gray bars are results if P flow to the sea is $22\ Tg\ y^{-1}$, and black bars are results if P flow to the sea is $32\ Tg\ y^{-1}$. For each rate of P flow to the sea, the first bar is the planetary boundary for the low target of $24\ mg\ m^{-3}$, the second bar is the planetary boundary for the high target of $160\ mg\ m^{-3}$, and the third bar is the current status.

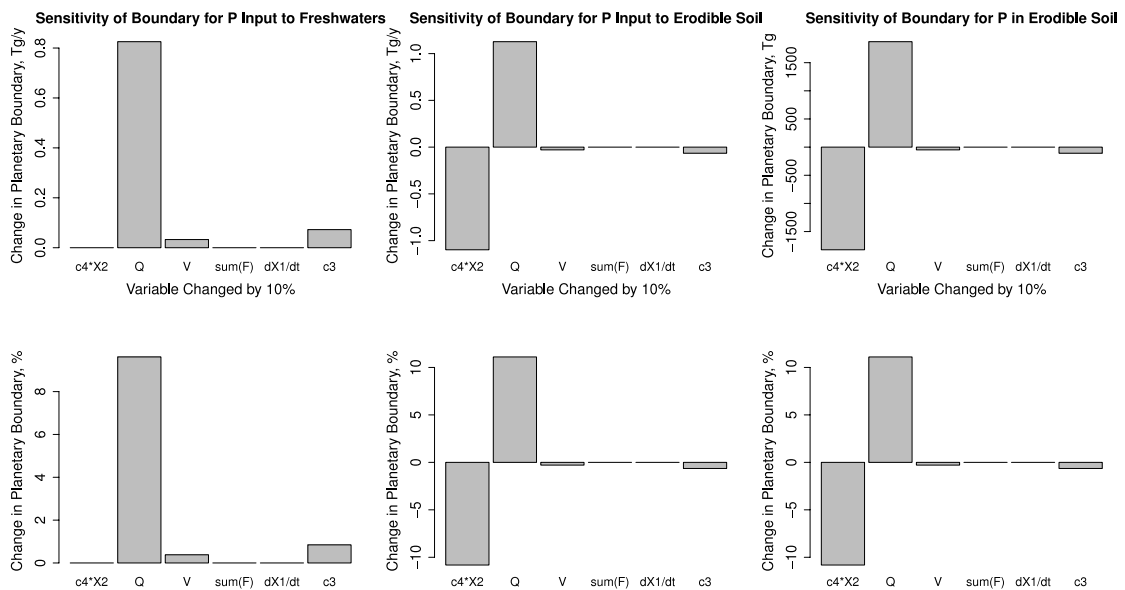


Figure 3. Effect on the calculated planetary boundaries of 10% changes (from 95% to 105% of nominal value) in the estimated quantities. Calculations used the $160\ mg\ m^{-3}$ water quality criterion. The top row shows the effects on the planetary boundaries in the natural units ($Tg\ y^{-1}$ or Tg) and the bottom row shows the effects on the planetary boundaries as per cent change. The columns are the three planetary boundaries for P: P input to freshwaters, P input to erodible soil, and P mass in erodible soil. The six estimated quantities are: (i) P flow from surface freshwaters to the sea c_4X_2 ; (ii) water flow into or out of surface freshwaters Q ; (iii) volume of surface freshwaters V ; (iv) flow of P in fertilizers and manure to erodible soil $sum(F)$; (v) current annual change in P mass of erodible soil dX_1/dt ; and (vi) sedimentation rate coefficient of P in surface freshwaters c_3 .

boundaries by about 10%. These boundaries are also somewhat sensitive to the sedimentation rate coefficient c_3 .

Overall, the sensitivity analyses indicate that the high variation among estimates of P flow to the sea (table 1) translates inversely and proportionally into uncertainty about the planetary boundaries for P input to and for P mass in soils. Uncertainties in the global hydrologic flows translate

directly and proportionally into uncertainties in all three planetary boundaries. Finally, all three planetary boundaries are discernibly affected by uncertainties in the P sedimentation coefficient. All three of these factors—P flux from freshwaters to the sea, water flows to and from surface freshwaters of the planet, and P sedimentation—are research priorities for refining the planetary boundaries for P.

5. Discussion

Eutrophication of freshwaters is a globally distributed environmental problem (Millennium Ecosystem Assessment 2005), yet it is often considered a local issue. Why, then, should there be a global boundary for P based on freshwater eutrophication? There are at least two reasons to consider P as a global process. First, freshwater impairment caused by P pollution is a widespread environmental problem, and has been so for decades. A global syndrome of repeated local impairment of freshwater creates global concern, equivalent to the crossing of a planetary boundary (Rockström *et al* 2009b). Second, there is the possibility that P readily available for mining will decline in coming decades, as the quality of remaining phosphate rock declines and production costs increase. Some estimates suggest that global P production by mining may peak around 2030 (Cordell *et al* 2009), whereas others believe this is unlikely (van Kauwenbergh 2010). This projection is highly uncertain but reflects growing concern about potential shortages of P, a resource for which there is no known substitute. If P becomes limiting for agriculture, then reallocation of existing P, by moving P from P-rich areas to P-poor ones or by improving recycling of manure and other P waste, becomes an important global policy option.

P flow to the oceans is a key driver of marine anoxia (Handoh and Lenton 2003). A sustained increase of more than 20% above the background weathering rate of P may have been enough to trigger ancient ocean anoxic events (Handoh and Lenton 2003). The key word is ‘sustained’; at current input rates it would take on the order of 10^4 years to double the amount of P in the oceans (Rockström *et al* 2009b). Based on the very slow rate of change of total oceanic P, Rockström *et al* (2009a, 2009b) concluded that humans have not yet crossed the planetary boundary for oceanic anoxic events triggered by P. Nonetheless, enrichment of coastal marine waters with N and P is an important driver of estuarine eutrophication and local oxygen depletion (Diaz and Rosenberg 2008, Rabalais *et al* 2009).

Our analyses indicate that planetary standards for eutrophication of freshwaters by P have already been surpassed. This finding holds whether the planetary boundary is defined for P input to surface freshwater, P input to soil, or P mass in soil. It also holds for three different values for current P flux to the sea.

5.1. Gaps and needs for further research

Our results are based on globally averaged flows of P and freshwater. Yet phosphorus and eutrophied freshwaters are distributed heterogeneously around the planet. Much more intensive and sophisticated analyses of spatial P dynamics are needed to refine estimates of planetary boundaries, to identify areas where P may be recycled profitably, and to design criteria and practices for P management.

Planetary boundaries may be different for rivers versus lakes and reservoirs. Most of the volume of surface freshwaters is in lakes and reservoirs, whereas all of the transport of surface freshwaters occurs in rivers. P concentrations tend to be lower in lakes and reservoirs than in rivers. Planetary

boundaries computed using the lower P target of 24 mg m^{-3} are appropriate for lakes and reservoirs. Planetary boundaries computed using the pre-industrial average P concentration of 160 mg m^{-3} are appropriate for rivers.

Nonlinear thresholds are likely for eutrophication of some lakes (Carpenter *et al* 1999). Our analyses are based on human preferences for P targets, rather than naturally occurring ecosystem thresholds. Measurements of nonlinear eutrophication thresholds are highly uncertain even for well-studied lakes (Carpenter and Lathrop 2008). Moreover, it is likely that nonlinear thresholds differ among lakes, and change over time even within a single lake. Given the current state of understanding of eutrophication thresholds, it is reasonable to use a single value based on human perceptions of water quality. As more information becomes available, more sophisticated analyses of the eutrophication boundary will become possible.

Planetary boundaries for P are sensitive to the flow of water through freshwater bodies. Human-driven changes to climate and the water cycle could therefore alter the planetary boundaries. Changes toward higher water flow raise the planetary boundaries, so that freshwater quality is less sensitive to P input. Changes toward lower water flow have the opposite effect: freshwater quality becomes more sensitive to P input.

5.2. Managing P

Several tools are available for mitigating excess P flow to surface freshwaters. Untreated sewage is a major source of P to freshwaters of some regions. More than 2.6 billion people worldwide lack access to adequate sanitation (Millennium Ecosystem Assessment 2005). Sewage treatment eases the burden of P pollution and directly improves human health. Sewage treatment can concentrate P in forms that are easy to transport and can be used to improve soil fertility.

Agricultural runoff of P, in contrast, is difficult to manage (Carpenter *et al* 1998). Although many tools exist for reducing nonpoint P pollution, successes are rare. Management approaches include efforts to change P cycling in the aquatic system (e.g., by modifying food webs) and efforts to reduce P flow to aquatic systems (e.g., by conservation tillage practices, establishment of riparian buffer strips of intact vegetation, or wetland restoration). However, the most effective long-term solution is to decrease the P enrichment of erodible soil, and thereby reduce runoff of P into surface freshwaters. Solutions that only block P flow to aquatic systems are subject to limits. For example, soils can become saturated with P, and riparian buffers reach a point where they can no longer effectively trap P. Decreasing the P content of erodible soil is the only management practice that does not suffer from limitations of this kind.

P (and N) budgets are out of balance for many agricultural soils (Vitousek *et al* 2009). Regions that are early in agricultural development or are on older, nutrient-poor soils are often deficient in nutrients. In many agriculturally intensive nations, soils are oversupplied with nutrients. In most cases, managers lack detailed regional or farm-scale nutrient budgets needed to manage P properly. Few countries have supported integrated, multiscale biogeochemical research to

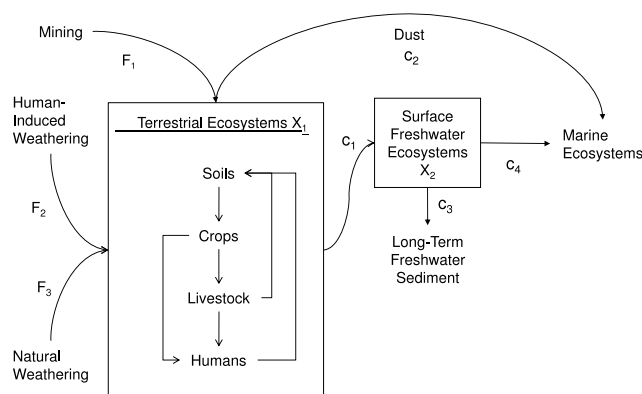


Figure 4. Pools and flows of phosphorus including major recycling flows within agricultural systems. P in surface freshwater ecosystems includes P in water as well as rapidly exchanging sediments.

obtain policy-relevant information on nutrient balances for agriculture (Vitousek *et al* 2009).

Recycling of P (especially using manure and human waste products as agricultural fertilizers) is an important practical solution that simultaneously solves the dual problem of running out of P and releasing too much P to surface waters (figure 4). Recycling closes the feedback loops between livestock, humans and the soil, thereby retaining P within the agricultural system. Less P is lost to surface water, and fewer new inputs of P are needed to maintain crop production. Better technology for managing animal and human waste is crucial for effective recycling of P. Digestors that convert liquid manure to lightweight solids with high P content could lower the cost of transporting P between areas of intensive animal production and crop fields where P supplements are needed. Practices that recycle P could be encouraged by pricing and other policy instruments (Naylor *et al* 2005).

Phosphorus zoning may be an effective strategy to cope with problems of agricultural runoff and global shortages of P. Some regions would be zoned for intensive agricultural production. Despite best practices there is likely to be

considerable runoff of P and eutrophication in these regions. Other watersheds would be zoned for production of potable water for domestic use and for support of other ecosystem services that cannot be produced without good quality water. The zoning system could incorporate recycling of P to mitigate eutrophication, redistribute P to places that need it, and thereby mitigate shortfalls in P available for mining.

6. Conclusion

Human release of P to the environment is causing widespread eutrophication of surface freshwaters. Yet the global distribution of P is uneven, and soils of many regions remain P-deficient even as soils of other regions are P-saturated (MacDonald *et al* 2011). Heterogeneity complicates the task of managing to provide both food and high quality freshwater, surely one of the key challenges of environmental management in the 21st century. The planetary boundary for freshwater eutrophication has been crossed while potential boundaries for ocean anoxic events and depletion of phosphate rock reserves loom in the future. The solution to this problem is widespread adoption of better practices for conserving P in agricultural ecosystems, so that P is cycled effectively among soil, crops, livestock and people without contributing to eutrophication of surface waters. At the same time, P-deficient regions of the world should be supplemented by P from P-rich regions. Such subsidies could come in the form of recycled P in fertilizer (e.g. solid P-rich material from manure digestors) or P in food.

Acknowledgments

We thank Will Steffen and Sybil Seitzinger for helpful discussions, and Marten Scheffer and two anonymous referees for constructive reviews of the manuscript. Financial support was provided by NSF grants to SRC and NSERC grants to EMB.

Appendix

Table A.1. Planetary boundaries for phosphorus eutrophication of freshwaters. Three boundaries are presented for each of three estimates of P flow to the sea, c_4X_2 , and for two water quality criteria: the mesotrophy–eutrophy boundary of 24 mg m^{-3} for lakes, and the pre-industrial average river concentration of 160 mg m^{-3} .

Water quality criterion	Planetary boundary	Value if $c_4X_2 = 9 \text{ Tg y}^{-1}$	Value if $c_4X_2 = 22 \text{ Tg y}^{-1}$	Value if $c_4X_2 = 32 \text{ Tg y}^{-1}$
24 mg m^{-3}	As flow of P from terrestrial ecosystems to freshwater, c_1X_1 , (Tg y^{-1})	1.22	1.22	1.22
	As flow of P to erodible soil (Tg y^{-1})	3.72	1.44	0.96
	As mass of P in erodible soil, X_1 (Tg)	6184	2388	1587
160 mg m^{-3}	As flow of P from terrestrial ecosystems to freshwater, c_1X_1 (Tg y^{-1})	8.58	8.58	8.58
	As flow of P to erodible soil (Tg y^{-1})	26.2	10.1	6.73
	As mass of P in erodible soil, X_1 (Tg)	43 545	16 814	11 172

Table A.2. Sensitivity of the three calculated planetary boundaries for P to 10% changes (from 95% to 105% of the nominal value) in six estimated quantities using the 24 mg m⁻³ water quality criterion. All main effects and interactions computed by Yates' algorithm are shown. The three planetary boundaries for P are: PB 1 = planetary boundary as P input to freshwaters, PB 2 = planetary boundary as P input to erodible soil, and PB 3 = planetary boundary as P mass in erodible soil. The six estimated quantities are: (i) P flow from surface freshwaters to the sea c_4X_2 ; (ii) water flow into or out of surface freshwaters Q ; (iii) volume of surface freshwaters V ; (iv) flow of P in fertilizers and manure to erodible soil $\text{Sum}(F)$; (v) current annual change in P mass of erodible soil dX_1/dt ; and (vi) sedimentation rate coefficient of P in surface freshwaters c_3 . For the six estimated quantities, 0 corresponds to the low value (95% of nominal) and 1 corresponds to the high value (105% of nominal). For the three planetary boundary columns (PB 1, PB 2, PB 3), the units are the same as the units of the planetary boundary (Tg y⁻¹ for PB 1 and PB 2, Tg for PB 3). The first row computed by Yates' algorithm is the mean value of the three planetary boundaries over all 64 (2⁶) perturbations of the six estimated values. In subsequent rows, entries of 1 indicate which estimated values contribute to the response computed by Yates' algorithm. For example, row 2 presents the effect of changing c_4X_2 alone, averaged over all 64 perturbations. Row 3 presents the effect of changing Q alone. Row 4 presents the interaction between c_4X_2 and Q . The interaction is inhibitory, meaning that if c_4X_2 is increased and also Q is increased, the effect of increased Q is reduced by the increase in c_4X_2 . Interactions can also be synergistic. For example, line 6 shows that the effect of increasing c_4X_2 and V together is greater than the sum of the two factors acting alone. Most of the interactions produce effects that are smaller than the number of digits presented in the table.

Row	c_3	dX_1/dt	$\text{Sum}(F)$	V	Q	c_4X_2	PB 1	PB 2	PB 3
1	0	0	0	0	0	0	1.219	1.442	2395
2	0	0	0	0	0	1	0	-0.156	-259
3	0	0	0	0	1	0	0.12	0.164	272
4	0	0	0	0	1	1	0	-0.008	-14
5	0	0	0	1	0	0	0.002	-0.008	-13
6	0	0	0	1	0	1	0	0	0
7	0	0	0	1	1	0	0	0	0
8	0	0	0	1	1	1	0	0	0
9	0	0	1	0	0	0	0	0	0
10	0	0	1	0	0	1	0	0	0
11	0	0	1	0	1	0	0	0	0
12	0	0	1	0	1	1	0	0	0
13	0	0	1	1	0	0	0	0	0
14	0	0	1	1	0	1	0	0	0
15	0	0	1	1	1	0	0	0	0
16	0	0	1	1	1	1	0	0	0
17	0	1	0	0	0	0	0	0	0
18	0	1	0	0	0	1	0	0	0
19	0	1	0	0	1	0	0	0	0
20	0	1	0	0	1	1	0	0	0
21	0	1	0	1	0	0	0	0	0
22	0	1	0	1	0	1	0	0	0
23	0	1	0	1	1	0	0	0	0
24	0	1	0	1	1	1	0	0	0
25	0	1	1	0	0	0	0	0	0
26	0	1	1	0	0	1	0	0	0
27	0	1	1	0	1	0	0	0	0
28	0	1	1	0	1	1	0	0	0
29	0	1	1	1	0	0	0	0	0
30	0	1	1	1	0	1	0	0	0
31	0	1	1	1	1	0	0	0	0
32	0	1	1	1	1	1	0	0	0
33	1	0	0	0	0	0	0.004	-0.017	-29
34	1	0	0	0	0	1	0	0	1
35	1	0	0	0	1	0	0	0	0
36	1	0	0	0	1	1	0	0	0
37	1	0	0	1	0	0	0	0	-1
38	1	0	0	1	0	1	0	0	0
39	1	0	0	1	1	0	0	0	0
40	1	0	0	1	1	1	0	0	0
41	1	0	1	0	0	0	0	0	0
42	1	0	1	0	0	1	0	0	0
43	1	0	1	0	1	0	0	0	0
44	1	0	1	0	1	1	0	0	0
45	1	0	1	1	0	0	0	0	0
46	1	0	1	1	0	1	0	0	0
47	1	0	1	1	1	0	0	0	0
48	1	0	1	1	1	1	0	0	0
49	1	1	0	0	0	0	0	0	0
50	1	1	0	0	0	1	0	0	0
51	1	1	0	0	1	0	0	0	0
52	1	1	0	0	1	1	0	0	0

Table A.2. (Continued.)

Row	c_3	dX_1/dt	$\text{Sum}(F)$	V	Q	c_4X_2	PB 1	PB 2	PB 3
53	1	1	0	1	0	0	0	0	0
54	1	1	0	1	0	1	0	0	0
55	1	1	0	1	1	0	0	0	0
56	1	1	0	1	1	1	0	0	0
57	1	1	1	0	0	0	0	0	0
58	1	1	1	0	0	1	0	0	0
59	1	1	1	0	1	0	0	0	0
60	1	1	1	0	1	1	0	0	0
61	1	1	1	1	0	0	0	0	0
62	1	1	1	1	0	1	0	0	0
63	1	1	1	1	1	0	0	0	0
64	1	1	1	1	1	1	0	0	0

Table A.3. Sensitivity of the three calculated planetary boundaries for P to 10% changes (from 95% to 105% of the nominal value) in six estimated quantities using the 160 mg m⁻³ water quality criterion. All main effects and interactions computed by Yates' algorithm are shown. The three planetary boundaries for P are: PB 1 = planetary boundary as P input to freshwaters, PB 2 = planetary boundary as P input to erodible soil, and PB 3 = planetary boundary as P mass in erodible soil. The six estimated quantities are: (i) P flow from surface freshwaters to the sea c_4X_2 ; (ii) water flow into or out of surface freshwaters Q ; (iii) volume of surface freshwaters V ; (iv) flow of P in fertilizers and manure to erodible soil $\text{Sum}(F)$; (v) current annual change in P mass of erodible soil dX_1/dt ; and (vi) sedimentation rate coefficient of P in surface freshwaters c_3 . For the six estimated quantities, 0 corresponds to the low value (95% of nominal) and 1 corresponds to the high value (105% of nominal). For the three planetary boundary columns (PB 1, PB 2, PB 3), the units are the same as the units of the planetary boundary (Tg y⁻¹ for PB 1 and PB 2, Tg for PB 3). The first row computed by Yates' algorithm is the mean value of the three planetary boundaries over all 64 (2⁶) perturbations of the six estimated values. In subsequent rows, entries of 1 indicate which estimated values contribute to the response computed by Yates' algorithm. For example, row 2 presents the effect of changing c_4X_2 alone, averaged over all 64 perturbations. Row 3 presents the effect of changing Q alone. Row 4 presents the interaction between c_4X_2 and Q . The interaction is inhibitory, meaning that if c_4X_2 is increased and also Q is increased, the effect of increased Q is reduced by the increase in c_4X_2 . Interactions can also be synergistic. For example, line 6 shows that the effect of increasing c_4X_2 and V together is greater than the sum of the two factors acting alone. Most of the interactions produce effects that are smaller than the number of digits presented in the table.

Row	c_3	dX_1/dt	$\text{Sum}(F)$	V	Q	c_4X_2	PB 1	PB 2	PB 3
1	0	0	0	0	0	0	8.581	10.15	16 861
2	0	0	0	0	0	1	0	-1.098	-1824
3	0	0	0	0	1	0	0.825	1.127	1873
4	0	0	0	0	1	1	0	-0.057	-94
5	0	0	0	1	0	0	0.033	-0.029	-49
6	0	0	0	1	0	1	0	0	0
7	0	0	0	1	1	0	0.001	0.001	2
8	0	0	0	1	1	1	0	0	0
9	0	0	1	0	0	0	0	0	0
10	0	0	1	0	0	1	0	0	0
11	0	0	1	0	1	0	0	0	0
12	0	0	1	0	1	1	0	0	0
13	0	0	1	1	0	0	0	0	0
14	0	0	1	1	0	1	0	0	0
15	0	0	1	1	1	0	0	0	0
16	0	0	1	1	1	1	0	0	0
17	0	1	0	0	0	0	0	0	0
18	0	1	0	0	0	1	0	0	0
19	0	1	0	0	1	0	0	0	0
20	0	1	0	0	1	1	0	0	0
21	0	1	0	1	0	0	0	0	0
22	0	1	0	1	0	1	0	0	0
23	0	1	0	1	1	0	0	0	0
24	0	1	0	1	1	1	0	0	0
25	0	1	1	0	0	0	0	0	0
26	0	1	1	0	0	1	0	0	0
27	0	1	1	0	1	0	0	0	0
28	0	1	1	0	1	1	0	0	0
29	0	1	1	1	0	0	0	0	0
30	0	1	1	1	0	1	0	0	0
31	0	1	1	1	1	0	0	0	0
32	0	1	1	1	1	1	0	0	0
33	1	0	0	0	0	0	0.073	-0.065	-108
34	1	0	0	0	0	1	0	-0.001	-1

Table A.3. (Continued.)

Row	c_3	dX_1/dt	$\text{Sum}(F)$	V	Q	c_4X_2	PB 1	PB 2	PB 3
35	1	0	0	0	1	0	0.002	0.002	3
36	1	0	0	0	1	1	0	0	0
37	1	0	0	1	0	0	0.002	-0.001	-2
38	1	0	0	1	0	1	0	0	0
39	1	0	0	1	1	0	0	0	0
40	1	0	0	1	1	1	0	0	0
41	1	0	1	0	0	0	0	0	0
42	1	0	1	0	0	1	0	0	0
43	1	0	1	0	1	0	0	0	0
44	1	0	1	0	1	1	0	0	0
45	1	0	1	1	0	0	0	0	0
46	1	0	1	1	0	1	0	0	0
47	1	0	1	1	1	0	0	0	0
48	1	0	1	1	1	1	0	0	0
49	1	1	0	0	0	0	0	0	0
50	1	1	0	0	0	1	0	0	0
51	1	1	0	0	1	0	0	0	0
52	1	1	0	0	1	1	0	0	0
53	1	1	0	1	0	0	0	0	0
54	1	1	0	1	0	1	0	0	0
55	1	1	0	1	1	0	0	0	0
56	1	1	0	1	1	1	0	0	0
57	1	1	1	0	0	0	0	0	0
58	1	1	1	0	0	1	0	0	0
59	1	1	1	0	1	0	0	0	0
60	1	1	1	0	1	1	0	0	0
61	1	1	1	1	0	0	0	0	0
62	1	1	1	1	0	1	0	0	0
63	1	1	1	1	1	0	0	0	0
64	1	1	1	1	1	1	0	0	0

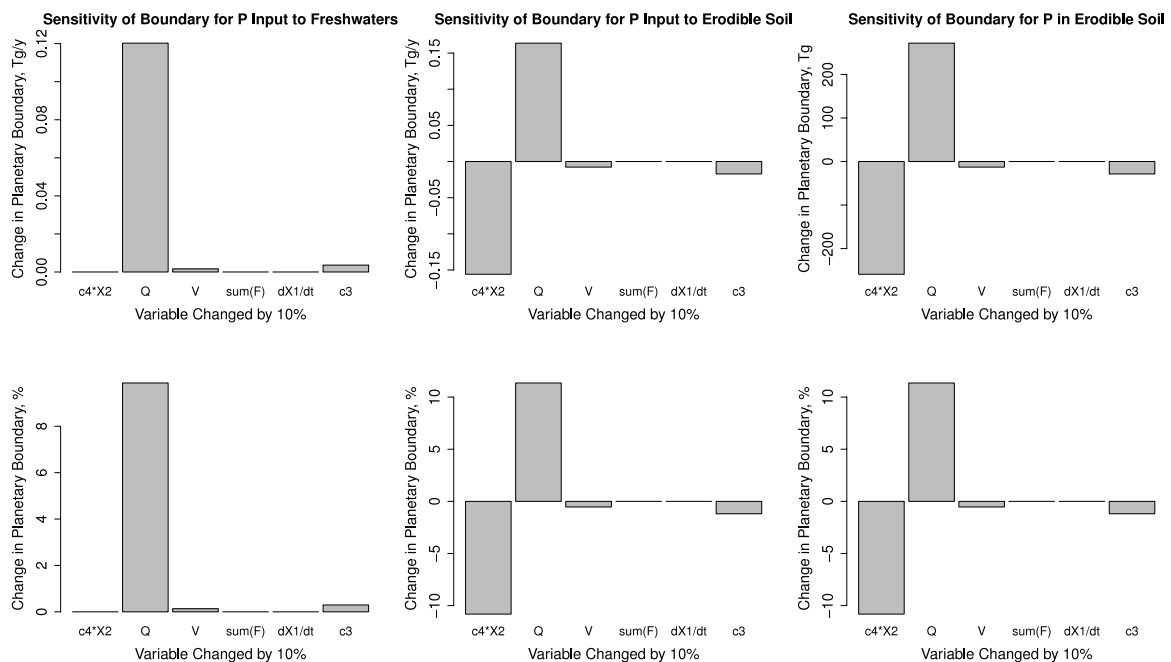


Figure A.1. Effect on the calculated planetary boundaries of 10% changes (from 95% to 105% of nominal value) in the estimated quantities. Calculations used the 24 mg m^{-3} water quality criterion. The top row shows the effects on the planetary boundaries in the natural units (Tg y^{-1} or Tg) and the bottom row shows the effects on the planetary boundaries as per cent change. The columns are the three planetary boundaries for P: as P input to freshwaters, as P input to erodible soil, and as P mass in erodible soil. The six estimated quantities are: (i) P flow from surface freshwaters to the sea c_4X_2 ; (ii) water flow into or out of surface freshwaters Q ; (iii) volume of surface freshwaters V ; (iv) flow of P in fertilizers and manure to erodible soil $\text{Sum}(F)$; (v) current annual change in P mass of erodible soil dX_1/dt ; and (vi) sedimentation rate coefficient of P in surface freshwaters c_3 .

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