Future agricultural phosphorus demand according to the shared socioeconomic pathways

Mogollón, J.M.; Beusena, A.H.W.; Grinsven, H.J.M van; Westhoek, H.; Bowman, A.F.

Global Environmental Change 50 (2018) 149–163

Contents lists available at ScienceDirect

Global Environmental Change

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

Future agricultural phosphorus demand according to the shared socioeconomic pathways

J.M. Mogollón[a,*], A.H.W. Beusen[a,b], H.J.M van Grinsven[b], H. Westhoek[b], A.F. Bouwman[a,b]

[a] Department of Earth Sciences – Geochemistry, Faculty of Geosciences, Utrecht University, P.O. Box 80021, 3508 TA, Utrecht, The Netherlands
[b] PBL Netherlands Environmental Assessment Agency, P.O. Box 30314, 2500 GH, The Hague, The Netherlands

ARTICLE INFO

Keywords:
Crop uptake
Fertilizer
Manure
Phosphorus
Shared socioeconomic pathways
Soil phosphorus pools

ABSTRACT

A spatially explicit, two-pool soil phosphorus (P) model was used to analyze cropland P dynamics and fertilizer demand based on future crop production as projected in the shared socioeconomic pathways (SSPs). The model was initialized with historical data on P inputs and uptake, which governed the soil P accumulation up to present day. In contrast to existing scenario studies, the model accounts for both soil characteristics relevant to P retention and changing land use. At the global scale, crop uptake and the fraction of the applied P fertilizer that is directly taken up by plant roots govern the P quantities present in the soil. Despite the differences in the storylines among the SSPs, the quantitative implementation results in estimates for crop production and P inputs that are quite similar, which contrasts with the stark divergence in terms of population and incomes. In addition to global fertilizer P inputs in croplands increasing from 14.5 Tg P yr^{-1} in 2005 to 22–27 Tg P yr^{-1} in 2050, this study also estimates that 4–12 Tg P yr^{-1} would be needed in 2050 in global intensively managed grasslands to maintain fertility. Our new model approach can pinpoint the contribution of area expansion and crop yield improvement toward the total production, whereby the latter is shown to contribute 100% to 69%, depending on the scenario.

1. Introduction

Phosphorus (P) is an essential nutrient for living organisms and has played an important role in agriculture since the start of the 20th century (Koning et al., 2008; Sattari et al., 2012). Early (pre-20th century) P applications in agriculture depended on manure and guano, bone meal, and urban waste (Beaton, 2006). Limited nitrogen (N) and P availability were key factors in the low crop yields. During the post-war industrial and population boom (1950–1970), the expansion of P mining allowed for the rapid development of mineral fertilizers, which took over as the leading agricultural P input in industrialized countries (Cordell et al., 2009). In the 1970s and 1980s, disproportionate fertilizer and manure P use in industrialized countries led to low P use efficiency, and consequently, large amounts of surplus P were retained as residual P in soils (Syers et al., 2008). After this accumulation phase, farmers in many industrialized countries have been able to increase their P use efficiency as a result of reduced input, mining of the accumulated residual soil P reserves, improved agricultural management, and enhanced crop uptake (Sattari et al., 2012); in many cases even increasing crop yields (Bouwman et al., 2017). In contrast, China and India are currently in the phase of increasing P surpluses and decreasing nutrient use efficiencies, similar to the industrial countries in the 1970s and 1980s. Many developing countries are in the early phases of agricultural development with minimal P application rates, which often coincide with low crop yields (Bouwman et al., 2017).

Future P usage will play an important role in sustaining food production for the projected world population growth from 7.3 in 2015 to 9.7 billion inhabitants in 2050 (medium variant of UN, 2016). Nevertheless, phosphate rock is a finite resource and the high-quality and high-grade phosphate rock reserves are decreasing, although the estimates are quite variable. Based on a Hubbert linearization, peak in P annual production has been estimated to have taken place in 1989 (Déry and Anderson, 2007). Adapting the Hubbert curve to account for all depleted and current reserves, peak P production was pushed to 2033 (Cordell et al., 2009). Another assessment, based on consumption and production models that included future changes in regional P production costs, projected a 20–60% resource depletion by 2100 (van Vuuren et al., 2010). Furthermore, based on revised definitions for reserves and resources, additional data that included a second production peak in 2008, and updated reserve estimates for Morocco, Van Kauwenbergh (2010) argued that P for fertilizer production would be available for 300–400 years. It is also important to note that, despite the

* Corresponding author. Current address: CML Institute of Environmental Sciences, Leiden University, P.O. Box 9518, 2300 RA, Leiden, The Netherlands.
E-mail address: j.m.mogollon@cml.leidenuniv.nl (J.M. Mogollón).

https://doi.org/10.1016/j.gloenvcha.2018.03.007
Received 21 July 2017; Received in revised form 21 March 2018; Accepted 25 March 2018
Available online 15 April 2018

importance of P as a resource, the fate of P surpluses in soils has been largely ignored in agricultural modeling studies (e.g. Bouwman et al., 2009, 2013; MacDonald et al., 2011).

Recently, Sattari et al. (2012; 2016) adapted the Dynamic Phosphorus Pool Simulator (DPPS) to capture the effects of residual P and even extrapolate the effects of increased P loads in future cropland production at the country scale. Zhang et al. (2017) further expanded DPPS to simulate the soil P stocks and crop uptake globally using a spatially explicit grid (0.5 by 0.5° resolution) during the 20th century, taking into account historical changes in cropland area and soil P retention potential. In our current study, we couple the spatially explicit version of DPPS with the Integrated Model to Assess the Global Environment (IMAGE; Stehfest et al., 2014). This IMAGE-DPPS model is used to evaluate the future demand for P in agriculture according to the five shared socioeconomic pathways (SSPs; van Vuuren et al., 2017). The SSPs represent scenarios developed to study the impact of future global change (population dynamics, economic growth, and consequent food and energy production, climate change, land use changes) and thus the main factors controlling future agricultural nutrient cycles.

2. Methods

2.1. Model and data

The spatially explicit (0.5 × 0.5°), yearly DPPS model (Fig. 1a) was recently described in Zhang et al. (2017). DPPS considers natural or unintentional inputs to the soil and how they affect the labile (*LP*) and stabile (*SP*) phosphorus pools. *LP* comprises both organic and inorganic P forms that can more or less readily replenish P taken up by plant roots (Schachtman et al., 1998). *SP* represents forms of P bound to soil minerals and organic matter that are not directly available to plants. Inputs to *LP* consist of weathering (*W*, kg P ha^{-1} yr^{-1}) and litter (*L*, kg P ha^{-1} yr^{-1}). Inputs to *SP* consist of atmospheric deposition (*D*, kg P ha^{-1} yr^{-1}), which enters as soil dust. Soil formation (*H*) is also a natural input for both *LP* and *SP* and is taken into account following Zhang et al. (2017). Anthropogenic P inputs include application of mineral P fertilizer (*S*, kg P ha^{-1} yr^{-1}) and animal manure spreading (*M*, kg Pha^{-1} yr^{-1}). In contrast to Zhang et al. (2017), here part of fertilizer and manure inputs enter the *LP* (γ and ε, respectively) and another part is channeled toward *SP* (1−γ and 1−ε, respectively). Furthermore, a fraction is directly taken up by plant roots (1−σ= 20% for fertilizer, 1−η= 10% for manure) and the remainder is available and becomes part of *LP* (σ= 80% for fertilizer and η= 90% for manure).

The rate of change of *LP* and *SP* (kg P ha^{-1} yr^{-1}) is calculated as follows:

$$\frac{\partial_{LP}}{\partial_t} = \frac{SP}{\mu_{SL}} - \frac{LP}{\mu_{LS}} + W + \sigma\gamma S + \eta\varepsilon M + H_{LP} + L - Q_{LP} - U \quad (1)$$

$$\frac{\partial_{SP}}{\partial_t} = \frac{LP}{\mu_{LS}} - \frac{SP}{\mu_{SL}} + (1-\gamma)\sigma S + (1-\varepsilon)\eta M + D + H_{SP} - Q_{SP} \quad (2)$$

where the variables μ_{LS} and μ_{SL} are transfer times (years) between *LP* to *SP* and *SP* to *LP*, respectively.

P outflows from the soil system include P withdrawal from *LP* by crops (*U*, kg P ha^{-1} yr^{-1}) and runoff (including erosion, see Beusen et al., 2015) from both *LP* and *SP* (*Q*, kg P ha^{-1} yr^{-1}). The model assumes that only a fraction (f_{av}) of *LP* is directly available for P uptake (*U*), which uses Michaelis-Menten kinetics (after Nijland et al., 2008) as follows:

$$U = \frac{U_{\max} f_{av} LP}{\frac{c\, U_{\max}}{I} + f_{av} LP} + (1-\sigma)S + (1-\eta)M \quad (3)$$

where $U_{\max}$ (kg P $ha^{-1}yr^{-1}$) is the maximum P uptake, and *I* is the initial recovery fraction (no dimension), which is the initial slope of the P response curve presented (Batjes, 2011) for all soil types distinguished in the legend of the FAO-Unesco soil map of the world (FAO-UNESCO, 1974). *c* is a constant to obtain the *AP* for which uptake is 0.5 times $U_{\max}$ (no dimension; $c = 0.5$). In contrast to Zhang et al. (2017), here we use the mid-range values of *I* (Batjes, 2011) and $U_{\max}$ is held constant with a value of 500 kg P ha^{-1} yr^{-1}. The calculation of the area-weighted value of *I* for each grid cell is based on the sub-grid distribution of soil classes.

For each crop area within a grid cell at a given time, the model consists of thee equations (Eqs. (1)–(3)) and three unknowns (*LP*, *SP*, and either f_{av} for historical mode or *S* for scenario mode, Fig. 1b). Eqs. (1) and (2) are implicitly integrated and solved simultaneously with Eq. (3) to calculate these three variables. The solution is obtained by minimizing the difference between the measured (imposed) uptake and the simulated uptake. The system of equations may not converge due to insufficient *LP* in the soil to satisfy the uptake demand. In this case the entire *LP* pool is channeled toward uptake and a slight underestimation in the modelled uptake may be introduced at that year. In historical mode, the unknown f_{av} is allowed to vary between a minimum value of 0 and a maximum value of 1. In scenario mode, f_{av} becomes a parameterized value that varies according to the SSP storyline, with a minimum value of 0.05 for each age-pool and a maximum value of 1.

In historical mode, each cell is initialized in 1900 with *LP* and *SP* from the global gridded soil P inventory (Yang et al., 2013), representing the pre-industrial conditions. Thus the P availability may increase or decrease, depending on the pool sizes.

For scenario mode, IMAGE-DPPS follows a tight coupling with the IMAGE model, which uses data on crop and livestock production and trade by the food and agriculture system model MAGNET (Woltjer and Kuiper, 2014). Calculated *LP* and *SP* pools and f_{av} based on the historical simulation period from 1900 to 2005 (the base year of IMAGE) provide the starting point for the scenario simulations from 2006 to 2050. Using spatially explicit land use and crop P uptake (*U*) distributions generated by the IMAGE model (van Vuuren et al., 2017), the future P fertilizer (*S*) requirements can be estimated for each SSP. Note that the spatial distribution of future gridded *U* is based on the 2005 gridded spatial distribution for each country. In grid cells where cropland expansion occurs, natural soil (without fertilizer history) with initial P pools (Yang et al., 2013) is added. For grid cells with land abandonment (arable land to natural land), IMAGE-DPPS assumes a 30 year period for abandoned land to revert to natural conditions (e.g. Yang et al., 2013), and in this period the P in litter and uptake increase linearly with time from zero to the natural flux (in which uptake equals litterfall). Further details on the data sources are depicted in the supplementary materials.

2.2. Scenarios

The various scenarios are implemented to contrast future socioeconomic behavior and their impact on both resource use and the health of the environment. The five SSP scenarios (Table 1) describe future socioeconomic behavior according to different adaptation and mitigation challenges. Projections for all scenarios were taken from IMAGE until the year 2050. SSP2 represents the current tendency; that is, the middle-of-the-road scenario that uses the baseline technical agricultural trends for crop yields and livestock productivity from the FAO Agriculture Towards 2050 projection (Alexandratos and Bruinsma, 2012). SSP3 (fragmentation) represents the scenario with the highest mitigation and adaptation challenges. It has the largest population increase (up to 10 billion by 2050) and cropland expansion (21% increase from 2010 to 2050). Furthermore, GDP and average crop yield in 2050 become the lowest among all the scenarios. SSP4 (inequality) is the scenario where developed countries improve their socioeconomic and environmental outlook whilst developing countries follow a more fragmented path. This scenario thus has high adaptation challenges with countries increasingly diverging in their sustainability practices. SSP5 (conventional development) assumes a world where fossil fuels

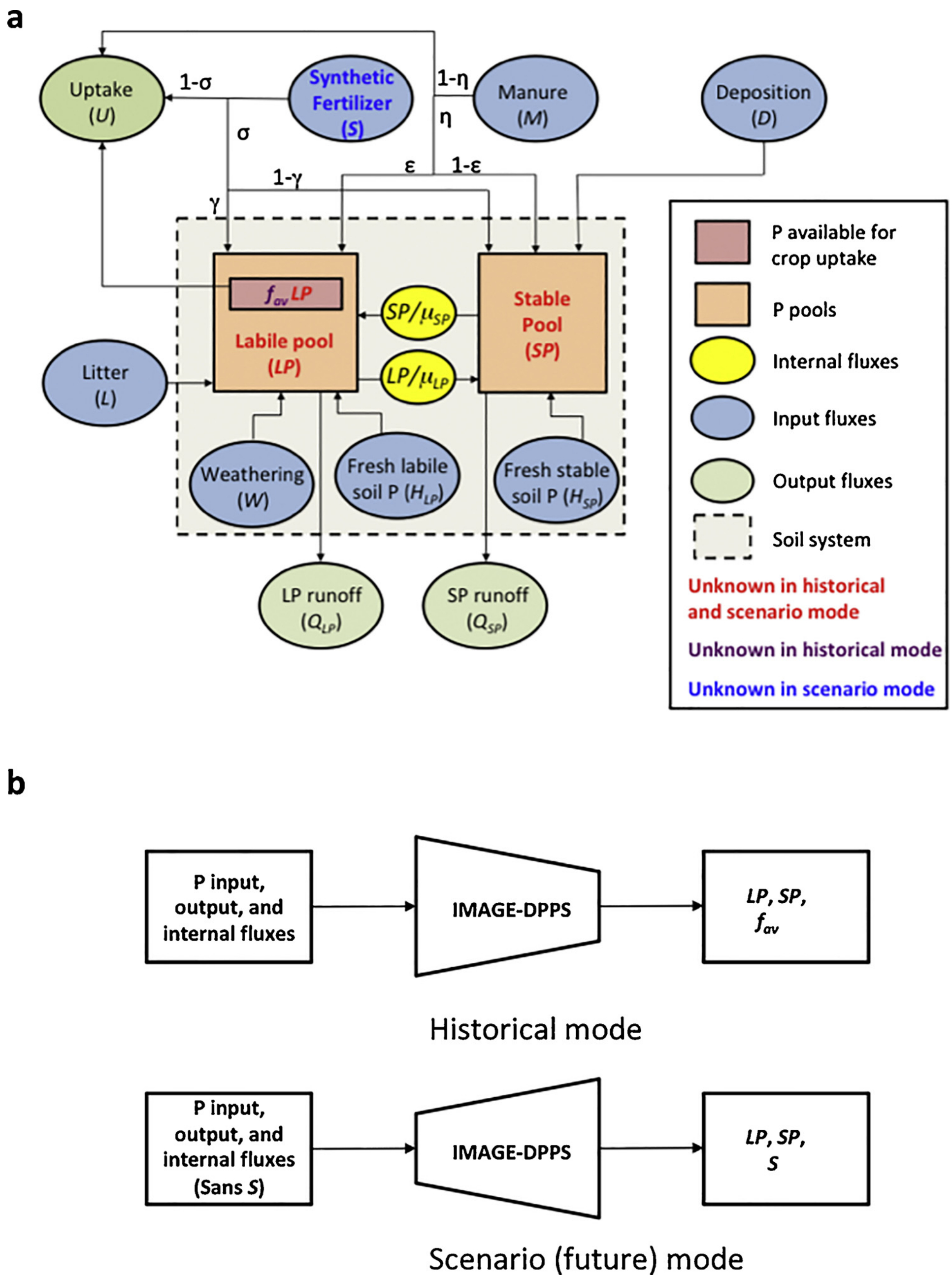

Fig. 1. a) Scheme of the IMAGE-DPPS model with two dynamic P pools, i.e. the labile pool (*LP*) and the stable pool (*SP*), comprising both of organic and inorganic P. Five inputs (blue boxes) of P to the system are distinguished (mineral fertilizer and manure, weathering, deposition, fresh soil and litter) and two outputs (Uptake and runoff). b) Calculation direction for historical and scenario mode of IMAGE-DPPS (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

remain the predominant energy source, and economic development takes precedence over environmental awareness. This scenario has the largest demanded crop yield P requirements in 2050 compared to all other scenarios and thus poses high mitigation challenges. Finally, SSP1 (sustainability) represents the scenario with the lowest adaptation and mitigation challenges. In this pathway, low population growth and greenhouse gas emissions, coupled to technological advancements in renewable clean energy, aid in controlling greenhouse gas emissions and decreasing the global cropland area (Table 1). Part of the animal manure ends outside the agricultural system, such as disposal of animal manure disposal by direct discharge into freshwater bodies or manure use as fuel or building material. In SSP1 we assume that all this manure will be recycled in agriculture by the year 2030. A final assumption for SSP1 is that P from human urine from inhabitants with improved sanitation but lacking a sewage connection will be recycled in crop production systems.

As a signal of improving technology, a major distinction between the SSPs is the change of f_{av}, i.e. the proportion of the labile soil P pool LP that is directly available for uptake by plant roots. We assumed that in SSP1, f_{av} will increase during the period 2005–2050 as a result of improved crop varieties and other strategies to increase the capability of plant roots to acquire soil P. This f_{av} increase is implemented for the 2006–2050 period at the same rate as the increase during the 1990–2005 period. For this, we take the difference between the minimum and maximum values of f_{av} during for the 1990–2005 period. In case of a decrease or no increase, we assumed no change during the 2006–2050 period. The rate of change in SSP5 equals that of SSP1, while for SSP2 and SSP3 we take half and one quarter of the SSP1 rate,

Table 1
Summary and driving factors of the five SSP scenarios according to the IMAGE 3.0 implementation, modified from Mogollón et al. (2018).

Property	Region[a]	2010 level	2050 level				
			SSP1	SSP2	SSP3	SSP4	SSP5
Keyword			Sustainability	Middle of the road	Fragmentation	Inequality	Conventional development
Technological development			Rapid	Medium	Slow	Slow	Rapid
Progress towards development goals			Good	Some	Failure to achieve goals	Highly unequal	Market-driven
Resource intensity			Low	Medium	None	Highly unequal	Conventional
Population(million inhabitants)	Global	6922	8531	9243	10038	9213	8629
	Industrialized	1044	1221	1191	1011	1123	1383
	BRIC	2948	3162	3408	3708	3166	3165
	Rest of world	2929	4147	4644	5319	4924	4081
GDP/capita (US$)	Global	7393	24563	17877	12024	17500	32449
	Industrialized	33313	60131	55180	50917	62996	70986
	BRIC	2803	25577	16765	10413	17474	34063
	Rest of world	2771	13318	9130	5752	7139	18138
Global greenhouse gas emissions (GtC-eq/yr)	Global	13.0	15.6	19.8	21.5	18.0	27.9
Global mean temperature increase relative to 1860 (°C)	Global	1.0	2.1	2.3	2.3	2.2	2.5
Crop production (Mton d.m.)	Global	3241	4749	5111	5069	4855	5215
	Industrialized	878	948	1082	1030	1066	1161
	BRIC	1173	1689	1782	1767	1687	1770
	Rest of world	1190	2112	2246	2272	2102	2284
Area arable and permanent crops (Mha)	Global	1581	1522	1735	1846	1732	1720
	Industrialized	412	355	420	422	392	427
	BRIC	528	487	547	586	533	534
	Rest of world	641	680	768	838	806	759
Average yield (Mg dry matter/ha/yr)	Global	2.0	3.1	2.9	2.7	2.8	3.0
	Industrialized	2.1	2.7	2.6	2.4	2.7	2.7
	BRIC	2.2	3.5	3.3	3.0	3.2	3.3
	Rest of world	1.9	3.1	2.9	2.7	2.6	3.0
Biofuel area (Mha)	Global	9	34	84	87	127	157
Biofuel area (% of cropland)	Global	2	9	17	17	24	27
Required crop P uptake (Tg P/yr)	Global	14.2	19.3	21.2	21.2	20.3	22.4
	Industrialized	4.3	4.6	5.3	5.1	5.2	5.9
	BRIC	5.4	6.9	7.4	7.4	7.1	7.9
	Rest of world	4.6	7.8	8.5	8.7	8.1	8.7
Manure recycling			Improved	No change	No change	No change	No change

[a] Industrialized = Canada, USA, Europe, Japan, Oceania; BRIC = Brazil, Russian Federation, India, China.

respectively. For SSP4 a mix with the top 5 regions with the highest gross domestic product per capita (GDP-pc) is assumed to follow the SSP1 trend, those with < 10% of the average of the top 5 GDP-pc regions to follow the SSP3 trend, and the rest to follow the SSP2 trend. These f_{av} variations reflect the various adaptation challenges of the SSP matrix (e.g. Kriegler et al., 2012).

2.3. Sensitivity analysis

The sensitivity of modelled P fertilizer use and the size of the SP and LP soil P pools for the year 2050 was investigated using Latin Hypercube Sampling (LHS), with uncertainty ranges for 10 model parameters (Table 2) and expressed with the Standardized Regression Coefficient (SRC). The number of runs was 100. Each model parameter was sampled by subdividing the pre-defined range of each of the 10 parameters into 100 disjunct equiprobable intervals according to the associated distribution in this interval (Table 2). Thus 100 sampled values were obtained for each parameter. The analysis was done for two contrasting scenarios, i.e. SSP1 and SSP3. Further details on this method are provided in Beusen et al. (2016).

Table 2
Ranges and default values of the 10 model parameters included in the sensitivity analysis.

Parameter	Minimum	Maximum	Default	Type[a]	Distribution[b]
Fraction direct uptake of fertilizer	0.1	0.3	0.2	V	unif
Fraction direct uptake of manure	0.05	0.15	0.1	V	unif
Maximum P uptake	400	600	500	V	unif
Initial labile pool size	0.75	1.25	1	M	unif
Initial total soil P ($LP + SP$)	0.75	1.25	1	M	unif
Initial P recovery fraction	0.75	1.25	1	M	unif
Target P uptake from SSP scenario	0.75	1.25	1	M	unif
Manure availability in cropland	0.75	1.25	1	M	unif
Minimum value of the f_{av} within LP	0.025	0.075	0.05	V	unif
Scenario increase of the f_{av} within LP	0.75	1.25	1	M	unif

[a] V = value; M = multiplier.
[b] unif = uniform.

3. Results

The model results and discussion are reported for various regions according to their historical P agricultural practices. This selection consists of 1) developed (USA, Western Europe) and transition (Eastern Europe and the Russian Federation) regions characterized by large P accumulation during the 1970 s–1990 s; 2) P accumulating regions (China and India); 3) Soybean producing regions (Brazil and rest of South America); and 4) low agricultural development regions (North,

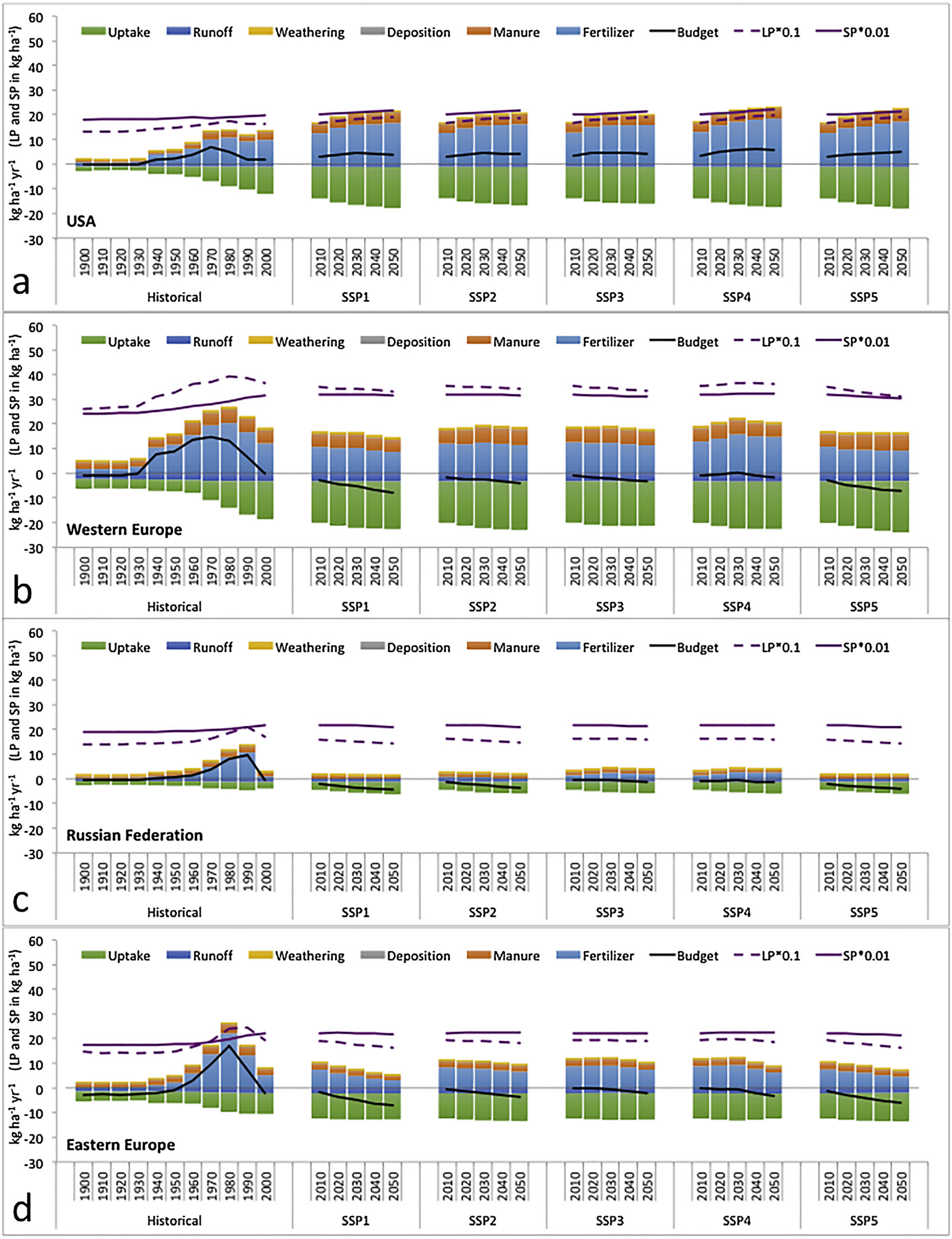

Fig. 2. P in outputs (Uptake, runoff), and inputs (weathering, deposition, fertilizer, manure), soil P budget (difference between inputs and outputs) in kg ha^{-1} yr^{-1}, and the labile and stable soil P pools (in kg ha^{-1}) during the historical period 1900–2005 and the 5 SSP scenario years 2006–2050 for USA (a), Western Europe (b), Russian Federation (c), Eastern Europe (d), India (e), China (f), Brazil (g), rest South America (h), North Africa (i), Eastern Africa (j), and Western Africa (k).

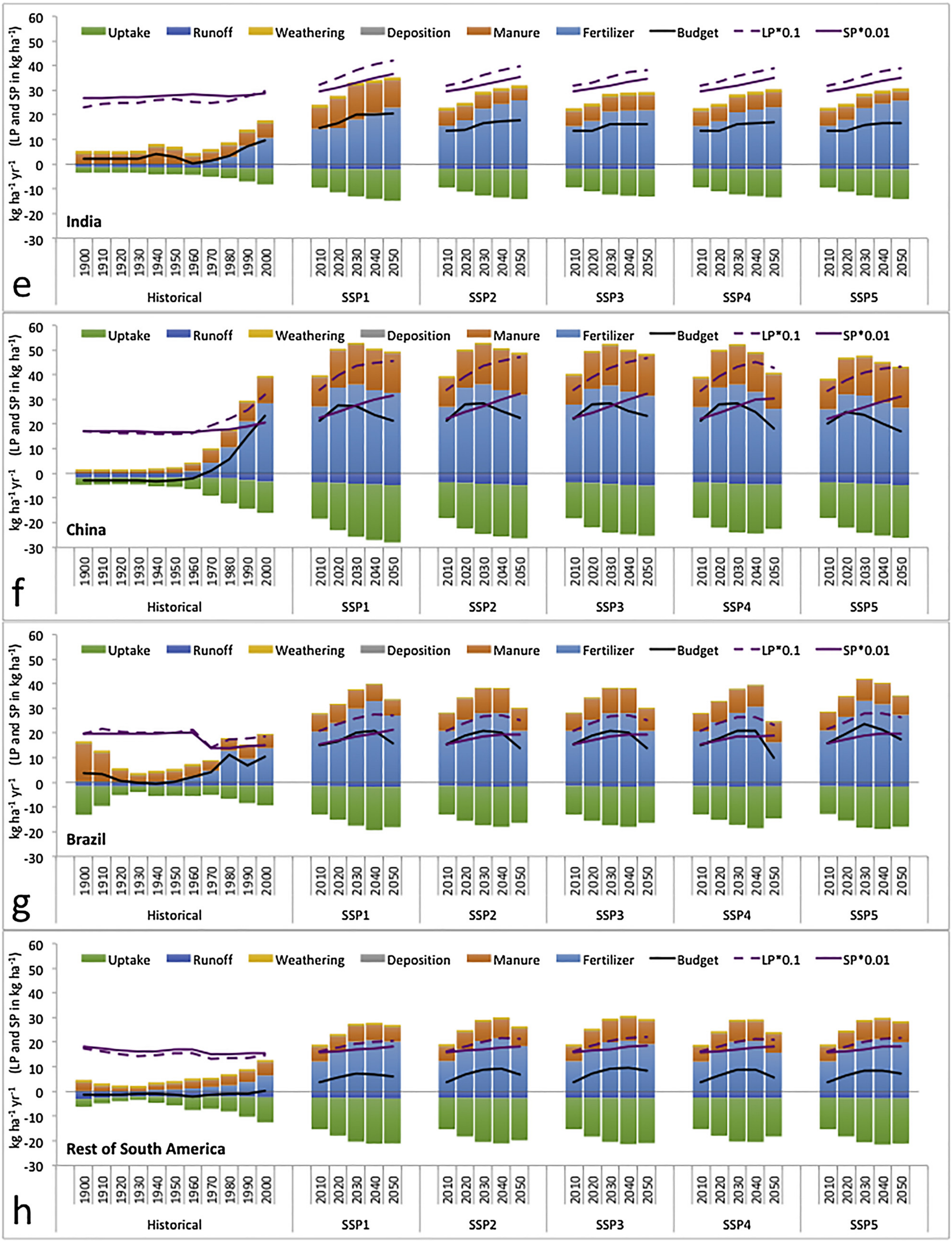

Fig. 2. (*continued*)

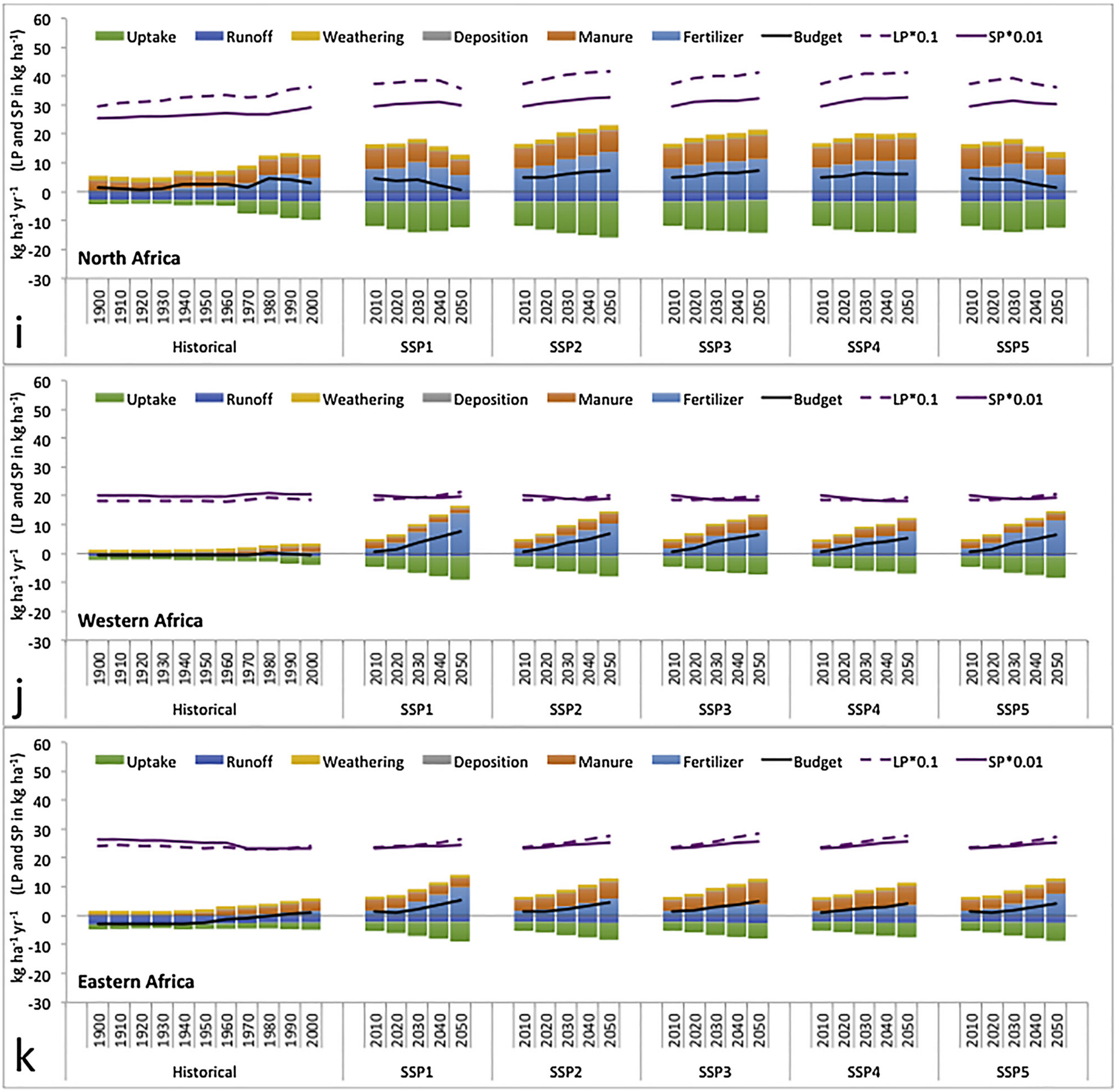

Fig. 2. (*continued*)

Western, and Eastern Africa). The definition for regions is presented in the Supporting information (see Table S1).

3.1. Soil P budgets and changes of soil P pools in croplands

The USA (Fig. 2a), Western Europe (Fig. 2b), the Russian Federation (Fig. 2c), and Eastern Europe (Fig. 2d), had high P application rates in the 1970s and 1980s (in Western Europe even prior to 1970), coupled to increasing soil P pools, particularly the *LP* pool. However, the initial (1900) soil P reserves were much larger in Western Europe than in the other regions of this group. Western Europe sustains high uptake rates with negative soil budgets for all future scenarios, with the sole exception being SSP4. The soil reserves are much smaller in the USA (Fig. 2a), however, input rates are higher and the soil P budgets remain positive in all scenarios (Fig. 2a). Future uptake rates are much smaller in Eastern Europe (Fig. 2d) and the Russian Federation (Fig. 2c) than in Western Europe, and are achieved with slightly negative soil P budgets in all scenarios (Fig. 2a, c and d).

The two major Asian countries, India and China, are currently accumulating soil P and the budgets have been increasing since the early 1970s with large surpluses by the 2000s (Fig. 2e and f). The major difference between the two countries is the soil P pool accumulation was far larger in India than in China in the beginning of the 20th century (Fig. 2e and f). However, with massive surpluses, the *LP* and *SP* pools have increased rapidly in China. The crop production levels out after 2030 and P inputs go down (China) or stabilize (India). The input rates in SSP3 are lower than in SSP1 in both India and China (Fig. 2e and f).

Soil P pools were small throughout the early 20th century in South America (Fig. 2g and h), and soil P depletion occurred until the early 1970s. P application rates have increased in Brazil, and a similar trend is visible in the Rest of South America in the 1990s and 2000s. As 2050 approaches, P inputs in Brazil drop and the production stabilizes (SSP1 and SSP5) or decreases (SSP2, SSP3, SSP4) (Fig. 2g). In the rest of South America production continues to increase after 2030 (Fig. 2h).

Finally, the data indicate major differences within Africa. Soils in

Northern Africa (Fig. 2i) have larger soil P pools than Eastern Africa (Fig. 2j) and Western Africa (Fig. 2k). Northern Africa shows a balanced system with a small positive soil P budget. Western and Eastern Africa show a low production and a slightly negative soil P budget during the past century, with soil P depletion. However, in both regions production has been rapidly increasing since the 1990s. All scenarios project a further rapid growth of P uptake in all parts of Africa, and a major increase in the application of fertilizers (Fig. 2i–k). Only SSP1 for Northern Africa shows declining uptakes and inputs after 2030 (Fig. 2i).

3.2. P inputs

The share of fertilizer to total P inputs varies widely throughout the studied regions. In USA the share of fertilizer P in total P inputs increases from 76% in 2005 to 79% for SSP1 and 81% for SSP3 in 2050. In Western Europe the share of fertilizer P is around 65% for the whole period 2005–2050 and increases to 67% in 2050 for SSP3. In Eastern Europe the share of fertilizer P to total inputs is 79% in 2005. In 2050, it will decrease to a range of 66% (SSP1) to 76% (SSP3). In the Russian Federation the contribution of P fertilizer to total inputs declines from 50% in 2005 to close to zero for SSP1 and to 58% in SSP3 in 2050. In India, fertilizer P makes up around 68% of total inputs over the whole 2005–2050 period for SSP1 but climbs up to 78% for SSP3. In China, the share of fertilizer P in total P inputs was 69% in 2005 and changes only slightly in both SSP1 and SSP3. In Brazil, fertilizer P contributed 73% to total inputs in 2005, and shows an increase to values of 83% in 2040 and 81% in 2050 for SSP1, and 70% in 2050 for SSP3. In North Africa, fertilizer P contributed 52% to total P inputs in 2005, and while it remains stable for SSP1, it increases to 59% in SSP3. In Western Africa, fertilizer inputs contributed a low 16% to total P inputs in 2005, which increases to 90% in SSP1 and 66% in SSP3 by 2050. In Eastern Africa, the share of fertilizer P to total inputs shows a similar rapid increase from 29% in 2005 to 77% for SSP1 and 35% for SSP3 in 2050.

The total global crop production expressed in terms of P uptake is projected to increase by close to 38% in SSP1 to 57% in SSP3 and SSP5 in the period 2005–2030, and another 10-15% in the period 2030-2050 (Table 1). The global cropland area increases between 2005 and 2030 (by 10–18%) in SSP2-5 or shows a slight decrease (SSP1). In the final two scenario decades, area expansion ranges from 3% (SSP1) to 12% (SSP3 and SSP4). Global crop P requirements in SSP1 are the lowest of all scenarios, and about 9% lower than in SSP2. The required P uptake in SSP3 is about equal to that of SSP2. As a result of the increasing crop uptake, all scenarios show a rapid increase of total global P inputs. The differences in global total P inputs between the scenarios are rather small in 2050. Starting from 36 Tg P yr^{-1} in 2005 and 41 Tg P yr^{-1} in 2010, SSP1 projects the lowest global P inputs (globally 53 Tg P yr^{-1} in 2050, Fig. 3). The other scenarios exceed the SSP1 global inputs by 11–22% (60 Tg P yr^{-1} in SSP4 to 65 Tg P yr^{-1} in SSP3). In all scenarios, fertilizer P use is about 40–42% of total P inputs for crop production. SSP1 projects the lowest P fertilizer use of 22 Tg P yr^{-1} in 2050. The other scenarios exceed the SSP1 fertilizer P use by 10–19% at the global scale (25–27 Tg P yr^{-1} in 2050).

3.3. Global P requirements for intensive grasslands

Ruminant production in intensively managed grasslands often depends on supplemental animal feed crops. Based on contemporary human and animal diets and animal product usage, about 3.1–3.5 Tg of P yr^{-1} is being withdrawn from intensive grasslands, which may eventually necessitate P fertilizer additions. Negative soil P budgets (deficits) in intensive grasslands are predicted to grow under all the SSP scenarios. In SSP1, however, this deficit oscillates around 3.6–3.9 Tg P, whereas all other scenarios it increases almost linearly to 7.8, 12, 10, and 8.4 Tg P for SSP2, SSP3, SSP4, and SSP5, respectively. The two to threefold difference among the various SSPs reflects both changes in animal diets, nutrient recycling practices, and wealth, with the latter directly correlated with meat consumption.

3.4. Sensitivity analysis

The results of the sensitivity analysis at the global scale show that, for the SSP1 scenario, the P uptake (U) in 2050 is the most important determinant of P fertilizer use (S) with a standardized regression coefficient (SRC) of 0.82. U also weighs heavily on the size of LP and SP (Table 3). These SRC values are positive, indicating that a U increase leads to an increase in S, and that a surplus of P inputs is required to fill the soil P pools and increase the availability for P uptake.

The second most important global parameter is the fraction of the applied P fertilizer that is directly taken up by plant roots ($1{-}\sigma$); an increase of this fraction causes a decrease of fertilizer input requirements (-0.40), and also less input to the soil P pools. Finally, the SSP1 scenario assumption for the increase of the available fraction of LP negatively influences the fertilizer needs in 2050 (-0.37), and the soil P pool sizes, as this mimics the availability of P for plant uptake (see Eqs. (1) and (2)).

The sensitivity of global fertilizer inputs, LP and SP for SSP3 in 2050 is very similar to that of SSP1 for all parameters. This is related to the relatively small differences between the scenarios. For example, the target scenario P uptake in SSP3 exceeds that in SSP1 by $< 10\%$, which is less than the $\pm$ 25% variation in the sensitivity analysis. Additional details on the sensitivity analysis are provided in SI 2.

4. Discussion

Future population growth will likely demand higher agricultural crop production on a global scale. Increases in crop production may stem from cropland area expansion, intensifying cropland production (more crops per year), and/or improving crop yields (higher production per crop). Management options to improve crop yields include strategies such as plant breeding, choice of crops, and soil conservation (George, 2014). Historically, however, cropland production has been stimulated mainly via a direct increase of P fertilizer use in croplands (Peñuelas et al., 2013; Van der Velde et al., 2014; Figs. 2 and 4). This practice has direct environmental consequences, as excess nutrients can reach the freshwater system via leaching and runoff (e.g. Beusen et al., 2016) and stimulate algal blooms and water column hypoxia (e.g. Diaz and Rosenberg, 2008). An improvement in both N and P management is crucial to limit anthropogenic pressures on global watersheds.

Past agricultural practices (together with socioeconomic development) in global regions have been in constant flux since the industrial age, and have shaped the current P pools present in soils (Figs. 2 and 4). Rampant fertilizer use in developed and transition regions during the 20th century has created large pools of legacy P (Bouwman et al., 2017, Fig. 2a–d). In the USA this trend has stimulated increasing P uptakes up to 2010 and is expected to sustain even further increases into the future under every SSP scenario. This occurs even in SSP1, where high P use efficiencies ($> 80\%$) maintain a total production increase despite the decreasing cropland areas (-10% by 2050). Comparatively, in SSP3 the required total P uptake is expected to increase by 31% in 2050. In this scenario, the expected expansion in cropland area ($+12\%$) will aid in providing additional P total inputs (fertilizer P by 39%) with only slight changes to the efficiency (Fig. 4a). In Western Europe, due to the large soil P reserves built during the aggressive fertilization in the second half of the 20th century, high uptake rates can be sustained even with slightly negative future soil P budgets under all scenarios (Figs. 2b and 4b). SSP1 yields a continuation of the observed improvement of P use efficiency in recent years, such that with lower production after 2010 and shrinking cropland areas (-10%), the required fertilizer input will also decrease (Fig. 4b). Comparatively, in SSP3 crop P uptake slightly increases after 2010, which together with expanding cropland areas ($\sim 10\%$), increases the P inputs resulting in only a slightly negative budget (Fig. 4b). The results for Eastern Europe are similar to

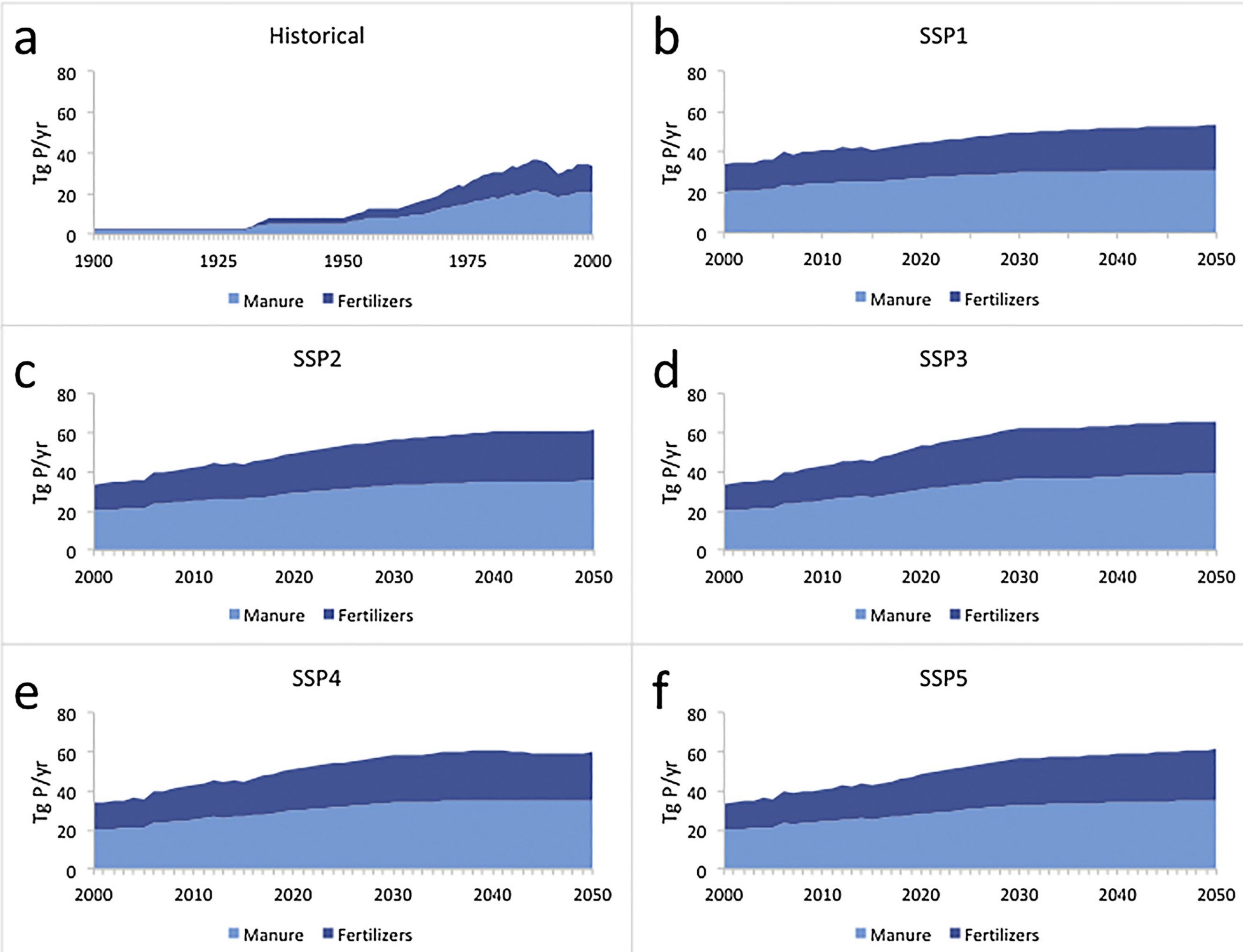

Fig. 3. Total manure and fertilizer inputs during the period 1900–2005 (historical, a), and 2006–2050 for SSP1 (b), SSP2 (c), SSP3 (d), SSP4 (e), SSP5 (f).

Table 3
Sensitivity to variation of 10 model parameters expressed as standardized regression coefficient of computed fertilizer use, and *LP* and *SP* size in the year 2050.

Parameter	SSP1			SSP3		
	Fertilizer	*LP*	*SP*	Fertilizer	*LP*	*SP*
Fraction direct uptake of fertilizer	-0.40	-0.53	-0.55	-0.39	-0.53	-0.57
Fraction direct uptake of manure	-0.07	-0.10	-0.12	-0.08	-0.10	-0.10
Maximum P uptake						
Initial labile pool size						
Initial total soil P (*LP*+*SP*)						
Initial P recovery fraction						
Target P uptake from scenario	0.82	0.65	0.69	0.81	0.65	0.70
Manure availability in cropland	-0.09	0.10	0.11	-0.10	0.10	0.10
Minimum value of the mobile fraction within *LP*	-0.18	-0.25	-0.24	-0.21	-0.27	-0.25
Scenario increase of the mobile fraction within *LP*	-0.37	-0.39	-0.29	-0.37	-0.37	-0.27

[a]Cells with no values represent insignificant SRC values; cells with values have significant SRC, cells with black color indicate values of $-0.2 < \text{SRC} < 0.2$; light and dark gray cells indicate values exceeding + 0.2 and −0.2, respectively. An SRC value of 0.2 implies an influence of $0.2^2 = 0.04$ (4%) on the model result considered.

Western Europe with an increasingly negative soil P budget in SSP1 and slightly negative but constant budget in SSP3 (Figs. 2d and 4d). Nevertheless, they include a considerable cropland area increase of 20% in SSP1 and slight area increase of 10% in SSP3. The Russian Federation shows slowly increasing total P uptake in both SSP1 and SSP3 (Fig. 4c). With only minor inputs variations and a constant

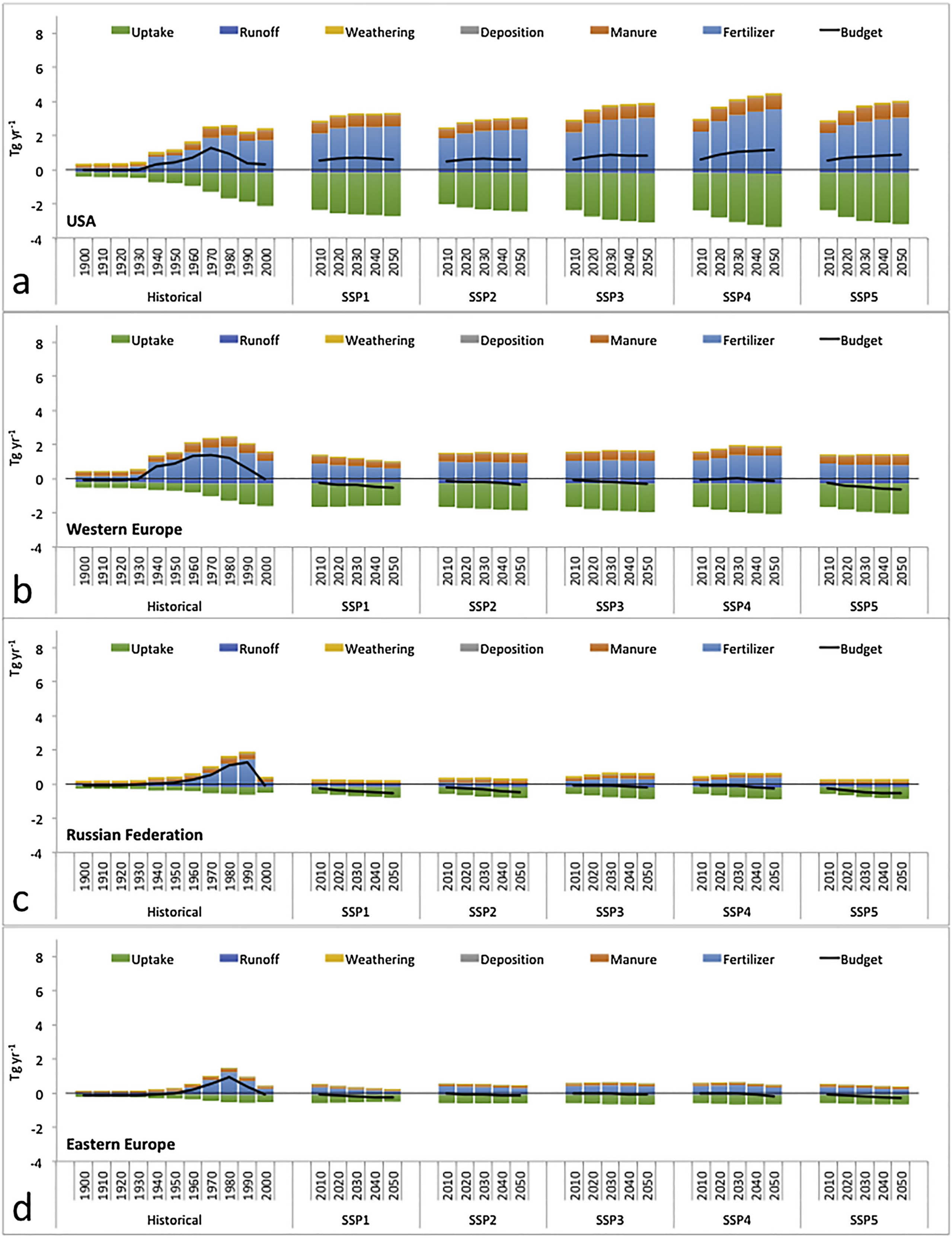

Fig. 4. P in outputs (Uptake, runoff), and inputs (weathering, deposition, fertilizer, manure), soil P budget (difference between inputs and outputs) in Tg yr^{-1} during the historical period 1900–2005 and the 5 SSP scenario years 2006–2050 for USA (a), Western Europe (b), Russian Federation (c), Eastern Europe (d), India (e), China (f), Brazil (g), rest South America (h), North Africa (i), Eastern Africa (*j*), and Western Africa (k).

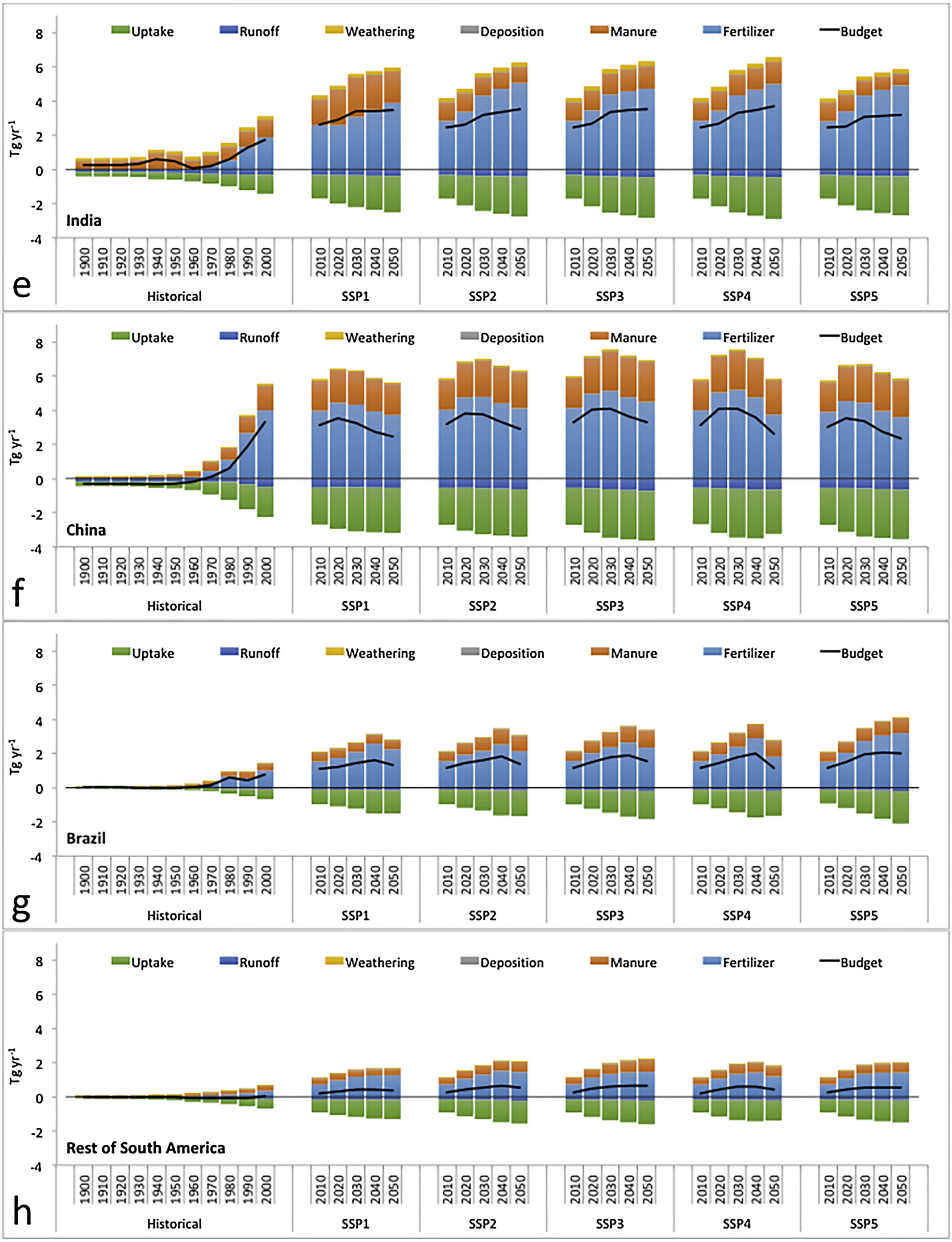

Fig. 4. (*continued*)

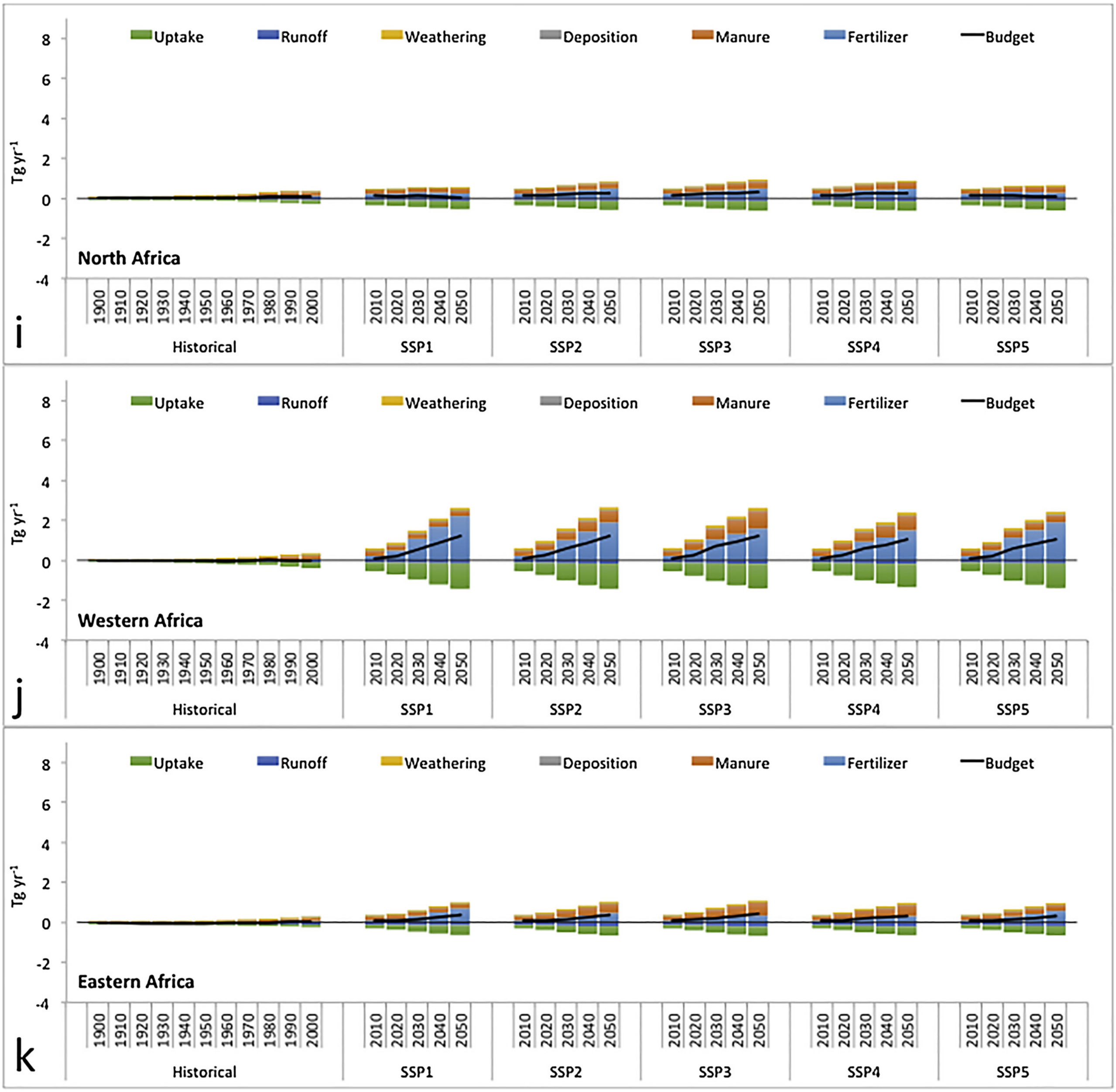

Fig. 4. (*continued*)

cropland area in SSP1, the soil P budget becomes more negative toward 2050. For SSP3, a 17% cropland expansion between 2010 and 2050, coupled to relatively constant P inputs, results in a slow change in the (negative) budget.

Due to the significant population increase and the concomitant food production requirements in China and India, P inputs to croplands will have to increase considerably to meet this accelerating P demand in these regions. These inputs will continue to increase under all scenarios and only level off after 2030 once the *LP* and *SP* pools have been built to sufficient capacity to maintain the demanded production. In India the SSP1 efficiency shows no real change in the coming decades (Fig. 4e). In SSP3, production and inputs increase at nearly the same rate, and with a ~20% cropland area increase, application rates and P use efficiency remain stable. In China, SSP1 shows a decline in the cropland area (−23% between 2010 and 2050), and with a slight decrease in the required production, inputs can be maintained at the same level, which implies a considerable increase in efficiency calculated as the ratio crop P withdrawal to inputs (33%–48% in the period 2010–2050) (Fig. 4f). SSP3 shows only slight changes in cropland area. Thus, to achieve a 33% increase in production, inputs need to increase up to 2030, after which they can decrease. The soil P budget also declines after 2030 (Fig. 4f).

South America comprises some major soybean producing countries (e.g. Brazil, Argentina). Soybeans fix N_2 and generally extract larger amounts of soil P than other crops. They thus may require larger amounts of P fertilizer inputs than non-leguminous crops (Cooke, 1982). Historically, the South American regions had very minor P inputs, leading to substantial P soil mining, a dominance of negative soil P budgets, and low soil P availability in both regions at present time (Fig. 4d and e). The estimated increase in P demand to meet 2050 production, coupled to the high proportion of soybean crops, indicates that P fertilizer inputs will have to increase considerably under all scenarios. In Brazil, both SSP1 (12%) and SSP3 (+49%) show increasing cropland areas. To achieve the production increase by 60% in SSP1 and 89% in SSP3, inputs need to increase until 2030, and can decline afterwards in all scenarios (Fig. 4g). The rest of South America shows a 50% (SSP1) to 80% (SSP3) increase of the required production between 2010 and 2050. With an area increase of 5% (SSP1) to 27%

(SSP3), inputs need to increase considerably in both scenarios, particularly in SSP3 (Fig. 4h).

In Africa, improving crop yields are insufficient to meet the rapidly growing food demand. Cropland areas will thus increase rapidly in all scenarios (Northern Africa 32% in SSP4 to 80% in SSP5; Western Africa 44% in SSP1 to 83% in SSP4; Eastern Africa 34% in SSP1 to 62% in SSP3 and SSP4). Total P inputs by 2050 will increase by a factor of 1.3–2.3 (Northern Africa, Fig. 4i), a factor of close to 9–10 (Western Africa, Fig. 4j) and a factor of 3–5 (Eastern Africa, Fig. 4k) with highest values in SSP3.

The IMAGE-DPPS model results show major differences in future P requirements and fertilizer use among world regions for the various scenarios. High-income countries with a history of P accumulation during the 1960s and 1970s, will require relatively low P inputs up to 2050. Western Europe has high P yields and can continue to apply an equilibrium fertilization scheme, with input equal to or slightly less than outputs. The USA also has high future P yields, but compared to Western Europe will need to apply P at higher rates because of lower residual P reserves. Due to lower future yields, soils in Eastern Europe and the Russian Federation can supply the required P under low P fertilization levels. In stark contrast, India and China are currently accumulating soil P by virtue of extensive soil P fertilizer application, a trend that is predicted to continue in order to increase crop production to meet high future P demand under all SSP scenarios. The low production regions will also have to scale up their level of P inputs to increase P uptake and keep up with the future agricultural production demand. These regions will have to reach P uptake values in the 10–20 kg ha^{-1} yr^{-1}, similar to the production levels of developed and transition regions.

Aside from socioeconomic and crop production factors, regional variations in future fertilizer demand may be instigated by soil properties, as limited P availability in soils may result from deficiency and/or severe P retention (Batjes, 2011). Soils high in soluble Fe and Al, 1:1 clay minerals, or high Ca activity react with phosphate to form insoluble compounds that are largely unavailable to plants. This is particularly problematic in many weathered tropical soils and volcanic ash soils, which are widespread in for example, Brazil, Eastern Africa, and Western Africa (Fairhurst et al., 1999). The low soil P availability in South America coupled to the projected increasing production target for 2050, indicates that P inputs (primarily via P fertilization) will have to increase considerably under all scenarios. All scenarios project a further rapid growth of P uptake in all parts of Africa, which induces a major increase in the required P application, particularly via fertilizers. However, the increase in crop P uptake per hectare is insufficient to meet the rapidly growing demand, leading to extensive cropland area expansion.

Globally, our results indicate that in SSP1 the entire increase in P uptake is due to increased production per hectare, with the other scenarios requiring a contribution from cropland expansion (Fig. 5). While

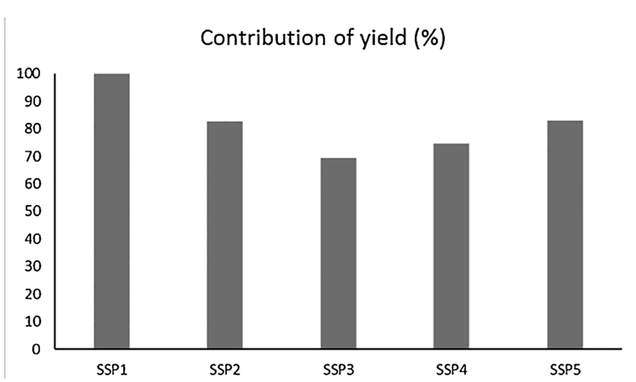

Fig. 5. Contribution of P yield improvements to production increase in SSP1-SSP5 during the period 2006–2050.

in South America, Africa, the Russian Federation, the Middle East, Southeast Asia, and Indonesia, the soil P reserves in land cleared for cropland expansion contribute to increased P uptake, most P uptake is attributable to crop yield improvement, despite a net reduction in the global cropland areas. Our results for SSP2 (baseline) for the developing countries indicate an 81% contribution from yield increase to total increased crop production. This is in close agreement with the 80% estimated by Alexandratos and Bruinsma (2012). In SSP1 (100%) and SSP3 (71%), SSP4 (69%) and SSP5 (81%) the contribution of P yield increase for developing countries is close to the baseline of Alexandratos and Bruinsma (2012). The uptake per hectare represents a weighted average for large world regions, and does not reflect differences between and within countries. Thus, our estimated application rate amounts at the grid scale (and the spatial distribution) for manure P and fertilizer P have a relatively high degree of uncertainty.

The total cropland P input required by the 5 different SSP scenarios is quite comparable, despite the marked differences in the population and income. SSP1 projects a global P fertilizer use for crop production of 22 Tg P yr^{-1} in 2050, and the other scenarios exceed SSP1 by 10–19% at the global scale (25–27 Tg P yr^{-1} in 2050). The SSP2 projection for 2050 of 26 Tg P yr^{-1} is almost 20% lower than that of the recent projection by the Food and Agriculture Organization of the United Nations (FAO) of 32 Tg P yr^{-1} (Alexandratos and Bruinsma, 2012), although SSP2 is based on the same agricultural production trend as this FAO study. This difference is due to the DPPS accounting for residual soil P within *LP* and *SP*. SSP2 differs from the FAO study even more at the regional scale. For example, Alexandratos and Bruinsma (2012) projects a P fertilizer use for Africa and Western Europe in 2050 of 1.2 Tg P yr^{-1} and 1.5 Tg P yr^{-1}, respectively; versus our SSP2 estimates of 3.3 Tg P yr^{-1} and 0.9 Tg P yr-1 for the same regions, respectively. These discrepancies reflect the ability for the IMAGE-DPPS model to capture the strong soil P retention of African soils (Batjes, 2011) and the large stock of residual soil P in European soils.

FAO projections for 2030 of 21 Tg P yr^{-1} (Bruinsma, 2003) are close to the SSP2 projection for 2030 of 24 Tg P yr^{-1}, but are considerably lower than Alexandratos and Bruinsma (2012), who estimated a global P fertilizer consumption of 27 Tg P yr^{-1} for 2030. Our scenarios are also generally lower than the projections by Steen (1998), who used an annual growth rate of 2.5% in P consumption reflecting a 2–2.5% increase of crop yields to estimate a global P fertilizer consumption of 26–31 Tg P yr^{-1} in 2050. Our fertilizer requirements, nevertheless, which take into account both the population and the soil P dynamics, reflect an attenuated increase in the fertilizer P inputs up to the year 2050 for all scenarios (Fig. 4).

Fertilizer P projections that ignored residual soil P made by Bouwman et al. (2009) for the Millennium Ecosystem Assessment (MEA) scenarios ranged from 19 to 33 Tg P yr^{-1}. The MEA Global Orchestration scenario estimated 21 Tg P yr^{-1} of fertilizer and 31 Tg P yr^{-1} of total P inputs in 2050. In comparison, our business as usual SSP2 scenario estimates of 26 Tg P yr^{-1} of P fertilizer and 36 Tg P yr^{-1} of total P inputs are roughly 20% higher. Our SSP2 results for Africa (3.3 Tg yr^{-1} of fertilizer P in 2050), South America (3.5 Tg yr^{-1}) and Asia excluding China and India exceed those for Global Orchestration by 20%, 38% and 17%, respectively, and better reflect the P requirements according to the target productions for the SSPs. There are several possible reasons for the higher P cropland requirements for the baseline scenario in our study with respect to Bouwman et al. (2009) and Sattari et al. (2012). 1) Our study includes an extension of the list of future crops with a series of fodder crops, which increases future P uptake estimates (21 Tg yr^{-1} in our SSP2 vs. 18 Tg P yr^{-1} for the baseline scenario). 2) The lumped continental-scale approach of Sattari et al. (2012) ignored soil properties relevant to soil P retention. 3) These previous studies assumed a constant future cropland area. This latter point may have important repercussions for the estimated P inputs. For example, SSP2 and SSP3 have about the same total production, but global cropland areas in SSP3 exceed those in SSP2 by close to 10% due to lower yields. As a result, P global requirements in SSP3 are 9% larger than in SSP2, as 9% more virgin soils are taken in production in the period 2005–2050.

If we consider the P deficits in intensively managed grasslands, another 4 Tg yr^{-1} of fertilizer P needs to be added to the cropland P requirements, totaling 26 Tg P yr^{-1} in 2050. For other scenarios with more meat and milk consumption, the additional P fertilizer requirement may rise to 12 Tg P yr^{-1}. This confirms the conclusion of Sattari et al. (2016) that large amounts of additional P fertilizers are required to support future ruminant meat and milk production.

According to the model sensitivity analysis for the year 2050, crop uptake ultimately exerts the largest control on P requirements, inputs, availability, and pool sizes for all scenarios. The second most important global parameter is the fraction of the applied P fertilizer that is directly taken up by plant roots. This reflects the direct importance that fertilizer efficiency and the overall soil P chemistry have on crop uptake.

5. Model limitations

IMAGE-DDPS has a simple biogeochemical representation of the soil system, which focuses on P from the point of view of two soil pools. The model could thus be improved by adding additional soil biogeochemical interactions. For instance, strongly weathered tropical soils with high chemical P retention are widespread in many developing countries, such as in large parts of South America and Africa, (Fairhurst et al., 1999). In these locations, high P inputs may be needed to achieve the necessary P availabilities that allow the large P uptakes in the SSP projections for the coming four decades. Furthermore IMAGE-DPPS does not explicitly account for the limitation of other nutrients such as nitrogen and potassium, whose input could also stimulate crop yields (e.g. Lassaletta et al., 2014; Mogollón et al., 2018).

IMAGE-DPPS simulates future P requirements starting from the conditions in the year 2005, with pools initialized on the basis of historical data on P inputs and P uptake by crops. The model thus assumes that the future interactions between the P crop uptake and that of other nutrients do not change after 2005. This indicates that this model does not incorporate the future effects of other nutrient limitations on cropland production. Furthermore, while SSP1 includes assumptions on better manure nutrient recycling, IMAGE-DDPS does not include changes to post-farm P recycling from slaughterhouse waste, urban waste, sewage sludge, etc. The simulations instead assume that a large P fraction is disposed of, or used as fuel or building material, rather than being used as fertilizer on cropland and grasslands. While such P recycling would allow for the substitution of mineral P fertilizer it would not change our total P input required to meet the SSP-specific production.

6. Concluding remarks

The IMAGE-DPPS model accounts for soil characteristics relevant to P retention along with changing land use with virgin soils taken into cultivation. It therefore yields a more accurate estimate of future P inputs than previous approaches, such as trend extrapolation and lumped continental-scale models. These added dimensions are able to provide insights into future projections for various global regions and how to better manage future P fertilization. For instance, developed regions will require little to no fertilizer inputs due to legacy P present in their croplands, whereas South America, India, and China will require substantial fertilization due to growing populations. Africa will require both cropland expansion and increasing P yields. On a global scale, results show that the increased global P uptake in the year 2050 could occur entirely due to yield increase (SSP1), but that under less environmentally friendly scenarios (SSP3), its role could diminish with cropland area expansion contributing 31%.

Despite the differences in the storylines among the SSPs, the global cropland P inputs are relatively similar. This indicates that growing populations under SSP3 and SSP4 will be consuming less P. In addition to fertilizer P inputs of 22–27 Tg P yr^{-1} in 2050, this study also estimates fertilizer P requirements of 4–12 Tg P yr^{-1} in global intensively managed grasslands, a variation that depends heavily on dairy and meat consumption as well as manure recycling. Even under our most sustainable scenario (SSP1), the total fertilizer P requirements required to maintain future populations would be 26 Tg P yr^{-1}.

Acknowledgements

Funding for this research was provided by Marie Skłodowska-Curie Individual Fellowship Grant number 661163 awarded to JMM. AFB and AHWB received support from PBL Netherlands Environmental Assessment Agency through in-kind contributions to The New Delta 2014 ALW projects no. 869.15.015 and 869.15.014.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2018.03.007.

References

Alexandratos, N., Bruinsma, J., 2012. World Agriculture Towards 2030/2050. The 2012 Revision. Food and Agriculture Organization of the United Nations, Rome.
Batjes, N.H., 2011. Global Distribution of Soil Phosphorus Retention Potential. ISRIC - Worls Soil Information. Wageningen. pp. 41.
Beaton, J., 2006. Efficient Use of Fertilizer Use Manual: History. Available at: http://academic.uprm.edu/dsotomayor/agro6505/History_of_Fertilizer_Beaton.pdf.
Beusen, A.H.W., Bouwman, A.F., Van Beek, L.P.H., Mogollón, J.M., Middelburg, J.J., 2016. Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. Biogeosciences 13, 2441–2451.
Beusen, A.H.W., Van Beek, L.P.H., Bouwman, A.F., Mogollón, J.M., Middelburg, J.J., 2015. Coupling global models for hydrology and nutrient loading to simulate nitrogen and phos- phorus retention in surface water – description of IMAGE–GNM and analysis of performance. Geosci. Model Dev. 8, 4045–4067. http://dx.doi.org/10.5194/gmd-8-4045-2015.
Bouwman, A.F., Beusen, A.H.W., Billen, G., 2009. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. Global Biogeochem. Cycles 23, GB0A04.
Bouwman, A.F., Klein Goldewijk, K., Van der Hoek, K.W., Beusen, A.H.W., van Vuuren, D.P., Willems, W.J., Rufino, M.C., Stehfest, E., 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. Proc. Natl. Acad. Sci. U. S. A. 110, 20882–20887. http://dx.doi.org/10.21073/pnas.1012878108.
Bouwman, A.F., Beusen, A.H.W., Lassaletta, L., Van Apeldoorn, D.F., van Grinsven, H.J.M., Zhang, J., Van Ittersum, M.K., 2017. Lessons from temporal and spatial patterns in global use of N and P fertilizer on cropland. Sci. Rep. 7, 40366. http://dx.doi.org/10.1038/srep40366.
Bruinsma, J.E., 2003. World Agriculture: Towards 2015/2030. An FAO Perspective. Earthscan, London.
Cooke, G.W., 1982. Fertilizing for Maximum Yield, 3d edition. Granada, London.
Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: global food security and food for thought. Global Environ. Change 19, 292–305. http://dx.doi.org/10.1016/j.gloenvcha.2008.1010.1009.
Déry, P., Anderson, B., 2007. Peak Phosphorus. Energy Bulletin 08/13/2007. Available: energybulletin.net/node/33164. .
Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.
Fairhurst, T., Lefroy, R., Mutert, E., Batjes, N., 1999. The importance, distribution and causes of phosphorous deficiency as a constraint to crop production in the tropics. Agrofor. Forum 9, 2–8.
FAO-UNESCO, 1974. Soil Map of the World: Vol. 1, Legend. UNESCO, Paris Available at: http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/.
George, T., 2014. Why crop yields in developing countries have not kept pace with advances in agronomy. Global Food Secur. 3, 49–58.
Koning, N.B.J., Van Ittersum, M.K., Becx, G.A., Van Boekel, M.A.J.S., Brandenburg, W.A., Van Den Broek, J.A., Goudriaan, J., Van Hofwegen, G., Jongeneel, R.A., Schiere, J.B., Smies, M., 2008. Long-term global availability of food: continued abundance or new scarcity? NJAS Wageningen J. Life Sci. 55, 229–292.
Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T., 2012. The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. Global Environ. Change 22, 807–822.
Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in

nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9, 105011.
MacDonald, G.K., Bennett, E.M., Potter, P.A., Ramankutty, N., 2011. Agronomic phosphorus imbalances across the world's croplands. Proc. Natl. Acad. Sci. U. S. A. 108, 3086–3091.
Mogollón, J.M., Lassaletta, L., Beusen, A., van Grinsven, H., Westhoek, H., Bouwman, A.F., 2018. Assessing future reactive nitrogen inputs into global croplands based on the shared socioeconomic pathways. Environ. Res. Lett. 13, 044008. http://dx.doi.org/10.1088/1748-9326/aab212.
Nijland, G.O., Schouls, J., Goudriaan, J., 2008. Integrating the production functions of Liebig, Michaelis-Menten, Mitscherlich and Liebscher into one system dynamics model. NJAS-Wageningen J. Life Sci. 55, 199–224. http://dx.doi.org/10.1016/S1573-5214(08)80037-1.
Peñuelas, J., Poulter, B., Sardans, J., Ciais, P., van der Velde, M., Bopp, L., Boucher, O., Godderis, Y., Hinsinger, P., Llusia, J., Nardin, E., Vicca, S., Obersteiner, M., Janssens, I.A., 2013. Human-induced nitrogen–phosphorus imbalances alter natural and managed ecosystems across the globe. Nat. Commun. 4.
Sattari, S.Z., Bouwman, A.F., Giller, K.E., van Ittersum, M.K., 2012. Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proc. Natl. Acad. Sci. 109, 6348–6354.
Sattari, S.Z., Bouwman, A.F., Martinez Rodriguez, R., Beusen, A.H.W., van Ittersum, M.K., 2016. Negative global phosphorus budgets challenge sustainable intensification of grasslands. Nat. Commun. 7.
Schachtman, D.P., Reid, R.J., Ayling, S.M., 1998. Phosphorus uptake by plants: from soil to cell. Plant Physiol. 116, 447–453. http://dx.doi.org/10.1104/pp.116.2.447.
Steen, I., 1998. Phosphorous availability in the 21st century. Phosphorous Potassium 217, 25–31.
Stehfest, E., van Vuuren, D.P., Kram, T., Bouwman, A.F., 2014. Integrated Assessment of Global Environmental Change With IMAGE 3.0. Model Description and Policy Applications. PBL Netherlands Environmental Assessment Agency. The Hague. http://themasites.pbl.nl/models/image/index.php/Main_Page.
Syers, J.K., Johnston, A.A., Curtin, D., 2008. Efficiency of Soil and Fertilizer Phosphorous Use. Reconciling Changing Concepts of Soil Phosphorous Behaviour With Agronomic Information. Food and Agriculture Organization of the United Nations (FAO), Rome, pp. 110.
UN, 2016. World Population Prospects: the 2015 Revision. United Nations Department for Economic and Social Affairs, New York. https://esa.un.org/unpd/wpp/.
Van der Velde, M., Folberth, C., Balkovič, J., Ciais, P., Fritz, S., Janssens, I.A., Obersteiner, M., See, L., Skalský, R., Xiong, W., Peñuelas, J., 2014. African crop yield reductions due to increasingly unbalanced nitrogen and phosphorus consumption. Global Change Biol. 20, 1278–1288.
Van Kauwenbergh, J., 2010. World Phosphorus Rock Reserves and Resources. International Fertilizer Development Center, Muscle Shoals, AL.
van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., van Meijl, H., Müller, C., van Ruijven, B.J., van der Sluis, S., Tabeau, A., 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environ. Change 42, 237–250.
van Vuuren, D.P., Bouwman, A.F., Beusen, A.H.W., 2010. Phosphorus demand for the 1970-2100 period: a scenario analysis of resource depletion. Global Environ. Change 20, 428–439. http://dx.doi.org/10.1016/j.gloenvcha.2010.1004.1004.
Woltjer, G.B., Kuiper, M.H., 2014. The MAGNET Model: Module Description. LEI Wageningen UR (University & Research centre), Wageningen, pp. 146.
Yang, X., Post, W.M., Thornton, P.E., Jain, A., 2013. The distribution of soil phosphorus for global biogeochemical modeling. Biogeosciences 10, 2525–2537.
Zhang, J., Beusen, A.H.W., Van Apeldoorn, D.F., Mogollón, J.M., Yu, C., Bouwman, A.F., 2017. Spatiotemporal dynamics of soil phosphorus and crop uptake in global cropland during the 20th century. Biogeosciences 14, 2055–2068.