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Phosphorus for Sustainable Development Goal target of doubling smallholder productivity

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Phosphorus (P) is an essential nutrient for life. In many tropical countries, P-fixing soils and very low historical P input limit uptake of P in crops and thus yields. This presents a serious obstacle for achieving the Sustainable Development Goal (SDG) target 2.3 of doubling productivity in smallholder farms. We calculated the geographic distribution of P limitation (1 – actual/potential P uptake) and the P input required to achieve this SDG target by 2030 in comparison to the Shared Socioeconomic Pathway (SSP2) scenario for five world regions where smallholder farms dominate. To achieve target 2.3, these regions require 39% more P application (126 Tg) between 2015 and 2030. While P limitation is most widespread in sub-Saharan Africa, it is the only region on track to achieving the doubling of productivity in the SSP2 scenario (increase by a factor of 1.8). Achieving the target requires a strong increase in P input, while protecting soils and waterways from excessive P runoff.

The marked expansion of phosphate rock mining has allowed for the rapid growth of global phosphorus (P) fertilizer production since the 1950s[1]. In the 1970s and 1980s, disproportionate fertilizer and manure P use in industrialized countries led to low P-use efficiency (PUE)[2,3]. Consequently, over time large amounts of surplus P were retained as residual P in soils, which increased both the P saturation and the P crop availability to its contemporary levels[4]. After this accumulation phase, farmers in many industrialized countries have been able to increase their PUE[5], often by using the accumulated residual soil P reserves[3]. In contrast, Brazil, China and India are currently in the phase of large P surpluses and low nutrient-use efficiencies. Many developing countries are in the early phases of agricultural development with minimal P application rates, mining of soil P and low crop yields[3,6].

P management is crucial to the SDGs

In view of the finite world phosphate rock reserves, the global P requirement over the coming century has become a major concern[7]. Furthermore, the widespread use of P fertilizers is a threat to SDG6 (clean water and sanitation) and SDG14 (life below water) due to P losses from farm fields by surface runoff and consequent eutrophication of freshwater and coastal seas[8,9]. Yet, the supply of P is crucial to food security[10]. Future P management will therefore play an important role in achieving SDG2 (zero hunger). Achieving this goal is critical as the world population is projected to grow from 7.3 billion in 2015 to perhaps >10 billion inhabitants in 2050[11].

P fixation can be overcome

Future crop yields depend on the availability of soil P for plant uptake; that is, on the concentration of phosphate ions in the soil solution and the soil's ability to replenish phosphate withdrawn by plants[4]. Soils can adsorb inorganic P with varying degrees of reversibility. Soils rich in soluble iron or aluminium, clay minerals like kaolinite or with a high calcium activity, react with P to form insoluble compounds[12]. This is often referred to as P fixation, which is especially important in weathered tropical soils[13,14].

P fixation can be overcome. For example, Brazil has been rapidly increasing its intensive soybean production on strongly weathered P-fixing soils by surplus P applications to quench much of the soil P fixation and sorption capacity[15,16]. Not only has Brazil overcome P fixation in large parts of its agricultural heartland but they have managed to build up large pools of legacy P that can be used in transitioning to a sustainable, low-input farming system[17,18]. The challenge of addressing global P fixation and limitation has been recently studied. Using Brazilian P input and surplus data, Roy et al.[19] estimated that globally 8–25% more P input is required on the world's P-fixing soils to raise crop yields to levels prevalent in Brazil. Kvakić et al.[20] estimated that, globally, cereal yields could be 22–55% higher if P limitation were addressed. P fixation and limitation therefore pose additional challenges to achieving SDG2. However, there are currently no estimates on how much P input is needed to double smallholder productivity (target 2.3), a key target of SDG2. In this study, our objectives were: (1) to map the geographic distribution of P limitation; and (2) to assess SDG2 target 2.3 from a P perspective.

P limitation and global scenarios

Where soils are P limited, crop growth cannot achieve its full potential. P limitation represents the relative yield gap[21,22], which is attributable to limited P availability for crops. Calculating P limitation involves estimating the actual crop growth, which is P limited, and potential crop growth under no P limitation. These estimates can either be based on crop growth models[20] or empirically based calculations using P budgets[19]. While the concept of potential growth is intuitively clear, calculation thereof is much more difficult, because it is at the limit of what can be observed in field trials. Pragmatic choices must be made for its calculation. In empirically based yield gap analyses, for example, the 90th or 95th percentile in a climatic bracket was considered potential yield[21,22]. Our choice was to model the P application of 50 kg $\text{ha}^{-1}\,\text{yr}^{-1}$ for 20 years for calculating a potential P uptake, assuming that this will eliminate P limitation in most places, and that water and other nutrients like nitrogen and potassium are available in adequate amounts relative to P. This choice was motivated by the Brazilian case, where highly P-fixing

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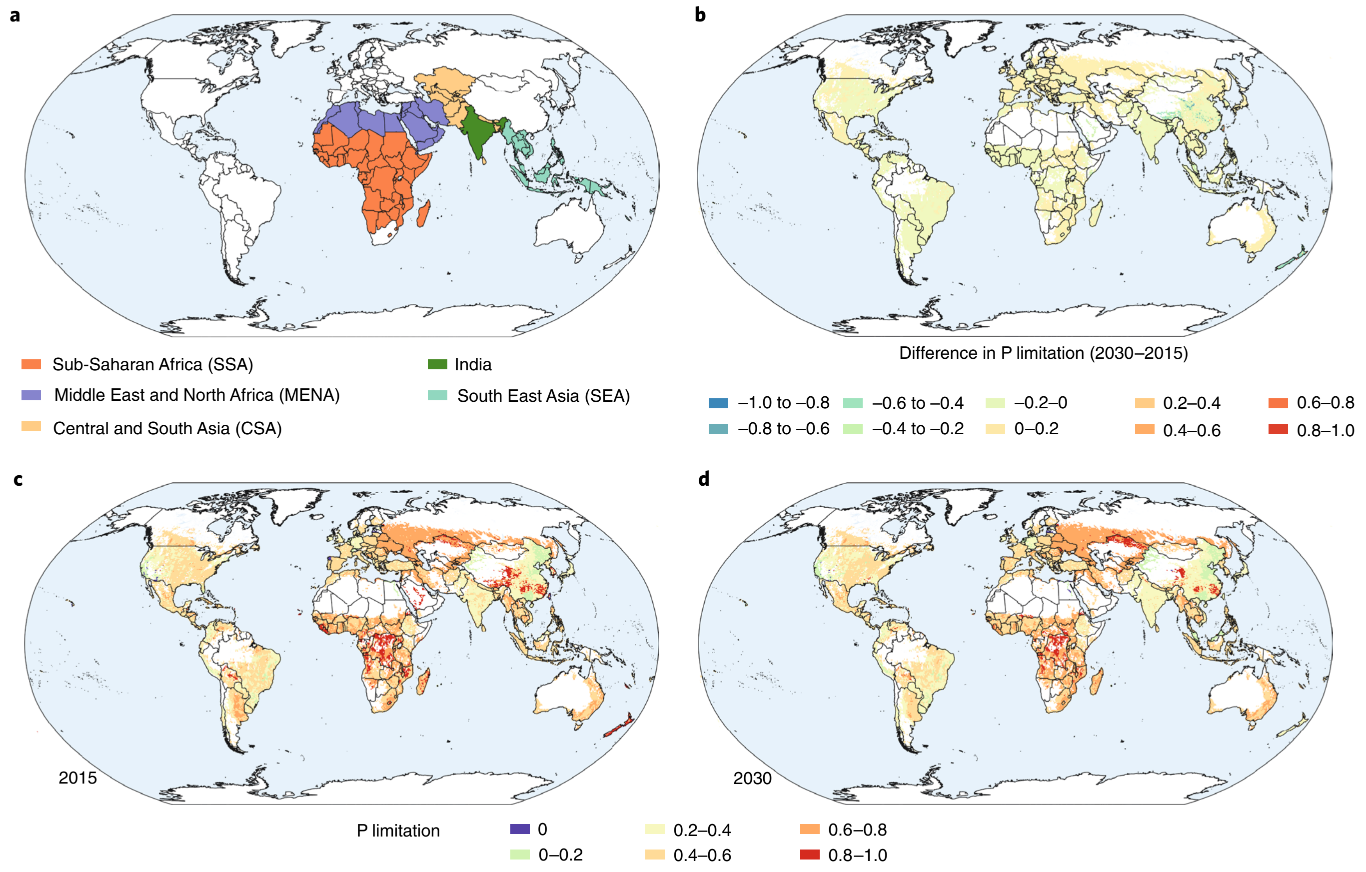

Fig. 1 | P limitation of agricultural areas and region definition. **a**, Illustration of the five regions where smallholder farming dominates. Country names in each region are given in Supplementary Table 2. **b**, Difference in P limitation between 2030 and 2015. **c**, P limitation (1 – actual/potential P uptake) for all agricultural areas in 2015. Actual P uptake is from modelled P uptake in the year after 2015 (2015 + 1), while potential P uptake is modelled after a 20 + 1-year quenching period. The additional year serves to reduce P input to zero, so that the ratio calculated is reflective of the pure soil P pool status. High P-limitation values (in red) mean that quenching has strongly increased P uptake compared to the actual P uptake, while, conversely, low P-limitation values (in blue) mean that quenching had little effect on P uptake; that is, P uptake was already high to start with. **d**, P-limitation map for 2030. Same calculation as for 2015, except that actual P uptake is modelled in the year after 2030 (2030 + 1) and the quenching period starts in 2030. P dynamics between 2015 and 2030 follow the BASE scenario.

soils can take decades to be saturated[16,19] yet after decades of high fertilizer input have approached the point where a maintenance fertilizer strategy becomes possible[17,18]. In our study, P limitation is calculated as 1 – actual/potential P uptake.

For the calculation of P limitation we made use of the Dynamic Phosphorus Pool Simulator (DPPS), which is coupled to an integrated assessment model (IMAGE-DPPS)[7,23–26]. This allows us to assess P limitation for a wide variety of crops and a future point in time (2030), using a scenario. This model uses total P-input data, including P fertilizer use, manure P, atmospheric P deposition and weathering. P fertilizer use between 2000 and 2015 is entirely based on FAO data[27].

The model was also used to calculate future P requirements in a scenario where the SDG2.3 target of doubling smallholder productivity is reached in 2030, compared to P requirements in the SSP2 scenario. The SSPs sketch a range of possible futures, where population and economic growth, energy and food demand, technological innovation and more factors develop along different lines[28]. These scenarios have been previously implemented in IMAGE-DPPS[7]. The SSP2 is the middle-of-the-road scenario, where assumptions are neither overly optimistic nor pessimistic. These scenarios are hereafter abbreviated as SDG2 (SDG2.3 target) and BASE (SSP2). In the SDG2 scenario we impose a doubling of P uptake in 2030 relative to the historical P uptake in 2015. Methodologically, the calculation of P requirements for achieving the SDG2.3 target is independent of the P-limitation calculation. The P-limitation calculation is a substantial result on its own and it gives context to the SDG2.3 scenario results.

Five world regions were selected for our analysis in which smallholder farming is dominant: sub-Saharan Africa (SSA), South East Asia (SEA), Middle East and North Africa (MENA), Central and South Asia (CSA) and India (Fig. 1a). In these regions, at least 75% of farms are smaller than 5 ha (ref. [29]) and production of food crops is the dominant activity on smallholder farms[30–32]. We excluded China, which is also dominated by smallholder farming for food production but which already has very high levels of P application.

P limitation is a global phenomenon

P limitation was a global phenomenon in 2015 (Fig. 1c), with the countries of the former Soviet Union, SSA, MENA, SEA and Australia standing out as the most P limited regions. Furthermore, parts of Bolivia, Argentina, some provinces of China and New Zealand were strongly P limited. Of the selected regions, SSA, SEA and India were characterized by substantial areas harbouring P-fixing soils (Fig. 3 in ref. [19]). Toward 2030, the majority of countries will either hold or reduce their P limitation according to the BASE scenario (Fig. 1b,d). The following countries, for example, are reducing their P limitation: Argentina, Brazil, Nigeria, India,

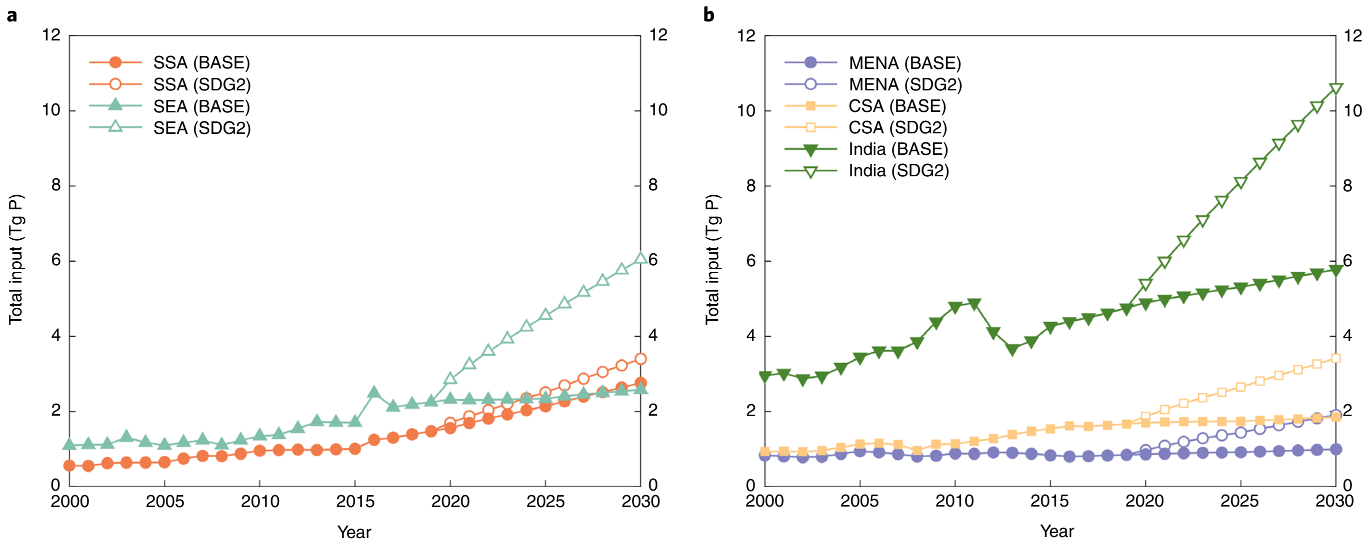

Fig. 2 | P input (Tg) per year for the BASE and SDG2 scenarios. **a**, P input for SEA and SSA. **b,** P input for MENA, CSA and India.

Pakistan, Malaysia, Indonesia, New Zealand and China. These countries have responded in the past, or are responding presently, to increased food demand by increasing P input and are expected to continue doing so[7]. A few countries, notably France and Spain, will see increasing P limitation. Not all regions in the world will try to eliminate P limitation, because economic or environmental considerations might require low P-input strategies[8,9,17].

Achieving the SDG2 target will require 39% more P input

P inputs in the SDG2 scenario clearly depart from the BASE scenario trend for all regions (Fig. 2a,b), with the upward trend mirrored in the P uptake (Extended Data Fig. 1a,b). SSA is the region where the BASE scenario is closest to the SDG2 target scenario. Of the six regions, only SSA therefore comes close to achieving the SDG2 target (P uptake increase by a factor of 1.8), while all other regions will only increase their P uptake by an average factor of 1.3 (Extended Data Fig. 2). To achieve the SDG2 target, SSA and SEA will need to more than triple their P input compared to 2015, while the remaining three regions will need to more than double their P input (Fig. 3). The high P requirement in SSA and SEA is partly due to the regions' high prevalence of P-fixing soils. Geographical variation of P input and P uptake within regions can be notable (Extended Data Figs. 3 and 4). Production data show that cereals were major contributors to P uptake in all selected regions. However, in SSA, root and tuber crops were the second contributor to P uptake; in SEA, oilcrops, particularly oil palm fruit, were more important than the cereals with regard to P uptake (Supplementary Table 1).

On aggregate, SEA as of recent has not been building up P reserves in the soil, which is reflected in a PUE of around 1 (Extended Data Fig. 5a), mainly because much P uptake is from recently deforested areas[7]. SSA has very low P-input rates, yet the region has nevertheless built-up residual P in the soil since 2000, because crop P uptake rates have been even lower than P input (Extended Data Figs. 5a and 6a,b). As input increases to achieve SDG2, PUE will decrease in all regions (Extended Data Fig. 5a,b). India, MENA and CSA, which already have low levels of PUE, will see further decreases.

On a per-area basis, all regions will have to substantially increase their P input and SEA, CSA and India will reach average input levels typical for industrializing countries of around $50\,\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$ in 2030 (Extended Data Fig. 6a). In the BASE scenario on the other hand, none of the regions will reach this input level. Average uptake is highest in SEA and lowest in SSA for all scenarios (Extended Data Fig. 6b). Achieving the SDG2 target implies large increases in average P input compared to the BASE scenario (Extended Data Fig. 6c).

In cumulative terms, between 2015 and 2030, India will need 30 Tg more P in the SDG2 scenario, compared to the BASE scenario, while the difference is only 4 Tg for SSA (Supplementary Fig. 1a,c). All five regions taken together need an additional 74 Tg of P, which is 39% more compared to the BASE scenario. This effort would result in an additional P uptake of 20 Tg between 2015 and 2030 (Supplementary Fig. 1b), which is 27% of the additional P input. This latter percentage can be viewed as the marginal PUE of achieving the SDG2 target between 2015 and 2030.

The substantial increases in P inputs needed to achieve SDG2 are not translated into higher P runoff in the short term (only 1% increase) (Supplementary Fig. 2). Regional P runoff depends on the size of the LP and SP pools and cropland expansion. The amount of residual P is relatively small compared to total soil P, which means that increasing residual P has only a small effect on P runoff. Cropland expansion accesses large new pools of total P, which is the main driver for increasing regional P runoff. The BASE and SDG2 scenarios have the same cropland expansion, so the very small difference in runoff is due only to differences in residual P. In the BASE scenario, 16 Tg of P are lost to runoff cumulatively between 2015 and 2030, which is 9% of cumulative P input during this period. In both scenarios, this is a serious loss for crop uptake. Although these are not global estimates, these P losses are similar to the global planetary boundary for a low estimate of river P export to coastal waters and a low target P concentration in inland waters[33]. P runoff is especially high in India which has a history of relatively high P input and therefore high residual soil P. While decreasing PUE through increased P input can, in the short term, seem like a problem, it is really the rate of P losses by runoff that subdue PUE in the long run. P management should therefore include soil and water conservation.

SDG2 target might not be ambitious enough for SSA

P-input rates of around or below $50\,\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$ are sufficient for all regions to achieve the SDG2 target (Extended Data Fig. 6a). All regions will need substantial increases in P input to achieve the SDG2 target. Two regions in particular, SSA and SEA, need to more than triple their P input compared to 2015 to achieve the target

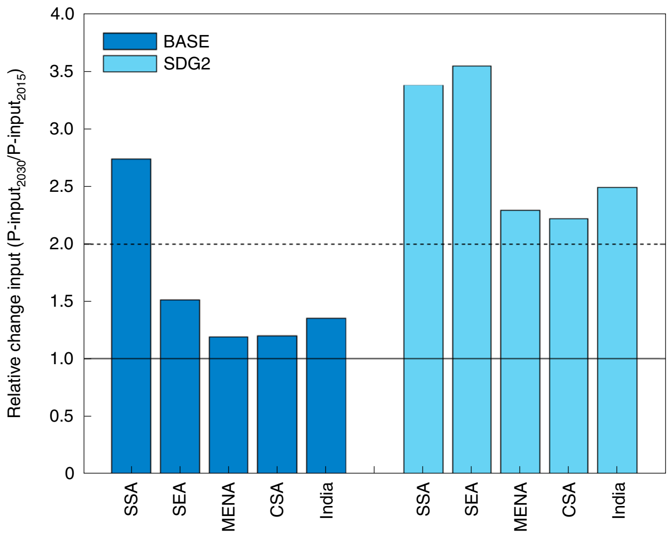

Fig. 3 | Relative change in P input. P input in 2030, relative to 2015 values, expressed as ratio, for the BASE and SDG2 scenarios.

in 2030. By doing so they can reduce P fixation and improve production beyond 2030. SSA in particular has large areas of P-fixing soils[34,35] but it is nevertheless on track to achieve the SDG2 target and only needs a modest extra P input of 4 Tg by 2030. Yet, it is worth noting that, in SSA, input and uptake of P are rising from an extremely low level per unit area (Extended Data Fig. 6a) and P fixation will not be overcome just yet (Fig. 1d). Furthermore, the population in SSA is expected to double by 2050[11] and therefore, by 2030, the regional gains in production will be diluted on a per capita basis requiring more effort than considered in our scenario. This is because our scenario considers doubling of P uptake per region and not doubling of P uptake per capita. While most regions will approach moderate to high levels of P input per area in the SDG2 scenario, SSA will achieve the goal with an average input of only 11 kg P ha^{-1} yr^{-1} (Extended Data Fig. 6a). Thus, considering population growth, strong P fixation and very low current P inputs and uptake, the target for SSA is probably not ambitious enough, while appropriate for the remaining regions. This is because the doubling target is, of course, in relative terms and when starting from very low levels of P uptake, more than doubling, or an absolute target could be more appropriate.

Possible futures

Scenarios are not predictions and model uncertainties and unexpected global developments, such as the current COVID19 pandemic, will influence the likelihood of a scenario[36]. For more information on uncertainty and to see a sensitivity analysis for the most influential parameter in the model, we refer to the Supplementary Fig. 3 and Supplementary Methods. We chose the SSP2 (BASE) scenario over other scenarios, since it is often referred to as middle-of the-road as it assumes a continuation of current trajectories and can therefore serve as a baseline reference against which to test the SDG2. Comparisons with other SSPs would naturally yield different results. It is important to note, however, that global P input in the five SSP scenarios varies much less than population growth in the corresponding scenarios[7] and that P input to achieve SDG2.3 would have to substantially increase any of the five scenarios. This means that even in more optimistic SSPs, SDG2 will not be achieved from a P perspective, except perhaps for SSA. Therefore, achieving the SDG2 requires a targeted effort in the regions where smallholder farming predominates.

Achieving the SDG2.3 target

Achieving the SDG2.3 target is realistic for countries with currently low levels of P input and has precedent in field trials. Long-term application of P, nitrogen and potassium in the tropics typically result in three to four times higher crop yields, within a range of 1.5 to over 20 times, compared to non-fertilized control yields. This estimate is based on four long-term field trials in India[37], Southern China[38], Kenya[39] and Senegal[40], ranging from 14 to 42 years with annual P application rates of 18–53 kg ha^{-1} yr^{-1}. Given that currently many smallholder farms in developing countries use little or no fertilizer[3], the field trial comparison confirms the plausibility of the possible P-uptake gains modelled in this paper.

We conclude that the SDG2.3 target is both achievable for all regions and perhaps not ambitious enough for SSA. Yet, it requires an effort that clearly goes beyond what is expected in the BASE scenario.

Challenges ahead

Not all additional P needed to achieve the SDG2.3 target needs to come from rock phosphate-based fertilizers. Better integration of animal manure in crop systems can help to reduce fertilizer needs and this may particularly be important in India where a large part of cow manure is used as fuel. Waste recycling may also be helpful. For example, human excreta are considered a waste but if recycled in, for example eco-sanitation or dry or low-flush systems[41,42], the high P content in urine could substitute large amounts of P fertilizers[43] and at the same time reduce P discharge to surface waters. More generally, P could be recycled across sectors where waste streams[44], such as food waste and wastewater, could provide a local supply of P and also alleviate the limited global availability of rock phosphate.

The drop in PUE following the start of quenching (Extended Data Fig. 5a,b) could be alleviated by measures that improve P uptake. Simultaneously increasing crop yields and cropping intensity, reducing nutrient limitation, avoiding land degradation, improving the efficiency of fertilizer use and minimizing environmental losses requires a fine-tuned combination of agronomic practices[45]. These include the use of high-yielding crop varieties that are adapted to the prevailing soils and climate, management of organic matter by recycling of crop residues and animal manure, crop protection against weeds, pests and diseases and soil nutrient management with a good balance between P, nitrogen, potassium and micronutrients, and liming to improve P availability in strongly P-fixing soils[46]. Avoiding crop production on steep slopes and applying soil conservation adapted to the local cropping system, climate and terrain conditions practices can minimize carbon and P losses through erosion[1,47]. This will reduce eutrophication risk for aquatic ecology and, at the same time, secure the soil's long-term productivity and the farm's future profitability[3,48]. Measures could be reduced tillage, cover crops, contour ploughing, deviation ditches, grassed waterways and terracing[49].

Farmers also need to be able to buy P fertilizer. Several factors contributed to the successful intensification of crop production on tropical P-fixing soils in Brazil, including large farm size, low land prices and capital availability for supplying P and other essential inputs[19]. In contrast to the Brazilian situation, the regions considered in this paper, particularly SEA and SSA, are dominated by smallholdings that often lack sufficient capital. Farmers' access to fertilizers can be ensured through specific credit lines to bridge the initial adoption costs or through subsidies during the quenching period[50]. Well-designed subsidies on fertilizers can contribute to the overall SDG2. However, in SSA, subsidies on fertilizers and other inputs are emergency policy response for the various food price crises and not a policy instrument for boosting agricultural productivity in the long run[51].

A further important aspect of smallholder's access to fertilizers containing P (and other nutrients) is a stable price. During the last two decades, agriculture faced both the highest sustained phosphate rock price (in 2008) and the largest price fluctuations of any 10-year periods since 1960[52]. In some countries, such as India, governments bear the burden of price hikes of P fertilizers through subsidies. With dwindling phosphate rock resources, the base material for P fertilizer production[53], the overall increase of the global P fertilizer requirement projected in this paper may result in a long-term price increase, whereby geopolitical tensions form an unpredictable element[54]. Fortunately, a large pool of residual P in the soil can act as a buffer against short-term price fluctuations and a transition to a more sustainable P management with lower P fertilizer input could be achieved[17,18].

Keeping the long-term perspective is essential, because the P-use efficiency is low during the quenching period. Achieving investments to build up soil P availability to secure future productivity by smallholders requires capacity building to strengthen nutrient and soil conservation management. This involves research, extension services, farmer's training, demonstration farms, incentives to motivate and support the learning phases, procure P fertilizers and other necessary inputs at fair prices and dedicated insurance schemes for risk management[50]. Especially in SSA, unfortunately the current targets for budgets to support capacity building from national and international organizations are generally not met[55,56].

Methods

This section describes the model and data used and how the model was set-up for our scenario calculations. Furthermore, we describe how P limitation was calculated.

Model description. The DPPS was originally developed to simulate crop uptake after field quenching experiments in various countries[23,24] and was recently used to simulate the long-term global P uptake and P status of soils[57]. DPPS was further developed to be applicable with the SSP scenarios implemented in the IMAGE framework[25], with the purpose of calculating future P demand and budgets for a period up to 2050[7] Here we apply the version of DPPS (IMAGE-DPPS) by Mogollón et al.[7]. IMAGE-DPPS can simulate the current soil P stocks (labile soil stock, LP, and stable soil stock, SP, in kg P ha^{-1}) with an annual temporal scale and a spatial resolution of 0.5 by 0.5 degrees for given P inputs. Each cell is initialized in the year 1900 with LP and SP from the global gridded soil P inventory[58], representing the pre-industrial conditions. LP comprises both organic and inorganic P forms and only a fraction of LP is directly available for plant uptake (fr$_{\mathrm{av}}$);[23] SP represents forms of P bound to soil minerals and organic matter that are not available to plants. Thus, the P availability for plants may increase or decrease, depending on the pool sizes. The equilibrium between LP and SP happens via first-order rate constants. The LP to SP transfer coefficient was set to 0.2 yr^{-1}, while the SP to LP coefficient was independently calculated for each grid cell on the basis of the maps of Yang et al.[58] for virgin soil P and assuming LP and SP to be at steady state. IMAGE-DPPS considers natural or unintentional inputs to the soil, that is, weathering (weathering, kg P ha^{-1} yr^{-1}) and litter (litter, kg P ha^{-1} yr^{-1}; litter is crop residues in crop systems and litterfall in natural vegetation), which are inputs to LP, and atmospheric deposition of soil dust (deposition, kg P ha^{-1} yr^{-1}) adds to the SP pool. To describe chemical P retention in soils, DPPS includes the parameter initial recovery fraction (no dimension) obtained from Batjes[59] for each of the soil classes of the legend of the FAO soil map of the world[60], which describes the effect of soil chemical properties such as iron and aluminium concentrations on the sequestration of P from labile to stable soil pools. Anthropogenic P inputs include application of mineral P fertilizer (fertilizer, kg P ha^{-1} yr^{-1}) and animal manure spreading (manure, kg P ha^{-1} yr^{-1}). A fraction of fertilizer and manure is directly taken up by plant roots from the soil solution (20% for fertilizer, 10% for manure) and the remainder is available and becomes part of LP (80% for fertilizer and 90% for manure) and can be taken up from LP indirectly. Crop uptake (U) is calculated assuming a Michaelis–Menten relation between uptake and f_{av} following equation (1):

$$U = \frac{U_{\max}\,\mathrm{fr}_{\mathrm{av}}\mathrm{LP}}{\frac{cU_{\max}}{I} + \mathrm{fr}_{\mathrm{av}}\mathrm{LP}} + f_S S + f_M M \tag{1}$$

where $U_{\max}$ is the maximum P uptake and I is the initial recovery fraction, which is the initial slope of the P response curve presented for all soil types distinguished in the legend of the FAO-UNESCO world soil map, c (=0.5) multiplies $U_{\max}$ to obtain the half-saturation value. The parameter $U_{\max}$ is held constant with a value of 500 kg P ha^{-1} yr^{-1}. The parameter S represents mineral fertilizer additions and f_S the fraction directly taken up by plants and M represents manure additions with f_M representing the fraction directly taken up by plants. P outflows from the soil system include P withdrawal from LP by crops (U, kg P ha^{-1} yr^{-1}) and runoff from both LP and SP (runoff, kg P ha^{-1} yr^{-1}). Calculated runoff loss accounts for changing soil LP and SP pools in certain locations but for aggregated world regions runoff P loss also reflects land-use changes with LP and SP pools for unfertilized soils lacking residual P from past management. P fertilizer requirement, which is the largest form of P input, in IMAGE-DPPS is most sensitive to the target P uptake (Supplementary Fig. 3a,b and Supplementary Methods). For a simplified scheme of the model see Supplementary Fig. 4. For further details on the model and its assumptions, see Mogollón et al.[7].

Scenarios and model set-up. We compared two scenarios: (1) SSP2, a middle-of-the-road scenario[6], was used as a reference scenario for expected future development (BASE scenario) and compared with (2) the SDG2 target 2.3 scenario, in which the target of doubling productivity is achieved (SDG2 scenario). In addition, the BASE scenario was used in the calculation of P limitation.

Both scenarios depart in the base year from the same historical set-up of the model. We use the calculated LP and SP pools based on simulation of the historical period from 1900 to 2015 (the base year of IMAGE) as a starting point for the future simulation using spatially explicit land use and crop uptake distributions generated by the IMAGE model[25]. In grid cells where cropland expansion occurs, natural soil (without fertilizer history) with initial P pools[58] is added. For grid cells with land abandonment (arable land to natural land), IMAGE-DPPS assumes a 30-yr period for abandoned land to revert to natural conditions[26] 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). For grid cells where P uptake through crops is less than what is available in the soil, P input is assumed to be zero, so depletion of residual P takes place. P uptake is distributed within the grid cell over different age-classes of pools (different years of conversion to cropland). In historical mode, the unknown fr$_{\mathrm{av}}$ is allowed to vary between a minimum value of 0 and a maximum value of 1. In scenario mode after 2015, fr$_{\mathrm{av}}$ becomes a parameterized value that varies according to the SSP storyline. The fraction fr$_{\mathrm{av}}$ will increase as a result of improved crop varieties and other strategies to increase the capability of plant roots to acquire soil P. In BASE it increases during the period 2015–2030 by half of the increased rate calculated for 1990–2005 to reflect increasing difficulty to develop crop varieties with enhanced root P uptake.

Scenario target productions. The scenarios require the setting of P-uptake targets. The future uptake in the BASE scenario was estimated from the P content in the projected crop production[7,25]. Future P uptake in the SDG2 scenario is determined by the SDG target 2.3 of doubling smallholder productivity. Here, we focus only on crop uptake and neglect livestock P uptake from grassland. For a justification of our interpretation of the target, see Supplementary Methods. As the target relates to smallholder farms, the scope of the target was limited to five world regions where smallholder farming dominates agriculture. The method for selecting these regions is given in the Supplementary Methods, too. For all countries in these regions, the target was set that P uptake will double between 2015 and 2030 and that this target is achieved by linear increase between 2020 and 2030 (Extended Data Fig. 1a,b). The increase starts in 2020, the time of writing, assuming that between 2015 and 2020 the world developed along the BASE path. The target was set for the countries as a whole rather than for individual farms or farmland area (a discussion of this choice is given in the Supplementary Methods). There is no specific reason for choosing a linear increase, except for keeping it simple. Other, equally possible increases, such as logarithmic or s-shaped would result in different cumulative estimates for the period 2015–2030 but would not change the uptake rate in the year 2030.

The P input required to achieve the scenario uptake values for each region consists of all forms of P from deposition, manure, mineral fertilizers and fertilizers produced from human excreta. IMAGE has scenario-specific consumption, domestic production of meat and milk, and distribution of livestock over pastoral and mixed systems, and within these systems the fraction of manure stored in animal houses and the amount available for spreading in croplands[25,28]. With these manure P inputs and deposition from existing data, the required inputs from fertilizer and human excreta are calculated as the difference between total P input and manure plus deposition.

P-limitation calculation. For P limitation, the potential P uptake was calculated as an extension to the BASE scenario. Here, we define soil P limitation as:

$$1 - \frac{U_{\mathrm{act}}}{U_{\mathrm{pot}}} \tag{2}$$

where U_{act} is actual P uptake and U_{pot} is potential P uptake. This index provides a metric to compare the P status of different soils. For calculating U_{pot} it was assumed that P was applied at 50 kg ha^{-1} yr^{-1} during a 20-yr quenching period in all grid cells with cropland. This application rate is similar to the rates in Brazil in the past decade[15,16]. For the 2015 P-limitation calculation historical (HIST) P inputs were used up to 2015, after which the quenching started. During the quenching period, relevant uptake conditions were assumed to stay the same as in 2015, in particular the fraction of the labile pool available for plant uptake, fr$_{\mathrm{av}}$.

Implicit in this assumption is that other limitations to crop growth, such as other nutrients, soil and water conditions are raised in tandem with P limitation, which means that these conditions are not more limiting to P uptake after quenching than they were in 2015. This optimistic assumption is necessitated by the model (equation (1)) but can be defended, because in any likely scenario quenching with P would be accompanied with other improvements of the soil status. In calculating P limitation, we were mostly interested in how much quenching can improve the P status of the soils. For this reason, U_{pot} was calculated in the year after the quenching period (20 + 1), in which zero manure and fertilizer P inputs were simulated, so all P comes from the stored available soil P. The parameter U_{act} was calculated for the year after 2015, in which also no P inputs were simulated. Thus, the P-limitation ratio represents the true soil supply and not direct supply from the fertilizer of manure applications. For the P-limitation calculation of 2030, the same calculation was performed, with the only difference being that the quenching period started in 2030 and that between 2015 and 2030 the BASE scenario was followed. For illustration, the meaning of a high P-limitation value of, for example, 0.8 in 2015 is that in that year the plant-available P in the soil pools was low and consequently P uptake was low. Through 20 years of quenching the plant-available P in the soil was replenished such that P uptake was five times higher in the year after quenching.

Data used. Simulated crop P uptake for BASE is obtained from the crop production for the second of five SSP scenarios implemented with the IMAGE model[25]. In 2020, IMAGE data and SSP scenarios were updated to base year 2015. Previously, as in Mogollón et al.[7], the base year was 2005. Among the changes were the number of crop groups in IMAGE considered, which increased from seven to 18; the production data for these 18 crop groups are aggregated from the 160 crops reported by FAOSTAT for the historical years up to 2015 and P uptake is calculated from P content of each crop. For the future, IMAGE projects production for the 18 crop groups and for P uptake we assume constant P contents after 2015.

IMAGE generates regional populations of non-dairy and dairy cattle, pigs, poultry, sheep and goats. Using P-excretion rates, the total manure P is calculated (Supplementary Table 3). Manure available for spreading in croplands differs between pastoral (mostly grazing, small amounts of manure collected in animal houses) and mixed systems (with a large proportion of confined animals from which manure is collected in animal houses) and excludes droppings in grassland, manure used as fuel or building material or manure otherwise ending outside the agricultural system (for example, in lagoons)[61].

Subsequently, IMAGE P uptake estimates and animal manure for world regions are distributed over countries within each region using FAO data[27] for the historical period up till 2015 and distributed over grid cells within countries on the basis of the spatial distribution of crops from IMAGE. For future years, the 2015 distribution over the countries within regions is used.

Atmospheric P deposition was obtained from recent model data[62]; since mineral aerosols from soil dust contribute 82% of total P deposition, we assumed deposition fields to be constant in time after 2015. Weathering is also constant at a level of 1.6 Tg P yr^{-1} (ref. [63]) and distributed on the basis of the apatite content of soil material obtained from Yang et al.[58].

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data underlying the figures and tables summarizing model input are available as a spreadsheet in the Supplementary Data. For further inquiries please direct all correspondence and requests regarding this study to the corresponding author.

Code availability

The computer code generated during the current study is available from the corresponding author on reasonable request. Please direct all correspondence and requests regarding this study to the corresponding author.

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Author contributions

C.L. was involved in the study design, writing, analysis, figures and editing. A.H.W.B. was involved in model development, coding and running code. J.M.M contributed to model development and figures. A.F.B. contributed to study design and writing.

Competing interests

The authors declare no competing interests.

Additional information

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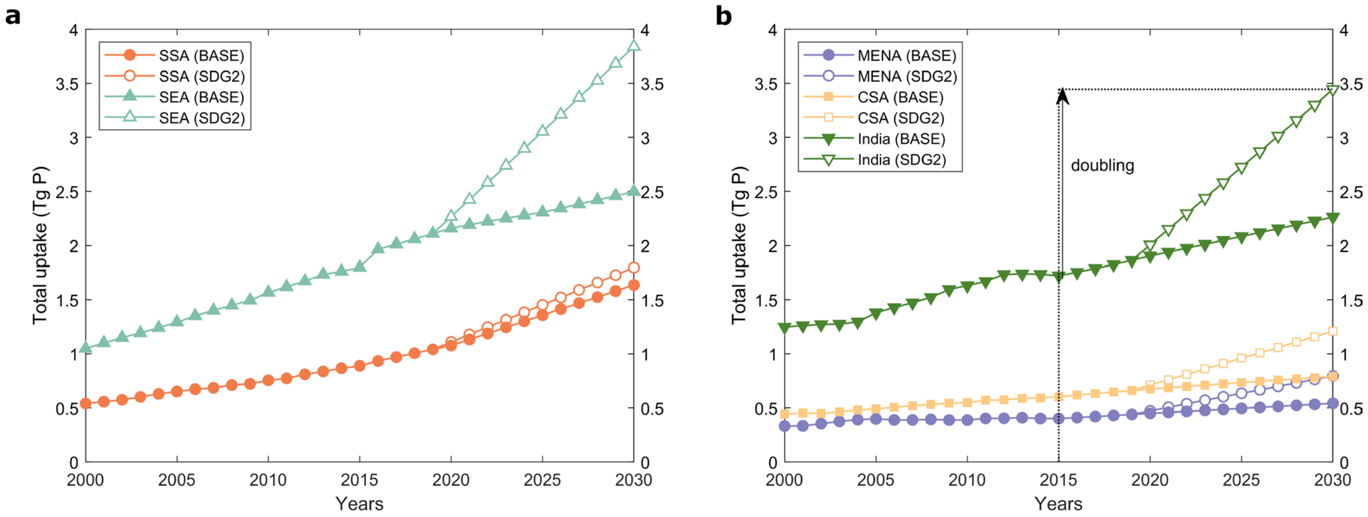
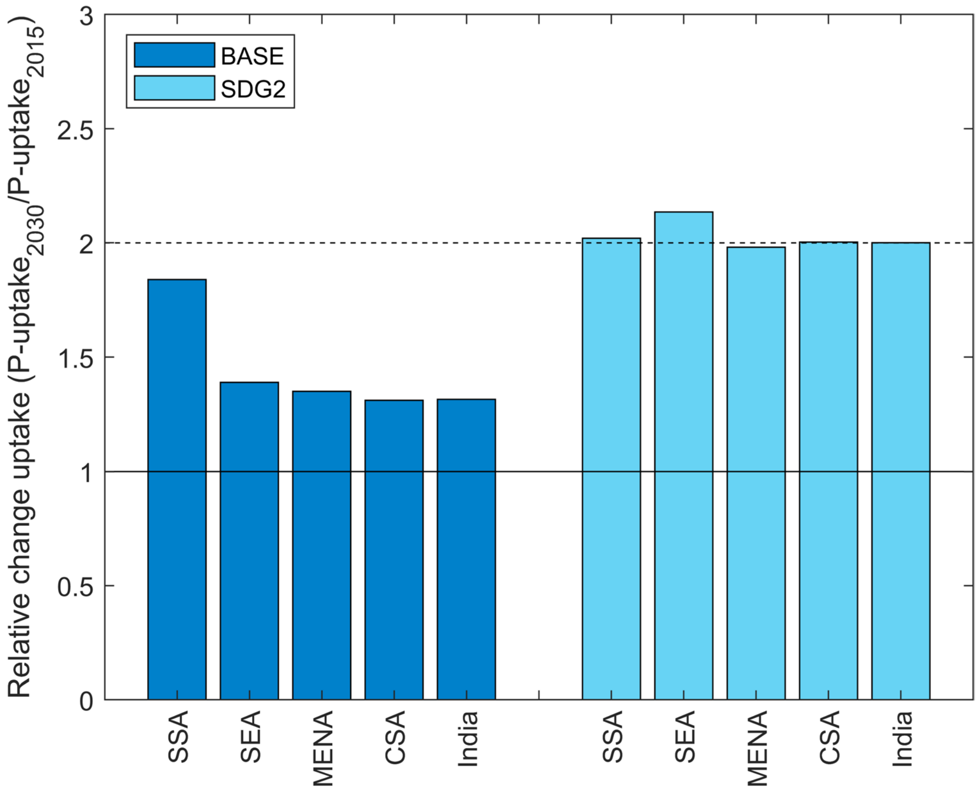
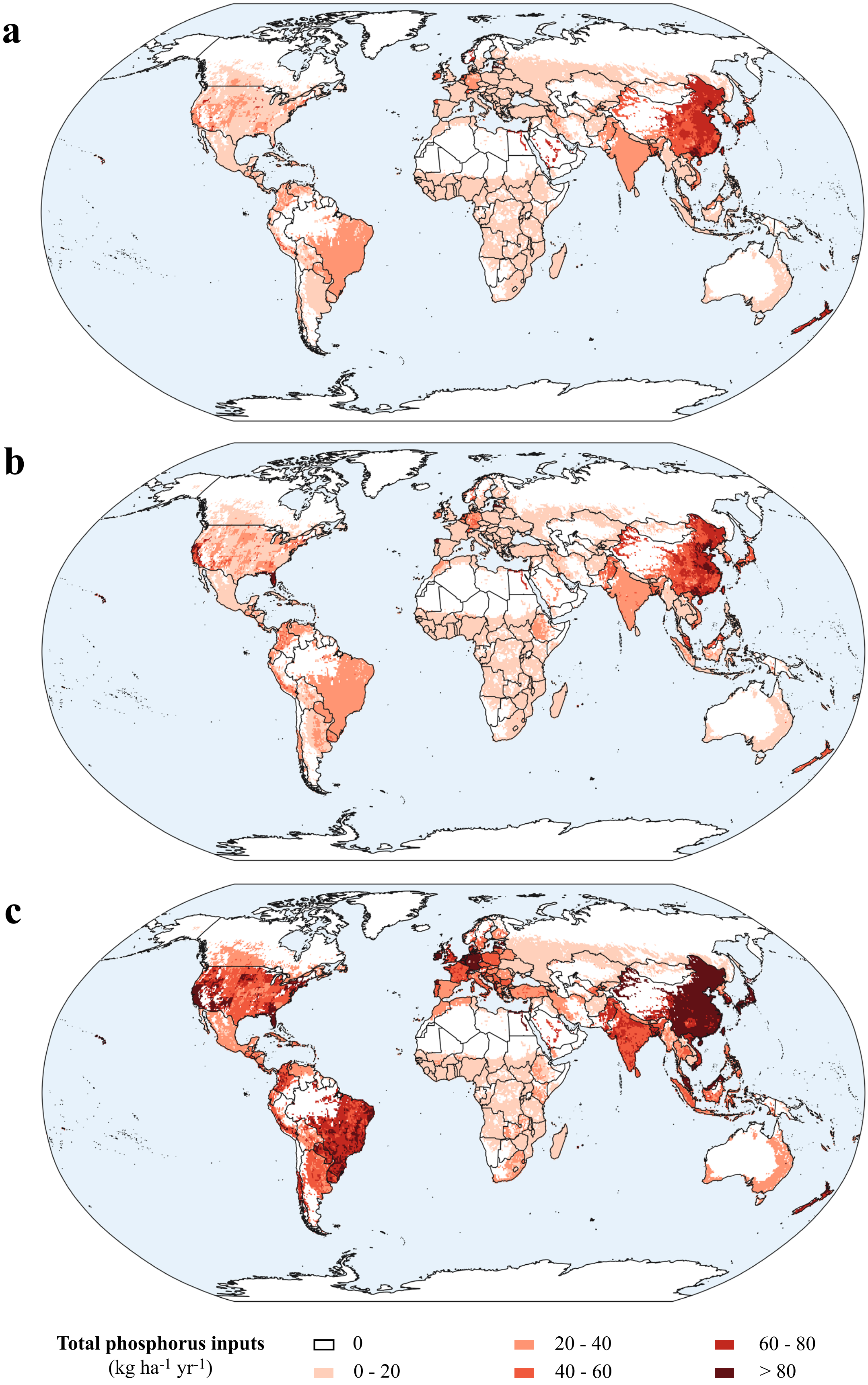


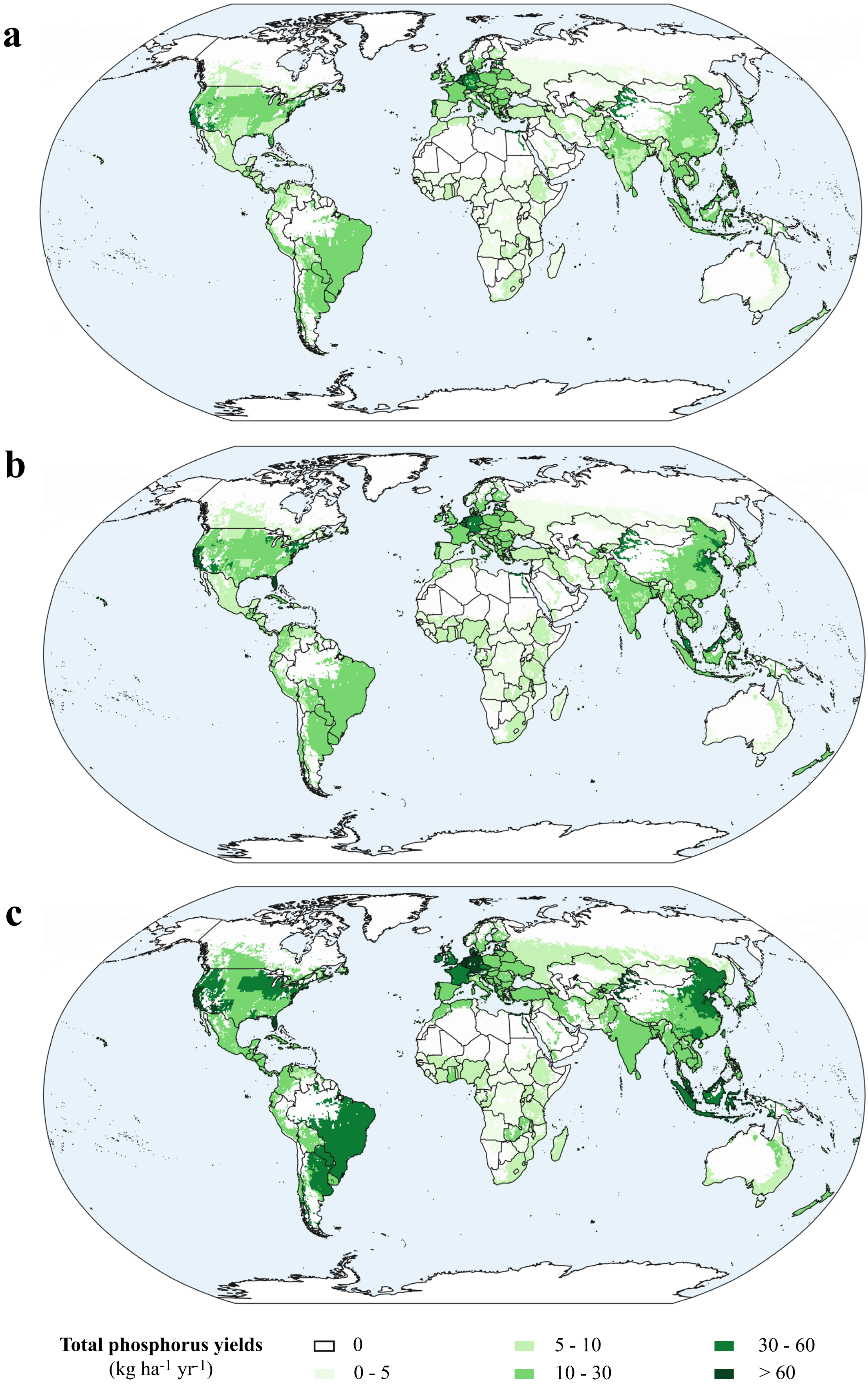
Extended Data Fig. 1 | P uptake (Tg) per year for the BASE and SDG2 scenarios. P uptake (Tg) per year for the BASE and SDG2 scenarios. (a) P uptake for Sub-Saharan Africa (SSA), South East Asia (SEA), (b) P uptake for Middle East and North Africa (MENA), Central and South Asia (CSA), and India. Definition of region are given in Fig. 1b of the main text and Table SI2. The arrow and 'doubling' graphically explain the SDG2 scenario for India, in which uptake is set to double between 2015 and 2030, with a linear increase setting in in 2020.



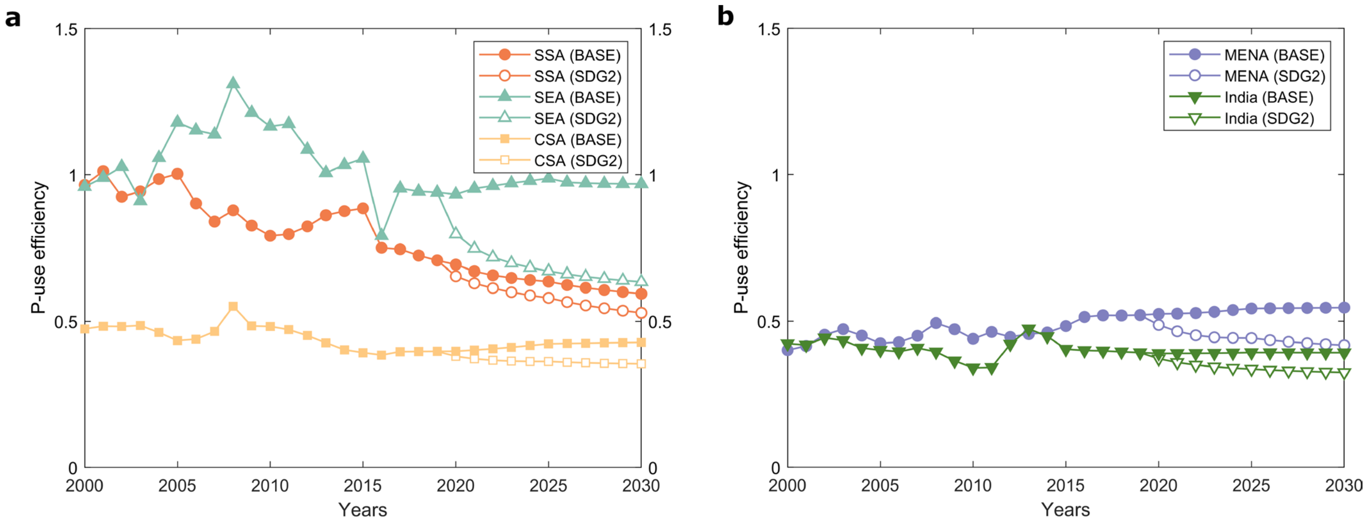
Extended Data Fig. 2 | Relative change in P uptake. P uptake in 2030, relative to 2015 values, expressed as ratio, for the BASE and SDG2 scenarios. Note that for the SDG2 P uptake, doubling (factor 2) was the target, imposed on the model. While the results are aggregated for regions, the calculations were performed on a country basis. Where (the agricultural area) of a country was newly added or removed in the model calculation between 2015 and 2030, this caused slight deviations from factor 2. Acronym description: SSA: Sub-Saharan Africa, SEA: South East Asia, MENA: Middle East and North Africa, CSA: Central and South Asia.



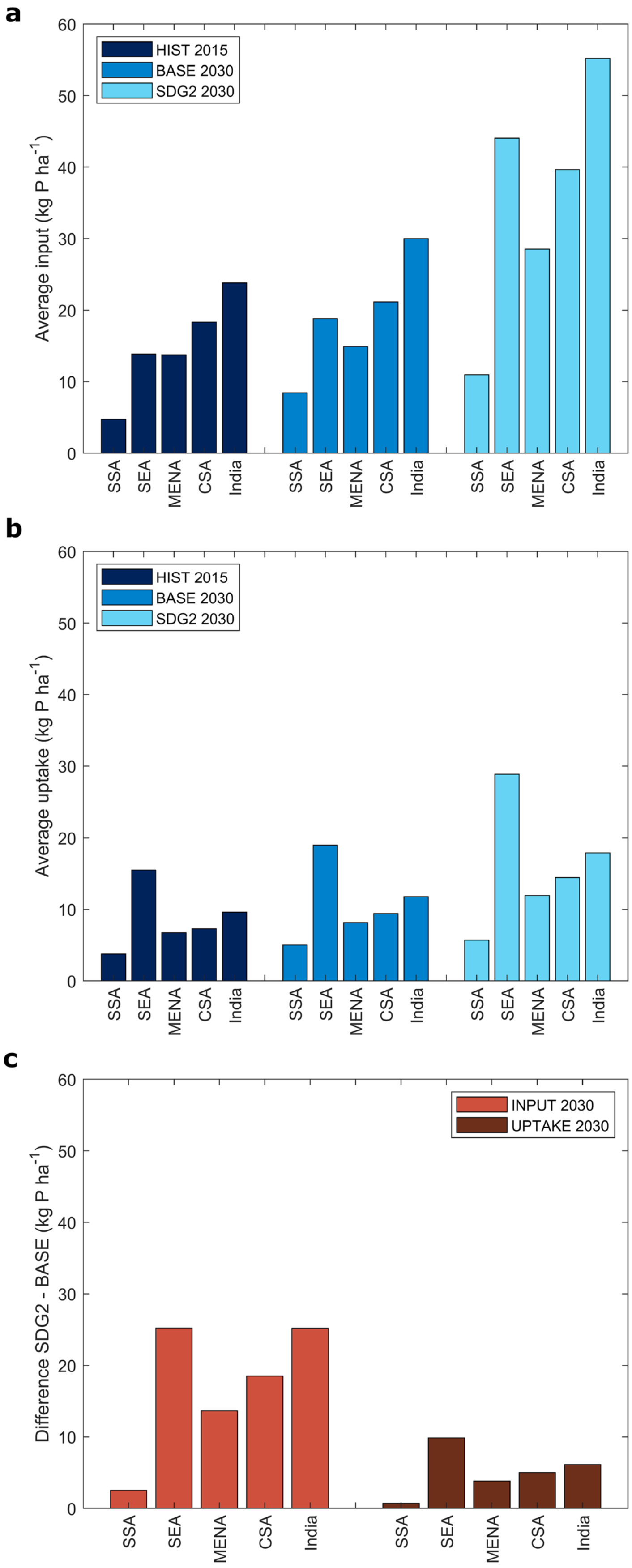
Extended Data Fig. 3 | Geographical distribution of total P input. Geographical distribution of total P input in kg ha yr^{-1} for (a) 2015 and (b) 2030 (BASE) and (c) 2030 (SDG2).



Extended Data Fig. 4 | Geographical distribution of total P uptake. Geographical distribution of total P uptake in kg ha yr^{-1} for (a) 2015 and (b) 2030 (BASE) and (c) 2030 (SDG2).



Extended Data Fig. 5 | Phosphorus use efficiency. Phosphorus use efficiency (PUE) over time for (a) Sub-Saharan Africa (SSA), South East Asia (SEA), Central and South Asia (CSA), (b) Middle East and North Africa (MENA), and India.



Extended Data Fig. 6 | Average P input, uptake, and difference between input and uptake, in kg P ha-1yr-1. Figure 6: (a) Average P input and (b) average P uptake, in kg P ha^{-1}yr^{-1}, for all five regions in 2015 (BASE) and 2030 (BASE and SDG2). (c) Difference (SDG2 – BASE) for input and uptake in 2030. Acronym description: SSA: Sub-Saharan Africa, SEA: South East Asia, MENA: Middle East and North Africa, CSA: Central and South Asia.

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Data collection was by simple download
Data analysis	The Dynamic Phosphorus Pool Simulator is a custom-made computer code, which was written in open-source Python language.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study makes use of historical data on global crop production per crop type and a Dynamic Phosphorus Pool Simulator in order to calculate global phosphorus demand for a middle-of-the-road scenario and a scenario in which the SDG2.3 target is achieved, between 2015 and 2030.
Research sample	Global dataset on crop production per crop type, provided by FAOSTAT
Sampling strategy	Not relevant
Data collection	Data was downloaded from the FAOSTAT website by co-autor (Arthur Beusen)
Timing and spatial scale	Not relevant
Data exclusions	Not relevant
Reproducibility	Data is publicly available (FAOSTAT), and model output can be requested from the authors.
Randomization	Not relevant
Blinding	Not relevant

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Antibodies used	*Describe all antibodies used in the study; as applicable, provide supplier name, catalog number, clone name, and lot number.*
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☐	☐	Confer resistance to therapeutically useful antibiotics or antiviral agents
☐	☐	Enhance the virulence of a pathogen or render a nonpathogen virulent
☐	☐	Increase transmissibility of a pathogen
☐	☐	Alter the host range of a pathogen
☐	☐	Enable evasion of diagnostic/detection modalities
☐	☐	Enable the weaponization of a biological agent or toxin
☐	☐	Any other potentially harmful combination of experiments and agents

ChIP-seq

Data deposition

☐ Confirm that both raw and final processed data have been deposited in a public database such as GEO.

☐ Confirm that you have deposited or provided access to graph files (e.g. BED files) for the called peaks.

Data access links *May remain private before publication.*	*For "Initial submission" or "Revised version" documents, provide reviewer access links. For your "Final submission" document, provide a link to the deposited data.*
Files in database submission	*Provide a list of all files available in the database submission.*
Genome browser session (e.g. UCSC)	*Provide a link to an anonymized genome browser session for "Initial submission" and "Revised version" documents only, to enable peer review. Write "no longer applicable" for "Final submission" documents.*

Methodology

Replicates	*Describe the experimental replicates, specifying number, type and replicate agreement.*
Sequencing depth	*Describe the sequencing depth for each experiment, providing the total number of reads, uniquely mapped reads, length of reads and whether they were paired- or single-end.*
Antibodies	*Describe the antibodies used for the ChIP-seq experiments; as applicable, provide supplier name, catalog number, clone name, and lot number.*
Peak calling parameters	*Specify the command line program and parameters used for read mapping and peak calling, including the ChIP, control and index files used.*
Data quality	*Describe the methods used to ensure data quality in full detail, including how many peaks are at FDR 5% and above 5-fold enrichment.*
Software	*Describe the software used to collect and analyze the ChIP-seq data. For custom code that has been deposited into a community repository, provide accession details.*

Flow Cytometry

Plots

Confirm that:

☐ The axis labels state the marker and fluorochrome used (e.g. CD4-FITC).

☐ The axis scales are clearly visible. Include numbers along axes only for bottom left plot of group (a 'group' is an analysis of identical markers).

☐ All plots are contour plots with outliers or pseudocolor plots.

☐ A numerical value for number of cells or percentage (with statistics) is provided.

Methodology

Sample preparation	*Describe the sample preparation, detailing the biological source of the cells and any tissue processing steps used.*
Instrument	*Identify the instrument used for data collection, specifying make and model number.*
Software	*Describe the software used to collect and analyze the flow cytometry data. For custom code that has been deposited into a community repository, provide accession details.*
Cell population abundance	*Describe the abundance of the relevant cell populations within post-sort fractions, providing details on the purity of the samples and how it was determined.*
Gating strategy	*Describe the gating strategy used for all relevant experiments, specifying the preliminary FSC/SSC gates of the starting cell population, indicating where boundaries between "positive" and "negative" staining cell populations are defined.*

☐ Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

Magnetic resonance imaging

Experimental design

Design type	*Indicate task or resting state; event-related or block design.*
Design specifications	*Specify the number of blocks, trials or experimental units per session and/or subject, and specify the length of each trial or block (if trials are blocked) and interval between trials.*
Behavioral performance measures	*State number and/or type of variables recorded (e.g. correct button press, response time) and what statistics were used to establish that the subjects were performing the task as expected (e.g. mean, range, and/or standard deviation across subjects).*

Acquisition

Imaging type(s)	*Specify: functional, structural, diffusion, perfusion.*
Field strength	*Specify in Tesla*
Sequence & imaging parameters	*Specify the pulse sequence type (gradient echo, spin echo, etc.), imaging type (EPI, spiral, etc.), field of view, matrix size, slice thickness, orientation and TE/TR/flip angle.*
Area of acquisition	*State whether a whole brain scan was used OR define the area of acquisition, describing how the region was determined.*

Diffusion MRI ☐ Used ☐ Not used

Preprocessing

Preprocessing software	*Provide detail on software version and revision number and on specific parameters (model/functions, brain extraction, segmentation, smoothing kernel size, etc.).*
Normalization	*If data were normalized/standardized, describe the approach(es): specify linear or non-linear and define image types used for transformation OR indicate that data were not normalized and explain rationale for lack of normalization.*
Normalization template	*Describe the template used for normalization/transformation, specifying subject space or group standardized space (e.g. original Talairach, MNI305, ICBM152) OR indicate that the data were not normalized.*
Noise and artifact removal	*Describe your procedure(s) for artifact and structured noise removal, specifying motion parameters, tissue signals and physiological signals (heart rate, respiration).*

Volume censoring	*Define your software and/or method and criteria for volume censoring, and state the extent of such censoring.*

Statistical modeling & inference

Model type and settings	*Specify type (mass univariate, multivariate, RSA, predictive, etc.) and describe essential details of the model at the first and second levels (e.g. fixed, random or mixed effects; drift or auto-correlation).*
Effect(s) tested	*Define precise effect in terms of the task or stimulus conditions instead of psychological concepts and indicate whether ANOVA or factorial designs were used.*

Specify type of analysis: ☐ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference (See Eklund et al. 2016)	*Specify voxel-wise or cluster-wise and report all relevant parameters for cluster-wise methods.*
Correction	*Describe the type of correction and how it is obtained for multiple comparisons (e.g. FWE, FDR, permutation or Monte Carlo).*

Models & analysis

n/a	Involved in the study
☐	☐ Functional and/or effective connectivity
☐	☐ Graph analysis
☐	☐ Multivariate modeling or predictive analysis

Functional and/or effective connectivity	*Report the measures of dependence used and the model details (e.g. Pearson correlation, partial correlation, mutual information).*
Graph analysis	*Report the dependent variable and connectivity measure, specifying weighted graph or binarized graph, subject- or group-level, and the global and/or node summaries used (e.g. clustering coefficient, efficiency, etc.).*
Multivariate modeling and predictive analysis	*Specify independent variables, features extraction and dimension reduction, model, training and evaluation metrics.*