# Phosphorus requirement for achieving the Sustainable Development Goal “Zero Hunger”

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**Phosphorus requirement for achieving the Sustainable Development Goal "Zero Hunger"**

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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 actual over potential P uptake (P limitation) and the P input required to achieve this SDG target in 2030 following 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). While P limitation is most widespread in Sub-Saharan Africa, it is the only region on path to achieving the doubling of productivity (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 expansion of phosphate rock mining allowed for the rapid growth of global 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], and consequently, large amounts of surplus P were retained as residual P in soils[4]. After this accumulation phase, farmers in many industrialized countries have been able to increase their PUE[5], often by utilizing 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]. Mining of soil P does not only occur in developing countries. Residual soil P that accumulated in the 1970s-1990s is currently being mined in the former Soviet Union and Europe[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 14 (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 Sustainable Development Goal 2 (SDG2, zero hunger). Achieving this goal is critical as the world population is projected to grow from 7.3 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, i.e., on the concentration of phosphate ions in the soil solution and the soil's ability to replenish phosphate withdrawn by plants[4]. Soils can absorb inorganic P with varying degrees of reversibility. Soils rich in soluble iron or alumina, 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 large part of the soil P fixation and sorption capacity[15,16]. The challenge of addressing global P fixation and limitation has been recently studied. Using Brazilian P input and surplus data, Roy et al.[17] estimated that globally 8-25% more P input is required on the world's P fixing soils in order to raise crop yields to levels prevalent in Brazil. Kvakić et al.[18] 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 SDG 2. In this study, our objectives were (1) to map the geographic distribution of P limitation to crop uptake and (2) to assess SDG2 target 2.3 from a P perspective.

[Figure 1]

**P limitation is a global phenomenon**

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 (Figure 1c). We excluded China, which is also dominated by smallholder farming, but which has already very high levels of P application. P limitation (actual over potential P uptake) is a global phenomenon in 2015 (Figure 1a) and the countries of the former Soviet Union, SSA, MENA, SEA and Australia stand out as the most P-limited regions, including some provinces of China. Of the selected regions, SSA, SEA and India are characterized by substantial areas harboring P-fixing soils (Figure 3 in reference[17]). Toward 2030, the majority of countries will either hold or reduce their P limitation according to the shared socioeconomic pathway middle of the road scenario (SSP2) (Figure 1b). The following countries, for example, are reducing their P limitation: Argentina, Brazil, Nigeria, India, Pakistan, Malaysia, Indonesia, New Zealand and China. A few countries, notably France and Spain, will see increasing P limitation. 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].

**Achieving the SDG2 target will require 39% more P input**

P inputs in the SDG2 target scenario clearly depart from the default SSP2 trend for all regions (Figure 2 a-b), with the upward trend mirrored in the P uptake (Figure SI1 a-b). SSA is the region where the SSP2 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 (Figure SI2). Within SSA, the projected increase stems mainly from West Africa[7]. In order 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 (Figure 3). The high P requirement in SSA and SEA is partly due to the regions' high prevalence of P fixing soils.

On aggregate, SEA is currently not building up P reserves in the soil, which is reflected in a PUE of around 1 (Figure SI3a), 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 (Figure SI 3a, SI4a - b). PUE will have to decrease in all regions in order to achieve SDG2 (Figure SI3a - 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 significantly increase their P input, and SEA, CSA and India will reach average input levels typical for industrializing countries of around 50 kg P $ha^{-1}yr^{-1}$ in 2030 (Figure SI4a). In the SSP2 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 (Figure SI4b).

In cumulative terms, between 2015 and 2030, India will need 30 Tg more P in the SDG2 scenario, compared to the SSP2 scenario, while the difference is only 4 Tg for SSA (Figure SI5a). All five regions taken together need an additional 74 Tg P, which is 39 % more compared to SSP2. This effort would result in an additional P uptake of 20 Tg between 2015 and 2030 (Figure SI5b), 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) (Figure SI6). Yet, in the SSP2 scenario 16 Tg 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. P runoff is especially high in India which has a history of relatively high P input and therefore high soil P pools legacies. 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 conservation.

**SDG2 target might not be ambitious enough for SSA**

P input rates of around or below 50 kg P $ha^{-1}yr^{-1}$ are sufficient for all regions to achieve the SDG2 target (Figure SI4a). All regions will need substantial increases in P input in order to achieve the SDG2 target. Two regions in particular, SSA and SEA, need to more than triple their P input compared to 2015 in order to achieve the target 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[19,20] 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 (Figure SI4a), and P fixation will not be overcome just yet (Figure 1b). 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. While most regions will approach moderate to high levels of P input per area in the SDG2 scenario, SSA will still only apply on average 11 kg P $ha^{-1}yr^{-1}$ (Figure SI4a). 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.

**Possible futures**

Scenarios are no predictions and model uncertainties and unexpected global developments, such as the current COVID19 pandemic, will influence the likelihood of a scenario[21]. A discussion on uncertainty and sensitivity is given in the supplementary information (SI2). While our analysis takes the SSP2 scenario as reference, 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 in our SDG2 scenario would diverge strongly upward in any of the five scenarios. This means that even in more optimistic SSPs, SDG2 will not be achieved from a phosphorus perspective, except perhaps for SSA. Therefore, achieving the SDG2 requires a targeted effort in the regions where smallholder farming predominates.

**Achieving the SDG 2.3 target**

Achieving the SDG 2.3 target is realistic for countries with currently low levels of P input and has precedent in field trials. Long-term P or NPK application in the tropics typically result in 3-4 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[22], Southern China[23], Kenya[24], and Senegal[25], ranging from 14 to 42 years with annual P application rates of 18 to 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 confirm the plausibility of the possible P uptake gains modelled in this paper.

Achieving an additional 39 % cumulative P input requires active and carefully tuned P management. In order to maximize the interest of these investments, to safeguard SDGs 6 and 14 regarding water quality, and to save non-renewable P deposits, runoff losses need to be minimized by avoiding crop production on steep slopes and by applying soil conservation practices such as reduced tillage, cover crops, contour ploughing, deviation ditches, grassed waterways, and terracing.

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 baseline scenario. The effort consists in strongly increasing P-input, while preventing excessive P runoff into the waterways.

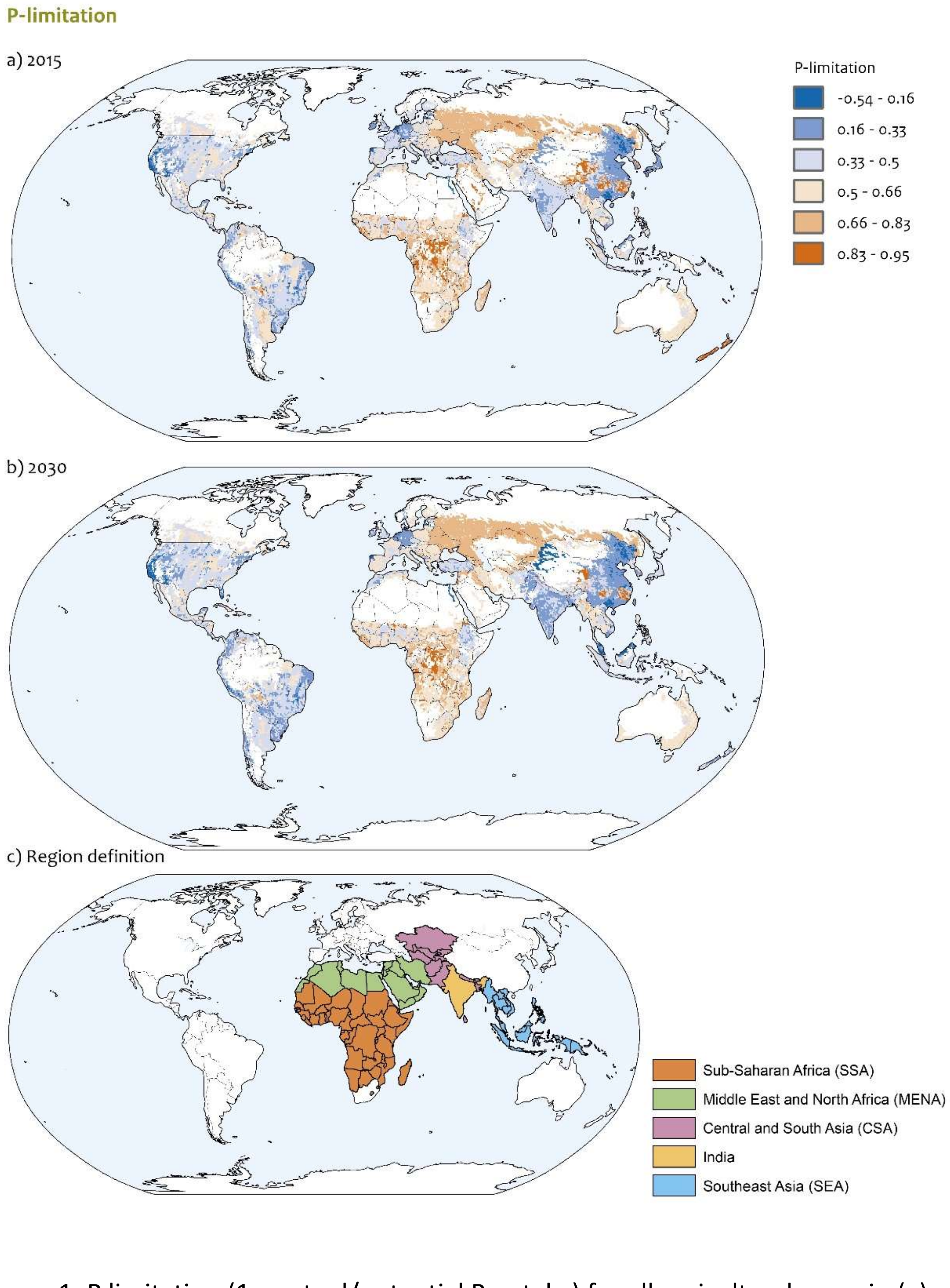
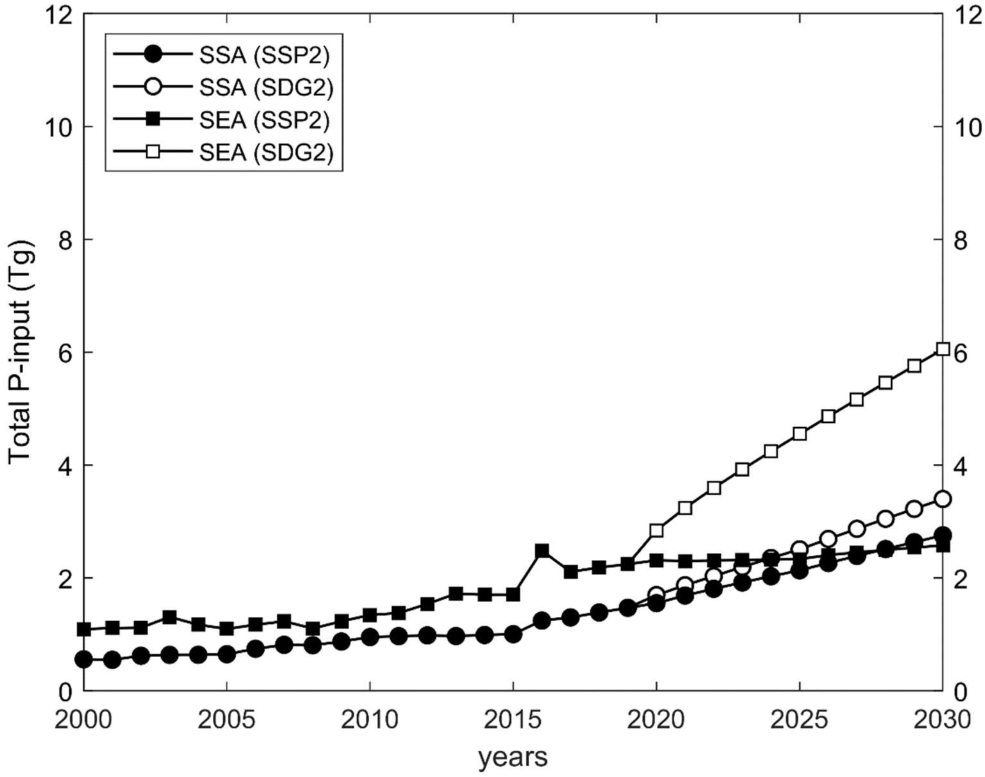



Figure 1. P limitation (1 – actual/potential P uptake) for all agricultural areas in (a) 2015 and (b) 2030. Actual P uptake is from modelled P uptake in the year after the base year 2015 (2015+1), while potential P uptake is modelled after a 20+1-year quenching period. The additional year serves to reduce P input to zero, so that the ratio calculated is reflective of the pure soil P pool status. (c) Region definition.

Country names of each region are given in Table SI2



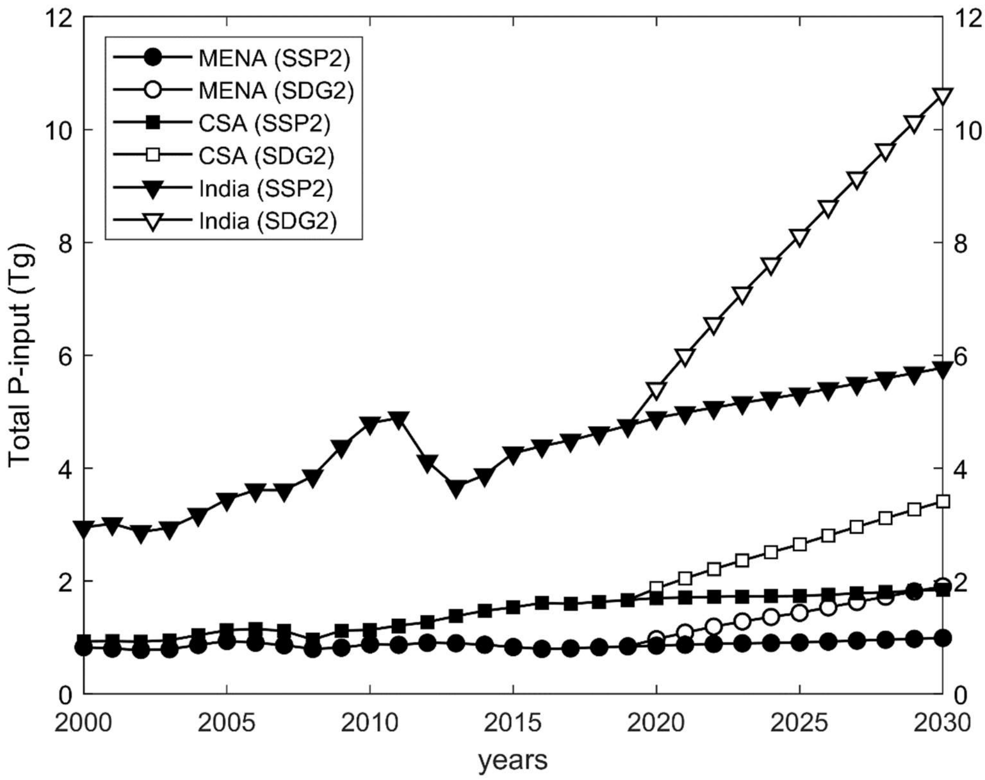



Figure 2: P input (Tg) per year for the SSP2 and SDG2 scenarios. (a) P input for South East Asia (SEA) and Sub-Saharan Africa (SSA), (b) P input for Middle East and North Africa (MENA), Central and South Asia (CSA), and India.

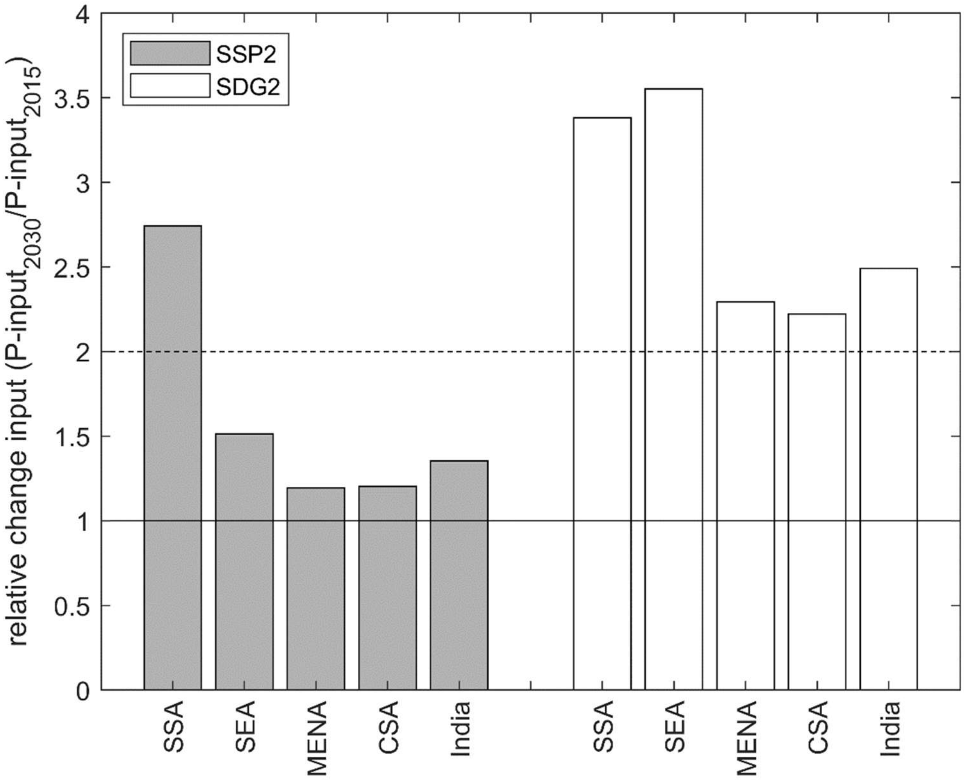



Figure 3: P input in 2030, relative to 2015 values, expressed as ratio, for the SSP2 and SDG2 scenarios.

## Methods

### Model description

The Dynamic Phosphorus Pool Simulator (DPPS) was originally developed to simulate crop uptake after field quenching experiments in various countries[26,27], and was recently used to simulate the long-term global P uptake and P status of soils[28]. DPPS was further developed to be applicable with the SSP scenarios implemented in the

IMAGE framework[29], 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. (2018)[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 1900 with *LP* and *SP* from the global gridded soil P inventory[30], 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 ($fr_{av}$ )[26]; *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. IMAGE-DPPS considers natural or unintentional inputs to the soil, i.e. weathering (*weathering,* kg P $ha^{-1}yr^{-1}$) and litter (*litter,* kg P $ha^{-1}yr^{-1}$), which are inputs to *LP*, and atmospheric deposition of soil dust (*deposition,* kg P $ha^{-1}yr^{-1}$) adds to the *SP* pool. 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 (20% for fertilizer, 10% for manure) and the remainder is available and becomes part of *LP* (80% for fertilizer and 90% for manure). P outflows from the soil system include P withdrawal from *LP* by crops (*uptake,* kg P $ha^{-1}yr^{-1}$) and runoff from both *LP* and *SP* (*runoff,* kg P $ha^{-1}yr^{-1}$). For a simplified scheme of the model see Figure SI7 in the supplementary information. For further details on the model and its assumptions, see Mogollón et al. (2018)[7]

**Scenarios and model set-up**

We compared two scenarios: (1) the Shared Socioeconomic Pathway SSP2, a middle of the road scenario [6], was used as a reference scenario for expected future development and compared with (2) the SDG2 target 2.3 scenario, in which the target of doubling productivity is achieved. In addition, the SSP2 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[29]. In grid cells where cropland expansion occurs, natural soil (without fertilizer history) with initial P pools[30] 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[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). The fraction $fr_{av}$ is assumed to depend on technology (e.g. crop varieties with improved root systems for more efficient P uptake), and it increases during the period of 2015-2030 by half of the increase rate calculated for 1990-2015.

**Scenario target productions**

The scenarios require the setting of P uptake targets. The future uptake in the SSP2 scenario was estimated from the P content in the projected crop production[7,29]. 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 the supplementary information (SI2). 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 information, too (SI2). 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 (Figure SI 1a-b). The increase starts in 2020, the time of writing, assuming that between 2015 and 2020 the world developed along the SSP2 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 SI2).

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. Since IMAGE generates the manure inputs, and deposition is from existing data, the required inputs from fertilizer and human excreta are calculated as the difference between total input and manure plus deposition.

**P limitation calculation**

For P limitation, the potential P uptake was calculated as an extension to the SSP2 scenario. Here we define soil P limitation as 1 – the ratio of actual to potential P uptake. This index provides a metric to compare the P status of different soils. For calculating potential P uptake it was assumed that P was applied at 50 kg $ha^{-1}yr^{-1}$ during a 20-year quenching period in the grid cells with cropland, starting in 2015 or in 2030. For clarity, the SSP2 scenario was used up to either 2015 or 2030, followed by a quenching period as described. This application rate is similar to the rates in Brazil in the past decade[15,16]. During this period crops can only take up P which is available in the LP pool in the year considered. We assume that during the quenching period relevant uptake conditions stay the same as in the base year, in particular the fraction of the labile pool available for plant uptake, $fr_{av}$. Actual uptake was calculated for the base year +1 and the potential uptake for the year after the quenching period (20+1), and for both years zero manure and fertilizer P inputs were simulated. Thus, the P limitation ratio represents the true soil supply and not direct supply from the fertilizer of manure applications.

**Data used**

Simulated crop P uptake for SSP2 is obtained from the crop production for the second of five SSP scenarios implemented with the IMAGE model[29]. In 2020, IMAGE data and SSP scenarios were updated to base year 2015. Previously, as in Mogollón et al. (2018)[7], the base year was 2005. Among the changes were the number of crops considered, which increased from 7 to 38 crops. Crops distinguished in the most recent Agriculture Towards 2030/2050 projection of the FAO[31], but that are not included in the IMAGE model crop groups, are assumed to be a fraction of the sum of the IMAGE crop groups expressed in dry matter equal to that in the FAO projection. P uptake is obtained from the crop yield and P content for each crop group (Table SI1).

IMAGE generates regional populations of nondairy and dairy cattle, pigs, poultry, sheep and goats. Using P excretion rates, the total manure P is calculated. 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 (e.g. in lagoons)[32].

Subsequently, IMAGE P uptake estimates and animal manure for world regions are distributed over countries within each region using FAO data[33] 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[34]; 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 $yr^{-1}$ ([35]) and distributed on the basis of the apatite content of soil material obtained from Yang et al.[30].

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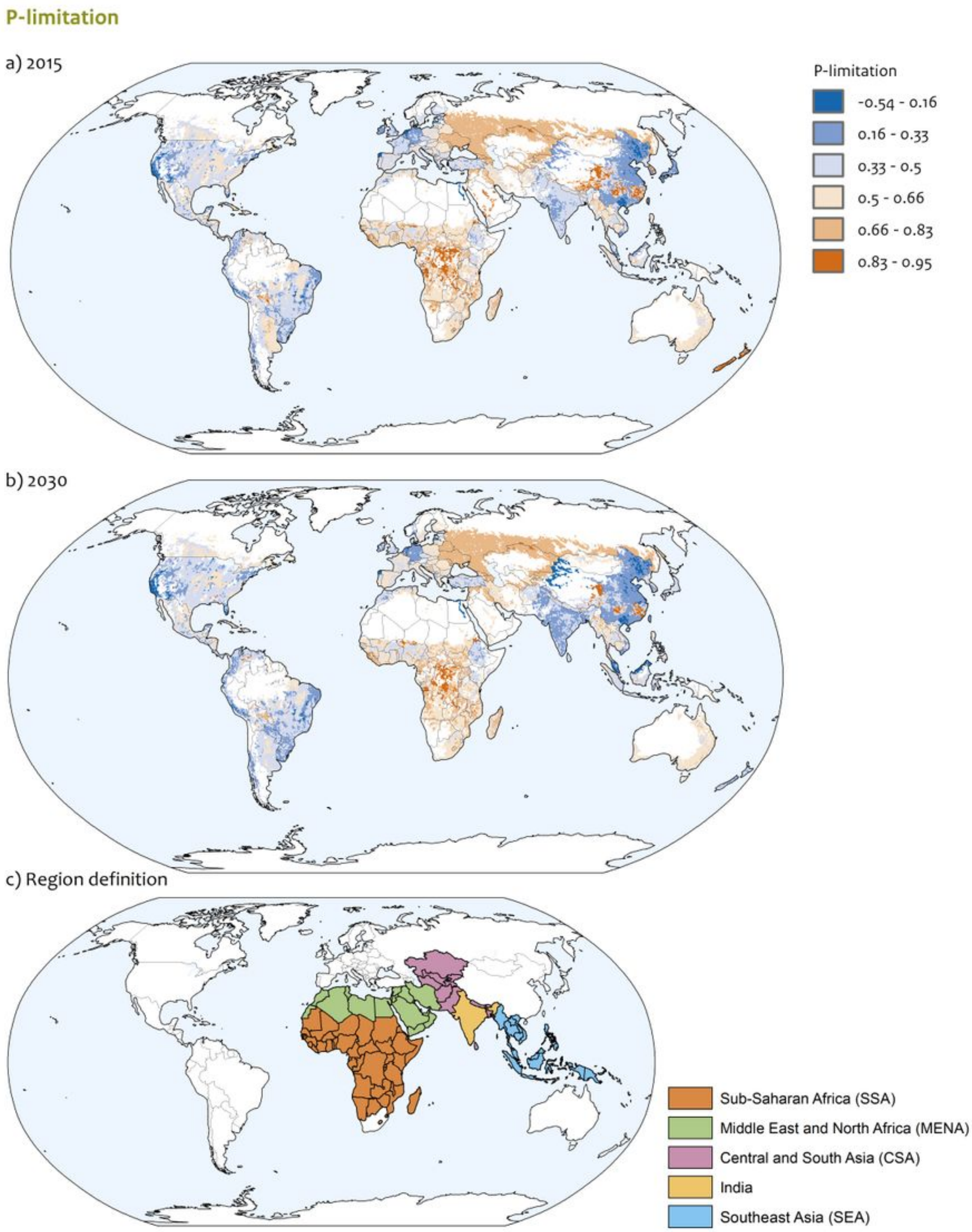
# Figures




### Figure 1

P limitation (1 – actual/potential P uptake) for all agricultural areas in (a) 2015 and (b) 2030. Actual P uptake is from modelled P uptake in the year after the base year 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. (c) Region definition. Country names of each region are given in Table SI2. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

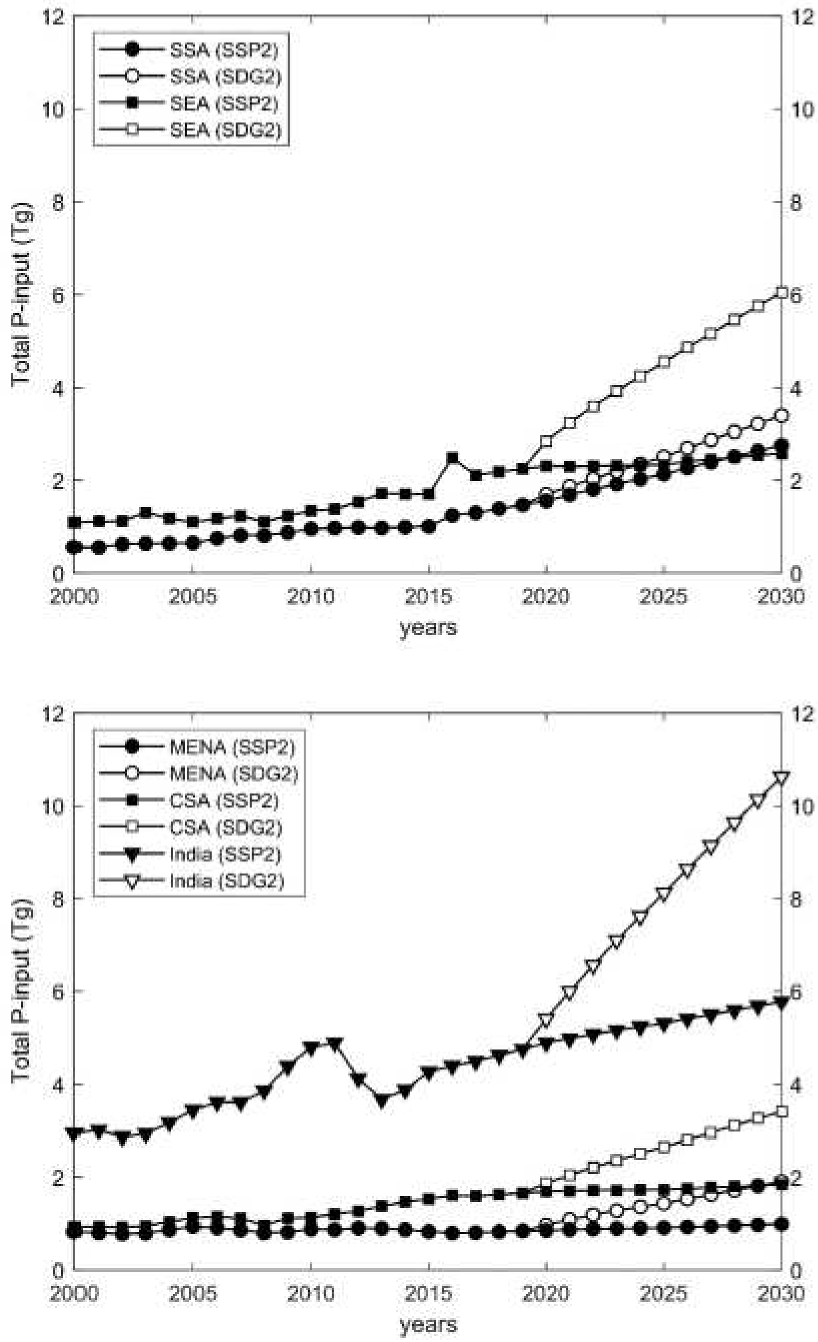



**Figure 2**

P input (Tg) per year for the SSP2 and SDG2 scenarios. (a) P input for South East Asia (SEA) and Sub-Saharan Africa (SSA), (b) P input for Middle East and North Africa (MENA), Central and South Asia (CSA), and India.

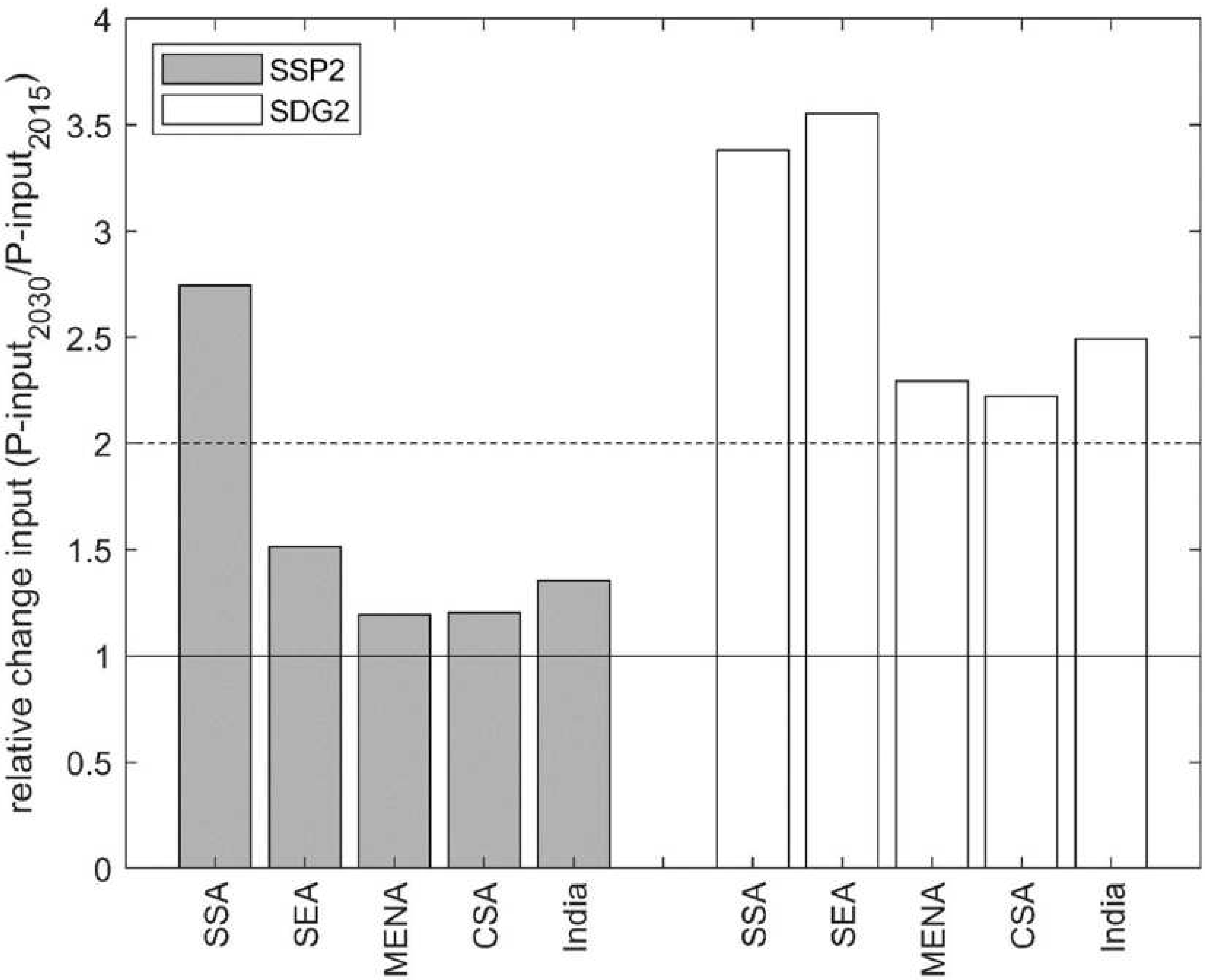



**Figure 3**

P input in 2030, relative to 2015 values, expressed as ratio, for the SSP2 and SDG2 scenarios.

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- supplementaryinformation.pdf