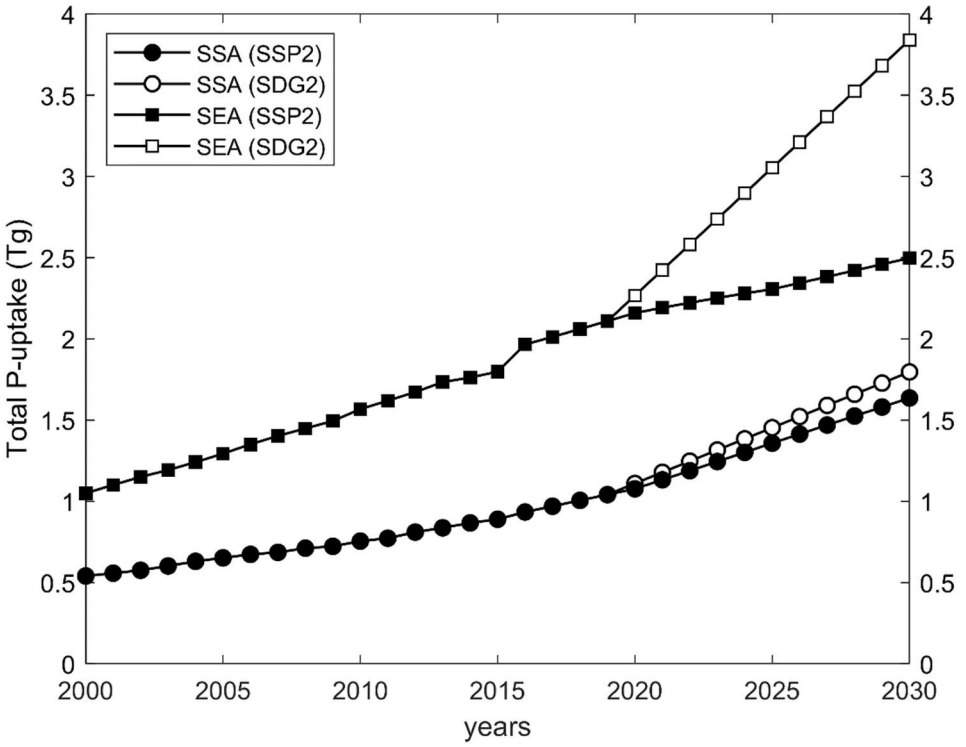
Supplementary information

SI 1: Supplementary figures and tables

(a)



(b)

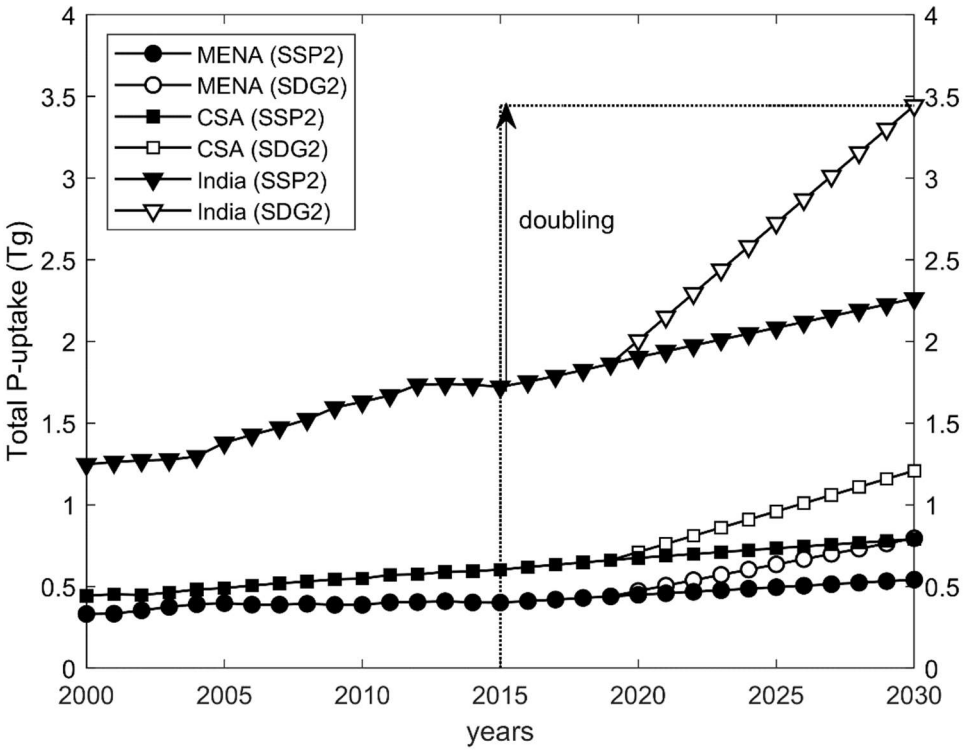


Figure SI1: P uptake (Tg) per year for the SSP2 and SDG2 scenarios. (a) P uptake for Sub-Saharan Africa (SSA), South East Asia (SEA) (b) P uptake for Middle East and North Africa (MENA), Central and South Asia (CSA), and India. Definition of region are given in Figure 1b of the main text and Table SI2. The arrow and 'doubling' graphically explains the SDG2 scenario for India, in which uptake is set to double between 2015 and 2030, with a linear increase setting in in 2020.

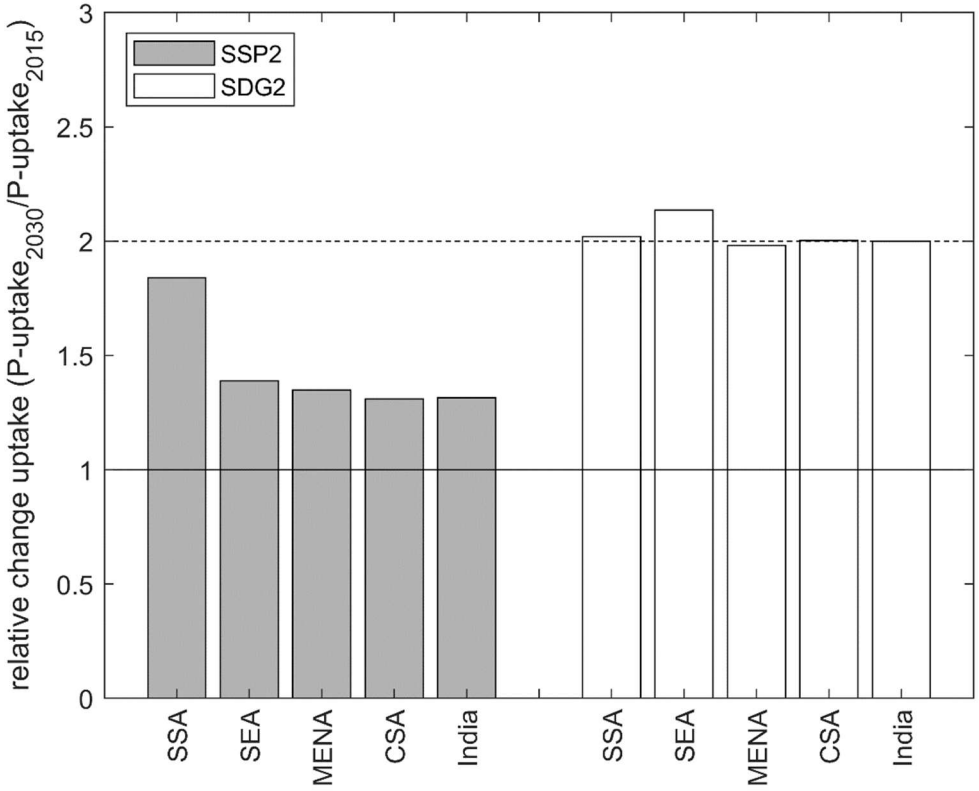
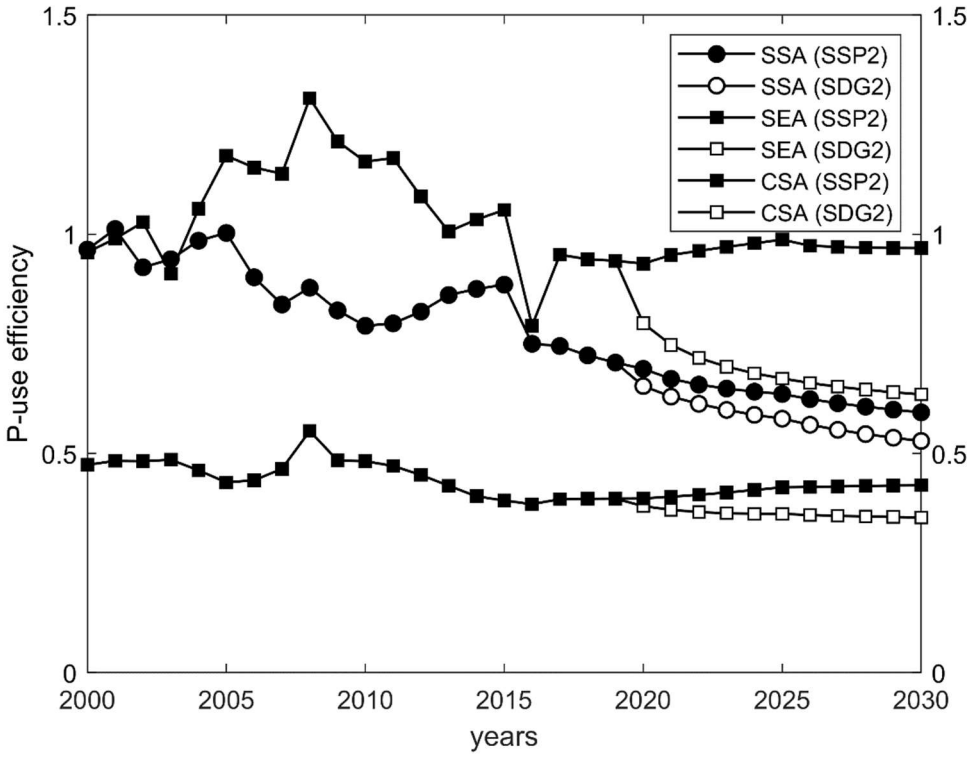


Figure SI2: P uptake in 2030, relative to 2015 values, expressed as ratio, for the SSP2 and SDG2 scenarios. Note that for the SDG2 P uptake, doubling (factor 2) was the target, imposed on the model. While the results are aggregated for regions, the calculations were performed on a country basis. Where (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.

(a)



(b)

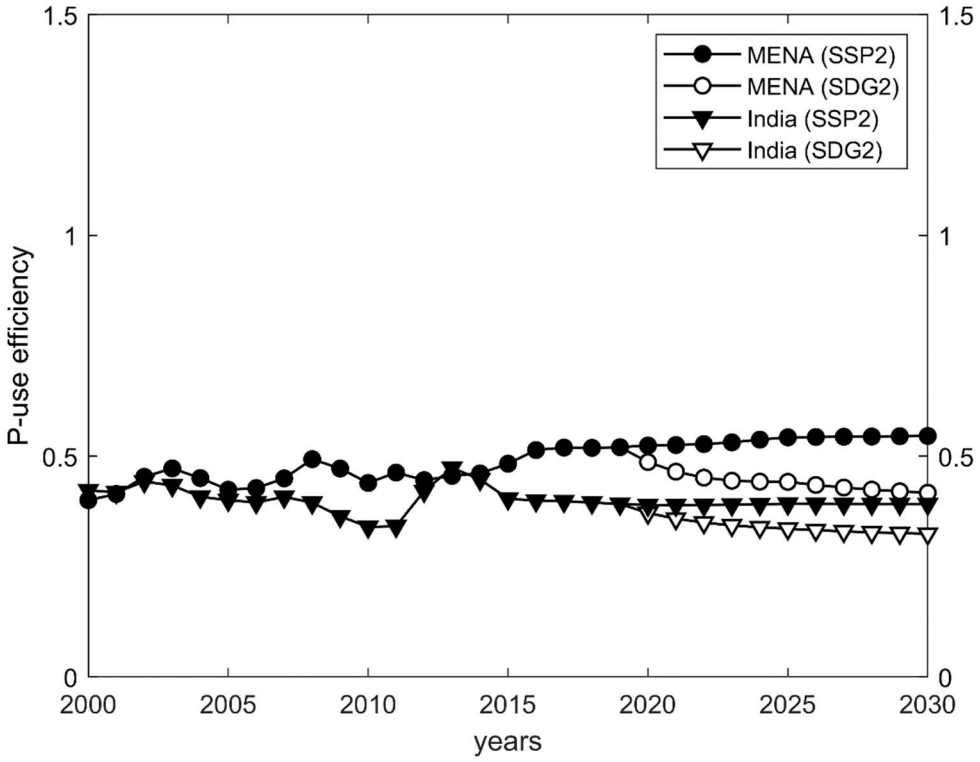
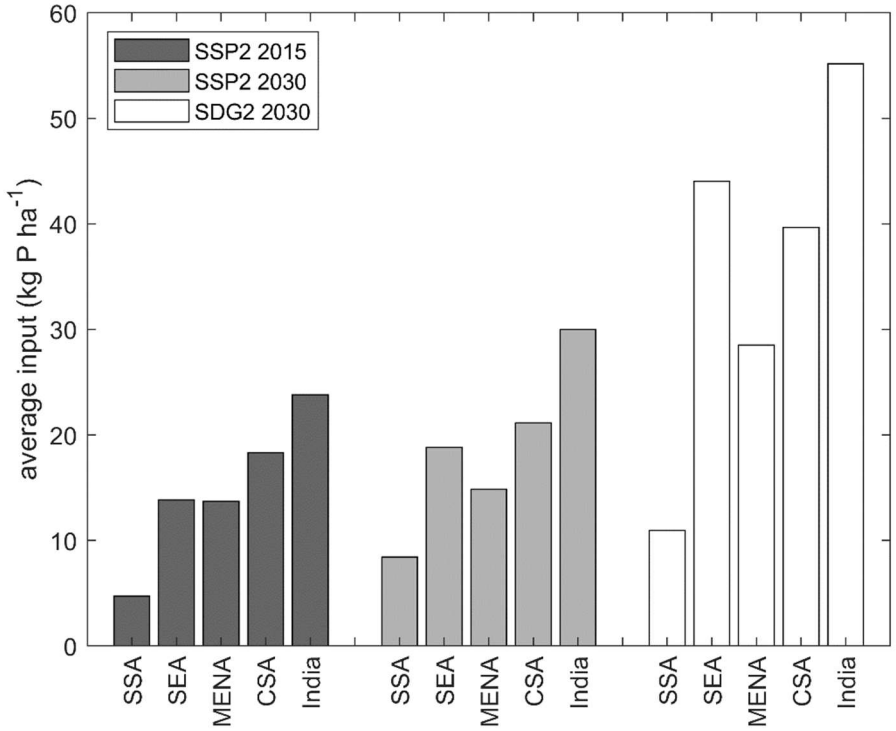


Figure SI3: Phosphorus use efficiency (PUE) over time for (a) SSA, SEA, CSA and (b) for MENA and India. PUE is defined as P uptake over P input.

(a)



(b)

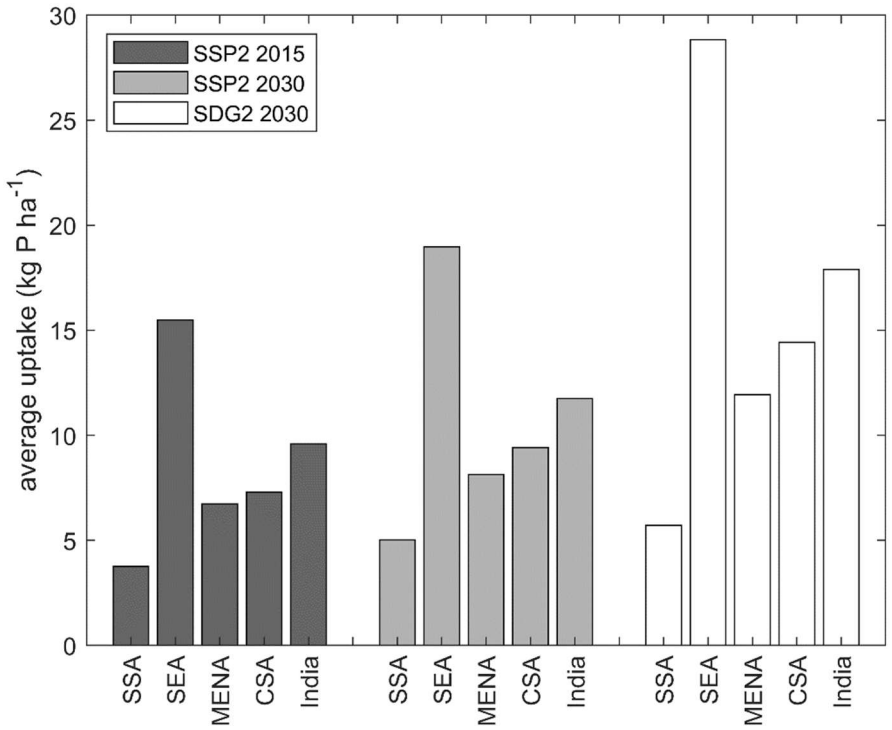
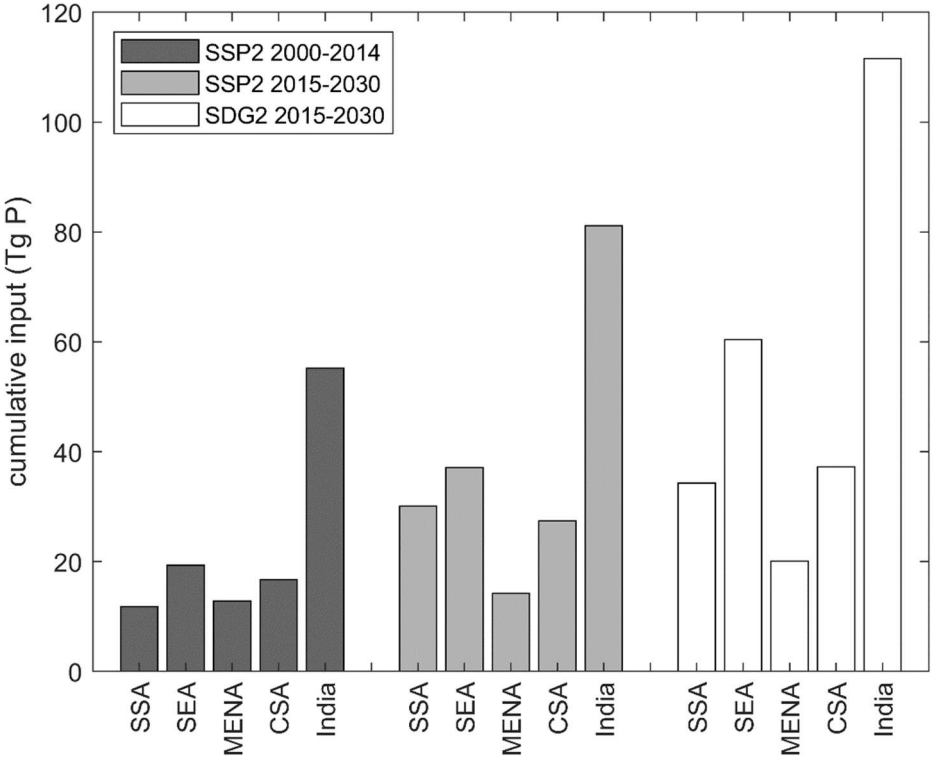


Figure SI4: (a) Average P input and (b) average P uptake, in kg P $ha^{-1}yr^{-1}$, for all six regions in 2015 (SSP2) and 2030 (SSP2 and SDG2)

(a)



(b)

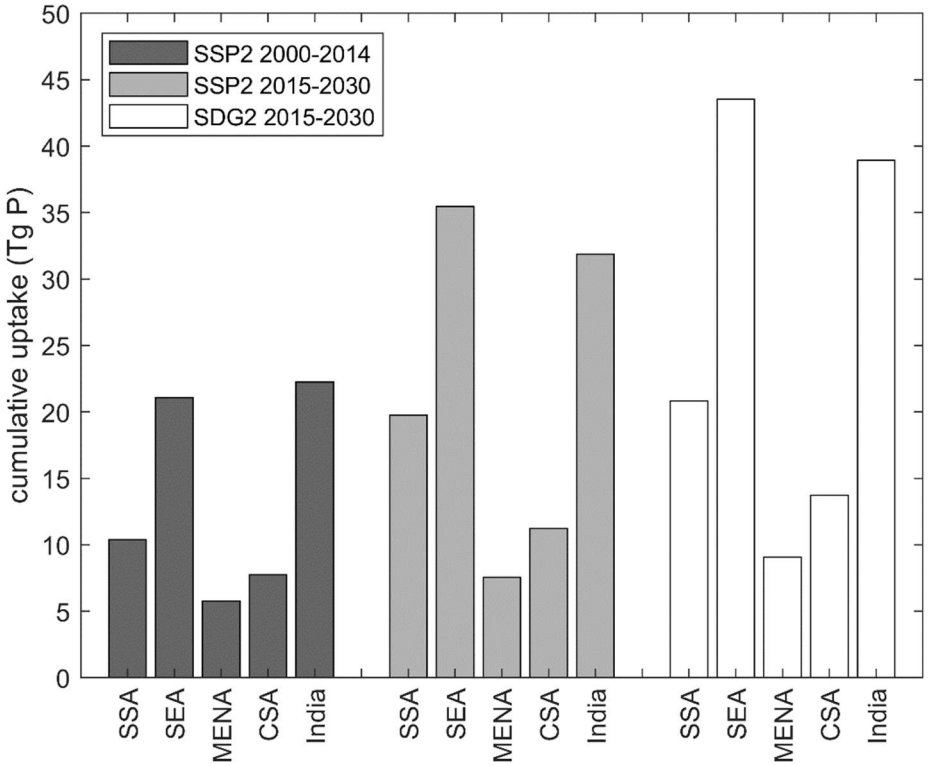


Figure SI5: (a) cumulative P input and (b) cumulative P uptake, in Tg P, for the years 2000-2014 (SSP2) and 2015-2030 (SSP2 and SDG2)

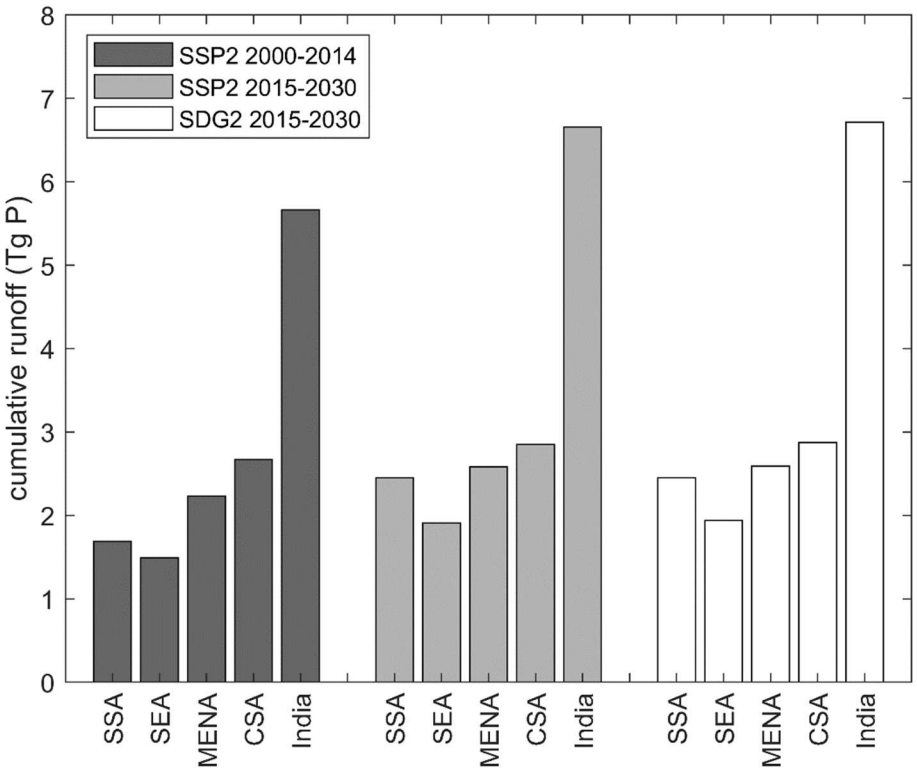


Figure SI6: Cumulative P runoff in Tg P for the years 2000-2014 (SSP2) and 2015-2030 (SSP2 and SDG2)

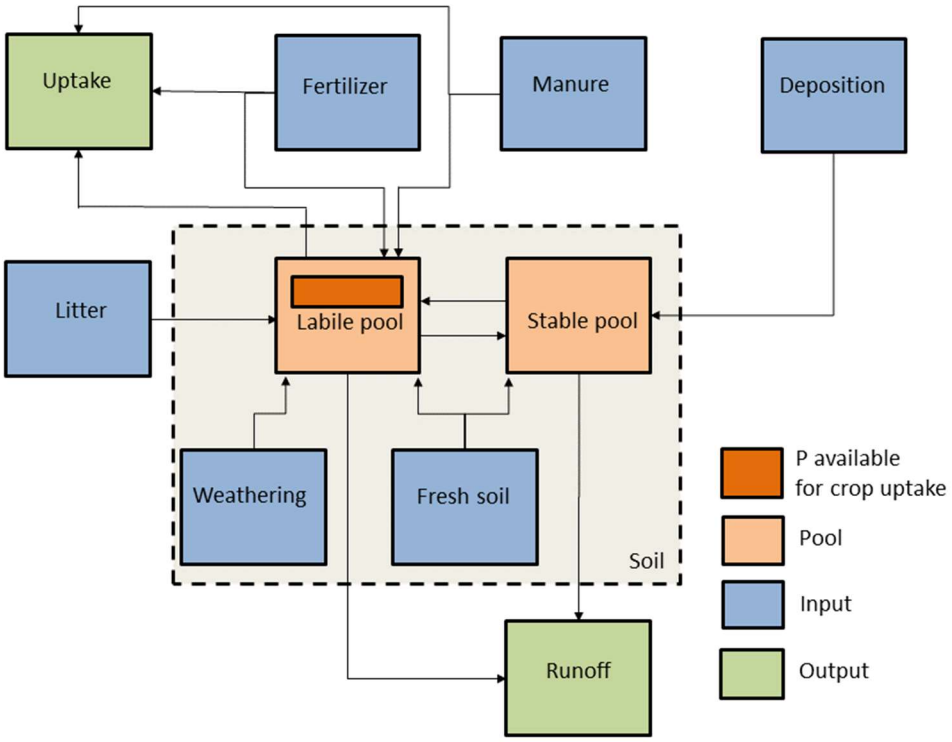


Figure SI7. Simplified scheme of the IMAGE-DPPS model.

Table SI1. Crop groups used as a basis for calculating crop P uptake, P content on dry matter basis, and dry matter content. Values taken from Bouwman et al. 2017[1]

Crops	Name	P content (-)	Dry matter (-)
1	Wheat	0.0034	0.880
2	Rice	0.0025	0.880
3	Maize	0.0029	0.880
4	Barley	0.0036	0.880
5	Millet	0.0030	0.850
6	Sorghum	0.0030	0.850
7	Other cereals	0.0031	0.870
8	Potato	0.0005	0.212
9	Sweet potato	0.0003	0.272
10	Cassava	0.0004	0.326
11	Other root crops	0.0004	0.270
12	Plantain	0.0003	0.653
13	Sugar beet	0.0004	0.260
14	Sugar cane	0.0004	0.232
15	Pulses	0.0025	0.850
16	Vegetables	0.0003	0.070
17	Banana	0.0002	0.257
18	Citrus	0.0001	0.103
19	Fruit crops	0.0001	0.131
20	Oil crops	0.0050	0.920
21	Rapeseed	0.0056	0.910
22	Oil palm	0.0031	0.940
23	Soybean	0.0050	0.850
24	Groundnut	0.0042	0.942
25	Sunflower	0.0045	0.920
26	Sesame seed	0.0056	0.940

27	Coconut	0.0004	0.896
28	Cocoa	0.0026	1
29	Coffee	0.0022	1
30	Tea	0.0150	0.525
31	Tobacco	0.0006	0.21
32	Cotton	0.0053	0.92
33	Fiber crops	0.0095	1
34	Rubber	0.0000	1

Table SI2: Countries counted towards the five regions

Region (Acronym)	Countries within region
Sub-Saharan Africa (SSA) *(excluding Republic of South Africa)*	Angola, Botswana, Burundi, Cameroon, Cabo Verde, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Benin, Equatorial Guinea, Ethiopia, Eritrea, Djibouti, Gabon, Gambia, Ghana, Guinea, Côte d'Ivoire, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Guinea-Bissau, Réunion, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, Zimbabwe, Former Sudan, Swaziland, Togo, Uganda, United Republic of Tanzania, Burkina Faso, Zambia
Middle East North Africa (MENA)	Algeria, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Tunisia, Egypt, Yemen
Central and South Asia (CSA)	Afghanistan, Bangladesh, Bhutan, Sri Lanka, Kazakhstan, Kyrgyzstan, Nepal, Pakistan, Tajikistan, Turkmenistan, Uzbekistan
India	India
South East Asia (SEA)	Myanmar, Cambodia, Indonesia, Lao People's Dem. Rep., Malaysia, Philippines, Timor-Leste, Viet Nam, Thailand, Papua New Guinea

SI2: supplementary information on methods

SDG2 target definition

The SDG2.3 target to "… *double [by 2030] the agricultural productivity and incomes of small-scale food producers, …*"[2] needed to be specified for the purpose of our study. First and foremost, IMAGE-DPPS does not include productivity or income data on a farm level. As a substitute, we used crop production (as expressed by P uptake) on a country level. While it is clear that the two terms are different, they both aim at the overarching goal of zero hunger (SDG2). Furthermore, while in the past production increases were often achieved through cropland expansion, the expectation is that in developing countries current and future expansion will be 80% attributable to yield increases[3]. Given the difficulty of translating SDG goals into specific indicators that capture the intention of the target comprehensively, we believe that some freedom is allowed in forming indicators for the target, that suit the study purpose.

Selection of world regions

We made use of the study by Lowder et al. [4], which analysed farm size data from a large number of countries worldwide. While there is no widely accepted definition of smallholder farming, relatively small farm size is an indicator which can be compared well between countries. For our study, we chose a threshold of 5ha to count as smallholder farm. We used the 26 world regions of IMAGE[5] to analyse the data set of Lowder et al.[4]. If more than 75% of farms in a region were smaller than 5ha, the region was considered dominated by smallholders. In a second step, the regions qualifying were further aggregated to five world regions which are the geographic unit in which our results are presented (Table SI2). There were no regions close to the threshold, but all regions either clearly surpassed or fell short of the threshold, which means that the choice of regions was not very sensitive to our definition. Actually, China was also a region where smallholder farms dominate. However, given that average P input levels are already above 60 kg P $ha^{-1}yr^{-1}$ in China (results not shown), and P limitation in most regions is negligible (Figure 1 a and b), we decided to exclude China from the analysis.

Uncertainties and sensitivity

Uncertainty in modelling results stem from the model structure and parameters used, and the data, which is often derived either from country datasets or modelling studies themselves. These uncertainties are not wholly quantifiable, but a sensitivity analysis of IMAGE-DPPS by Mogollón et al.[3] showed that results are most sensitive to fr_{av} and the fraction of direct P uptake from fertilizers,

which means that errors that stem from the calibration of fr_{av}, and the estimate of direct uptake are relevant sources of uncertainty. Furthermore, spatial distribution (allocation) of country level data, such as P fertilizer and manure, on a spatial grid gives rise to uncertainty[3].

Another source of uncertainty lies in the construction and interpretation of our scenarios. The translation of the SDG2 target 2.3 into a quantity that can be calculated in our model (P uptake by crops on a country level) and serves the purpose of our study, was discussed above. Furthermore, we focused on crop uptake and not livestock P uptake. This translation and necessary reduction of the SDG target can be unsatisfying for readers viewing the SDGs with different backgrounds. The effect of choosing SSP2 over other SSPs was discussed in the main text. Finally, the COVID19 pandemic, occurred during the time of writing and could not be integrated in any of the analysis or scenarios. The pandemic is likely to affect future scenarios profoundly, and mostly in a negative way, making it even harder for the five regions with smallholder-dominated farms to reach the SDG zero hunger goal[6].

References

1. Bouwman, A. F. *et al.* Lessons from temporal and spatial patterns in global use of N and P fertilizer on cropland. *Sci. Rep.* **7**, 1–11 (2017).
2. UNSTAT. Sustainable development goals. https://unstats.un.org/sdgs/metadata?Text=&Goal=2&Target=2.3 (2021).
3. Mogollón, J. M., Beusen, A. H. W., van Grinsven, H. J. M., Westhoek, H. & Bouwman, A. F. Future agricultural phosphorus demand according to the shared socioeconomic pathways. *Glob. Environ. Chang.* **50**, 149–163 (2018).
4. Lowder, S. K., Skoet, J. & Raney, T. The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide. *World Dev.* **87**, 16–29 (2016).
5. Stehfest, E., van Vuuren, D., Bouwman, L. & Kram, T. *Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications*. (Netherlands Environmental Assessment Agency (PBL), 2014).
6. Naidoo, R. & Fisher, B. Reset Sustainable Development Goals for a pandemic world. *Nature* (2020) doi:10.1038/d41586-020-01999-x.