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.

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\(^{15,18}\). The challenge of addressing global P fixation and limitation has been recently studied. Using Brazilian P input and surplus data, Roy et al.\(^{7}\) 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. Kvačič et al.\(^{16}\) 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\(^{11,12}\), 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\(^{25}\) or empirically based calculations using P budgets\(^{26}\). 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\(^{11,12}\). Our choice was to model the P application of 50 kg ha\(^{-1}\) 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...
soils can take decades to be saturated yet after decades of high fertilizer input have approached the point where a maintenance fertilizer strategy becomes possible. In our study, P limitation is calculated as $1 - \frac{\text{actual}}{\text{potential}} P \text{ uptake}$.

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). 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.

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. These scenarios have been previously implemented in IMAGE-DPPS. 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 dominates: sub-Saharan Africa (SSA), South East Asia (SEA), Middle East and North Africa (MENA), Central and South Asia (CSA) and India. In these regions, at least 75% of farms are smaller than 5 ha and production of food crops is the dominant activity on smallholder farms. 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, SEA, MENA, 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. We excluded China, which is also dominated by smallholder farming for food production but which already has very high levels of P application.
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. 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.

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. 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 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. 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 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
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 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 205011 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 scenario6. 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 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, Southern China, Kenya and Senegal, 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, 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, the high P content in urine could substitute large amounts of P fertilizers and at the same time reduce P discharge to surface waters. More generally, P could be recycled across sectors where waste streams, 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. 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 limiting to improve P availability in strongly P-fixing soils. 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. 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. Measures could be reduced tillage, cover crops, contour ploughing, deviation ditches, grassed waterways and terracing.

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. 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. 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.

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 196022−24. 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 production25, 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 element54. 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 achieved17,18.

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 management25. Especially in SSA, unfortunately the current targets for budgets to support capacity building from national and international organizations are generally not met26−28.

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 countries23,24 and was recently used to simulate the long-term global P uptake and P status of soils29. DPPS was further developed to be applicable with the SSP scenarios implemented in the IMAGE framework30, with the purpose of calculating future P demand and budgets for a period up to 2050. Here we apply the version of DPPS (IMAGE-DPPS) by Mogollón et al.1. 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 inventory58, representing the pre-industrial conditions. LP consists both organic and inorganic P forms and only a fraction of LP is directly available for plant uptake (frav); 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; 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) developed to be applicable with the SSP scenarios implemented in the IMAGE model31. In grid cells where crop production occurs, natural soil (without fertilizer history) with initial P pools58 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 conditions32 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 frav is allowed to vary between a minimum value of 0 and a maximum value of 1. In scenario mode after 2015, frav becomes a parameterized value that varies according to the SSP storyline. The fraction frav 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 production7,25. 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 croplands33,34. 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:

\[
\text{U}_{\text{act}} = \min(\text{U}_{\text{max}}, \text{U}_{\text{pot}}) - \text{U}_{\text{act}} + \text{U}_{\text{pot}}
\]

where \(\text{U}_{\text{act}}\) is actual P uptake and \(\text{U}_{\text{pot}}\) is potential P uptake. This index provides a metric to compare the P status of different soils. For calculating \(\text{U}_{\text{pot}}\), 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 decade35,36. 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, \(\text{fr}_{\text{av}}\).
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 will 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, \( U_{\text{P}} \) was calculated in the year after the quenching period started in 2030, and in which zero manure was simulated, so all P comes from the stored available soil P. The parameter \( U_{\text{P}} \) 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 N. Potolli et al., 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 as a spreadsheet in the Supplementary Data. For further inquiries please direct all requests regarding this study to the corresponding author.

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.

Received: 12 March 2021; Accepted: 27 September 2021; Published online: 22 November 2021

References
1. Cordell, D., Drangert, J. O. & White, S. The story of phosphorus: global food security and food for thought. Glob. Environ. Change 19, 292–305 (2009).
2. Powers, S. M. et al. Long-term accumulation and transport of anthropogenic phosphorus in three river basins. Nat. Geosci. 9, 353–356 (2016).
3. Bouwman, A. F. et al. Lessons from temporal and spatial patterns in global use of N and P fertilizer on cropland. Sci. Rep. 7, 40366 (2017).
4. Syers, J. K., Johnston, A. E. & Curtin, D. Efficiency of Soil and Fertilizer Phosphorus Use FAO Fertilizer and Plant Nutrition Bulletin 18 (FAO, 2008).
5. Sattari, S. Z., Bouwman, A. F., Giller, K. E. & Van Ittersum, M. K. Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proc. Natl Acad. Sci. USA 109, 6348–6353 (2012).
6. MacDonald, G. K., Bennett, E. M., Potter, P. A. & Ramankutty, N. Agronomic phosphorus imbalances across the world’s croplands. Proc. Natl Acad. Sci. USA 108, 3086–3091 (2011).
7. Mogollón, J. M., Reusen, 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. Change 50, 149–163 (2018).
8. Justic, D., Rabalais, N. N. & Turner, R. E. Stoichiometric nutrient balance and origin of coastal eutrophication. Mar. Pollut. Bull. 30, 41–46 (1995).
9. Tessensohn, J. P. A. Properties and Management of Soils in the Tropics 1st edn (John Wiley & Sons, 1976).
10. Koning, N. B. J. et al. Long-term global availability of food: continued abundance or new scarcity. NJAS-Wagen. J. Life Sci. 55, 229–292 (2008).
11. Samir, K. C. & Lutz, W. The human core of the Shared Socioeconomic Pathway: population scenarios by age, sex and level of education for all countries to 2100. Glob. Environ. Change 42, 181–192 (2017).
12. Brady, N. C. The Nature and Properties of Soils (Macmillan, 1990).
13. Fairhurst, T., Lefroy, R., Mutert, E. & Batjes, N. The importance, distribution and causes of phosphorus deficiency as a constraint to crop production in the tropics. Agrofor. Forum 9, 61–66 (1999).
14. Srinivas, M. A. Properties and Management of Soils in the Tropics 1st edn (John Wiley & Sons, 1976).
15. Riskin, S. H., Porder, S., Schipanski, M. E., Bennett, E. M. & Neill, C. Regional differences in phosphorus budgets in intensive soybean agriculture. BioScience 63, 49–54 (2013).
16. Riskin, S. H. et al. The fate of phosphorus fertilizer in Amazon soybean fields. Philos. Trans. R. Soc. B https://doi.org/10.1098/rstb.2012.0154 (2013).
17. Withers, P. J. A. et al. Transitions to sustainable management of phosphorus in Brazilian agriculture. Sci. Rep. 8, 2357 (2018).
18. Pavinao, P. S. et al. Revealing soil legacy phosphorus to promote sustainable agriculture in Brazil. Sci. Rep. 10, 15615 (2020).
19. Roy, E. D. et al. The phosphorus cost of agricultural intensification in the tropics. Nat. Plants 2, 16043 (2016).
20. Kvacík, M. et al. Quantifying the limitation to world cereal production due to soil phosphorus status. Glob. Biogeochem. Cycles 32, 143–157 (2018).
21. Licker, R. et al. Mind the gap: how do climate and agricultural management explain the ‘yield gap’ of crops around the world? Glob. Ecol. Biogeogr. 19, 769–782 (2010).
22. Mueller, N. D. et al. Closing yield gaps through nutrient and water management. Nature 490, 254–257 (2012).
23. Wolf, J., Wit, C. T., Janssen, B. H. & Lathwell, D. J. Modeling long-term crop response to fertilizer phosphorus. I. The model. Agron. J. 79, 445–451 (1987).
24. Janssen, B. H., Lathwell, D. J. & Wolf, J. Modeling long-term crop response to fertilizer phosphorus. II. Comparison with field results. Agron. J. 79, 452–458 (1987).
25. Stenhof, E. et al. Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model Description and Policy Applications (Netherlands Environmental Assessment Agency, 2014).
26. Mogollón, J. M. et al. More efficient phosphorus use can avoid cropland expansion. Nat. Food 2, 509–518 (2021).
27. FAOSTAT Database (FAO, accessed 1 March 2021); https://www.fao.org/faostat/en/#data/FBS
28. van Vuuren, D. P. et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Glob. Environ. Change 42, 237–250 (2017).
29. Louwer, 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).
30. Richard, V., Ramankutty, N., Mehrabi, Z., Jarvis, L. & Chookolingo, B. How much of the world’s food do smallholders produce? Glob. Food Sec. 17, 64–72 (2018).
31. Herrera, M. et al. Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet. Health 1, e33–e42 (2017).
32. Samberg, I. H., Gerber, J. S., Ramankutty, N., Herrera, M. & West, P. C. Subnational distribution of average farm size and smallholder contributions to global food production. Environ. Res. Lett. 11, 124010 (2016).
33. Carpenter, S. R. & Bennett, E. M. Reconsideration of the planetary boundary for phosphorus. Environ. Res. Lett. 6, 014009 (2011).
34. Magnone, D. et al. Efficiency of phosphorus resource use in Africa as defined by soil chemistry and the impact on crop production. Energy Procedia 123, 97–104 (2017).
35. Magnone, D. et al. Soil chemistry aspects of predicting future phosphorus requirements in sub-Saharan Africa. J. Adv. Model. Earth Syst. 11, 327–337 (2019).
36. Naidoo, R. & Fisher, B. Reset Sustainable Development Goals for a pandemic world. Nature 583, 198–201 (2020).
37. Bhattacharyya, P. et al. Effects of 42-year long-term fertilizer management on soil phosphorus availability, fractionation, adsorption–desorption isotherm and plant uptake in flooded tropical rice. Crop J. 3, 387–395 (2015).
38. Zhang, H. M., Wang, B. R., Xu, M. G. & Fan, T. L. Crop yield and soil responses to long-term fertilization on a red soil in southern China. *Pedosphere* 19, 199–207 (2009).

39. Rötter, R. & Van Keulen, H. Variations in yield response to fertilizer application in the tropics: II. Risks and opportunities for smallholders cultivating maize on Kenya's arable land. *Agric. Syst.* 53, 69–95 (1997).

40. Haelefe, S. M., Wopereis, M. C. S. & Wiechmann, H. Long-term fertility experiments for irrigated rice in the West African Sahel: agronomic results. *Field Crops Res.* 78, 119–131 (2002).

41. Erni, M. et al. Bad for the environment, good for the farmer? Urban sanitation and nutrient flows. *Irrig. Drain. Syst.* 24, 113–125 (2010).

42. Simha, P. & Ganapathi, M. Ecological sanitation and nutrient recovery from human urine: how far have we come? A review. *Sustain. Environ. Res.* 27, 107–116 (2017).

43. van Puijenbroek, P. J. T. M., Beusen, A. H. W. & Bouwman, A. F. Global nitrogen and phosphorus in urban waste water based on the Shared Socio-economic Pathways. *J. Environ. Manag.* 231, 446–456 (2019).

44. Brownlie, W. J. et al. Global actions for a sustainable phosphorus future. *Nat. Food* 2, 71–74 (2021).

45. de Wit, C. T. Resource use efficiency in agriculture. *Agric. Syst.* 40, 125–151 (1992).

46. Roy, E. D. et al. The phosphorus cost of agricultural intensification in the tropics. *Nat. Plants* 2, 2–7 (2016).

47. Borrelli, P. et al. An assessment of the global impact of 21st century land use change on soil erosion. *Nat. Commun.* 8, 2013 (2017).

48. Smil, V. Phosphorus in the environment: natural flows and human interferences. *Annu. Rev. Energy Environ.* 25, 53–88 (2000).

49. Hudson, N. *Soil Conservation* (Cornell Univ. Press, 1971).

50. The Future of Food and Agriculture—Alternative Pathways to 2050 (FAO, 2018).

51. Agricultural Policy Incentives in Sub-Saharan Africa in the Last Decade (2005–2016): Monitoring and Analysing Food and Agricultural Policies (MAFAP) Synthesis Study 2143-2 (FAO, 2018).

52. Commodity Markets `Pink Sheet` Data (World Bank, 2021); https://www.worldbank.org/en/research/commodity-markets

53. Edixhoven, J. D., Gupta, J. & Savenije, H. H. G. Recent revisions of phosphate rock reserves and resources: a critique. *Earth Syst. Dyn. 5*, 491–507 (2014).

54. Geissler, B., Mew, M. C. & Steiner, G. Phosphate supply security for importing countries: developments and the current situation. *Sci. Total Environ.* 677, 511–523 (2019).

55. Paarlberg, R. L. & Paarlberg, R. *Food Politics: What Everyone Needs to Know* (Oxford Univ. Press, 2013).

56. McIntyre, B. D., Herren, H. R., Wakhungu, J. & Watson, R. T. (eds) *Agriculture at a Crossroads: A Synthesis of the Global and Sub-global IAASTD Reports* (Island Press, 2009).

57. Zhang, J. et al. Spatiotemporal dynamics of soil phosphorus and crop uptake in global cropland during the 20th century. *Biogeoosciences* 14, 2055–2068 (2017).

58. Yang, X., Post, W. M., Thornton, P. E. & Jain, A. The distribution of soil phosphorus for global biogeochemical modeling. *Biogeoosciences* 10, 2525–2537 (2013).

59. Batjes, N. *Global Distribution of Soil Phosphorus Retention Potential Report no.* 2011/06 (ISRIC—World Soil Information, 2011).

60. FAO & UNESCO *Soil Map of the World Vol. 1* (UNESCO, 1974).

61. Beusen, A. H. W., Bouwman, A. F., Van Beek, L. P. H., Mogollón, J. M. & Middelburg, J. J. *Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum*. *Biogeoosciences* 13, 2441–2451 (2016).

62. Mahowald, N. et al. Global distribution of atmospheric phosphorus sources, concentrations and deposition rates, and anthropogenic impacts. *Glob. Biogeochem. Cycles* 22, GB4026 (2008).

63. Liu, Y., Villalba, G., Ayres, R. U. & Schroeder, H. Global phosphorus flows and environmental impacts from a consumption perspective. *J. Ind. Ecol.* 12, 229–247 (2008).

Acknowledgements

The study was conducted as part of a contribution by the Netherlands Environmental Assessment Agency (PBL) to the Global Land Outlook (GLO), commissioned by the United Nations Convention to Combat Desertification (UNCCD) secretariat.

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

Extended data is available for this paper at https://doi.org/10.1038/s41893-021-00794-4.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-021-00794-4.

Correspondence and requests for materials should be addressed to A. F. Bouwman.

Peer review information *Nature Sustainability* thanks Thomas Nesme, Amin Soltangheisi and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2021.
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⁻¹ 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⁻¹ 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⁻¹ yr⁻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.
Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section. For further information on scientific reporting, please see the Nature Portfolio Author Instructions.

- **n/a**
- The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
- A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
- The statistical test(s) used AND whether they are one- or two-sided
- Only common tests should be described solely by name; describe more complex techniques in the Methods section.
- A description of all covariates tested
- A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
- A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
- For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted
  - Give P values as exact values whenever suitable.
- For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
- For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- Estimates of effect sizes (e.g. Cohen’s d, Pearson’s r), indicating how they were calculated

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 analysis |
|----------------|--------------|
| Data collection was by simple download | 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.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- Description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The datasets and computer code generated during the current study are available from the corresponding author upon reasonable request. Please direct all correspondence and requests regarding this study to the corresponding author.
Field-specific reporting
Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

- Life sciences
- Behavioural & social sciences
- Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

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-author (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 |

Did the study involve field work?  
- Yes  
- No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

| Materials & experimental systems | Methods |
|---|---|
| n/a | n/a |
| Involved in the study | Involved in the study |
| - Antibodies | - ChIP-seq |
| - Eukaryotic cell lines | - Flow cytometry |
| - Palaeontology and archaeology | - MRI-based neuroimaging |
| - Animals and other organisms | |
| - Human research participants | |
| - Clinical data | |
| - Dual use research of concern | |

Antibodies

- Antibodies used
  - Describe all antibodies used in the study; as applicable, provide supplier name, catalog number, clone name, and lot number.

- Validation
  - Describe the validation of each primary antibody for the species and application, noting any validation statements on the manufacturer’s website, relevant citations, antibody profiles in online databases, or data provided in the manuscript.

Eukaryotic cell lines

Policy information about: cell lines

- Cell line source(s)
  - State the source of each cell line used.
Note that full information on the approval of the study protocol must also be provided in the manuscript.

### Animals and other organisms

Policy information about [studies involving animals](https://arrive-qm.org/about/arrive-guidelines/) recommended for reporting animal research

**Laboratory animals**
For laboratory animals, report species, strain, sex and age OR state that the study did not involve laboratory animals.

**Wild animals**
Provide details on animals observed in or captured in the field; report species, sex and age where possible. Describe how animals were caught and transported and what happened to captive animals after the study (if killed, explain why and describe method; if released, say where and when) OR state that the study did not involve wild animals.

**Field-collected samples**
For laboratory work with field-collected samples, describe all relevant parameters such as housing, maintenance, temperature, photoperiod and end-of-experiment protocol OR state that the study did not involve samples collected from the field.

**Ethics oversight**
Identify the organization(s) that approved or provided guidance on the study protocol, OR state that no ethical approval or guidance was required and explain why not.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

### Human research participants

Policy information about [studies involving human research participants](https://www.icmje.org)

**Population characteristics**
Describe the covariate-relevant population characteristics of the human research participants (e.g. age, gender, genotypic information, past and current diagnosis and treatment categories). If you filled out the behavioural & social sciences study design questions and have nothing to add here, write “See above.”

**Recruitment**
Describe how participants were recruited. Outline any potential self-selection bias or other biases that may be present and how these are likely to impact results.

**Ethics oversight**
Identify the organization(s) that approved the study protocol.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

### Clinical data

Policy information about [clinical studies](https://www.clinicaltrials.gov)

All manuscripts should comply with the ICMJE guidelines for publication of clinical research and a completed [CONSORT checklist](https://consort-statement.org) must be included with all submissions.

**Clinical trial registration**
Provide the trial registration number from ClinicalTrials.gov or an equivalent agency.

**Study protocol**
Note where the full trial protocol can be accessed OR if not available, explain why.

**Data collection**
Describe the settings and locales of data collection, noting the time periods of recruitment and data collection.

**Outcomes**
Describe how you pre-defined primary and secondary outcome measures and how you assessed these measures.
Dual use research of concern

Policy information about dual use research of concern

Hazards

Could the accidental, deliberate or reckless misuse of agents or technologies generated in the work, or the application of information presented in the manuscript, pose a threat to:

No  Yes
☐ ☐ Public health
☐ ☐ National security
☐ ☐ Crops and/or livestock
☐ ☐ Ecosystems
☐ ☐ Any other significant area

Experiments of concern

Does the work involve any of these experiments of concern:

No  Yes
☐ ☐ Demonstrate how to render a vaccine ineffective
☐ ☐ 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.

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

Specify voxel-wise or cluster-wise and report all relevant parameters for cluster-wise methods.

*See Eklund et al. 2016*

#### 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.