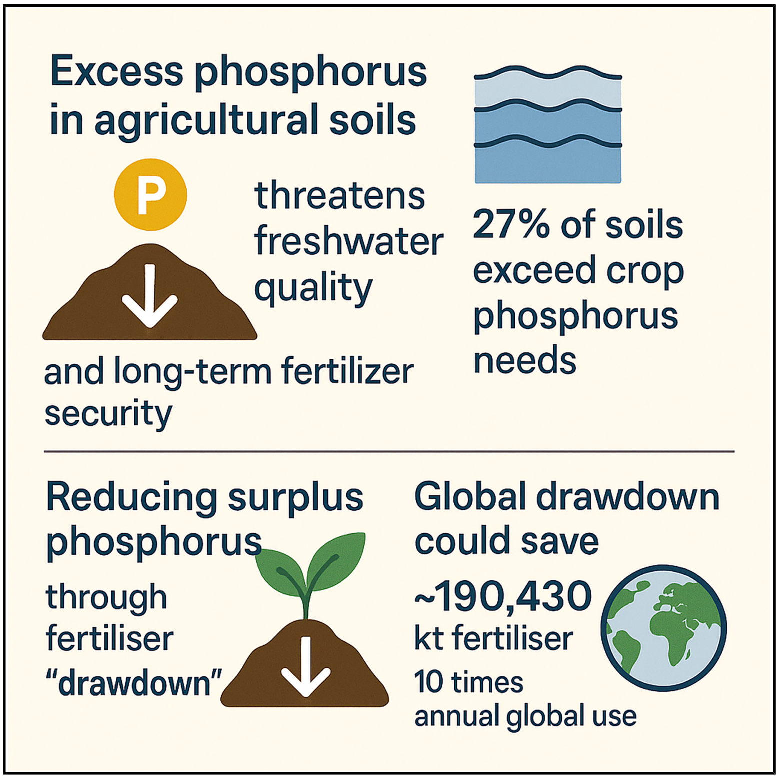
One Earth

Article

Managing the reduction of soil phosphorus can prolong global reserves of fertilizer phosphorus and improve water quality

Graphical abstract



Highlights

- Overuse of phosphorus (P) fertilizer harms waterways and wastes a limited resource
- Halting excess fertilizer use lowers soil phosphorus and decreases losses to water
- Drawdown of soil P saves 230 B USD and helps 3 B people affected by algal blooms

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In brief

Phosphorus fertilizer helps crops grow but comes from limited resources. Many farms have used too much, raising soil levels beyond what is needed, thus increasing phosphorus losses to rivers and lakes and causing harmful algal blooms. By stopping unnecessary use, soil phosphorus drops over time. A global study found this could save large amounts of fertilizer, worth around 230 billion USD, and improve water quality for about 3 billion people, all while still supporting strong crop growth. Efficient phosphorus use means less waste, lower costs, and less pollution.

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Managing the reduction of soil phosphorus can prolong global reserves of fertilizer phosphorus and improve water quality

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SCIENCE FOR SOCIETY Phosphorus fertilizers are vital for food production but come from limited global sources. Overuse has led to excess phosphorus in soils, which can run off into waterways, causing harmful algal blooms and fish kills. A simple fix is to stop applying fertilizer, but the rate at which soil phosphorus drops varies by soil type and crop. Using global trial data, we modeled how long it takes for soil phosphorus to reach optimal levels for six key crops and improved grassland. Regions like Europe, with high phosphorus buildup, will take the longest. Still, reducing phosphorus to optimal levels could save 10 years' worth of global fertilizer use, about 230 billion USD, and significantly improve water quality for up to 3 billion people. Smarter phosphorus management can maintain yields, save money, and reduce environmental harm.

SUMMARY

Excess phosphorus in agricultural soils threatens freshwater quality and long-term fertilizer security. Globally, 27% of soils exceed crop phosphorus needs (plant-available soil test phosphorus as Olsen phosphorus), contributing to runoff that degrades water quality for 3 billion people. Reducing surplus phosphorus through fertilizer cessation (“drawdown”) is low cost, but rates remain poorly understood. We analyzed ∼12,700 observations from 225 trials in 21 countries to model the time for Olsen phosphorus to reach optimal agronomic thresholds across major crops and improved grassland. Drawdown rates ranged from 9 (Oceania and Asia) to 14 (Europe) years. Our model suggests that global drawdown could save ∼190,430 kt of fertilizer, 10 times the annual global use. These findings highlight opportunities to maintain yields, improve water quality, and deliver economic benefits, supporting better-informed agricultural practice and environmental polices worldwide.

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INTRODUCTION

Long-term overuse of phosphorus fertilizer for crop growth has led to excessive plant-available soil test phosphorus concentrations in approximately 27% of global agricultural soils, particularly in temperate, highly developed regions.[1] These enriched concentrations exceed crop-specific thresholds in soil test phosphorus and pose sustainability concerns because they waste a finite resource[2,3] and increase the risk of phosphorus losses to water bodies, where it can promote algal blooms. It is estimated that undesirable levels of algal growth negatively impact water resources for an estimated 3 billion people.[4]

Reducing or stopping phosphorus fertilizer inputs is a management practice that can lower soil test phosphorus concentrations cost effectively and may also limit losses to water.[5,6] However, the rate at which soil test phosphorus decreases (termed "drawdown"), and hence the time that soil test phosphorus may take to reach a desired concentration (like an agronomic crop threshold), varies widely depending on soil properties (e.g., pH, texture, organic matter, aluminum, iron, and calcium concentrations), crop type, climate, and removal via harvest.[6,7] As a result, drawdown times may range from a few years to many decades.[8,9]

Early studies, particularly from long-term trials in Europe and North America, identified factors influencing phosphorus accumulation.[10–12] With a change of emphasis toward increasing agronomic and economic phosphorus use efficiency and minimizing water quality impact, some of those same trials ceased applying phosphorus fertilizer, while some new trials were established to study drawdown.[8,9,13] Because they were established for different purposes, the phosphorus data from many of these trials have not been published. However, their experimental design, which includes a control (i.e., nil fertilizer) and data on soil, climate, and management, allows for their use in modeling drawdown.

Despite these data, existing research has not been generalized to broader geographic contexts. Most drawdown studies are site specific and lack extrapolation, and no model currently predicts drawdown rates at the regional or global scale.[14] However, by including trials with an unfertilized control or those designed with staggered initial soil phosphorus concentrations (termed "phosphorus-gradient trials"[15]), it is possible to expand spatial coverage and predictive capacity.

Here, we modeled the time required for phosphorus-enriched soils to drawdown to an agronomic threshold in soil test phosphorus (Olsen method) of 15 mg kg^{-1}[16] using ∼12,700 observations from 225 trials across 21 countries. Our model accounted for variation in soil properties and climate across six globally important[17] crops (barley [*Hordeum vulgare*], maize [*Zea mays*], rice [*Oryza sativa*], rye [*Secale cereale*], soybean [*Glycine max*], and wheat [*Triticum aestivum*]) and improved grassland, which was included for beef or dairy cattle production that received fertilizer to support pasture growth for forage or hay using the same soil test threshold.[18] We found that drawdown times varied by region, ranging from 9 years in Oceania and Asia to 14 years in Europe. The analysis also found the potential to save approximately 190,430 kt of phosphorus fertilizer, nearly 10 times the current annual global consumption, without compromising yields. These findings demonstrate that strategic reductions in fertilizer inputs may prolong global reserves of fertilizer phosphorus, reduce economic waste, and mitigate phosphorus-driven water quality impacts.

RESULTS

We collated data for soil test phosphorus and metadata for 225 trials. We fitted these data to a model of the decrease of Olsen phosphorus concentrations over time as a function of a drawdown rate coefficient (k). We then used an array of soil and climatic variables to predict the coefficient with the aim of estimating the possible time to draw down Olsen phosphorus and savings in phosphorus fertilizer for areas with Olsen phosphorus exceeding the agronomic optimum (of 15 mg kg^{-1}) for six globally important crops and improved grassland. This process required a series of checks to ensure that the data were fit for purpose, converting soil test phosphorus concentrations into Olsen phosphorus (the most reported measure of plant available phosphorus, globally[19]) and inputting associated parameters for modeling drawdown from suitable global databases where local observations were missing. The model's output of mean drawdown rates and savings in phosphorus fertilizer was summarized by continent. We also included estimates for all other cropland, on the assumption that, with time, cultivars will become more phosphorus efficient.[20,21] However, we recognize that in the interim, these other crops will have higher agronomic optima.[16]

Observed and modeled declines in soil test phosphorus

Across 225 trials, the time of measured drawdown ranged from 4 to 108 years, with a median length of 17 years (Table 1). Trials were from 21 countries (Figure 1), largely from Germany ($n = 41$), the United States ($n = 37$), and the United Kingdom ($n = 20$) (Table 1), collectively representing 43% of global cropland and 60% of global grassland areas >15 mg kg^{-1} (see Note S1 and Table S1). Among land uses, 177 trials were annual cropping (i.e., with good representation of barley, maize, rye, soybean, and wheat but only two trials under rice), 24 were improved grassland (i.e., hay or silage), and 24 were grazed improved grassland (Figure 1). The initial Olsen phosphorus concentration ($Olsen\text{-}P_i$) was greatest in grazed improved grassland, followed by improved grassland and cropping trials, but drawdown rates (k) were greatest in improved grassland, then grazed improved grassland, and finally cropland (Figure S1; Table S2).

To predict the drawdown rate coefficient (k), we confirmed that data parameters used in the model from global databases could be used where observations were missing (Tables S2 and S3), and that phosphorus-gradient trials (with multiple $Olsen\text{-}P_i$ treatments studied over a maximum of 6 years) could be used when phased like trials with a single drawdown phase (termed control) (Note S2; Figure S2). We also note that while drawdown rates tended to be higher in soils with higher Olsen phosphorus concentrations, the quotient of k by $Olsen\text{-}P_i$ was similar across land uses (Table 2). No difference in drawdown was noted despite the fact that the cycling of phosphorus is likely to be faster in grazed than improved grassland.[22] We therefore pooled the data across land uses when modeling drawdown rates but present the outputs by land use (crops and improved grassland) to be more relevant for land management. We also

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Table 1. Descriptive statistics for trial observations

Country	Count of trials	Most common sampling depth (cm)	Median length of record (years)	Median initial Olsen phosphorus (mg kg^{-1})	Mean years to 15 mg kg^{-1}
Argentina	14	20	11	11	2.1
Australia	10	10	5	47	5.2
Austria	18	25	28	56	–[a]
Brazil	2	15	13	6	–
Canada	10	15	6	59	8.5
China	8	20	14	8	1.3
Denmark	10	23	21	38	8.1
Finland	3	20	7	41	13.3
France	5	25	18	18	–
Germany	41	25	30	34	13.3
India	3	15	21	24	3.8
Ireland	13	10	12	53	4.1
Israel	2	20	5	39	3.8
Italy	2	30	13	34	–
Korea	1	20	34	39	–
Netherlands	4	5	17	60	17.5
New Zealand	9	7.5	21	22	9.5
Sweden	8	20	44	23	–
Switzerland	5	20	26	14	0.9
United Kingdom	20	23	20	23	7.9
USA	37	20	15	20	8.3
World	225	20	17	31	6.9

Count and the mean sampling depth, length of record, and starting Olsen phosphorus concentration for trials in each country.

[a] A high share of trials were without a significant *Olsen-P$_i$* or *k* coefficient or with Olsen phosphorus concentrations <15 mg kg^{-1}, which prevented the calculation of an average value.

compared the representativeness of our observational data against the same variables globally, separating cropland from improved grassland but combining grazed and ungrazed improved grassland, as it was more likely that grazed and ungrazed improved grassland would be managed together than used as part of a cropland rotation. We do note, however, that ∼10% of sites overlapped between land uses, and for these areas, we set the land use to cropland (i.e., as the more widespread land use). It is possible that the inclusion of grassland in a rotation may have reduced the frequency of tillage and potentially drawdown rates in these areas. However, we have no data to suggest if the frequency was significantly different from other cropland, nor could we justify investigating this further, as there was no difference among land uses (Table 2). For improved grassland, five out of eight predictors were similar between the trial and global data, while for croplands, four out of eight predictors exhibited no difference between the trial and global data (Tables S4 and S5).

Model performance

Once filtered to include only those with statistically significant ($p < 0.01$) drawdown rates (*k*), 142 studies (developed from a total of 8,062 observations) were available to predict *k* (99, 21, and 22 for cropland, improved grassland, and grazed improved grassland, respectively). Of the 15 predictors considered for the model of *k*, 10 were significant ($p < 0.05$) and included in the fitted model. After tuning the hyperparameters, the model produced a coefficient of determination of 0.70 and root-mean-square error of 0.044 $years^{-1}$ (compared to the standard deviation of *k* of 0.080 $years^{-1}$; Figure 2). The model outputs the most important predictor as location (i.e., country), followed by soil type (World Reference Base) and a group of soil predictors including organic carbon, clay, pH, and cation exchange capacity. We note that country is likely capturing a combination of climate and soil predictors but also variation in soil sampling depths that tend to vary by jurisdiction or land use. For example, samples are taken at shallower depths (compared to the mean) in countries like New Zealand, Ireland, and the Netherlands with large proportions of grassland (Table 1). *Olsen-P$_i$* was considered important, as was the sum of evapotranspiration during the main growing period of spring–summer. The mean annual phosphorus exported with crop harvest was the least important predictor, despite the different crop types included, but this is not surprising given that most of the crops remove a set amount of phosphorus (i.e., concentration), so the variation of phosphorus removal (by yield and export) is likely constrained relative to soil and climatic drivers/predictors.[23]

The parameters chosen in our model are consistent with other studies of soil test phosphorus drawdown. The only difference is that the importance of our parameters varies from others because of their much smaller sample size; our study is the

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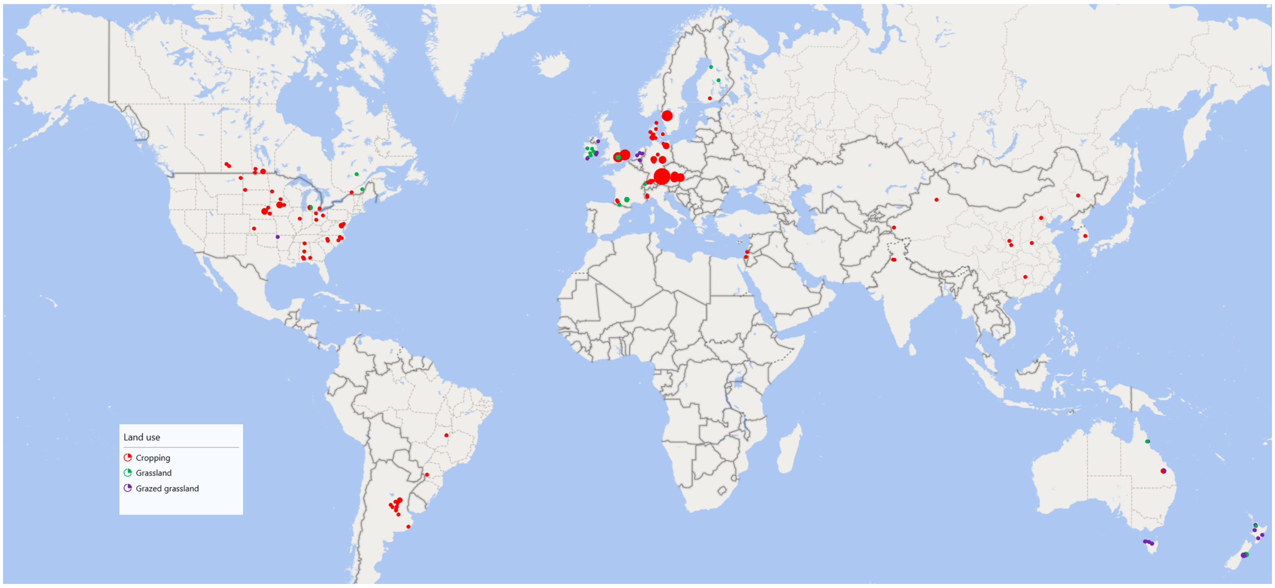

Figure 1. Locations of the 225 soil test phosphorus drawdown trials by land use
Note that the size of the circle is proportional to the number of trials in the location. The base map used data sourced from OpenStreetMap, contributors available under an Open Database License (https://www.openstreetmap.org/copyright).

only one to capture all known drawdown data. However, all studies commonly demonstrated a faster rate of decline with increasing soil test phosphorus concentration, annual rainfall, and/or proportion of silt or clay-sized soil particles and decreasing soil organic matter or carbon.[7,8,24–27] Soil pH was also an important factor for drawdown rates but can be negatively correlated in cropland and positively correlated in improved grassland because liming in these land uses moves soil pH toward the optimal solubility range of 6–7 over time.[5,7,28,29] The inclusion of these parameters in the model points toward a link between the drawdown rate and the extent of soil phosphorus sorption and the crop-specific phosphorus removal rate.[5,30,31] Additional researchers have also found that the rate of drawdown will be buffered by the age of phosphorus inputs, noting that phosphorus buildup and decline will preferentially accumulate in bioavailable inorganic forms that may become increasingly recalcitrant over time.[32–35] It is possible that the different buildup and bioavailability of soil phosphorus enrichment from mineral fertilizer compared to manures could also influence drawdown.[36]

Mean *Olsen Pi* exceeded the agronomic optimum threshold of 15 mg kg^{-1} for cropland and improved grassland by nearly 3-fold, averaging 41–42 mg kg^{-1} globally (Table 3). The greatest *Olsen Pi* concentrations for both land uses occurred in Europe and the least in Africa and Oceania (Table S6). Using drawdown rates, the mean time to reach 15 mg kg^{-1} was shorter for the six annual crops than improved grassland and decreased in the same continental order as *Olsen Pi* concentrations (Tables 3 and S7; Figure 3). Commensurate drawdown rates (k) were faster for the six annual crops than for grassland (Table 3) and fastest generally in Asia (Table S8). The reasons for these differences, as noted above, lie in the interaction between where the crops and improved grassland are grown and the array of different growing conditions and soil types.

DISCUSSION

Our work aimed to determine how long it would take excess soil Olsen phosphorus concentrations to drawdown to an agronomic optimum if fertilizer applications ceased and what the resulting savings in phosphorus fertilizer would be. The time to reach a minimum agronomic optimum threshold has been studied for over half a century in response to an increasing emphasis on phosphorus use efficiency and minimizing phosphorus losses to freshwater.[37] However, before being used as a farm management strategy, it is important to determine if the cessation of phosphorus fertilizer applications results in yield penalties that could impair food supply and, potentially, farm profitability. Fortunately, many studies in Europe and North America have shown that grain yields and liveweight gains (of beef cattle grazing improved grassland) are seldom impaired for 6–20 years when phosphorus fertilizer is stopped, when initial soil test phosphorus concentrations are high (usually at least twice the agronomic optimum),[6,38–42] and when supplied with sufficient nitrogen to encourage crop phosphorus uptake.[9,43–45] Interestingly, a recent meta-analysis found that soil test phosphorus concentrations across 56 sites required 8.4–15.9 years to be reduced by half.[13]

If used as a farm management strategy, we estimated that there could be large savings in phosphorus fertilizer that could prolong current phosphorus reserves and be of economic benefit. The data in Table 3 suggest that the mass phosphorus fertilizer saved (∼190,430 kt, varying from 159,880 to 233,183 kt, continentally the greatest in Europe and the least in Oceania; Table S9) is approximately 10 times the current global annual usage (20,500 kt from 2019 to 2023[46]), potentially prolonging phosphorus reserves for future use. These savings in phosphorus fertilizer translate to economic savings of about 230 billion USD (192–281 billion) at 2024 prices (assuming a

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Table 2. Contrast of coefficients by land use

Coefficient	Land use	Count	Median value	Difference (*p* value)
K	cropping	66	−0.058	0.026
	grassland	14	−0.180	
	grazed grassland	17	−0.069	
Olsen-P_i	cropping	160	28.4	0.041
	grassland	19	38.2	
	grazed grassland	22	54.0	
k/Olsen-P_i	cropping	66	−0.0025	0.132
	grassland	14	−0.0041	
	grazed grassland	17	−0.0016	

Contrasts were made using a Kruskal-Wallis one-way analysis of variance. Different coefficient counts were caused by the lack of a significant fit of Equation 2 to the data. Improved grassland is separated into grazed grassland and grassland that is used to, for example, produce hay.

phosphorus concentration of 12.6% phosphorus and a cost of 152 USD per tonne phosphate rock). Economic savings could be greater in areas with high livestock densities, where phosphorus fertilizer could be replaced with manure that would otherwise be transported elsewhere to help reduce high soil test phosphorus concentrations and the risk of water quality impairment.[47]

The loss of phosphorus and enrichment of streams and rivers has been implicated in causing undesirable levels of algal growth that affect about 3 billion people.[4] However, compared to the agronomic or economic impact, information on the benefit of drawdown in preventing phosphorus loss and improving water quality is less clear because phosphorus can be lost directly from phosphorus fertilizer soon after application, as well as dissolving from previous applications that have been incorporated into the soil or eroding as sediment-bound phosphorus. The rate of dissolved and sediment-bound phosphorus loss declines exponentially after application and is dependent upon runoff to transport phosphorus to surface waters, but annual loss estimates average about 10% of the phosphorus applied.[48–50] We also know that, once phosphorus is in the soil, the rate of dissolved phosphorus loss is proportional to the quotient of soil test phosphorus and phosphorus sorption capacity[51–53] and will likely parallel drawdown rates, while sediment-bound phosphorus is lost via runoff and erosion processes. Global estimates of phosphorus loss by erosion associated with sediment are thought to be halved under a drawdown scenario,[54] but no data exist for the contribution of dissolved phosphorus. When combined with avoiding fertilizer loss soon after application, the combined effect of drawdown may reduce phosphorus losses by ∼60%. Indeed, field-scale modeling estimated that the combined effect of conservation practices and drawdown yielded an average reduction of 62% in phosphorus losses in Maryland,[52] while other researchers have measured reductions in dissolved phosphorus of approximately 50%–65% for wheat-canola fields in Canada.[55] These data infer that while there may be quick economic benefits of ceasing phosphorus fertilizer additions, reducing phosphorus losses and improving water quality may take much longer and require additional strategies if improvements are sought quickly.

It is also important to note that the drawdown rate of environmentally significant phosphorus, as predicted by water- or calcium chloride-extractable phosphorus, is likely to be quicker than soil test phosphorus.[28] Past work has been used to set thresholds in environmental policies, such as specific soil test phosphorus concentrations.[56] However, more recent work has shown that, depending on soil phosphorus sorption capacity, environmental targets may be met faster than drawdown to achieve a minimum agronomic optimum.[57] As environmental targets have the potential to be reached before soils reach an agronomic optimum, it is also important to consider the risk of impairing yield or profit. Yield penalties (e.g., 10%–30%) are well documented when Olsen phosphorus slips below the agronomic optimum.[58–61] Common agronomic advice is to maintain Olsen phosphorus within the lower bound of a range (e.g., 15–20 mg kg^{-1}).[18,62,63] Such an approach may be prudent given the uncertainty that exists in the model (Figure 2; Table 3) and in agronomic thresholds[64] while still allowing for considerable savings in phosphorus fertilizer and water quality improvement.

METHODS

Data

We searched the Google Scholar and SCOPUS databases for articles whose title or abstract contained the terms “soil test,” “phosphorus” or “phosphate,” and “drawdown,” “decline,” “legacy,” or “residual.” We inspected each article to select those with data for the decrease in annual (or more frequently sampled) soil test phosphorus concentrations over 4 or more years for plots not receiving phosphorus (although they may have previously received phosphorus) in either improved grassland or mixed-cropping land uses (combinations of barley, maize, rye, soybean, and wheat or monocultures of rice). Globally, these represented the two most common land-use and crop types that are likely to have phosphorus-enriched soils[19,65]; grazed rangeland, forests, and other land types, like mountainous areas or deserts, are commonly unfertilized and thus lower in soil test phosphorus. Four years was determined to be the minimum possible time over which the residual effect of previous fertilizer applications would be detected.[66] We accepted two types of studies for inclusion into the database. The first and more common type (termed “control”) examined the decline in soil test phosphorus over time from a single starting point. The second type examined the decline from a range of initial soil test

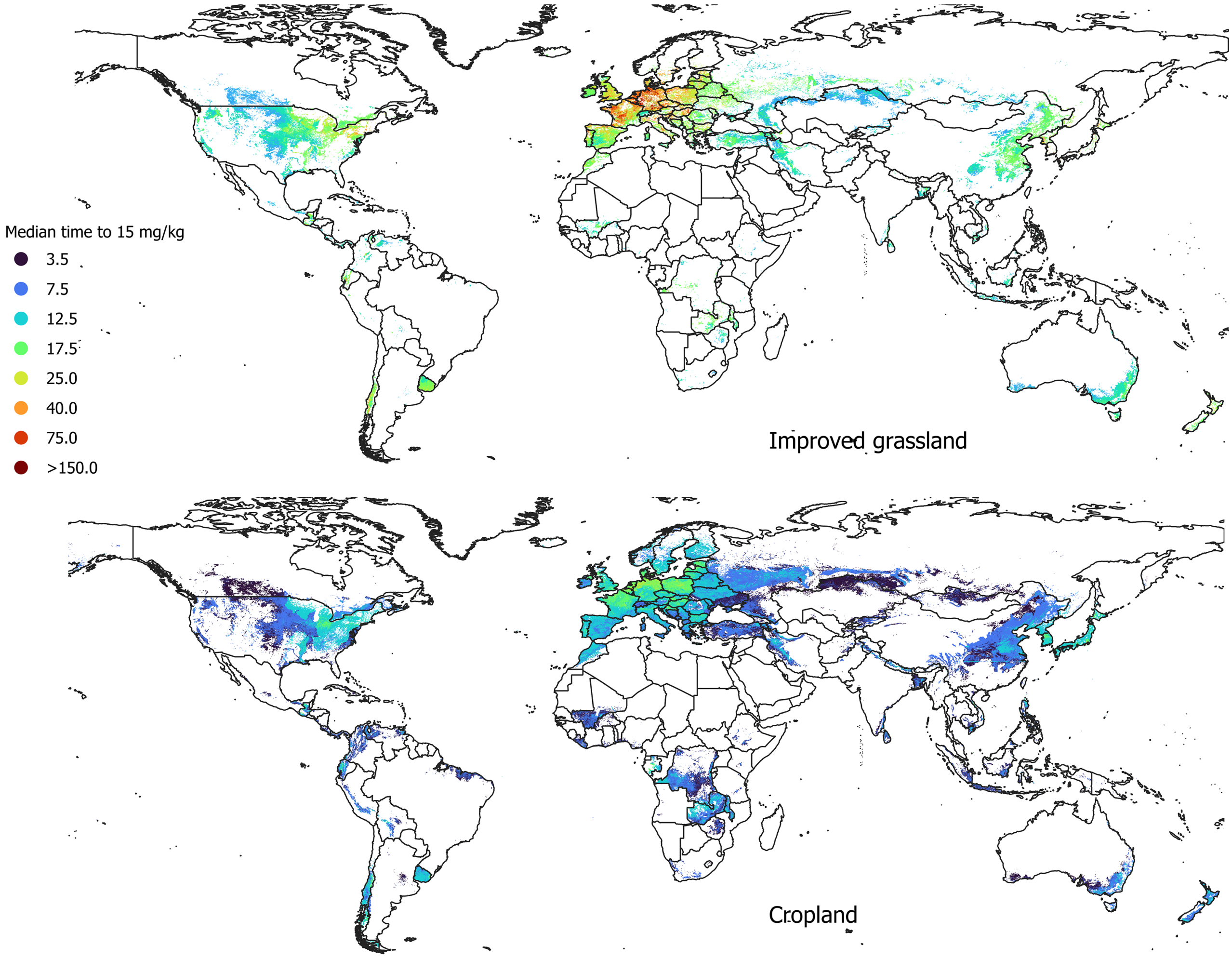

Figure 2. Median time (years) to reach Olsen soil test concentrations of 15 mg kg^{-1} from six crops (consisting of barley, maize, rice, rye, soybeans, and wheat) and improved grassland from their present-day Olsen phosphorus concentrations under nil fertilizer (drawdown)
Note that estimates are for 1 km^2 points and can overlap if improved grassland is included as part of a crop rotation. The base map is from GADM (https://gadm.org/data.html).

phosphorus concentrations, often established using different rates of phosphorus fertilizer. This second approach was termed "phosphorus gradient" and allowed for the measurement of soil test phosphorus decline over a shorter period than the control approach by beginning each treatment at a different soil test phosphorus concentration. Data for the phosphorus gradient approach were linked by phasing their starting year according to predictions of soil test phosphorus decline from the highest initial soil test phosphorus concentration.[56] See Note S2 for the validation of this approach.

Where data were only presented in graph form and unavailable digitally from the corresponding authors, we extracted data from the published graphs using the WebPlotDigitizer (https://automeris.io/). To estimate uncertainty, we manually extracted soil test phosphorus data (n = 197) from the graphs of five studies.[5,15,24,28,38] Extracted data were, on average, within 2% of digital copies of the graphed data.

Some locations had multiple trials; we considered those as a single trial unless the soil had been modified significantly by experimental treatments (e.g., tillage or fertilization), which we considered to be altering the soil's pH by ≥1 unit or organic C by 0.5% (n = 10). Differences in these parameters have been found to be influential in crop uptake and soil test phosphorus drawdown.[8] Since 64% of the soil test phosphorus observations collected were measured as Olsen phosphorus and because Olsen phosphorus is the most widely reported globally,[19] we converted ammonium acetate phosphorus, Bray-I phosphorus, ammonium lactate phosphorus, Colwell phosphorus, Mehlich-I or -III phosphorus, Morgan's phosphorus, Truog phosphorus, and water-extractable phosphorus into Olsen phosphorus concentrations using published equations[19,67] (Table S10 and supplemental data file[68]).

After collecting the data, we inspected each trial and removed outliers if they exhibited a value of >1 in a Cook's distance plot.[69] These checks and filters resulted in ∼9,415 observations from 225 trials and 134 locations in 21 countries (Tables 1 and S11). Some (∼15%) of the data were sourced from an existing analysis[8] that fit two equations:

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Table 3. Global area, mean Olsen phosphorus concentration, drawdown rate coefficient, mean time to 15 mg kg^{-1}, and the amount of phosphorus fertilizer saved (kt) during drawdown for areas with Olsen phosphorus concentrations >15 mg kg^{-1} for each crop, improved grassland, and all croplands

Crop[a]	Area (km^2)	Mean Olsen phosphorus (mg kg^{-1})	Drawdown rate coefficient (k)	Mean time to 15 mg kg^{-1} (years)	Phosphorus fertilizer saved (kt)
Barley	306,920	42.7	−0.088 (−0.071 to −0.106)	10.3 (9.4 to 11.6)	18,332 (16,340 to 21,555)
Maize	603,620	39.2	−0.085 (−0.068 to −0.103)	10.0 (9.2 to 11.3)	21,054 (19,041 to 23,965)
Rice	288,507	44.8	−0.084 (−0.067 to −0.102)	9.1 (8.4 to 10.2)	7,162 (6,526 to 8,222)
Rye	74,832	30.3	−0.091 (−0.073 to −0.109)	10.5 (9.5 to 11.9)	6,287 (5,453 to 7,776)
Soybean	316,682	37.3	−0.087 (−0.070 to −0.105)	9.8 (8.9 to 11)	9,444 (8,541 to 10,560)
Wheat	858,999	41.7	−0.087 (−0.070 to −0.105)	10.2 (9.3 to 11.6)	40,163 (35,895 to 46,755)
All six crops	2,449,560	40.6	−0.087 (−0.069 to −0.104)	10.0 (9.1 to 11.3)	102,442 (91,796 to 118,833)
Improved grassland	1,361,540	41.9	−0.079 (−0.063 to −0.096)	12.3 (10.4 to 15.3)	87,988 (68,084 to 115,350)
All cropland	8,012,538	39.9	−0.085 (−0.068 to −0.103)	11.6 (10 to 9.4)	295,210 (328,458 to 382,537)

[a] Crops are identified as per Grogan et al.[65]

$$\text{Olsen} - P_t = (Olsen - P_i) \times e^{(-k \times t)} + C, \qquad \text{(Equation 1)}$$

and a simplified version,

$$\text{Olsen} - P_t = (Olsen - P_i) \times e^{(-k \times t)}, \qquad \text{(Equation 2)}$$

where $Olsen\text{-}P_t$ is the Olsen phosphorus concentration (mg kg^{-1}) at year t, $Olsen\text{-}P_i$ is the Olsen phosphorus concentration in the first year of the trial, k is the coefficient describing the annual rate of Olsen phosphorus decline ($year^{-1}$), t is the number of years since the trial began, and C is the lowest possible Olsen phosphorus concentration. Most of the data did not fit Equation 1, but almost all the data fit Equation 2. For consistency, we therefore used Equation 2 in our analysis but only included those fits that were significant ($p < 0.01$ and $r^2 > 0.65$) for the equation and its coefficients ($p < 0.01$). Statistically non-significant estimates were not biased in terms of representativeness (e.g., across soil types) and therefore may contain information useful for the model. We considered incorporating the non-significant estimates in a multi-level model but concluded that the added model complexity did not yield a better result (see Note S3). It should be noted that the predicted effect of including non-significant sites would have increased drawdown rates and that we temper our interpretations accordingly.

Predicting drawdown rates

To determine drawdown rates and times, we extracted associated data for parameters from each of the studies thought likely to predict k. Where not available, we extracted estimates of associated data for each parameter using global datasets (Table S12), using the following rules.

(1) For estimates of the yield for crops and improved grassland, we used the estimates of barley, maize, rice, rye, soybean, and wheat yield at 30 arc-second resolution.[65,70] Land area for improved grassland was calculated as land identified in the European Space Agency's database as grassland[71] but as cropland in the National Aeronautics and Space Administration (NASA) 2010 World Cropland database,[72] which includes improved grasslands (i.e., grassland that is improved and used for grazing or for hay) but not rangelands that receive no fertilizer phosphorus.

(2) For estimates of plant-available phosphorus, we used the mean of two recently published global datasets of Olsen phosphorus to estimate concentrations for areas identified as cropland or improved grassland.[19,73] Owing to slightly different methods to isolate land use, we used concentrations from McDowell et al.,[19] where land use was cropland or improved grassland, but not in the database of Ringeval et al.[73] We chose to combine databases for cropland to help avoid over- or underestimating soil Olsen phosphorus concentrations.

(3) Estimates of phosphorus retention (i.e., the amount of added phosphorus that is retained, analogous to sorption capacity) were classed via a global raster[74] as low (<40%), medium (40.1%–60%), high (60.1%–80%), and very high (>80%). This raster also listed phosphorus retention in 10% intervals. We checked the validity of these intervals by first checking estimates against observations of phosphorus retention made in 2023 and kept by the ISRIC-World Soil Information database[75] and estimates made specifically for Brazil.[76] If observations were found to fit outside the estimated 10% interval (or greater than 5% of estimates for Brazil), phosphorus retention defaulted to the quartile class.

(4) Mean phosphorus export was calculated using yield estimates and mean concentrations of phosphorus in the crop of 0.23%, 0.58%, 0.36%, and 0.30% for maize, soybean, wheat, and grassland, respectively, adjusted for moisture contents.[23,70]

The final spatial scale was 1 km^2, resulting in approximately 8.1 million data points of cropland and 1.3 million data points of grassland and grazed grassland with >15 mg kg^{-1} Olsen phosphorus.

We constructed models to predict k using gradient boosted regression trees (BRTs)[77] from the parameters in Table S12. We chose BRTs because they consider a combination of

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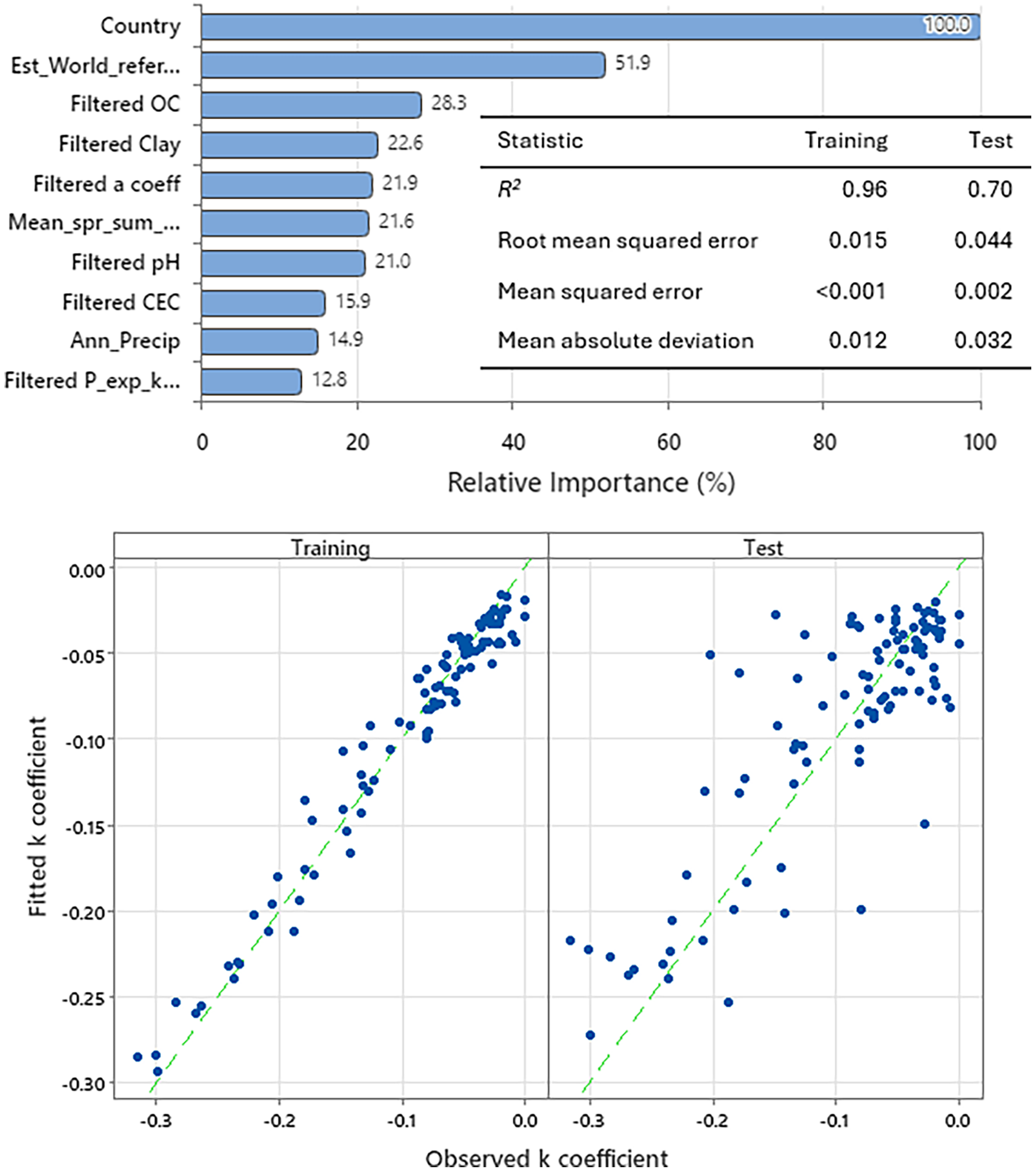

Statistic	Training	Test
R^2	0.96	0.70
Root mean squared error	0.015	0.044
Mean squared error	<0.001	0.002
Mean absolute deviation	0.012	0.032

Figure 3. Final model output performance

Relative importance plots for predictor variables, performance statistics, and plots of the observed versus fitted values of the training and test data for the tuned boosted regression tree model for the prediction of the *k* coefficient in Equation 2.

continuous and categorical data, missing data, and data that cannot be transformed to a normal distribution.[67] Observations of clay, silt, sand, phosphorus retention, cation exchange capacity, organic carbon, pH, phosphorus export, mean precipitation (including snowfall), and mean temperature were available for, on average, 64% of sites. Where observations were not available, we used estimates from the global datasets in Table S12. The correlation between estimates and sites with observations is shown in Table S2.

We used 70% of the data to train the model, with the remainder used to test the output. We eliminated predictor variables one at a time according to their contribution to the coefficient of determination and mean absolute error. We allowed for interactions between the predictors. For the final, most parsimonious model, we tuned hyperparameters to balance model accuracy and generalization. We specified six terminal nodes per tree to constrain overfitting, a learning rate of 0.1 to control the contribution of each tree to the ensemble and prevent unstable updates, and 600 trees to ensure sufficient iterations for convergence given the moderate learning rate.

The final model was used to compare the median values for each predictor between the observations and the global dataset by land use as an estimate of similarity and representativeness. Despite the natural log transformation, some of the predictors remained skewed. Owing to the presence of skew and a small ($n < 200$) sample size, we used a non-parametric Mann-Whitney test to make comparisons between medians (Tables S4 and S5).

Calculating drawdown times and fertilizer saved

The model was used to estimate the k coefficient for each data point globally. We used the current Olsen phosphorus concentration[19,73] to represent $Olsen\text{-}P_i$. Confidence intervals were also generated via bootstrap resampling (1,000 times with replacement) of the dataset and rerunning the models.

The predictions of k were used with Olsen phosphorus concentrations to estimate drawdown times (in years) to 15 mg kg^{-1} for up to 2, 5, 10, 15, 20, 30, 50, 100, and 150 years after the cessation of phosphorus fertilizer additions. These intervals (or drawdown classes) were chosen to recognize the potential for uncertainty in estimates and minimize the presentation of inaccurate values. Drawdown times were mapped in Q-GIS and summed by country and continent.

We calculated the fertilizer saved (by ceasing annual application during drawdown) as the difference between the annual maintenance rate required to maintain the soil Olsen phosphorus concentration at $Olsen\text{-}P_i$ and 15 mg kg^{-1} multiplied by the drawdown time. Since maintenance rates of fertilizer vary by soil phosphorus sorption capacity and strength,[18,78] we intersected a global map of phosphorus retention (an estimate of phosphorus sorption capacity and strength).[74]

RESOURCE AVAILABILITY

Lead contact

Please contact Prof. Rich. McDowell (richard.mcdowell@lincoln.ac.nz) for information related to the data and model used in this study.

Materials availability

This study did not generate new unique materials.

Data and code availability

- All drawdown data that support the findings of this study have been deposited in Figshare.[68]
- Publicly available datasets are available for the cropland extent from https://lpdaac.usgs.gov/news/release-of-gfsad-30-meter-cropland-extent-products/ and for land cover from https://www.esa.int/ESA_Multimedia/Images/2014/10/Land_cover_2010.
- The data used to isolate land above the Olsen phosphorus threshold are available for two databases[16,63]: https://doi.org/10.6084/m9.figshare.14241854 and https://doi.org/10.57745/XZTW7Z.

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AUTHOR CONTRIBUTIONS

R.W.M. co-initiated the study, did the analysis, and wrote the manuscript. O.F., C.D., K.S., Z.P.S., J.D.M., A.J.M., A.E.E., P.A.M., B.J.C.-M., P.S.P., A.S., T.Q.Z., and L.B. aided with data collation. Z.P.S. also helped with the analysis. All authors helped co-author the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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One Earth, Volume *8*

Supplemental information

Managing the reduction of soil phosphorus can prolong global reserves of fertilizer phosphorus and improve water quality

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Supplemental Information

The drawdown of soil test phosphorus can prolong global reserves of fertiliser phosphorus and improve water quality

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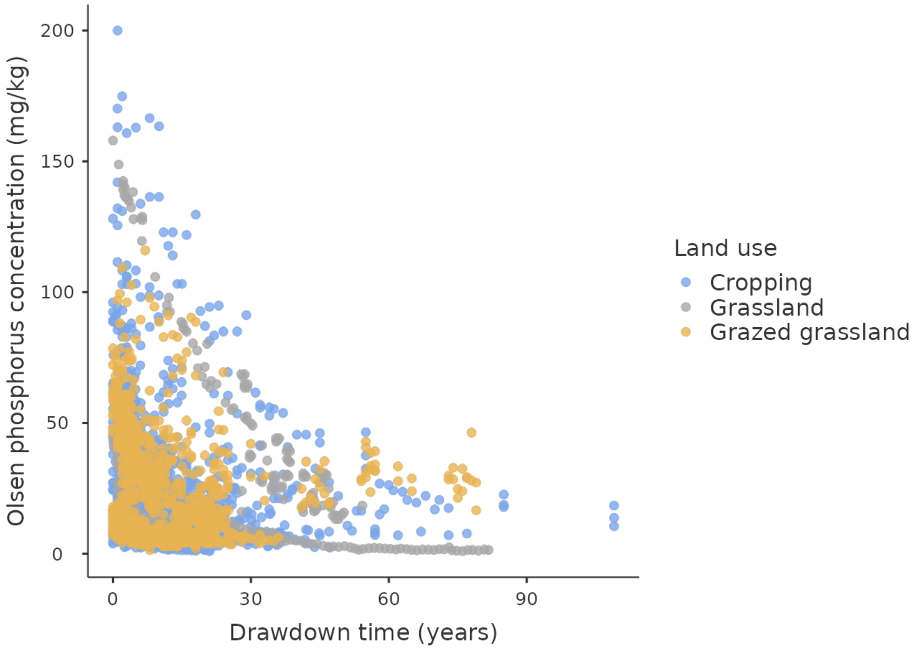
Supplemental Note 1: Spatial representativeness

Data were not available for all countries (n = 172) with areas having Olsen phosphorus concentration > 15 mg kg^{-1}. However, the 21 countries with drawdown data (Supplemental Table 1) comprised 43% of cropland and 60% of grassland global area. They are therefore more spatially representative of areas with Olsen phosphorus concentration > 15 mg kg^{-1} than average. It is also worth noting that because country was the most important predictor of areas with Olsen phosphorus concentration > 15 mg kg^{-1}, predictions in countries with drawdown sites will, on average, be more accurate than those without drawdown sites. Excluding ‘country’ from the list of predictors reduced the coefficient of determination to 0.53 and increased the root mean square error by 25%.

Supplemental Table S1. Cropland and grassland areas (and fractions of the global extent) with Olsen phosphorus concentration > 15 mg kg^{-1} for countries with drawdown sites and studies.

Country (number of sites)	Sum cropland area (km^2)	Sum grassland area (km^2)
China (8)	1199689 (0.149)	97810 (0.071)
United States (37)	1015241 (0.126)	296816 (0.218)
France (4)	276160 (0.034)	79629 (0.058)
Germany (41)	191032 (0.023)	24883 (0.018)
Italy (2)	185151 (0.023)	7940 (0.005)
Canada (10)	138558 (0.017)	24268 (0.017)
New Zealand (9)	93104 (0.011)	2148 (0.001)
Australia (10)	77893 (0.009)	143793 (0.105)
United Kingdom (20)	72302 (0.009)	80717 (0.059)
Brazil (2)	35709 (0.004)	119 (8.740)
Sweden (8)	35200 (0.004)	725 (0.000)
India (3)	34919 (0.004)	752 (0.000)
Denmark (10)	32120 (0.004)	1157 (0.000)
South Korea (1)	26092 (0.003)	148 (0.000)
Austria (18)	24850 (0.003)	2717 (0.001)
Finland (3)	24043 (0.003)	98 (7.197)
Netherlands (4)	12874 (0.001)	10519 (0.007)
Switzerland (5)	11010 (0.001)	2535 (0.001)
Ireland (13)	9946 (0.001)	40859 (0.030)
Israel (1)	3582 (0.000)	253 (0.000)
Argentina (14)	2380 (0.000)	36 (2.644)
Sum represented	3501855 (0.43)	817922 (0.60)
World	8012538	1361540



Supplemental Figure S1. Drawdown rates for extracted data. Olsen phosphorus concentrations (mg kg^{-1}) with drawdown time (years) by land use for the 128 sites (out of 225) for which annual data were available or could be extracted.

Supplemental Note 2: Check of the phosphorus gradient approach

Data collected from short term studies of phosphorus drawdown with treatments representing different starting concentrations were fitted to an exponential decay function where the change in Olsen phosphorus concentrations (Olsen-P_t mg kg^{-1}) over time was a function of the initial concentration (Olsen-P_i mg kg^{-1}) and the exponential of time (t, years) and a decay constant (k, $years^{-1}$) likely to reflect site management and soil type:

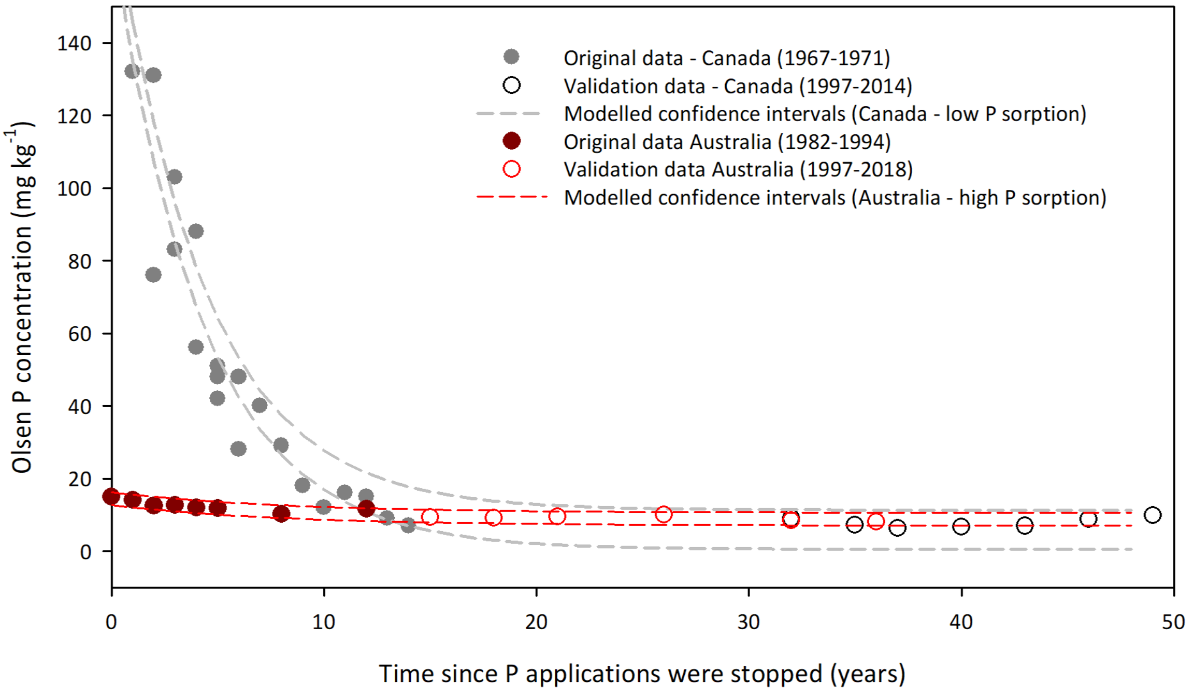
$$P = P_0 . e^{k.t} \qquad \text{[Supplemental Eq 1]}$$

After log-transforming Supplemental Equation 1, *k* can be derived for each treatment from the slope of the linear relationship between time and the natural log of the rate of decline in *Olsen-P* and *Olsen-P_i*. The *Olsen-P_i* from the most enriched treatment was used as a reference from which *t* was estimated for the next most enriched treatment.

While analysing this phosphorus gradient data gives a trial-specific *k* estimate by substituting variance over longer periods of time with variance in initial Olsen phosphorus, there is a risk that it is not exchangeable with the *k* derived from a single continuous nil treatment covering the same variation in initial Olsen phosphorus. To test the validity of the phosphorus gradient approach we augmented the original validation assessment (which was tested in 23 grassland soils in Ireland [1]) with data for drawdown parameters from two independent trials on the same site and soil type in Canada and another two in Australia.

For the Canadian trials, phosphorus fertiliser was applied once in 1967 and Olsen phosphorus was measured each year from 1967 to 1971 [2], and for 19 successive crops (over 5 years) in the greenhouse using the same soil. These data were phased with a new starting point P_0 for the subsequent drawdown treatment for 14 years and the fit of Equation 1 to these data projected out for 50 years (original dataset). The projections were compared to a second independent dataset (validation dataset) [3] that collected data from 1997 to 2014 on adjacent plots established at the same time, but which did not receive any P fertilisation. These independent data validated the approach by sitting within the 95% confidence intervals for the predicted drawdown rates (Supplemental Fig. 1).

Although found to be of low importance in predicting drawdown, we also checked if phosphorus sorption (measured as phosphorus retention; see Supplemental Table 11) and land use (cropland versus grazed grassland) would affect predictions. To do this we incorporated two periods from a long-term trial incorporating a contrast of cropland and grazed grassland on a high phosphorus sorbing soil (phosphorus retention >70%) in Australia. For the Australian trials, phosphorus fertiliser was applied from 1965-1982 then stopped and continuously cropped in sorghum and winter wheat until 2004 when it was converted into permanent pasture [66]. A second trial received the same phosphorus fertiliser but was converted into permanent pasture in 1982. Data from the first trial from 1982-1994 was modelled and the predictions compared to the data from the second trial. Like the trials conducted on the low phosphorus sorbing Canadian trials, the Olsen phosphorus concentrations in the trials conducted on the high phosphorus sorbing Australia soil were within the confidence intervals predicted under drawdown, despite the contrasting land use (Supplemental Fig. 2).



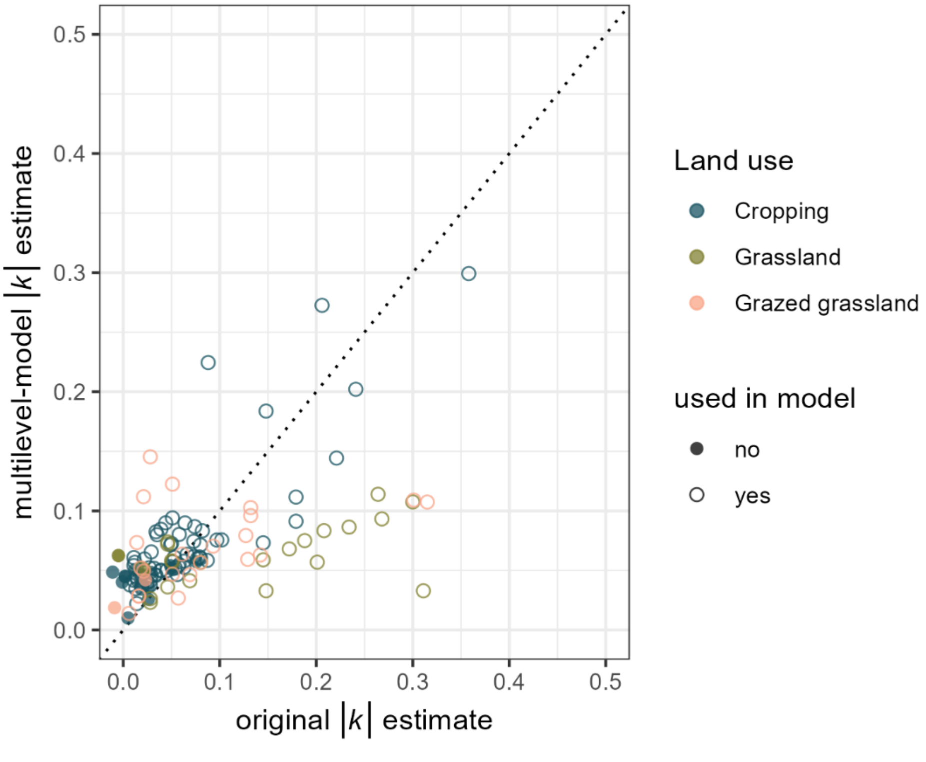
Supplemental Figure S2. The decline in Olsen phosphorus concentration over time observed using: A) the phosphorus gradient approach with field and greenhouse data, projected out for 50 years for two Canadian trials on a low P sorbing soil and B) two adjacent Australian trials on a high P sorbing soil under cropping and grazed grassland. Independently collected data (1997-2014) on adjacent plots without P fertilisation validated the gradient approach by sitting within the 95% confidence intervals for the projected drawdown rates. Likewise, independently collected data for the grazed grassland trial confirmed that different land use and P sorption status did not influence predictions of drawdown from a different land use.

Supplemental Note 3: trial-specific regressions compared to a multilevel model for k

Estimates of *k* were generated on a trial-specific basis via a regression for Equation 1. However, only *k* estimates at the 99% confidence level were kept, resulting in 143 estimates. This 'filter' of *k* induces a potential exaggeration bias [4], since under-powered datasets tend to yield 'significant' parameter estimates that are larger than reality. In other words, the magnitude of estimated *k* for a specific trial is potentially overestimated depending on the trial's power. However, for the 82 missing *k* estimates, only 21 of the corresponding trials had available Olsen phosphorus timeseries.

We tested a multilevel model form of Supplemental Equation 1 that could improve power in at least the 21 cases with missing *k* (but whose *k* was calculated using the gradient approach in Supplemental Note 2). We did not include the remaining 61 trials whose raw data were unavailable. This multilevel model allowed *k* and *Olsen-*P_i to vary across trials but according to common distributions, thus partially pooling information across all available trials [5]. For the 106 trials where both the trial-specific and multilevel estimates of *k* were available (Supplemental Fig. 3), there was reasonable correspondence (median absolute deviation of 0.022, 0.068, and 0.030 yr^{-1} for cropping, grassland, and grazed grassland land uses, respectively) and good correlation (Pearson's correlation of 0.83, 0.53, and 0.46 for cropping, grassland, and grazed grassland land uses, respectively; all significant at 99% confidence level). Notably, in the grassland land use, 11 out of 24 trials originally had *k* estimates more than two-fold (max 9-fold) greater than the multilevel estimate, which may indicate the potential exaggeration bias.

Considering that (1) more *k* estimates are available via the trial-specific regressions, (2) lost *k* estimates due to low power at the trial-level but potentially recoverable via a multilevel model comprise only 21 estimates, and (3) the most worrisome differences between the two statistical estimates are only 11 grassland trials, we opted to use just the trial-specific *k* estimates for consistency. Still, we caution that some of these *k* estimates are likely larger than would be estimated for trials with greater power and, therefore, drawdown times are potentially faster (more conservative) than in reality.



Supplemental Figure S3. Comparisons of the drawdown parameter, *k*, via trial-specific regressions (*x*-axis) and via a multilevel model across all available data (*y*-axis). Dotted line is the 1:1. Solid points were not included in the global models for phosphorus drawdown as they were not statistically significant at the 99% confidence level.

Alignment to global datasets and descriptive statistics for the observations of improved grassland and cropland land uses

Supplemental Table S2. Pearson correlation coefficients between observed values and those estimated from global datasets for each variable. All correlations are significant at the $P<0.01$ level.

Variable	Pearson correlation coefficient
pH	0.62
Clay (%)	0.61
Silt (%)	0.76
Sand (%)	0.77
Organic C (%)	0.68
Cation exchange capacity (meq 100 g^{-1})	0.48
Phosphorus retention (%)	0.65
Phosphorus export (kg ha^{-1})	0.31
Annual precipitation (mm)	0.84
Mean annual air temperature (^{o}C)	0.97

Supplemental Table S3. Descriptive statistics for observations (Q1 and Q3 are quartiles 1 and 3, respectively) for all variables.

Variable	Count	Mean	Standard Deviation	Q1	Median	Q3
pH	219	6.3	0.8	5.8	6.2	6.9
Clay (%)	221	22	11	16	22	28
Silt (%)	211	41	17	28	40	52
Sand (%)	212	36	21	17	33	52
Organic C (%)	224	4.09	3.29	2.15	2.85	4.76
Cation exchange capacity (meq 100 g^{-1})	187	21.0	7.9	19.0	22.2	24.0
P retention (%)	219	37.7	16.7	26.0	26.0	44.0
Total N (%)	186	3.43	1.36	2.39	3.43	4.28
Bulk density (g m^{-3})	186	1.25	0.18	1.07	1.25	1.40
Volumetric water content (%)	186	39.7	4.1	36.9	40.7	42.6
P export (kg ha^{-1})	221	23.1	11.6	16.1	21.6	29.5
Annual precipitation (mm)	224	810	267	611	778	977
Mean annual evapotranspiration (mm)	224	1050	331	793	886	1227
Mean spring-summer evapotranspiration (mm)	224	123	31	100	110	143
Aridity Index (mm mm^{-1})	224	0.83	0.30	0.61	0.81	0.96
Mean annual air temperature (^{o}C)	224	10.4	4.3	8.4	9.4	12
Drawdown rate k coefficient (yr^{-1})	99	-0.093	0.080	-0.134	-0.064	-0.032
Olsen-P_i (mg kg^{-1})	203	38.9	34.2	16.0	30.7	49.2

Supplemental Table S4. Descriptive statistics (N = count, StDev = standard deviation, and IQR = interquartile range) for the global extent and observations in improved grassland for all variables included in the predictive model. The significant difference is given for the contrast of variable median using a Mann-Whitney test with *** indicating significance at the *P*<0.001 level.

Variable	------------- Global extent -------------					----------- Observations -----------					
	N	Mean	StDev	Median	IQR	N	Mean	StDev	Median	IQR	Sig. Diff.
Organic C (g kg^{-1})	1361540	16	19	13	25	48	84	44	69	5	***
Clay (%)	1361540	17	14	20	28	47	20	8	21	9	-
pH	1361540	4.3	3.4	5.9	7.3	48	5.9	0.5	5.8	0.7	-
Olsen Pi (mg kg^{-1})	1361540	42	36	27	27	43	45	31	42	45	-
Mean spring-summer evapotranspiration (mm)	1361460	148	37	149	51.	48	113	30	106	48	***
Cation exchange capacity (meq 100 g^{-1})	1361540	24	7	24	7	45	22	8	23	10	-
Mean annual precipitation (mm yr^{-1})	1361460	717	389	651	498	48	981	253	1017	373	***
P export (kg ha^{-1} yr^{-1})	1163915	25	14	21	15	47	23	10	22	10	-

Supplemental Table S5. Descriptive statistics (N = count, StDev = standard deviation, and IQR = interquartile range) for the global extent and observations in cropland for all variables included in the predictive model. The significant difference is given for the contrast of variable median using a Mann-Whitney test with *** indicating significant at the *P*<0.001 level.

Variable	------------- Global extend -------------					----------- Observations -----------					
	N	Mean	StDev	Median	IQR	N	Mean	StDev	Median	IQR	Sig. Diff.
Organic C (g kg^{-1})	7819591	35	25	29	25	176	29	15	26	15	-
Clay (%)	7821951	27	8	27	10	174	23	11	21	14	***
pH	7820030	6.5	0.8	6.5	1.1	171	6.4	0.9	6.3	1.0	-
Olsen Pi (mg kg^{-1})	8012538	40	30	29	22	159	37	35	28	28	-
Mean spring-summer evapotranspiration (mm yr^{-1})	8011133	72	44	59	50	176	125	31	110	46	***
Cation exchange capacity (meq 100 g^{-1})	7819834	23	7	23	4	142	21	8	22	4	***
Mean annual precipitation (mm)	8011133	823	468	653	437	176	763	251	704	274	-
P export (kg ha^{-1} yr^{-1})	7412742	29	17	28	26	174	23	12	21	14	***

Supplemental Table S6. Areas >15 mg kg^{-1} and mean *Olsen-Pi* (mg kg^{-1}) for each major crop, all six major crops combined, improved grassland, and all cropland by continent.

Parameter	Crop	Africa	Asia	Europe	North America	Oceania	South America
Area of crop (km^2)	Barley	16,850	42,019	216,758	23,017	6,534	1,741
	Maize	22,717	185,551	128,587	259,707	254	6,804
	Rice	3,742	264,749	4,478	9,600	422	5,514
	Rye	26	4,651	68,918	1,181	48	7
	Soybean	377	52,496	8,559	254,191	34	1,026
	Wheat	26,177	290,723	383,170	139,889	14,286	4,754
	All six crops	69,890	840,190	810,471	687,585	21,578	19,847
	Improved grassland	29,476	354,266	426,284	333,282	145,942	72,290
	All cropland	908,931	2,178,008	3,269,250	1,198,919	171,442	285,988
Olsen Pi	Barley	24.8	29.1	57.6	29.8	32.8	33.6
	Maize	23.8	29.1	54.1	30.0	34.8	29.2
	Rice	36.1	28.5	57.5	31.0	21.1	31.7
	Rye	22.8	30.0	36.8	32.4	22.2	27.5
	Soybean	25.7	29.4	49.6	30.7	22.4	25.8
	Wheat	25.3	29.1	57.1	30.2	32.8	30.9
	All six crops	25.2	28.9	55.0	30.3	32.6	30.5
	Improved grassland	31.2	24.6	77.8	25.5	23.9	38.2
	All cropland	23.7	28.4	56.8	29.7	31.8	29.4

Supplemental Table S7. Mean drawdown times (years) by continent to reach 15 mg kg^{-1} for each major crop, all six major crops combined, improved grassland, and all cropland. The 95 percent confidence intervals are given in parentheses.

Crop	Africa	Asia	Europe	North America	Oceania	South America
Barley	9.1 (8.4 to 10.1)	8.1 (7.5 to 9.0)	12.2 (11.0 to 14.0)	8.7 (8.3 to 9.6)	8.4 (7.7 to 9.2)	11.0 (10.2 to 12.3)
Maize	8.7 (8.0 to 9.7)	8.3 (7.7 to 9.3)	11.9 (10.7 to 13.7)	9.1 (8.5 to 10)	8.8 (8.1 to 9.7)	9.8 (9.1 to 11)
Rice	8.5 (7.8 to 9.5)	8.5 (7.8 to 9.5)	10.4 (9.4 to 11.4)	11.1 (10.4 to 13)	7.7 (7.2 to 8.8)	9.7 (9.0 to 10.9)
Rye	11.6 (10.8 to 12.4)	7.9 (7.4 to 8.8)	12.2 (10.9 to 14.0)	9.0 (8.5 to 9.9)	7.2 (6.7 to 8.2)	10.3 (9.4 to 12)

Soybean	9.2 (8.5 to 10.2)	8.2 (7.6 to 9.2)	11.4 (10.2 to 13.0)	9.3 (8.7 to 10.3)	8.0 (7.3 to 9.0)	9.8 (9.2 to 11)
Wheat	9.2 (8.5 to 10.3)	8.1 (7.5 to 9)	12.1 (10.9 to 14)	9.1 (8.5 to 10.1)	8.4 (7.7 to 9.2)	10.3 (9.5 to 11.6)
All six crops	9.0 (8.3 to 10.0)	8.3 (7.6 to 9.2)	12.1 (10.9 to 13.9)	9.2 (8.6 to 10.2)	8.3 (7.7 to 9.2)	10.0 (9.3 to 11.2)
Improved grassland	11.7 (10.6 to 13.5)	7.8 (7.1 to 8.7)	20.5 (15.8 to 27.4)	8.5 (7.8 to 9.7)	8.3 (7.7 to 9.3)	12.4 (11.1 to 15.6)
All cropland	10.1 (8.7 to 8.4)	9.0 (8.1 to 7.5)	14.0 (12.1 to 11.0)	9.6 (9.0 to 8.3)	9.2 (8.8 to 7.7)	12.3 (9.9 to 10.2)

Supplemental Table S8. Drawdown rate coefficient (*k*; absolute value shown for clarity) for each major crop, all six major crops combined, improved grassland, and for all cropland >15 mg kg^{-1} Olsen phosphorus by continent. The 95 percent confidence intervals are given in parentheses.

Crop	Africa	Asia	Europe	North America	Oceania	South America
Barley	0.061 (0.046 to 0.076)	0.104 (0.085 to 0.123)	0.082 (0.066 to 0.100)	0.094 (0.077 to 0.113)	0.098 (0.080 to 0.117)	0.074 (0.058 to 0.091)
Maize	0.062 (0.047 to 0.078)	0.099 (0.081 to 0.118)	0.082 (0.065 to 0.099)	0.085 (0.068 to 0.103)	0.100 (0.082 to 0.119)	0.071 (0.055 to 0.087)
Rice	0.060 (0.045 to 0.075)	0.098 (0.080 to 0.117)	0.084 (0.067 to 0.101)	0.056 (0.042 to 0.071)	0.075 (0.059 to 0.092)	0.068 (0.053 to 0.085)
Rye	0.079 (0.062 to 0.096)	0.108 (0.089 to 0.127)	0.082 (0.065 to 0.100)	0.094 (0.077 to 0.113)	0.076 (0.059 to 0.092)	0.074 (0.058 to 0.090)
Soybean	0.064 (0.049 to 0.079)	0.102 (0.083 to 0.121)	0.084 (0.067 to 0.101)	0.083 (0.067 to 0.101)	0.073 (0.057 to 0.090)	0.062 (0.047 to 0.078)
Wheat	0.062 (0.047 to 0.077)	0.104 (0.085 to 0.123)	0.082 (0.066 to 0.100)	0.087 (0.070 to 0.105)	0.098 (0.080 to 0.117)	0.072 (0.056 to 0.089)
All six crops	0.061 (0.047 to 0.077)	0.101 (0.082 to 0.120)	0.082 (0.066 to 0.100)	0.085 (0.068 to 0.103)	0.098 (0.080 to 0.117)	0.070 (0.055 to 0.087)
Improved grassland	0.058 (0.043 to 0.073)	0.092 (0.074 to 0.110)	0.070 (0.055 to 0.087)	0.085 (0.068 to 0.102)	0.079 (0.062 to 0.096)	0.054 (0.040 to 0.068)
All cropland	0.061 (0.046 to 0.077)	0.098 (0.080 to 0.117)	0.082 (0.066 to 0.100)	0.086 (0.069 to 0.104)	0.110 (0.091 to 0.130)	0.071 (0.055 to 0.087)

Supplemental Table S9. The sum of fertiliser phosphorus saved (kt) in drawdown to 15 mg kg^{-1} Olsen phosphorus for each major crop, all major crops combined, improved grassland, and all cropland by continent. The 95 percent confidence intervals are given in parentheses.

Crop	Africa	Asia	Europe	North America	Oceania	South America
Barley	573 (535 to 609)	697 (648 to 775)	16,650 (14,763 to 19,722)	286 (276 to 311)	78 (72 to 86)	48 (46 to 52)
Maize	420 (387 to 473)	4,239 (3,824 to 4,800)	9,182 (8,257 to 10,679)	7,054 (6,428 to 7,830)	7 (7 to 8)	152 (140 to 177)
Rice	55 (51 to 62)	6,322 (5,752 to 7,248)	322 (289 to 369)	333 (316 to 392)	6 (5 to 7)	124 (113 to 144)
Rye	1 (1 to 1)	96 (90 to 106)	6,159 (5,334 to 7,633)	31 (28 to 35)	1 (1 to 1)	<1 (0 to 1)
Soybean	6 (5 to 6)	1,340 (1,213 to 1,507)	571 (525 to 669)	7,507 (6,780 to 8,356)	<1 (0 to 1)	19 (18 to 22)
Wheat	956 (902 to 1,018)	5,996 (5,322 to 6,673)	30,694 (27,318 to 36,306)	2,175 (2,036 to 2,378)	173 (159 to 194)	169 (157 to 186)
All six crops	2,011 (1,881 to 2,169)	18,691 (16,849 to 21,109)	63,577 (56,486 to 75,377)	17,386 (15,864 to 19,302)	264 (243 to 295)	512 (473 to 581)
Improved grassland	863 (782 to 1,008)	6,054 (5,439 to 6,872)	69,743 (51,603 to 93,954)	6,679 (6,076 to 7,948)	2,278 (2,099 to 2,548)	2,372 (2,084 to 3,019)
All cropland	15,814 (14,593 to 17,670)	46,258 (42,047 to 52,635)	223,561 (199,244 to 264,585)	30,411 (27,951 to 33,932)	5,211 (4,728 to 5,607)	7,201 (6,647 to 7,201)

Supplemental Table S10. Equations (sourced from McDowell *et al.* [6] and Steinfurth *et al.* [7]) used to estimate Olsen phosphorus from other soil test phosphorus methods and the soil test phosphorus value equivalent to the threshold of 15 mg kg^{-1}.

Soil test phosphorus method	Equation to convert each soil test phosphorus (x) method to Olsen phosphorus	Concentration (mg kg^{-1}) in soil test phosphorus equivalent to 15 mg kg^{-1} Olsen phosphorus
Bray-I	$0.49x + 3.1$	27.5
Colwell	$(x/2.869) + 2.93$	34.7
Ammonium acetate	$2.58x$	5.8
Ammonium lactate	$0.35x$	42.8
Morgan's	$2.91x + 5.8$	3.2
Mehlich-I	$(1.52x).0.47 + 2.4$	17.7
Mehlich-III	$0.47x + 2.4$	29.5
Truog	$1.38x + 0.06$	10.8
Water extractable	$25x$	0.6

Supplemental Table S11. Summary data for the 225 trials included in the study. Blank cells indicate no available value.

Country	Trial type	Latitude	Longitude	Land use	First year	Observed runtime (yrs)	Soil type	pH	Clay (%)	Silt (%)	Sand (%)	Organic C (g kg^{-1})	Cation exchange capacity (meq 100 g^{-1})	P retention (%)	P export (kg ha^{-1} yr^{-1})	Annual pre-cipitation (mm)	Spring-Summer ET (mm/month)	*k* coeff	Olsen-Pi (mg kg^{-1})	Reference
Argentina	Control	-35.145	-60.892	Cropping		7	Phaeozems	6.6	15	20	65	25	22	26	10	1022	170	-0.039	7	[8]
Argentina	Control	-31.723	-60.608	Cropping	2008	9	Solonetz	7.2	43	52	6	40			16.3	1035	173			*[a]
Argentina	Control	-34.241	-61.543	Cropping	2007	11	Phaeozems	6.6	16	43	41	27	24		19.5	972	171			*
Argentina	Control	-34.239	-61.588	Cropping	2001	17	Phaeozems	6.7	12	53	35	27	22	26	21.4	971	172	-0.033	9	*
Argentina	Control	-32.567	-61.137	Cropping	2001	10	Phaeozems	6.5	25	73	3	31	24	26	16.4	979	173	-0.039	9	*
Argentina	Control	-34.008	-61.56	Cropping	2001	17	Phaeozems	6.3	18	62	20	39	24	26	26.5	965	171	-0.029	9	*
Argentina	Control	-33.49	-62.529	Cropping	2001	17	Phaeozems	6.2	16	56	28	26	21	26	24.7	920	176	-0.028	12	*
Argentina	Control	-33.377	-61.362	Cropping	2001	16	Phaeozems	6.1	18	79	3	24	22	26	23.4	947	172			*
Argentina	Control	-32.944	-63.052	Cropping	2009	7	Phaeozems	6.8	18	55	25	31	21	26	26.9	833	178			*
Argentina	Control	-31.787	-60.505	Cropping	2008	9	Solonetz	6.3	32	66	19	31	22	26	20.4	1086	174			*
Argentina	Control	-37.843	-58.156	Cropping	2001	8	Phaeozems	6.6	23	32	41	63	26	44	16.6	842	149			*
Argentina	Control	-32.219	-61.733	Cropping	2001	17	Phaeozems	6	21	77	3	37	23	26	30.9	947	173	-0.053	31	*
Argentina	P gradient	-31.848	-60.538	Cropping	2007	10	Luvisols	6.1	32	66	2	31	23	26	47.8	1035	173	-0.066	11	*
Argentina	P gradient	-31.848	-60.538	Cropping	2006	11	Vertisols	7.2	43	52	6	40	23	26	47.8	1035	173	-0.074	30	*
Australia	Control	-24.81	149.8	Cropping	1982	36	Vertisols	6.6	32	18	50	16	24	50	5.9	686	209	-0.014	13	*
Austria	Control	48.2	16.75	Cropping	1976	28	Chernozems	7.5	18	42	40	22	24	44	21.4	529	132		28	[9]
Austria	Control	48.2	16.75	Cropping	1976	23	Chernozems	7.4	18	42	40	22	24	44	18.4	529	132		56	*
Austria	Control	48.2	16.75	Cropping	1976	23	Chernozems	7.4	18	42	40	22	24	44	21.4	529	132		98	*
Austria	Control	48.2	16.75	Cropping	1976	28	Chernozems	7.5	18	42	40	22	24	44	18.7	529	132	-0.007		*
Austria	Control	48.2	16.75	Cropping	1976	28	Chernozems	7.4	18	42	40	22	24	44	19.8	529	132	-0.451	109	*
Austria	Control	48.13	15.22	Cropping	1987	32	Luvisols	5.5	16	77	7	16	21	26	25.1	836	110		18	[10]
Austria	Control	48.13	15.22	Cropping	1987	32	Luvisols	5.3	16	77	7	17	21	26	33.3	836	110	-0.137	19	*
Austria	Control	48.13	15.15	Cropping	1976	28	Luvisols	6.4	30	67	3	27	22	26	22.5	778	110			*
Austria	Control	48.13	15.15	Cropping	1976	23	Luvisols	6.6	30	67	3	27	22	26	21.7	778	110			*
Austria	Control	48.13	15.15	Cropping	1976	23	Luvisols	6.3	30	67	3	27	22	26	25.2	778	110			*
Austria	Control	48.13	15.15	Cropping	1976	28	Luvisols	6.3	30	67	3	27	22	26	22.9	778	110			*
Austria	Control	48.13	15.15	Cropping	1976	28	Luvisols	6.5	30	67	3	27	22	26	25.7	778	110			*
Austria	Control	48.21	16.63	Cropping	1982	37	Chernozems	7.6	23	52	26	39	24	44	24	540	130		34	[10]
Austria	Control	48.21	16.63	Cropping	1982	37	Chernozems	7.6	23	52	26	42	24	44	17.8	540	130		32	*
Austria	Control	48.61	15.2	Cropping	1976	28	Planosols	4.9	16	36	48	20	20	26	22	661	97			[9]
Austria	Control	48.61	15.2	Cropping	1976	28	Planosols	4.8	16	36	48	20	20	26	16.6	661	97	-1.193	40	*
Austria	Control	48.61	15.2	Cropping	1976	28	Planosols	4.6	16	36	48	20	20	26	17.2	661	97	-0.416	66	*
Austria	Control	48.61	15.2	Cropping	1976	23	Planosols	4.9	16	36	48	20	20	26	16.4	661	97		39	*
Brazil	Control	-15.6	-47.7	Cropping	1999	17	Ferralsols	4.5	54	5	41	55	9	86	36.9	1570	125	-0.032	6	[11]
Brazil	P gradient	-25.73	-53.05	Cropping	2009	8	Leptosols	4.9	72	25	3	45	12	32	14	1329	141			[12]
Canada	P gradient	50.282	-107.757	Cropping	1967	4	Kastanozems	6.7	24	42	34	33	20	44	6.2	387	142	-0.221	158	[2]
Canada	P gradient	50.63	-108.46	Cropping	1967	4	Kastanozems	7.6	65	28	7	26	45	44	5.8	347	146	-0.241	153	*
Canada	P gradient	49.78	-100.47	Cropping	1967	4	Chernozems	7.4	30	39	31	89	28	44	8.5	483	123	-0.206	87	*
Canada	P gradient	49.1	-100.61	Cropping	1967	4	Chernozems	7.2	30	45	25	34	29	44	11.3	464	132	-0.358	187	*
Canada	Control	42.217	-82.733	Cropping	2008	10	Gleysols	6.6	37	28	35	31	21	26	20.4	838	130	-0.077	76	[13]
Canada	Control	49.333	-98.367	Cropping	2007	6	Greyzems	6.8	27	40	32	44	35	26	16.1	550	115	-0.097	32	[14]
Canada	Control	49.333	-98.367	Cropping	2007	7	Greyzems	6.8	27	40	32	44	35	26	16.1	550	115	-0.079	21	*
Canada	P gradient	45.43	-73.933	Cropping	1992	5	Cambisols	6.5	71	19	10	35	21	26	72.8	929	116	-0.027	62	[15]
China	Control	26.753	111.876	Cropping	1991	14	Acrisols	5.7	61	42	29	24	18	92	4.9	1408	121			[16,17]
China	Control	34.298	108.013	Cropping	1991	14	Anthrosols	8.6	17	52	22	11	19	32	10.8	525	137	-0.087	10	*
China	Control	34.79	113.678	Cropping	1991	14	Fluvisols	8.3	13					32	23.4	646	160			*
China	Control	40.22	116.256	Cropping	1991	14	Luvisols	8.2	15					44	8.4	530	164			*
China	Control	43.973	87.433	Cropping	1990	14	Anthrosols	8.1	28	43	24	14	18	50	5.7	242	195			*
China	Control	44.8	126.5	Cropping	1991	14	Phaeozems	6.6	25	50	25	24	29	26	44.4	600	141	-0.102	29	[18]
China	Control	35.267	107.5	Cropping	1978	20	Cambisols	8.2	34	43	23	16	21	44	4.3	540	134	-0.073	6	[19]
China	Control	40.278	116.314	Cropping	1991	18	Luvisols	8.2	21	41	38	14	17	50	8.2	600	156	-0.058	5	[20]
Denmark	Control	55.55	9.32	Cropping	1975	20	Luvisols	6	11	18	71	25	20	50	12.9	862	90	-0.237	31	[21]
Denmark	Control	55.91	8.5	Cropping	1975	22	Podzols	5.5	6	16	79	25	28	50	11.6	846	103		32	*

Denmark	Control	55.06	8.74	Cropping	1976	10	Podzols	7	15	23	62	16	32	44	21.6	702	89	-0.064		*
Denmark	Control	55.45	9.31	Cropping	1975	17	Podzols	5.6	5	8	87	45	20	50	9	862	90			*
Denmark	Control	56.37	10.03	Cropping	1976	19	Luvisols	6.3	9	28	60	31	22	26	18.7	630	93	-0.053	23	*
Denmark	Control	54.98	9.9	Cropping	1975	28	Luvisols	6.7	15	30	55	35	22	26	25.1	695	89	-0.035		*
Denmark	Control	55.58	11.9	Cropping	1975	22	Cambisols	6.3	12	24	65	27	23	26	15	585	99		21	*
Denmark	Control	57.3	10.16	Cropping	1976	20	Podzols	5.7	3	13	85	33	25	50	12.9	668	92		47	*
Denmark	Control	55.467	9.117	Cropping	1994	29	Podzols	5	5	8	87	27	19	50	7.3	926	92			[22]
Denmark	Control	54.9	9.117	Cropping	1994	26	Podzols	3.6	4	21	75	37	29	44	3	890	91			[23]
Finland	Control	60.783	24.917	Cropping	1978	39	Podzols	6.6	12	57	31	115	38	44	12	618	95	-0.022	62	[24]
France	Control	43.87	-0.73	Cropping	1986	15	Podzols	5.9	6	14	81	20	4	44	24.9	1060	122			[25]
France	Control	43.58	-0.5	Cropping	1975	18	Luvisols	7.3	12	52	36	18	6	50	24.1	1351	120	-0.073		*
Germany	Control	51.37	11.83	Cropping	1982	29	Chernozems	7.1	21	68	11	40	21	44	29.3	484	106			[26]
Germany	Control	51.37	11.83	Cropping	1984	25	Chernozems	4.6	21	68	11	40	21	44	28.5	484	106			*
Germany	Control	51.37	11.83	Cropping	1987	21	Chernozems	6.2	21	68	11	40	21	44	28.9	484	106			*
Germany	Control	51.37	11.83	Cropping	1985	25	Chernozems	5.1	21	68	11	40	21	44	28.3	484	106			*
Germany	Control	51.22	9.43	Cropping	1973	14	Cambisols	7.2	23	48	26	33	23	26	21.2	650	103			[27]
Germany	Control	51.22	9.43	Cropping	1989	8	Cambisols	7.2	18	48	26	25	23	26	29.7	650	103			*
Germany	Control	51.22	9.39	Cropping	1986	11	Luvisols	6.5	25			25		26	25.9	620	100	-0.036		*
Germany	Control	52.27	10.53	Cropping	1986	35	Cambisols	5.4	5	55	40	25		26	21.2	612.9	106	-0.049		[28]
Germany	Control	51.23	9.5	Cropping	1984	24	Luvisols	6	15			20		44	26.5	640	102		21	[27]
Germany	Control	48.4	11.69	Cropping	1978	37	Luvisols	6.1	24	63	17	21		26	34.9	790	103	-0.126	10	[29]
Germany	Control	48.4	11.69	Cropping	1978	37	Luvisols	6.4	24	63	17	21		26	35.7	790	103	-0.061	8	*
Germany	Control	48.4	11.69	Cropping	1978	37	Luvisols	5.3	24	63	17	21		26	28	790	103	-0.249	13	*
Germany	Control	48.4	11.69	Cropping	1981	35	Luvisols	6.2	20	63	17	23		26	27.7	790	103		31	*
Germany	Control	48.4	11.69	Cropping	1981	35	Luvisols	6.2	20	63	17	23		26	28.2	790	103			*
Germany	Control	48.4	11.69	Cropping	1981	35	Luvisols	6.3	20	63	17	23		26	32.1	790	103			*
Germany	Control	48.4	11.69	Cropping	1981	35	Luvisols	6.3	20	63	17	23		26	32.1	790	103		28	*
Germany	Control	48.4	11.69	Cropping	1980	35	Luvisols	6.2	20	63	17	23		26	30.3	790	103			*
Germany	Control	48.4	11.69	Cropping	1980	35	Luvisols	6.2	20	63	17	23		26	30.6	790	103			*
Germany	Control	48.4	11.69	Cropping	1980	35	Luvisols	6.3	20	63	17	23		26	35.8	790	103			*
Germany	Control	48.4	11.69	Cropping	1980	35	Luvisols	6.2	20	63	17	23		26	35.7	790	103		26	*
Germany	Control	48.4	11.69	Cropping	1980	36	Luvisols	6.2	20	63	17	26		26	26	790	103			*
Germany	Control	48.4	11.69	Cropping	1980	36	Luvisols	6.1	20	63	17	26		26	28.1	790	103		22	*
Germany	Control	48.4	11.69	Cropping	1980	36	Luvisols	6.1	20	63	17	26		26	31.7	790	103			*
Germany	Control	48.4	11.69	Cropping	1980	36	Luvisols	6	20	63	17	26		26	33.8	790	103			*
Germany	Control	48.4	11.69	Cropping	1980	35	Luvisols	6.1	20	63	17	26		26	29.1	790	103			*
Germany	Control	48.4	11.69	Cropping	1980	35	Luvisols	6	20	63	17	26		26	30.5	790	103		21	*
Germany	Control	48.4	11.69	Cropping	1980	35	Luvisols	6.1	20	63	17	26		26	35.4	790	103			*
Germany	Control	48.4	11.69	Cropping	1980	35	Luvisols	6	20	63	17	26		26	35.8	790	103			*
Germany	Control	51.45	9.41	Cropping	1984	25	Cambisols	6.3	15			22		26	30	669	100		33	[27]
Germany	Control	51.45	9.41	Cropping	1973	9	Cambisols	6.3	15			23		26	15.6	669	100		45	*
Germany	Control	51.45	9.41	Cropping	1997	7	Cambisols	6.3	24			35		26	34	717	100	-0.058		*
Germany	Control	53.71	12.85	Cropping	1998	26	Luvisols	6.1	6	22	67	13	22	26	29.7	557	101		27	[30]
Germany	Control	53.71	12.85	Cropping	1998	26	Luvisols	5.9	8	22	67	15	22	26	31.1	557	101	-0.02		*
Germany	Control	53.71	12.85	Cropping	1998	26	Luvisols	6.1	8	22	67	15	22	26	32.7	557	101	-0.019		*
Germany	Control	51.2	9.43	Cropping	1973	13	Cambisols	6.4	10	50	27	21	23	26	19.8	621	102			[27]
Germany	Control	51.2	9.43	Cropping	1998	9	Cambisols	7.2	12	50	27	35	23	26	30.7	661	102			*
Germany	Control	51.5	11.97	Cropping	1973	30	Phaeozems	5.5	13			29		44	22.7	466	111	-0.02		[31]
Germany	Control	51.5	11.97	Cropping	1973	30	Phaeozems	5.8	13			29		44	23.6	466	111	-0.125	19	*
Germany	Control	51.16	9.38	Cropping	1981	7	Cambisols	6.1	18	49	26	25	26	26	21.4	674	101		38	
Germany	Control	51.15	9.38	Cropping	1974	12	Cambisols	7	16	48	27	22	25	26	19.9	620	102		67	*
Germany	Control	54.05	12.08	Cropping	1999	19	Luvisols	5.6	10	27	60	18	26	26	30.6	600	101	-0.025		
India	Control	30.9	75.8	Cropping	1975	29	Lixisols	7.5	9	5	86	68	11	32	5.3	900	195	-0.019	12	
India	Control	30.933	75.45	Cropping	1971	21	Calcisols	8.2	7	4	88	4	5	32	1.2	900	197			
India	P gradient	30.9	75.783	Cropping	2011	10	Lixisols	7.3	10	6	84	57	5	32	26.6	733	195	-0.082	37	
Israel	P gradient	32.712	35.186	Cropping	1965	5	Vertisols	7.9	41	41	17	22	67	44	24.2	568	187	-0.179	49	
Israel	P gradient	31.567	34.834	Cropping	1965	5	Luvisols	8.2	35	38	27	10	23	44	24.4	364	208	-0.145	29	*

Italy	Control	44.833	7.633	Cropping	2001	15	Cambisols	6.5	13	35	52	19	9	26	27.4	702	141	-0.014	34	
Italy	Control	44.567	7.667	Cropping	2001	11	Cambisols	6.5	10	48	42	21	11	26	24.6	760	142			*
Korea	Control	36.36	128.45	Cropping	1967	34	Gleysols	5.3	20	65	15	30	4		10	1217	139	0	0	
Sweden	Control	58.35	13.13	Cropping	1971	42	Cambisols	5.7	35	49	12	39	19	44	16.9	578	101			
Sweden	Control	58.35	13.13	Cropping	1971	42	Cambisols	6.3	35	49	12	37	19	44	19.1	578	101		11	*
Sweden	Control	58.35	13.13	Cropping	1971	42	Cambisols	6.2	35	49	12	35	19	44	18.3	578	101		10	*
Sweden	Control	58.35	13.13	Cropping	1971	42	Cambisols	6.5	35	49	12	39	19	44	18.6	578	101		10	*
Sweden	Control	58.35	13.13	Cropping	1969	46	Cambisols	5.6	35	49	12	35	19	44	14.5	578	101	-0.204	11	*
Sweden	Control	58.35	13.13	Cropping	1969	46	Cambisols	6.2	35	49	12	35	19	44	16.7	578	101	-0.198	8	*
Sweden	Control	58.35	13.13	Cropping	1969	46	Cambisols	6.2	35	49	12	39	19	44	16.2	578	101	-0.268	9	*
Sweden	Control	58.35	13.13	Cropping	1969	46	Cambisols	6.5	35	49	12	39	19	44	17.8	578	101	-0.278	7	*
Switzerland	Control	47.61	9.14	Cropping	1990	26	Cambisols	7	33	37	31	45	25	26	31.2	947	109	-0.233	6	
Switzerland	Control	47.28	7.73	Cropping	1990	26	Gleysols	6.7	38	39	23	49	27	26	31.2	1129	109	-0.183	4	*
Switzerland	Control	47.44	8.53	Cropping	1990	26	Cambisols	7.4	38	39	23	52	25	26	26.5	1054	112	-0.237	6	
Switzerland	Control	47.44	8.53	Cropping	1990	26	Cambisols	7.9	24	30	46	39	21	26	20.9	1042	112	-0.284	4	40
UK	Control	51.81	-0.38	Cropping	1966	35	Luvisols	7.5	25	39	33	22	22	26	14	704	96			
UK	Control	51.81	-0.38	Cropping	1966	35	Luvisols	7.6	25	39	33	21	22	26	9.9	704	96			*
UK	Control	51.81	-0.38	Cropping	1974	35	Luvisols	7.3	20	39	33	17	22	26	3.9	704	96			*
UK	Control	51.81	-0.38	Cropping	1974	35	Luvisols	7.4	20	39	33	21	22	26	9.2	704	96	-0.098	4	*
UK	Control	51.81	-0.38	Cropping	1974	35	Luvisols	7	20	39	33	17	22	26	3.7	704	96			*
UK	Control	51.81	-0.38	Cropping	1974	35	Luvisols	7	20	39	33	17	22	26	7.3	704	96		4	*
UK	Control	51.81	-0.38	Cropping	1974	35	Luvisols	7.4	20	39	33	17	22	26	8.4	704	96		4	*
UK	Control	52.22	1.47	Cropping	1969	15	Luvisols	6.9	25	24	55	16	23	26	6.7	611	91		3	*
UK	Control	52.22	1.47	Cropping	1969	15	Luvisols	6.9	25	24	55	19	23	26	11	611	91		5	*
UK	Control	52.22	1.47	Cropping	1969	15	Luvisols	6.9	25	24	55	20	23	26	15.6	611	91	-0.161	8	*
UK	Control	52.22	1.47	Cropping	1969	15	Luvisols	6.9	25	24	55	24	23	26	18.3	611	91	-0.134		*
UK	Control	52.22	1.47	Cropping	1969	15	Luvisols	6.9	25	24	55	24	23	26	18.9	611	91	-0.123	14	*
UK	Control	52.22	1.47	Cropping	1969	15	Luvisols	6.9	25	24	55	21	23	26	18.4	611	91	-0.134	13	*
UK	Control	52.22	1.47	Cropping	1969	15	Luvisols	6.9	25	24	55	21	23	26	19	611	91	-0.173	19	*
UK	Control	52.22	1.47	Cropping	1969	15	Luvisols	6.9	25	24	55	21	23	26	17.1	611	91			*
UK	Control	51.806	-0.358	Cropping	1969	14	Luvisols	7.1	33	40	32	29	23	26		696	95	-0.056	70	*
UK	Control	51.806	-0.358	Cropping	1969	14	Luvisols	7.1	33	40	32	47	23	26		696	95	-0.073	64	*
USA	Control	35.874	-76.659	Cropping	1963	26	Acrisols	6	18	31	53	39	20	68	16	658	152	-0.088	63	
USA	P gradient	41.621	-97.922	Cropping	1975	27	Phaeozems	6.2	26	50	25	56	21	26	42.1	682	161	-0.025	10	
USA	P gradient	41.621	-97.922	Cropping	1975	27	Phaeozems	6.2	26	50	25	56	21	26	44	682	161	-0.05	19	*
USA	P gradient	41.621	-97.922	Cropping	1975	27	Phaeozems	6.2	26	50	25	56	21	26	45.5	682	161	-0.058	33	*
USA	Control	42.936	-92.569	Cropping	1975	24	Phaeozems	6.5	22	45	33	38	17	26	46.1	883	135	-0.028	16	*
USA	P gradient	42.936	-93.793	Cropping	1975	27	Phaeozems		30	39	32	65		26	37.3	778	136	-0.019	10	*
USA	P gradient	42.936	-93.793	Cropping	1975	27	Phaeozems		30	39	32	65		26	42.5	778	136	-0.049	18	*
USA	P gradient	42.936	-93.793	Cropping	1975	27	Phaeozems		30	39	32	65		26	44.5	778	136	-0.064	30	*
USA	P gradient	44.075	-93.525	Cropping	1974	20	Luvisols	6	30	48	28	25	25	26	57.2	760	133	-0.057	24	
USA	P gradient	45.594	-95.879	Cropping	1974	20	Chernozems	7.6	28	43	30	51	24	44	42.7	618	136	-0.063	20	*
USA	P gradient	41.153	-96.51	Cropping	1993	4	Phaeozems	6.2	25	67	8	19	21	26	24.8	493	160	-0.039	30	
USA	Control	35.31	-80.47	Cropping	1973	6	Acrisols	5.4	21	37	41	24	10	62	53.6	1169	155	-0.054	8	
USA	Control	38.817	-76.75	Cropping	2000	15	Acrisols							62	16.3	1080	149	-0.044	132	
USA	Control	38.617	-76.733	Cropping	2000	15	Acrisols	4.8	16	30	54	35	12	62	20.3	1086	147	-0.029	98	*
USA	Control	38.983	-76.117	Cropping	2000	15	Acrisols	5.5	22	53	25	43	14	68	21.3	1126	147	-0.039	118	*
USA	P gradient	38.617	-76.733	Cropping	2000	15	Acrisols	4.8	16	30	54	35	12	62	20.3	1086	147	-0.034	182	*
USA	Control	35.697	-80.623	Cropping	1975	8	Plinthosols	5.8	38	30	31	20	11	86	13	1131	150	-0.051	10	
USA	Control	36.126	-77.17	Cropping	1975	14	Plinthosols	5	10	21	69	31	15	86	17	1186	147	-0.051	43	*
USA	Control	35.377	-77.56	Cropping	1975	8	Plinthosols	4.9	15	42	43	34	19	86	13.5	1265	153	-0.035	73	*
USA	Control	48.133	-104.534	Cropping	1967	16	Kastanozems	6.5	36	47	17	35	24	44	3.2	347	179	-0.08	26	
USA	Control	39.861	-83.679	Cropping	2006	8	Luvisols	6.7	28	49	23	18	13	26	51	995	134	-0.179	19	
USA	Control	40.779	-81.839	Cropping	2006	8	Luvisols	5.8	27	51	22	18	11	26	45	977	129	-0.08	17	*
USA	Control	41.213	-83.764	Cropping	2006	8	Luvisols	6.1	38	42	20	28	23	26	48	878	134	-0.063	15	*
USA	P gradient	31.356	-85.323	Cropping	1929	49	Acrisols	5.8	15	15	69	19	4	86	21	1385	164	-0.011	31	
USA	P gradient	31.463	-87.32	Cropping	1929	49	Acrisols	5.6	20	23	57	23	6	86	18.9	1550	159	-0.011	28	*

USA	P gradient	31.142	-87.048	Cropping	1929	49	Acrisols	5.9	12	25	62	22	4	86	19.6	1635	160	-0.012	16	*
USA	P gradient	32.84	-86.97	Cropping	1929	49	Acrisols	6.2	22	30	48	11	3	62	24.9	1440	159	-0.011	13	*
USA	P gradient	34.689	-86.886	Cropping	1929	49	Acrisols	5.8	38	48	14	17	11	86	21.1	1442	154	-0.007	12	*
USA	Control	42.396	-85.375	Cropping	2008	8	Luvisols	6.2	15	24	76	29	15	26	15.6	1005	133	-0.034	18	[53]
USA	Control	40.105	-88.226	Cropping	1913	108	Phaeozems	5.9				43	15	26	8.6	840	143	-0.013	64	[54]
USA	P gradient	37.99	-100.816	Cropping	1973	7	Arenosols	7.9	32	43	25	12	18	26	31.2	493	211	-0.015	5	[55]
USA	P gradient	45.899	-103.305	Cropping	1951	9	Regosols	7.3	35	37	35	19	46	44	16	411	170	-0.148	25	[56]
USA	Control	38.206	75.676	Cropping	2000	5	Leptosols	7.7	24	42	34	23	21	50	0	96	104			[57]
USA	Control	41.162	-96.459	Cropping	1972	13	Phaeozems	6.8	35	54	11	20	23	26	57.9	798	159	-0.045	10	[58]
USA	Control	42.379	-96.953	Cropping	1972	13	Phaeozems	6.3	34	51	15	21	22	26	28.2	692	155	-0.018	7	*
Australia	P gradient	-17.25	145.333	Grassland	1981	5	Acrisols	6	25	19	55	16	9	62	1.2	782	180	-0.069	8	[59]
Canada	Control	46	-71	Grassland	1998	8	Podzols	5.8	13	46	41	142	37	44	20	692	99	-0.05	18	[60]
Canada	Control	48.833	-72.55	Grassland	2001	15	Podzols	6.1	49	43	8	43	33	44		439	102	-0.019	15	[61]
Finland	Control	63.133	27.317	Grassland	2003	7	Cambisols	6	6	34	44	31			20.2	517	90	-0.046	41	[62]
Finland	Control	64.733	25.25	Grassland	2003	7	Podzols	6.2	8	48	39	180	41	50	24.2	515	85	-0.046	37	*
France	Control	44	2	Grassland	1998	13	Cambisols	5.5	21	39	57	72	25	44	35	960	143			[60]
France	Control	44	2	Grassland	1998	7	Cambisols	5.5	21	22	57	72	25	44	35	960	143			[63]
France	Control	43	0	Grassland	1999	5	Cambisols	5.9	25	51	25	108	29	32	35	1200	123	-0.145	15	*
Ireland	Control	52.299	-6.497	Grassland	1995	16	Luvisols	6.4	22	29	49	57	27		28.2	1050	85	-0.028	13	[64]
Ireland	Control	52.298	-6.499	Grassland	1995	16	Luvisols	6.2	16	33	49	56	27		22.1	1050	85	-0.028	13	*
Ireland	Control	52.137	-7.918	Grassland	1997	12	Cambisols	5.5	16	25	59	70	14	44	7.7	1433	84	-0.208	53	[1]
Ireland	Control	52.438	-6.743	Grassland	1997	12	Cambisols	6	27	43	30	66	25	44	11.9	1169	83	-0.188	44	*
Ireland	Control	51.768	-8.719	Grassland	1997	12	Cambisols	5.5	14	35	51	65	19	44	32.4	1015	79	-0.234	63	*
Ireland	Control	52.786	-7.179	Grassland	1997	12	Gleysols	6.3	30	43	27	68	18	26	31	1144	83	-0.264	38	*
Ireland	Control	53.238	-7.61	Grassland	1997	12	Luvisols	6.9	15	28	57	94	25	26	39.4	1045	82	-0.3	60	*
Ireland	Control	53.291	-8.882	Grassland	1997	12	Luvisols	7.4	19	34	47	174	42	32	35.4	1088	86	-0.268	47	*
Ireland	Control	52.494	-8.13	Grassland	1997	12	Luvisols	5.5	21	33	46	61	16	26	29.9	1199	85	-0.172	69	*
New Zealand	Control	-43.648	172.468	Grassland	1994	28	Cambisols	5.8	22	22	56	62	12	18	13	620	134	-0.311	37	
New Zealand	Control	-43.648	172.468	Grassland	1994	28	Cambisols	5.7	22	22	56	62	10	22	15.4	620	134	-0.148	42	*
New Zealand	P gradient	-37.71	175.19	Grassland	1954	4	Andosols	5.7	22	32	46	108	25	92	29.3	1274	130	-0.201	29	
Switzerland	Control	47	7	Grassland	1992	16	Cambisols	5.4	28		21	154		44	7.5	1400	111			[60]
UK	Control	51.804	-0.372	Grassland	1980	26	Luvisols	6.2	22	66	12	63	23	26	24.9	698	95	-0.046	170	
UK	Control	51.804	-0.372	Grassland	1856	108	Luvisols	6.2	22	66	12	63	23	26	24.9	698	95	-0.051	47	*
USA	Control	42.396	-85.375	Grassland	2008	8	Luvisols	6.2	15	24	62	29	15	26	5.8	1005	133	-0.08	16	
Australia	P gradient	-41.081	145.771	Grazed grassland	2005		Nitisols	5.8	23	30	47	186	21	74	21	976	131	-0.127	82	
Australia	P gradient	-41.387	146.62	Grazed grassland	2005		Acrisols	5.4	23	22	58	55	9	62	15.8	1062	132	-0.093	80	*
Australia	P gradient	-40.991	144.677	Grazed grassland	2005		Leptosols	4.6	5	4	90	95	19	62	21	1074	121	-0.132	19	*
Australia	P gradient	-41.434	146.564	Grazed grassland	2005		Acrisols	5.5	11	19	70	51	5	74	19.3	1062	134	-0.069	70	*
Australia	P gradient	-41.427	146.554	Grazed grassland	2005		Acrisols	5.2	18	31	51	117	24	74	28	1062	133	-0.08	54	*
Australia	P gradient	-40.957	144.872	Grazed grassland	2005		Acrisols	5.3	14	9	77	170	13	62	49	1125	124	-0.132	62	*
Australia	Control	-24.81	149.8	Grazed grassland	1982		Vertisols	7	32	18	50	16	24	50	21.7	686	209	-0.018	11	
Australia	Control	-17.233	145.567	Grazed grassland	1981		Nitisols	5.7				46		68	38.7	1289	168	-0.051	40	
Ireland	Control	52.292	-6.502	Grazed grassland	1999		Luvisols	6	18	37	42	125	27	44	23.6	1018	83	-0.057	61	
Ireland	P gradient	52.45	-6.71	Grazed grassland	1996		Gleysols	6.2	24	35	40	47	24	44	20.9	1117	85	-0.142	40	
Ireland	P gradient	51.591	-8.929	Grazed grassland	2020		Cambisols	6	23	34	43	81	30	44	22	1153	79	-0.301	77	[b]
Ireland	P gradient	52.61	-6.29	Grazed grassland	2020		Gleysols	6.3	31	35	34	85	21	44	22.1	960	84	-0.315	61	[b]
Netherlands	Control	52.43	6.26	Grazed grassland	1996		Podzols	5.6	3	12	82	58	18	44	20.5	850	95	-0.028	60	
Netherlands	Control	51.31	5.56	Grazed grassland	1996		Podzols	5.6	2	20	68	60	18	44	19.5	777	101	-0.021	54	*
Netherlands	Control	52.52	5.55	Grazed grassland	1996		Fluvisols	7.1	20	45	25	88	28	44	13	873	96	-0.014	103	*
Netherlands	Control	52.13	4.83	Grazed grassland	1996		Histosols	5	23	42	33	88	38	26	21.8	877	89			*
New Zealand	Control	-43.787	171.795	Grazed grassland	1959		Cambisols	6.1	21	21	58	58	11	21	27.1	746.6	133	-0.016	7	
New Zealand	Control	-43.787	171.795	Grazed grassland	1959		Cambisols	6.1	21	21	58	60	11	21	29.4	746.6	133	-0.016	7	*
New Zealand	P gradient	-37.48	175.129	Grazed grassland	1985		Cambisols	5.1	30	34	43	155	26	55	29	1600	130	-0.006	41	*
New Zealand	Control	-38.58	174.861	Grazed grassland	1983		Cambisols	5.6	13	34	40	106	18	22	7.7	1350	126	-0.129	16	
New Zealand	P gradient	-40.308	175.84	Grazed grassland	1980		Cambisols	5.3	22	27	47	118	26	27.5	10.7	1200	121	-0.021	10	
New Zealand	Control	-39.62	176.95	Grazed grassland	1977		Luvisols	5.4	28	19	53	100	25	20	20.7	838	145			
UK	P gradient	54.454	-5.917	Grazed grassland	1987		Gleysols	5.6	21	31	48	136	21	44	20	923	84	-0.061	53	

USA	Control	36.15	-94.317	Grazed grassland	1995	Acrisols	5.9	12	76	12	25	19	86	28.1	1167	162	-0.051	69

[a] As the numbered reference above

[b] Rebecca Hall (unpublished data), Teagasc, Wexford, Ireland.

Supplemental Table S12. Parameters extracted from each trial and used in modelling soil test phosphorus drawdown rates. Where data were missing, we used global datasets to estimate their value.

Variable	Unit	Global database for variable estimates
Year trial began and ended	year	-
Number of soil test phosphorus observations	-	-
Sampling depth	mm	-[a]
Country	-	-
Soil type	-	-
Land use	Cropland, grassland, grazed grassland	[79–82]
Ploughed	Yes/no	-
Phosphorus retention	%	[83,84]
Clay, silt, sand	%	[85]
Organic C	g kg^{-1}	[85]
Olsen phosphorus	mg kg^{-1}	[6,86]
Cation exchange capacity	meq 100 g^{-1}	[85]
pH (in water)	-	[85]
Aridity index	mm mm^{-1}	[87]
Mean annual evapotranspiration	mm	[88]
Mean summer-autumn evapotranspiration	mm	[88]
Mean annual air temperature	°C	[88]
Mean annual precipitation	mm	[88]
Potential annual yield	Mg (dry matter) ha^{-1}	[80]
Plot size	m^2	-
Crop type and yield	kg ha^{-1}	[79]
Mean phosphorus exported	kg ha^{-1}	See Methods

[a] All global data were extracted for the 0-20 cm soil depth.

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