

Global Distribution and Influencing Factors of Plant-Available Phosphorus in (Semi-)Natural Soils

Global Biogeochemical Cycles

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Global Biogeochemical Cycles®

RESEARCH ARTICLE

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Key Points:

- Globally, plant-available soil phosphorus (P) varied over four orders of magnitude, from 0.01 to 99.2 mg kg⁻¹
- The variation of global plant-available soil P was best explained by parent material type and total soil P concentration
- Global stock of plant-available soil P was estimated to be 0.73 and 1.59 Pg at 0–30 cm and 30–100 cm soil depths

Supporting Information:

Supporting Information may be found in the online version of this article.

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Global Distribution and Influencing Factors of Plant-Available Phosphorus in (Semi-)Natural Soils

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Abstract Phosphorus (P) is frequently a limiting nutrient for plant growth in natural ecosystems. Determining plant-available P concentration in soil is essential for pinpointing areas where P availability might restrict plant growth and terrestrial carbon sequestration. However, the worldwide distribution and factors influencing plant-available P in (semi-)natural soils are not well understood. Here, we have developed a comprehensive global database that compiles plant-available P measurements using five prevalent analytical methods: Olsen, Bray-I, Mehlich III, Colwell, and AB-DTPA. The data set encompasses 6,253 plant-available P measurements in (semi-)natural soils (under natural ecosystems and >10 years since anthropogenic activities) at 3,353 globally distributed sites. Leveraging this extensive database, we initially examined the global distribution and influencing factors of plant-available soil P. Subsequently, we utilized a random forest model to delineate a detailed global map of plant-available soil P patterns. Globally, plant-available P varied over four orders of magnitude, from 0.01 to 99.2 mg kg⁻¹. The variation was best explained by parent material types and total soil P concentration. Random forest predicted plant-available P increased significantly with latitude in both hemispheres, though with large longitudinal variations. Global stock of plant-available P was estimated to be 0.73 Pg and 1.59 Pg at 0–30 cm and 30–100 cm soil depths. Our analysis provides insight into the underlying drivers of plant-available P in (semi-)natural soils, presents a spatially explicit assessment of plant-available soil P, which can provide a basis for assessing, predicting, and understanding global patterns of terrestrial P limitation and the functioning of the Earth system.

Plain Language Summary In this study, we compiled a global database of 6,253 plant-available soil phosphorus (P) observations from 3,353 (semi-)natural sites, screened from over 36,000 publications referencing five common extraction methods and reported in 887 studies. Using random forest models, we identified global patterns and key environmental drivers of plant-available soil P, with parent material types and total soil P concentration as top predictors, followed by climate and topography. Concentrations ranged from 0.01 to 99.0 mg kg⁻¹ and increased with latitude despite large regional variation. Global plant-available soil P stocks were estimated at 0.7 Pg (0–30 cm) and 1.59 Pg (30–100 cm). These findings help identify P-limited ecosystems and inform global soil nutrient management.

1. Introduction

Phosphorus (P) is frequently a limiting nutrient for plant production in terrestrial ecosystems (Elser et al., 2007; Hou et al., 2020; Vitousek et al., 2010). The soil is the primary source of P for plant growth, and plant-available soil P is the fraction of total soil P that is readily available to plants, especially plants without specialized carboxylate-releasing roots. Therefore, soil P availability affects the structure, functioning, and processes of terrestrial ecosystems and varies by up to four orders of magnitude across the globe (Brownlie et al., 2021; Jiang et al., 2025; Lambers et al., 2010, 2014; Shangguan et al., 2013; Zemunik et al., 2015). Despite the large variation in plant-available P concentration, its global patterns and drivers remain poorly resolved. Examining the spatial patterns and environmental drivers of plant-available P in soil is fundamentally important for understanding the role of P in determining terrestrial primary production and carbon sequestration and its response to global change,

such as rising atmospheric CO₂ concentration, nitrogen deposition, and warming (Ellsworth et al., 2017; Jiang et al., 2020; Liu et al., 2023; Terrer et al., 2019; Tian et al., 2020; Zhou et al., 2024).

Plant-available soil P concentration is typically governed by a suite of interrelated processes, including adsorption/desorption, precipitation/dissolution, immobilization/mineralization, weathering, and solid-phase P transformation, such as solid-phase diffusion or penetration, recrystallization, and migration in aggregates (Barrow, 1983; Frossard et al., 2000; Hou et al., 2020; Turner et al., 2005; Vitousek et al., 2010). These processes are interactively influenced by biotic and abiotic factors such as climate, soil properties, parent material types, and vegetation, and thus, vary among ecosystems (Hou et al., 2020). Soil P is derived from the parent material, and soil P availability typically decreases with increasing soil age due to continuous loss via leaching and runoff during soil development (Delgado-Baquerizo et al., 2020; Turner et al., 2018; Vitousek et al., 2010; Walker & Syers, 1976; Wardle et al., 2004). Climate (e.g., mean annual temperature (MAT), mean annual precipitation (MAP)) influences the release of P from bedrock and the loss of P in soil and the uptake of P by plants, and thus affects plant-available soil P (Hou et al., 2020). Moreover, soil properties (e.g., soil pH, soil organic carbon (SOC), and clay content) affect the transformation of soil organic P and non-labile inorganic P to plant-available soil P or the transformation of plant-available soil P to other soil P fractions (He et al., 2023; Zhu et al., 2021). However, few studies have examined whether environmental variables are important to predict plant-available soil P concentration in (semi-)natural soils (i.e., without anthropogenic influence) at a global scale (Augusto et al., 2017; He et al., 2023; Yang & Post, 2011). Such an understanding is crucial for improving maps of plant-available soil P and ultimately simulating ecosystem functioning, such as plant P-acquisition strategies (Achat et al., 2016; Lambers et al., 2008) and carbon-sequestration potential (Fleischer et al., 2019; Goll et al., 2012).

With key drivers identified, plant-available soil P concentration can be mapped across the globe, which would be helpful to address the pressing global issues such as P limitation of ecosystem productivity and carbon sequestration (Alewell et al., 2020; Beusen et al., 2015; Goll et al., 2012). There are several published global maps of plant-available soil P (Ballabio et al., 2019; McDowell et al., 2023; Ringeval et al., 2024). However, all focus on a range of land uses, often including croplands with heavy human influence. Given that available P in agricultural soils is mainly driven by anthropogenic inputs and outputs (Demay et al., 2023) in addition to soil forming factors, it is questionable to predict plant-available soil P in (semi-)natural soils with the same model. Additionally, these predicted maps only focused on the surface layers of soils (≤ 20 cm), even though subsoils (>20 cm) are known to contribute to the P nutrition of plants (Rodionov et al., 2020).

Here, we constructed a global database of plant-available soil P concentrations of 6,253 (semi-)natural measurements from 887 published studies. We defined literature-described natural, intact, or pristine terrestrial ecosystems as natural-terrestrial ecosystems. We defined semi-natural terrestrial ecosystems as ecosystems that have not been disturbed for more than 10 years after fire, fertilization, wood harvest, heavy grazing (i.e., the grazing rate is in excess of production rate), forest conversion, or afforestation. These disturbances may affect plant-available soil P concentration, but likely to be in a small extent after >10 years of recovery. We defined ecosystems with any recorded history of fire, fertilization, wood harvest, heavy grazing, forest conversion, or afforestation as moderately to seriously disturb terrestrial ecosystems. These ecosystems were excluded from our data set. We then used random forest algorithms to quantify the relative importance of soil-forming variables for predicting plant-available soil P concentration and finally mapped it to global grids. Our objectives were: (a) to quantify which factors are the most crucial for predicting the spatial variation in the plant-available soil P concentrations down to 100 cm soil depth and (b) to explore the global distribution of plant-available soil P concentrations and stocks among soil layers down to 100 cm soil depth on a global scale. The predicted global map of plant-available soil P will be a vital resource for studying P cycling, ecosystem productivity limitations, and future land carbon sinks.

2. Methods

2.1. Data Compiling and Processing

We collected plant-available soil P measurements in (semi-)natural terrestrial ecosystems, excluding Antarctica, to explore the background values and natural drivers of soil P availability. There are few locations and ecosystems that are never affected by any human activities. Hence, we defined literature-described natural, intact, or pristine terrestrial ecosystems as natural-terrestrial ecosystems. We defined semi-natural terrestrial ecosystems as ecosystems that have not been disturbed for more than 10 years after fire, fertilization, wood harvest, heavy grazing,

forest conversion, or afforestation. We defined ecosystems with any recorded history of fire, fertilization, wood harvest, heavy grazing, forest conversion, or afforestation as moderately to seriously disturb terrestrial ecosystems. These ecosystems were excluded from our data set. It is possible that we may have included ecosystems that have an unrecorded history of fertilization, forest land cover change, or heavy grazing. We acknowledge that the use of 10 years to group slightly versus moderately/seriously disturbances is somewhat arbitrary, but these disturbances are unlikely to affect plant-available soil P concentration much, especially after more than 10 years of recovery.

There are currently more than two dozen methods for determining plant-available soil P (Yli-Halla et al., 2016). To be comparable across sites, we compiled the measurements of plant-available soil P determined by the five most commonly used methods (Table S1 in Supporting Information S1; Yli-Halla et al., 2016): the Olsen method (Olsen et al., 1954), the Bray-1 method (Bray & Kurtz, 1945), the Mehlich III method (Mehlich, 1984), the Colwell method (Colwell, 1963), and AB-DTPA method (Soltanpour & Schwab, 1977). Our procedure to select studies is summarized in a PRISMA flow diagram (Figure S1 in Supporting Information S1) and described in detail as follows.

We selected all publications citing Olsen et al. (1954), Bray and Kurtz (1945), Mehlich (1984), Colwell (1963), and Soltanpour and Schwab (1977) to collect plant-available soil P measurements in (semi-)natural terrestrial ecosystems from Google scholar (<http://scholar.google.com/>) up to December 2020. We first screened the publications by titles and abstracts to remove inaccessible full-texts and studies conducted in pots, mine zones, intertidal zones, and cropland ecosystems. After this selection, we retained 7,266 publications. Second, we checked the main text and the supplementary files to further remove the publications with a documented history of fertilization and other anthropogenic activities (warming, elevated CO₂, logging or deforestation). After this selection, we retained 3,718 publications. Third, we removed publications that did not fulfill our collection criteria, for example, lack of location information (site description, or latitude and longitude). In the end, we obtained 6,253 measurements of plant-available P concentration at 3,353 sites from 887 publications, comprising 5,089 measurements at 0–30 cm soil depth and 1,164 at 30–100 cm soil depth. A list of the selected publications is presented in the Supplemental Information. According to the methods to define reference conditions (i.e., without human influence) (Tromboni et al., 2024; Webb et al., 2014), we used the analysis of covariance (ANCOVA) on the entire data set to test if biome types better explained concentrations of plant-available soil P independent of human influences. The human influence was indicated by land use, that is, percentage of forest area, which was collected from the European Space Agency Climate Change Initiative land cover map (<https://maps.elie.ucl.ac.be/CCI/viewer/>). The ANCOVA was necessary to include categorical (biome types) and continuous land use (percentage of forest area) as the categorical predictor using “*anova_test*” in “*rstatix*” package. This categorization includes six biome types, including tropical forest, temperate forest, boreal forest, mediterranean forest, desert, and tundra. The ANCOVA result using our entire data set indicated that human influences did not significantly affect plant-available soil P ($p = 0.528$) in our database (Table S2 in Supporting Information S1). Thus, we used this data set to explore the background values and natural drivers of soil P availability.

In addition to plant-available soil P concentration, we also included key associated soil properties and environmental variables, such as geographical location (latitude and longitude), vegetation productivity, climate characteristics (i.e., MAP and MAT), soil physicochemical properties (e.g., total soil P concentration, soil sand and clay content, soil pH, and SOC), topography (elevation and slope), soil orders, and parent material types. The environmental variables were obtained from global data sets, as detailed in Table S3 in Supporting Information S1. Plant-available soil P concentration in natural ecosystems is thought to be affected by five soil-forming factors: climate, parent material types, topography, organisms (e.g., net primary production, NPP), and soil age (Delgado-Baquerizo et al., 2020; Jenny, 1941; Turner et al., 2018; Vitousek, 1994; Walker & Syers, 1976). Among these five factors, soil orders, climate, and topography directly affect plant-available soil P status via changing the release of P from bedrock, and the loss of P in soil, and vegetation also directly affects plant-available soil P levels by influencing the uptake of P by plants and its accumulation in topsoil with biological uplift (Jobbágy & Jackson, 2001; Hou et al., 2020; Luo et al., 2020). Parent material indirectly affects plant-available soil P via influencing total soil P, and soil age indirectly affects plant-available soil P via the weathering of bedrock over time (Augusto et al., 2017; Vitousek et al., 2010). Total soil P was also included in the model because plant-available soil P is the fraction of total soil P, and is directly determined by it. In this study, we used soil orders in the United States Department of Agriculture (USDA) system of soil taxonomy as an agent for soil age (i.e., soil development) with three weathered extents (slightly, intermediately, and strongly weathered).

(Wilding et al., 1983; Yang & Post, 2011). Among the 12 soil orders in the USDA system, the Andisols, Gelisols, Entisols, Inceptisols, and Histosols are regarded as slightly weathered soils; the Aridisols, Alfisols, Mollisols, and Vertisols are regarded as intermediately weathered soils; the Oxisols, Ultisols, and Spodosols are regarded as strongly weathered soils.

In addition to the influence of predictors such as soil-forming factors in affecting plant-available soil P concentration, soil properties such as the concentration of total soil P and SOC, soil sand and clay content, soil pH, and soil depth (Table S4 in Supporting Information S1) also affect solid-phase P transformation, which potentially affects plant-available soil P concentration (Hou et al., 2020). These soil properties were used as additional predictors. Missing values of elevation (validation $R^2 = 0.84$), MAT (validation $R^2 = 0.83$), and MAP (validation $R^2 = 0.77$) were derived from global maps (Table S3 and Figure S2 in Supporting Information S1) based on the geographical coordinates of the measurement sites. Due to the low validation ($R^2 = 0.10\sim 0.42$, Figure S2 in Supporting Information S1) of soil pH, sand content, total soil P, and SOC, missing values of these indexes were therefore filled using the multivariate imputation by the chained equations with random forest method in the “*miceRanger*” package (Figure S3 in Supporting Information S1) (Wilson, 2020). The co-correlated predictors can be substituted for the corresponding predictors to make the estimated importance smaller than the actual value (Strobl et al., 2008). Therefore, we excluded the aridity index as it is strongly correlated with MAP ($R^2 = 0.65$), and soil nitrogen concentration as it is correlated with SOC ($R^2 = 0.60$). We also excluded variables that are rarely reported in published studies, such as soil aluminum and iron oxide concentrations.

2.2. Statistical Analyses and Model Training

Some studies determined plant-available soil P concentration by more than two methods, which enabled us to construct an empirical correlation between them to standardize the measurements based on our collected database. Before analyzing and training the collected measurements of plant-available soil P, we normalized the measurements by converting all Bray-1 extracted P and Colwell extracted P data into soil Olsen P concentration data using the regression equations ($y = 0.715X$ and $y = 0.355X$, respectively) with more than 50 pairs of measurements (Figure S4 in Supporting Information S1). We also replaced conversion coefficients for methods with less than 50 pairs of measurements (i.e., Mehlich III extracted P and AB-DTPA methods) by the values (i.e., 0.31 and 0.87, respectively) reported in Steinfurth et al. (2021). We further validated the converted values using the model: $\text{lmer}(y(\text{converted values}) \sim x(\text{observations}) + (x(\text{observations})||\text{site}))$, and found that the converted values of plant-available P were significantly correlated with the observation of plant-available soil P ($R^2 = 0.997$) (Table S5 in Supporting Information S1). We also removed 88 extremely high values (i.e., excluded values falling in the interval between 99% and 100%) (Figure 1b). The high values were possibly derived from special soils (very young volcanic soils) or unusual geological contexts (Porder & Ramachandran, 2013) or the case of soil that was heavily P-fertilizer in the past, but this information was not available in the original article, particularly in western Europe and the eastern USA (De Schrijver et al., 2012). We also excluded these extremely high values from model training and Spearman correlations to avoid their large biased influence on their correlations with all numeric predictors.

We compared a suite of algorithms that included generalized linear model, random forest model, cubist model, boosted tree model, gradient boosting machine model, and lasso regression model as affected by the 16 predictors (parent material types (Table S6 in Supporting Information S1), Parent material P concentration (the values derived from the predicted map of Hartmann et al. (2012)), % forest (i.e., land use proportion, the values derived from <https://maps.elie.ucl.ac.be/CCI/viewer/>), soil order, elevation, NPP, slope, the concentration of total soil P and SOC, soil depth, soil pH, soil sand and clay content, biomes, MAT and MAP) (Table S4 in Supporting Information S1). The model performances were assessed using the coefficient of determination (R^2), root-mean-square-error (RMSE) and mean absolute error (MAE). A five-fold cross-validation method was used to evaluate the performance of the models using the “*Caret*” package in R 4.1.2 (Kuhn, 2020). In this method, the whole data set was randomly split into five groups, each comprising 20% of the data. One group of data was used as test data, while the other four groups were used as training data, and so forth for a total of five times. Based on the average of five sets of R^2 and RMSE through a five-fold cross-validation method, the random forest model performed the best ($R^2 = 0.60$) with smaller RMSE (9.8 mg kg^{-1}) among all six algorithms (Table S7 in Supporting Information S1) and was thus selected for the following prediction of the global data set of plant-available soil P. We performed the random forest analysis using the package “*randomForest*” version 3.1 with an automated “*mtry*” parameter and “*ranger*” method (Liaw & Wiener, 2002) to evaluate the relative importance of each factor for

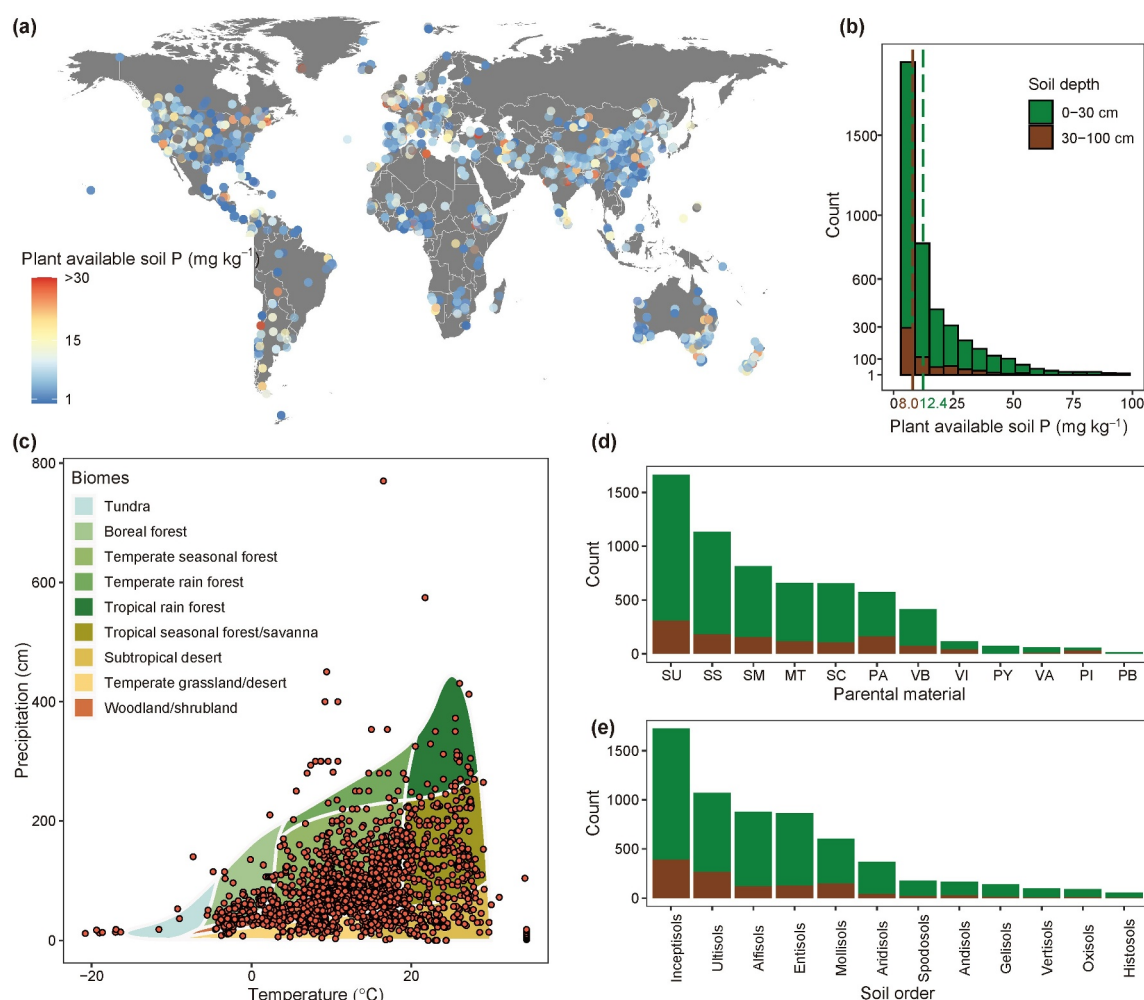


Figure 1. Distribution of our site-level training data. The database contained 6,253 observations covering all major terrestrial biomes (a, b, c), 12 parent material types (d), and 12 soil orders (e). The green and brown dashed lines in panel (b) indicate the mean of plant-available soil phosphorus (P) (12.4 mg kg^{-1} and 8.0 mg kg^{-1} at 0–30 cm and 30–100 cm soil depth, respectively). The abbreviations in panel (d): SU, unconsolidated sedimentary; SS, siliciclastic sedimentary; SM, mixed sedimentary; MT, metamorphics; SC, carbonate sedimentary; PA, acid plutonic; VB, basic volcanic; VI, intermediate volcanic; PY, pyroclastics; PI, intermediate plutonic; VA, acid volcanic; PB, basic plutonic.

predicting plant-available soil P concentration. The marginal effect of each variable for predicting plant-available soil P concentration was assessed using the increase in mean squared error (%IncMSE) and was visualized using partial dependence plots.

2.3. Upscaling Procedure

We used the above trained model (i.e., random forest model) associated with global databases of the above-mentioned 16 predictors to generate a global map of plant-available soil P concentration. Predictor variables were all re-gridded to a spatial resolution of $0.05^\circ \times 0.05^\circ$ and used to predict global plant-available soil P concentration (Table S4 in Supporting Information S1). In the predicted global map of plant-available soil P concentration, we assume that cropland and other anthropogenic areas (e.g., roads and cities) in their original states possessed the same series of correlations between plant-available soil P concentration and all predictors as in (semi-)natural regions. Therefore, cropland or any other heavily influenced areas were not removed so that this predicted global map could be used to represent the initial state of soil P availability without direct anthropogenic activities.

To predict plant-available soil P concentration for any given soil depth, we used soil depth as a covariate in the trained model (Hengl et al., 2017). In the partial dependence plot, plant-available soil P concentration decreased

Table 1
Plant-Available Soil Phosphorus Concentration (mg kg^{-1}) in Natural Ecosystems for Major Biomes at Both 0–30 cm and 30–100 cm Soil Depth

Biomes	Min	P ₂₅	Mean	P ₇₅	Max	Number of obs.
0–30 cm						
Tundra	0.19	3.6	16.9	26.6	91.0	314
Boreal	0.08	5.4	15.3	16.0	84.0	175
Temperate	0.01	3.1	13.8	18.8	98.7	1,339
Mediterranean	0.01	2.9	12.5	15.8	97.0	1,687
Tropics	0.04	2.1	10.4	13.3	99.2	1,161
Desert	0.07	2.7	8.7	10.0	86.0	413
Global	0.01	2.8	12.4	15.4	99.2	5,089
30–100 cm						
Tundra	1.79	3.6	6.9	5.9	28.6	23
Boreal	0.14	2.3	6.8	6.0	33.7	41
Temperate	0.02	0.8	7.6	7.8	57.9	285
Mediterranean	0.20	1.4	6.4	7.5	48.6	327
Tropics	0.10	2.0	9.9	13.0	66.0	383
Desert	0.02	1.6	7.1	8.1	33.7	105
Global	0.02	1.4	8.0	9.6	66.0	1,164

Note. Results are based on our site-level database. P₂₅ and P₇₅ indicate the percentile ranks of 25% and 75%.

nearly linearly with soil depth at 0–30 cm, and there was no obvious change pattern with soil depth at 30–100 cm (Table 1 and Figure 4h). Therefore, the global plant-available soil P concentration was predicted at 0 cm, 10 cm, 20 cm, 30 and 100 cm to present the plant-available soil P concentration. Averages of global plant-available soil P concentration in depth intervals (at 0–30 cm and 30–100 cm soil depth) were derived from the weighted average of the predicted global plant-available soil P concentration within the corresponding depth. The content and stock of plant-available soil P at global and continental scales at 0–30 cm and 30–100 cm soil depth were calculated from the soil bulk density (Hengl et al., 2017) and the predicted plant-available soil P concentration at corresponding depths, respectively.

In the predicted global map of plant-available soil P concentration, the uncertainty of each grid was assessed using the quantile regression forests approach with bootstrap samples (Koenker & Bassett, 1978). The uncertainty was presented as the standard deviation using the package “*quantregForest*” (Meinshausen, 2017). Predictors of each tree in the random forest model (the number of trees = 500) were returned to evaluate the variation in predicting global plant-available soil P concentration, and these results were calculated to evaluate the standard deviation of global plant-available soil P concentration. All statistical analyses were conducted, and figures were drawn in R 4.1.2 (R Core Team, 2019).

3. Results

3.1. Characteristics of Plant-Available P Concentration in Soils

Our plant-available soil P concentration database included 6,253 observations from 3,353 geographically distinct sites and covered six continents, all 12

USDA soil orders, and all nine major biomes in terrestrial ecosystems (Figures 1a–1c, and 1e and Table S3 in Supporting Information S1). The distribution of plant-available soil P concentration in this database was right-skewed (Figure 1b). The concentration of plant-available soil P in (semi-)natural soils of terrestrial ecosystems ranged from 0.01 to 99.2 mg kg^{-1} at 0–30 cm soil depth and from 0.02 to 66.0 mg kg^{-1} at 30–100 cm soil depth (Table 1). The database included plant-available soil P concentration observations from topsoil to 100 cm deep soil, with 81% of observations from the topsoil. The mean of plant-available soil P concentrations were 12.4 mg kg^{-1} at 0–30 cm soil depth, respectively, and 8.0 mg kg^{-1} at 30–100 cm soil depth, respectively (Table 1).

Plant-available soil P concentrations varied within and among biomes. Plant-available soil P concentration in tundra and boreal biomes was the highest among biomes, followed by Mediterranean and temperate regions, and was the lowest in the tropics and deserts at 0–30 cm soil depth (Table 1 and Figure 2a). Plant-available soil P concentration also varied with parent material types and was higher in carbonate sedimentary (SC) and siliciclastic sedimentary (SS) material than in other types of parent material (Figure 2b). Additionally, plant-available soil P concentration varied among soil orders (Table 2 and Figure 2c). Plant-available soil P concentration significantly decreased from slightly weathered soil (14.0 mg kg^{-1}) to intermediately weathered soil (12.1 mg kg^{-1}) and strongly weathered soil (10.0 mg kg^{-1}) at 0–30 cm soil depth (Figure 2c).

3.2. Global Drivers of Plant-Available Soil P Concentration

Based on the average of five sets of R^2 and RMSE through a five-fold cross-validation method, the random forest model performed the best ($R^2 = 0.60$) with smaller RMSE (9.8 mg kg^{-1}) among all six algorithms (Table S7 in Supporting Information S1). The random forest regression model explained 60% of plant-available soil P concentration variability across all reported sites. The model revealed that the two most-important predictors were parent material types and total soil P concentration (Figure 3). Although soil orders, elevation, slope, MAP, soil depth, biome, SOC, soil pH, net primary productivity (NPP), soil sand content, MAT and soil clay content showed significant influences on plant-available soil P concentration (Figure 3 and Figure S5 in Supporting Information S1), their relative importance was less than that of the above two variables. The partial dependence plots

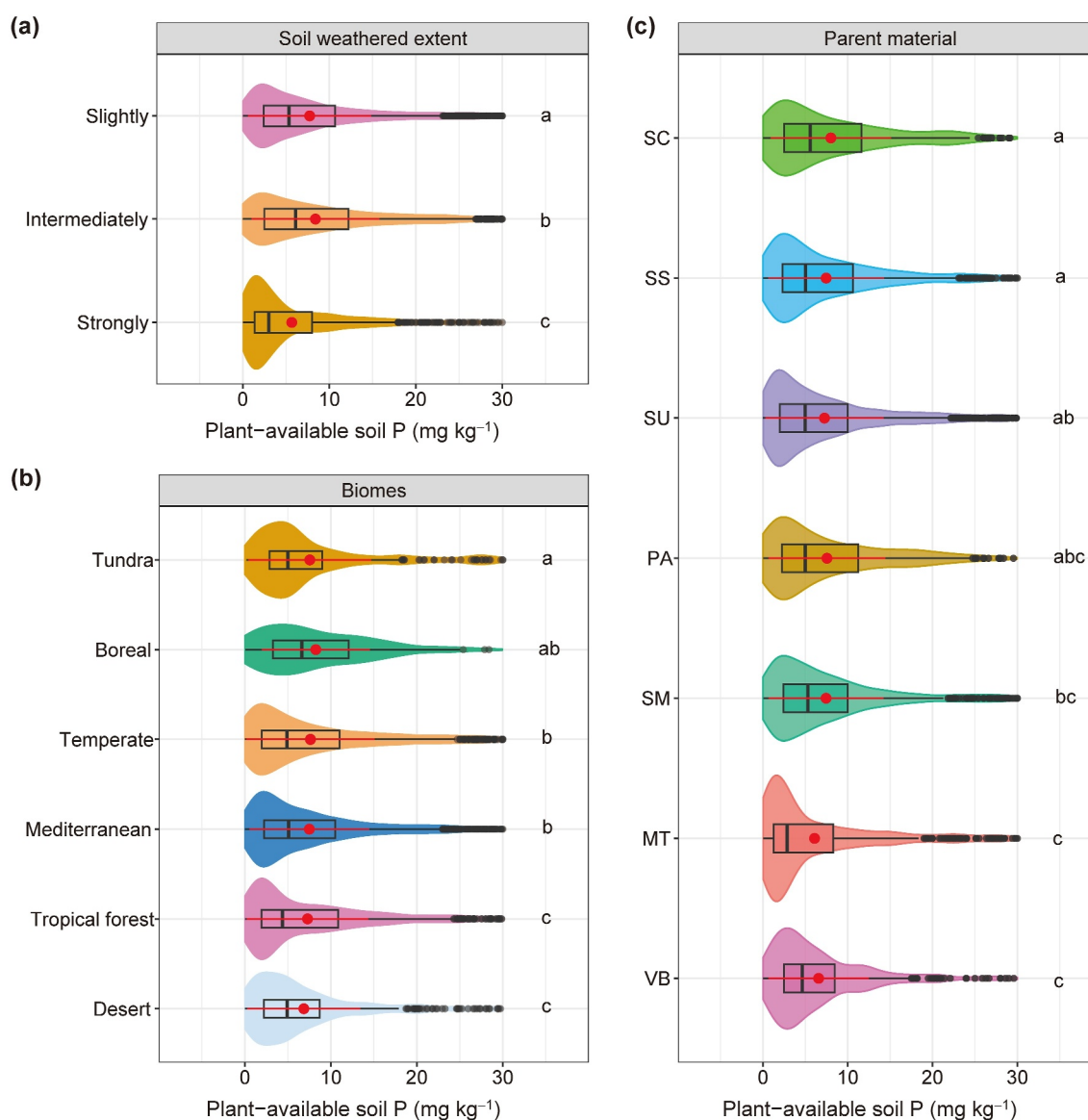


Figure 2. Plant-available soil phosphorus (P) concentration in relation to biomes, parent material types, and extent of soil weathering. The y-axis in data visualization was limited to 30 mg kg⁻¹; the parent material types with more than 150 observations in database were shown. Plant-available soil P concentration in relation to biomes (a), parent material types (b), and extent of soil weathering (c). The abbreviations in panel (c): SS, siliciclastic sedimentary; SC, carbonate sedimentary; SU, unconsolidated sedimentary; PA, acid plutonic; SM, mixed sedimentary; MT, metamorphics; VB, basic volcanic.

showed a positive relationship between plant-available soil P concentration and total soil P concentration at the global scale (Figure 4 and Figure S6 in Supporting Information S1). Plant-available soil P concentration was also positively correlated with soil total P and SOC, and the corresponding correlation coefficients were 0.26 and 0.20, respectively (Figures S5 and S6 in Supporting Information S1). In contrast, plant-available soil P concentration was negatively correlated with MAP, MAT, depth, soil sand and clay content, and the corresponding correlation coefficients were -0.07 , -0.13 , -0.17 , -0.03 , and -0.05 , respectively (Figure S5 in Supporting Information S1).

3.3. Mapping Plant-Available P Concentration in Global Soils

The random forest model was used to generate spatial predictions of global plant-available soil P concentration and its standard deviation at two depths (Figure 5 and Figure S7 in Supporting Information S1). In our predicted global map, we did not remove cropland or other heavily influenced areas (e.g., roads and cities), so the predicted map can be used to represent a natural background without direct anthropogenic activities. The predicted plant-

Table 2*Plant-Available Soil Phosphorus (mg kg⁻¹) in 12 USDA Soil Orders and Three Weathering Stages at Both 0–30 cm and 30–100 cm Soil Depth*

	Min	P ₂₅	Mean	P ₇₅	Max	Number of obs.
0–30 cm						
Slightly weathered	0.04	3.2	14.0	17.7	99.2	2,351
Andisols	0.35	2.2	9.6	11.1	78.0	137
Gelisols	0.08	4.5	12.5	17.0	69.1	125
Entisols	0.04	2.6	10.1	11.1	97.0	719
Inceptisols	0.12	3.7	16.6	24.0	99.2	1,317
Histosols	0.12	4.9	15.3	27.0	84.0	53
Intermediately weathered	0.01	3.1	12.1	16.3	94.2	1,610
Aridisols	0.04	2.1	10.3	14.3	86.0	321
Alfisols	0.01	2.8	12.6	17.2	85.4	748
Mollisols	0.07	4.0	12.7	15.5	94.2	449
Vertisols	0.25	3.6	12.2	18.3	49.2	92
Strongly weathered	0.04	1.8	10.0	11.3	92.9	1,029
Oxisols	0.04	1.6	6.9	7.3	50.1	84
Ultisols	0.05	1.8	9.9	10.7	92.9	789
Spodosols	0.04	3.5	12.4	16.8	60.0	156
30–100 cm						
Slightly weathered	0.02	1.7	7.9	9.6	57.9	558
Andisols	0.02	0.6	3.4	3.0	17.8	27
Gelisols	1.00	3.1	5.9	7.7	15.0	14
Entisols	0.22	2.0	6.5	7.5	52.0	128
Inceptisols	0.20	1.7	8.8	11.0	57.9	387
Histosols	8.0	10.5	13.0	15.5	18.0	2
Intermediately weathered	0.07	2.0	8.6	9.6	66.0	317
Aridisols	0.07	1.5	9.2	13.0	33.7	41
Alfisols	0.14	2.4	8.4	8.5	48.6	121
Mollisols	0.14	1.9	8.9	10.7	66.0	148
Vertisols	0.72	1.4	3.5	4.6	7.2	7
Strongly weathered	0.02	0.8	7.3	9.3	56.5	289
Oxisols	0.88	1.1	3.4	3.1	9.6	9
Ultisols	0.02	0.7	7.2	9.0	56.5	260
Spodosols	0.31	3.14	10.2	14.3	39.9	20

Note. Results are based on our database. P₂₅ and P₇₅ indicate the percentile ranks of 25% and 75%.

available soil P concentration indicated that the estimated area-weighted average concentration, content and stock of plant-available soil P were 14.5 (standard deviation 4.9) mg kg⁻¹, 5.7 (1.8) g m⁻², and 0.73 (0.20) Pg (1 Pg = 10¹⁵ g) at 0–30 cm soil depth, respectively, and 12.9 (standard deviation 5.2) mg kg⁻¹, 12.9 (4.9) g m⁻², and 1.59 (0.50) Pg at 30–100 cm soil depth, respectively.

The estimated global map of plant-available soil P concentration revealed latitudinal patterns at two depths (Figures 5b and 5d), which were also found from analysis of the site-level data (Figure S61 in Supporting Information S1). Plant-available soil P concentration significantly increased with increasing latitude in both hemispheres ($p < 0.01$). Plant-available soil P concentration varied greatly among regions at the same latitude.

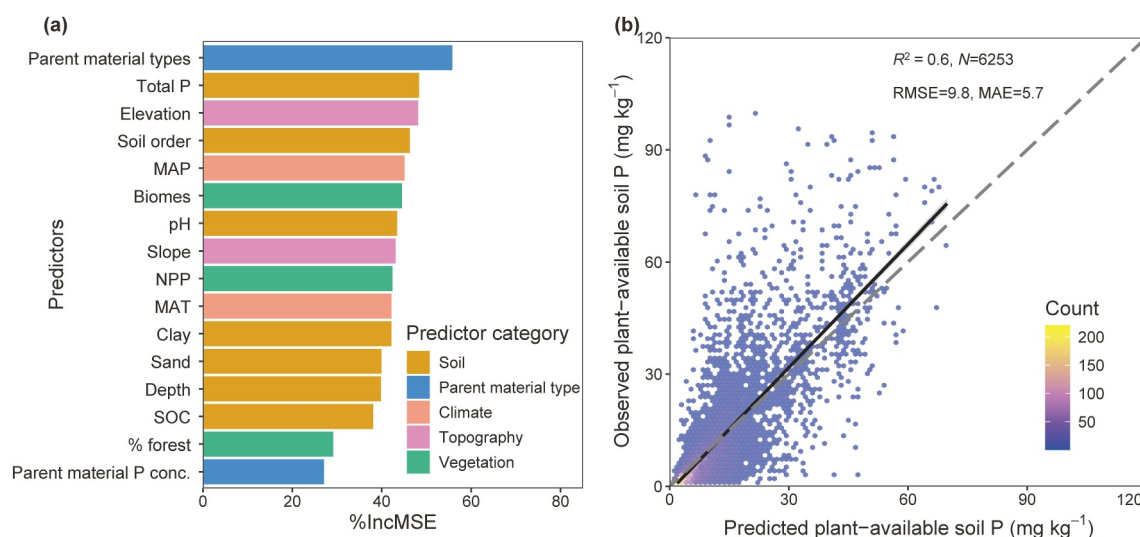


Figure 3. Random forest model results for predicting plant-available soil phosphorus concentration. (a) Relative importance of predictors in the random forest model for affecting plant-available soil phosphorus (P). (b) Comparison of observed versus predicted plant-available soil P concentration; the dashed line indicates the 1:1 line; the black line indicates the regression line between observed versus predicted values. The abbreviations in panel (a): MAP, mean annual precipitation; MAT, mean annual temperature; SOC, soil organic carbon; NPP, net primary productivity; RMSE, root-mean-square-error; MAE, mean absolute error.

For instance, mountains and highlands at low latitudes (African highlands, Andes, north Canada, and Tibetan plateau) had high plant-available soil P concentrations. Our map also showed some regional differences in plant-available soil P concentration; for example, plant-available soil P concentration in central Africa was lower than that in southern Africa. On a continental scale, plant-available soil P concentrations in Africa, South America, Oceania, and Asia were lower than the global average, while those in North America and Europe were higher than the global average (Table 3). The estimated plant-available soil P concentrations at 0–30 cm soil depth showed similar patterns to those at 30–100 cm soil depth (Table 3 and Figure 5).

4. Discussion

With our data set of plant-available soil P concentration determined by the five most commonly used methods (Olsen method, Bray-1 method, Mehlich III method, Colwell method, and AB-DTPA method; Table S1 in Supporting Information S1), we quantified available P concentration in (semi-)natural ecosystems, identified its key drivers, and predicted it for terrestrial ecosystems globally. We included measurements of soils from (semi-)natural ecosystems and excluded measurements of human-affected soils, and thus can distinguish natural drivers from anthropogenic factors (e.g., tillage, irrigation, overgrazing, fertilization, mining and land-use type). In addition, we mapped global plant-available soil P concentration by considering more crucial predictors (parent material types and total soil P concentration, which substantially affect plant-available soil P concentration) and two soil depths (0–30 and 30–100 cm soil depth).

4.1. Variation and Drivers of Plant-Available P Concentration Across Soils

Given the larger number of observations considered in the present study, plant-available soil P concentration ranged from 0.01 to 99.2 mg kg⁻¹. The average plant-available soil P concentrations in our site-level database (12.4 and 8.0 mg kg⁻¹ at 0–30 cm and 30–100 cm depth, respectively) were lower than the global mean concentration of 26 mg kg⁻¹ at 0–20 cm soil depth (McDowell et al., 2023) because their data set consisted of 54% agricultural sites according to their uploaded data file. The other reason is that the missing factors (total soil P and parent material types) can cause substantial uncertainties in the predicted values. Total soil P is the reserve of plant-available P, and parent material indirectly affects plant-available P by impacting soil mineral ions (He et al., 2023).

The variation in plant-available soil P concentration was largely predicted by total soil P concentration and parent material types based on random forest analysis (Figure 3). Plant-available soil P concentration was positively correlated with total soil P concentration, which is consistent with findings at local (Augusto et al., 2017; Deiss

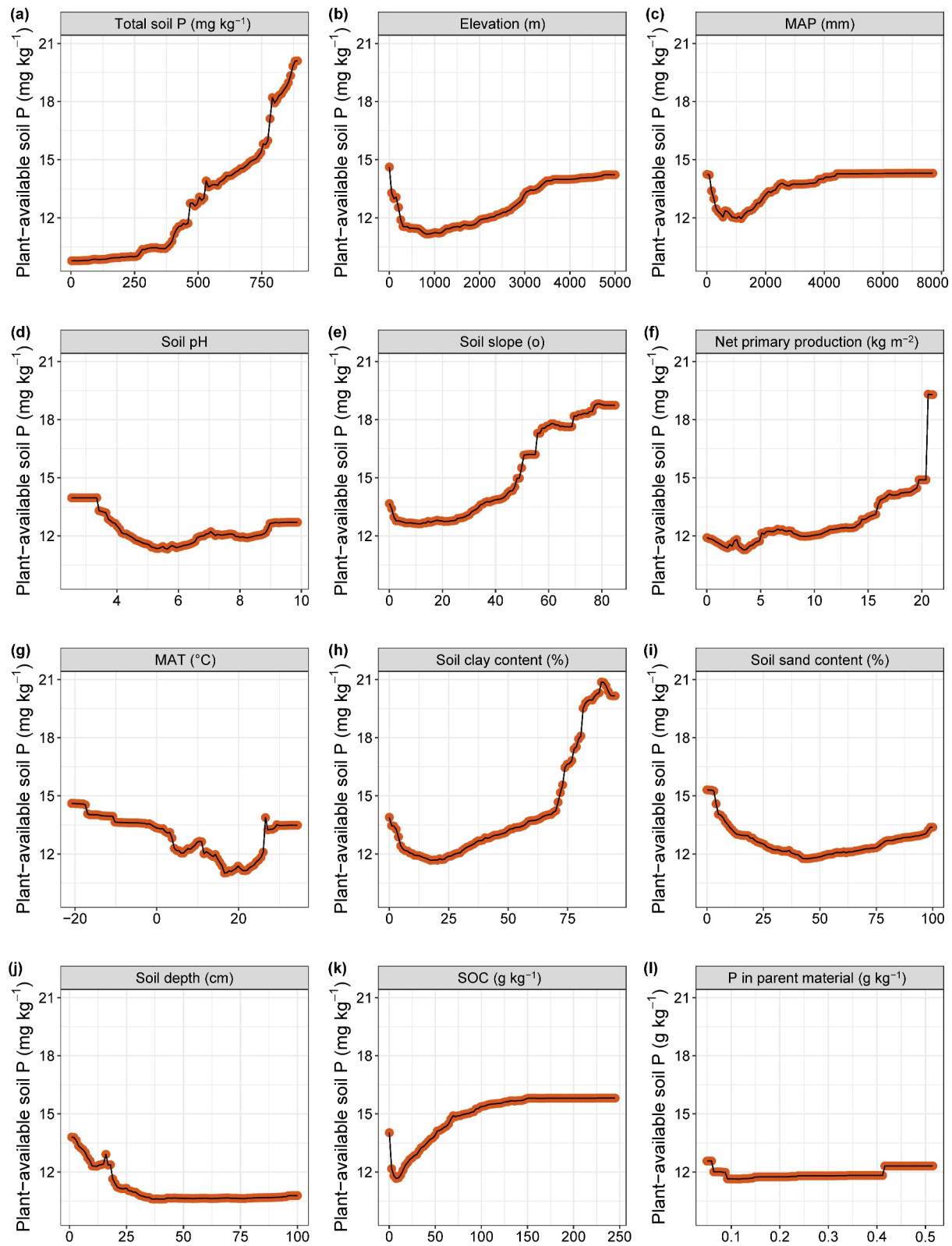


Figure 4. Partial dependence plots showing the dependence of plant-available soil phosphorus on main continuous predictors. Plant-available soil phosphorus (P) concentration in relation to (a) total soil P, (b) elevation, (c) MAP, (d) soil pH, (e) soil slope, (f) MAT, (g) net primary production, (h) soil depth, (i) soil sand content, respectively.

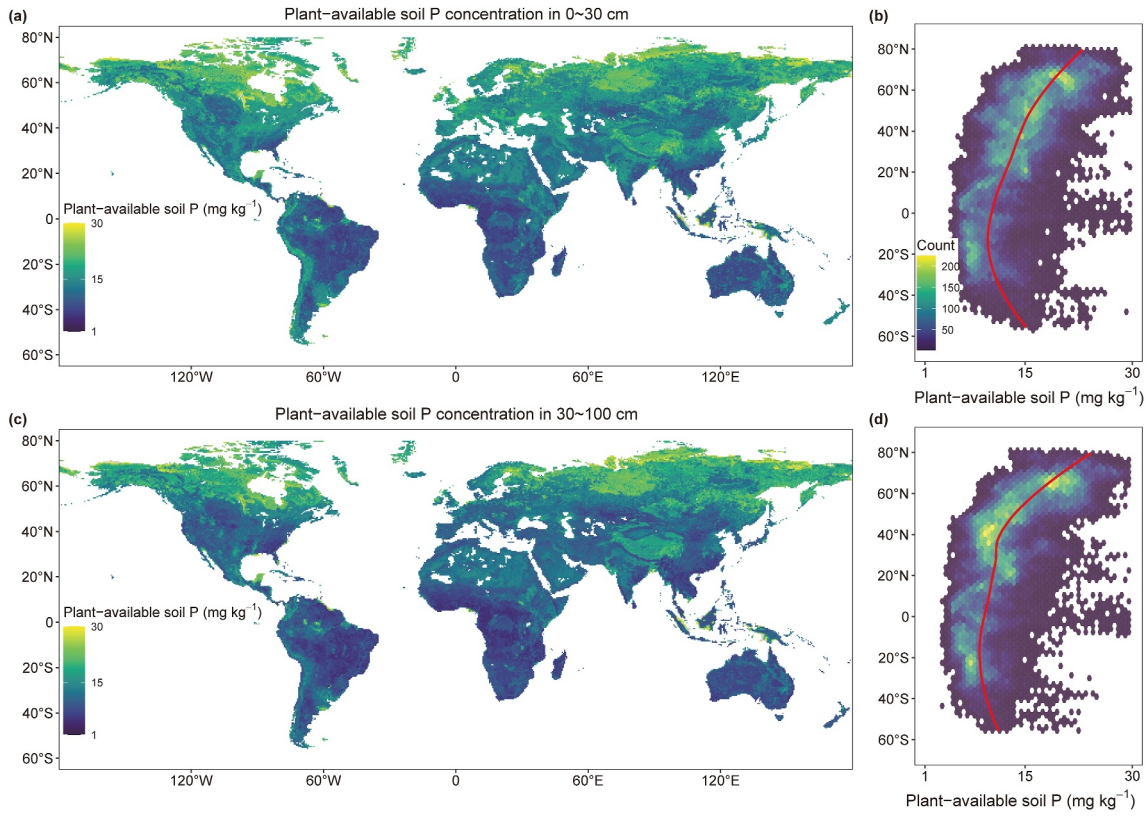


Figure 5. Global maps of plant-available soil phosphorus (P) concentration at the 0–30 cm and 30–100 cm soil depths. Maps of topsoil (0–30 cm) and subsoil (30–100 cm) plant-available soil phosphorus (P) concentration in panels (a) and (b), respectively. Red lines in panels (c) and (d) indicate the regression between plant-available soil P concentration and latitude in global maps. In these predicted global maps, cropland or any other human disturbed areas were not removed, and the plant-available soil P concentration from predicted global maps can be used to represent soils without anthropogenic activities.

et al., 2018; Lambers et al., 2010; Turner et al., 2018) and global (Hou et al., 2020) scales. Thus, total soil P concentration provides an integrated measure of factors that determine the size of plant-available soil P in natural ecosystems (Lang et al., 2017). Total soil P is influenced by multiple soil-forming factors (e.g., parent material types, climate, soil organic carbon, and soil texture) (Jenny, 1941). Parent material can affect the concentrations of

Table 3
Analysis of the Random Forest Model Predicting Plant-Available Soil Phosphorus (P) Concentration and Stock

Continents	0–30 cm			30–100 cm		
	Plant-available soil P concentration (mg kg ⁻¹)	Plant-available soil P content (g m ⁻²)	Plant-available soil P stock (Pg)	Plant-available soil P concentration (mg kg ⁻¹)	Plant-available soil P content (g m ⁻²)	Plant-available soil P stock (Pg)
Oceania	10.0 ± 2.9	4.3 ± 1.3	0.04 ± 0.01	8.9 ± 2.3	9.2 ± 2.4	0.08 ± 0.02
South America	10.7 ± 3.8	4.3 ± 1.6	0.08 ± 0.03	9.0 ± 3.3	8.8 ± 3.4	0.16 ± 0.06
Africa	10.8 ± 3.1	4.6 ± 1.5	0.14 ± 0.04	9.4 ± 2.9	9.6 ± 3.4	0.29 ± 0.10
Asia	13.4 ± 3.8	5.8 ± 1.7	0.25 ± 0.07	11.4 ± 3.7	12.1 ± 3.9	0.53 ± 0.17
North America	17.2 ± 4.6	6.6 ± 1.6	0.16 ± 0.04	15.2 ± 5.1	14.7 ± 4.7	0.35 ± 0.11
Europe	17.9 ± 3.8	6.7 ± 1.4	0.07 ± 0.01	17.0 ± 4.7	16.2 ± 4.3	0.16 ± 0.04
Global	14.5 ± 4.9	5.7 ± 1.8	0.73 ± 0.20	12.9 ± 5.2	12.8 ± 4.9	1.59 ± 0.50

Note. Values are means ± standard deviation (SD). The area-weighted average plant-available soil phosphorus (P) concentrations and stocks was calculated based on our predicted map. Converting plant-available soil P concentration to plant-available soil P stock used the soil bulk density (Hengl et al., 2017).

plant-available soil P indirectly, which is supported by the use of parent material to map total soil P and labile P concentrations at the global scale (Augusto et al., 2017; He et al., 2021). Some parent materials tend to have higher P concentrations, which translate into higher plant-available soil P concentrations (Porder & Ramachandran, 2013). Additionally, parent materials indirectly affect plant-available soil P concentration via the influence of soil physiochemical properties such as soil pH, soil iron (Fe) and aluminum (Al) oxides, and soil texture (Mehmood et al., 2018). For instance, the retention and transformation of P in soil can be influenced by soil clay content, soil pH, soluble calcium, and Al/Fe oxides and hydroxides (Delgado-Baquerizo et al., 2020). As such, parent material types and total soil P concentration are critical predictors of plant-available soil P concentration from local to global scales.

The variation of plant-available soil P concentration across weathering stages predicted by our model was similar to the patterns of total soil P concentration (He et al., 2021), and supported Walker and Syers (1976)' theory based on a soil chronosequence (i.e., soil development or soil weathering). It is also consistent with more nuanced models of soil P dynamics that consider variations in tectonic uplift and geological composition (Buendia et al., 2010). The decrease in plant-available soil P concentration from slightly weathered soil to intermediately- and strongly weathered soils can be explained by the following three aspects. First, the parent material P is depleted and most of the total P has been lost through leaching and erosion during soil development. Second, these soils (i.e., strongly weathered soils) usually have enormous P-sorption capacities because of their high content of soil Fe and Al minerals (McGroddy et al., 2008), although there is evidence that Fe-bound P declines with increasing soil weathering extent (Hou et al., 2020). We found that parent material P concentration explained a smaller proportion of variation in plant-available P than parent material types (Figure 3). This result may be explained by two reasons. One is that the accuracy of the existing global map of parent material P concentration is still low. The other explanation is that parent material types affect plant-available P not only via its P concentration but also via other pathways, such as its impact on soil pH and texture (Hartmann et al., 2012).

Moreover, plant-available soil P concentration was also positively impacted by elevation and site slope (Figures S5 and S6 in Supporting Information S1), in line with a previous study (He et al., 2023). The positive impact of elevation might be attributed to the lower temperature and thus less-weathered soil at high elevations and steeper slopes (Jenny, 1941; Qin et al., 2023) and soils are eroded and hence younger than soils in plains (Deiss et al., 2018). This proposition was supported by the negative correlation between plant-available P and MAT observed in both our study (Figures S5 and S6 in Supporting Information S1) and a previous study on soil P fractions (Hou et al., 2020). High MAT at low elevations favors soil weathering, leading to more loss of P in older soils (Vitousek et al., 2010). In addition, high MAT and MAP generally promote plant growth and P uptake besides P leaching or runoff, consequently resulting in the depletion of plant-available soil P (Huston, 2012). Further, we found that plant-available P decreased from 0 to 30 cm soil depth to 30–100 cm soil depth, which may be explained by the biological uplift effect that can transfer P and other nutrients from subsoils to topsoil via litterfall (Jobbágy & Jackson, 2001; Laliberté et al., 2012; Porder & Chadwick, 2009).

4.2. Global Estimates and Distributions of Plant-Available Soil P

Based on our predicted global map, our estimate of the area-weighted average plant-available soil P concentration and content at 0–30 cm soil depth was lower than previous global estimates by Ballabio et al. (2019), McDowell et al. (2023), and Ringeval et al. (2024), who all included a majority of sites influenced by anthropogenic activities and focused on topsoil (usually 0–20 cm).

Our predicted plant-available soil P concentration decreased significantly from the pole to the equator in both hemispheres. This result is similar to the patterns of total soil P concentration (He et al., 2021) and agrees with a recent meta-analysis that revealed a significant decrease in P limitation to plant growth with latitude (Hou et al., 2021). By comparing plant-available soil P concentrations across the major biomes, the highest plant-available soil P concentration was found in the tundra biomes and the lowest in the tropical and subtropical forests. This result is consistent with our theoretical understanding of the distinguished differences in soil age and weathering intensity between low- and high-latitude regions (Yang & Post, 2011). Lowland tropical soils tend to be more weathered than soils at high latitudes due to warmer and more humid climates, which promote weathering (Hou et al., 2020; Vitousek, 1994). In addition, the last glaciation eroded soils at more northern higher latitudes and caused relatively young and P-enriched soils, as in tundra biomes (Vitousek et al., 2010).

Although we found a latitudinal gradient in plant-available soil P concentration, the heterogeneity in plant-available soil P concentration at the regional and local scales was large. For example, we found that plant-available soil P concentration was higher in Siberia than in central Europe and East Asia (McDowell et al., 2023). Such patterns might be explained by the following two aspects: First, this difference may be due to the fact that glaciation, which affected plant-available soil P via influencing total soil P concentration, was more regular and intense in East Asia and central Europe than in Siberia, which is dominated by young soils (Wassen et al., 2021), leading to a more intensive rejuvenation of soils. Second, the warmer and wetter climate in central Europe and East Asia may promote weathering to release P from the parent material (Goll et al., 2014) and to make it subject to loss. Regional variation in plant-available soil P concentration may also be attributed to the variation in total soil P concentration. For instance, the lower plant-available soil P concentrations in central Africa than in South Africa, and in central Australia than in eastern Australia are possibly due to the highly weathered of soils with lower total soil P as a result of the rainy and hot climate (Hengl et al., 2021). Additionally, higher plant-available soil P concentration on the Tibetan Plateau than in eastern China may result from higher elevation and lower MAT on the Tibetan Plateau, and thus lower relative soil age (Zhang et al., 2005).

4.3. Limitation and Prediction Uncertainty

While we aimed to successfully construct a database and perform global predictions, we recognize that there are limitations to the present study. First, subsoils (>30 cm depth) were not well represented in our data set (19%), and, therefore, predicted plant-available soil P concentrations of subsoils may be associated with larger uncertainties, especially for the soil variables. This may have caused some uncertainties in the predicted plant-available soil P concentration. Second, some regions were underrepresented, for example, northern Canada, Russia, and central Australia, which may have resulted in a low accuracy of predicted values for these regions (Ploton et al., 2020). Third, our assumption that soils that are or have been in agricultural use can be characterized in their native state by the same correlations as (semi-)natural soils might not hold entirely true (Gatiboni et al., 2025). For example, fertile soils are preferred to be cultivated in agriculture. Finally, 40% of the variation in plant-available soil P concentrations was not explained, despite including 16 predictors using an advanced machine-learning approach. This may be because of uncertainty in input data (both plant-available soil P and the corresponding covariates) or methodological constraints (i.e., regression equations among the five methods of plant-available soil P measurements). These limitations highlight the need for more measurements of plant-available soil P concentration and closely associated variables, especially from underrepresented regions, as well as more advanced statistical methods for spatial predictions.

5. Conclusion

By constructing a database of global plant-available soil P concentrations, we quantified the relative importance of multiple soil-forming variables for predicting plant-available soil P concentrations and further estimated these at a global scale. Our results indicate that no single variable can be used to predict plant-available soil P concentration. Instead, a combination of variables is needed to reliably predict plant-available soil P concentration, among which total soil P concentration and parent material are the two most important predictors. Plant-available soil P concentration was positively correlated with total soil P concentration, and was lowest in basic volcanic among 12 kinds of parent material. Our predicted map captures the latitudinal gradient in potential plant-available soil P concentration expected from our theoretical understanding of global plant P limitation. We estimated that plant-available soil P stocks at 0–30 cm and at 30–100 cm soil depth of natural ecosystems (excluding Antarctica) were 0.73 and 1.59 Pg, respectively. Our global map of plant-available soil P will be an important resource for future studies aimed at tackling issues related to P cycling and the P limitation of ecosystem productivity, as well as predicting future land carbon sinks.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The plant-available soil P geochemical data for calibration and validation, R code, and global maps generated in this study are available in figshare at <https://doi.org/10.6084/m9.figshare.24088368> (Luo et al., 2025).

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