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# The phosphorus status of German cropland—An inventory of top- and subsoils

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## Abstract

***Background***: In search for more sustainable crop production, the subsoil has recently come into focus as considerable reservoir of nutrients and water.
***Aims***: Dimensions of subsoil phosphorus (P) reserves are yet largely unknown but crucial for identifying regions suitable to include subsoil into sustainable management strategies.
***Methods***: We analyzed stocks of total and plant-available (calcium acetate lactate-extractable) P in 96 representative soil profiles of German arable land down to 1 m depth.
***Results***: We found that the German arable soils stored, on average, 8 t $ha^{-1}$ of total P, of which nearly 500 kg $ha^{-1}$ were readily plant-available. Notably, one third of plant-available P was located below the plow layer and one fifth even at depths below 0.5 m. The depth gradients of plant-available P stocks were affected more by major reference soil group than by texture. Generally, Chernozem but also Anthrosol, Gleysol and Fluvisol exhibited the largest P stocks in German cropland. The contribution of plant-available P to total P stocks was larger in sandy and extremely acidic (pH < 4.5) soils compared with more fine-grained and slightly acidic to alkaline soils, possibly because fertilization compensated for overall lower total P stocks at these sites. Generally, the more P was stored in topsoils, the more P was stored also in subsoils.
***Conclusions***: A hypothetical crop utilization of 10% from plant-available P stocks and 0.1% from total P stocks from shallow subsoil could compensate for P fertilization by ca. 8 kg $ha^{-1}$, but the rate of plant-available P replenishment in subsoil likely remains the crucial factor for the role of subsoil P stocks in crop nutrition. Generally, the large P reserves found in subsoil could act as an 'insurance' system for crops.

**Key words:** agricultural soils / German Agricultural Soil Inventory / phosphorus pools / plant-available P / subsoil

Supporting Information available online

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## 1 Introduction

Phosphorus (P) is an essential nutrient element for plant growth, and is a major limiting factor for crop production worldwide (*Kvakić* et al., 2018). Most arable soils contain considerable amounts of total P, originating from P-containing minerals and external sources such as fertilizers, dust, and biomass returns. However, only a minor portion of the inorganic P pool in soil is available in dissolved form for plant uptake (*Kruse* et al., 2015), and thus usually supplemented by fertilization in agricultural production systems. This management strategy is nowadays increasingly criticized for being unsustainable, because of the negative side effects of water eutrophication from cropland with high P status due to diffuse P losses into adjacent water bodies (*Horrigan* et al., 2002; *Withers* et al., 2014).

Recently, increasing attention has been paid to the subsoil as additional nutrient reservoir, since subsoils may contain between 25 and 70% of total soil P, and often higher and less variable water contents in subsoil may increase the portion of dissolved P, thus compensating for larger distances between roots and nutrient sources (*e.g.*, *Godlinski* et al., 2004; *Kautz* et al., 2013; *Barej* et al., 2014). Moreover, subsoil P is less prone to be lost to water systems since most P loss occurs *via* topsoil erosion (*Kruse* et al., 2015). Quantitative knowledge on P resources below the topsoil is scarce and has hardly been resolved for different major reference soil groups, yet such knowledge would be valuable because most crops are able to root far beyond the plow layer, with maximum rooting depth averaging at 2 m (*Canadell* et al., 1996). In the following, the term subsoil refers to the depth interval between 0.3 m (the average depth of the plow layer in Germany) and 1 m depth, since the latter is a conventional lower border for the pedon scale. Studies from long-term field trials confirmed that significant stocks of plant-available P are located in subsoil (*Gransee* and *Merbach*, 2000; *Kautz* et al., 2013; *Barej* et al., 2014), which are utilized by the crops in case of nutrient

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deficiency in topsoil (*Kuhlmann* and *Baumgärtel*, 1991), and likely even at larger amount in case of sufficient N supply in the surface soil (*Bauke* et al., 2018). Also, biopores in subsoils, although their contribution to overall P stocks is low, may serve as hotspots of nutrient elements like P and could thus provoke or enforce root growth into subsoil (*Barej* et al., 2014).

At European scale, agricultural topsoils have been surveyed for their P status (*Tóth* et al., 2014), whereas respective knowledge on subsoils is scarce. In Denmark, a national inventory for agricultural soils down to 1 m depth revealed that, compared to deciduous forest soils, soil P pools were elevated to at least 0.75 m depth due to long-term over-fertilization (*Rubæk* et al., 2013). For Siberian forest and grassland sites, subsoil (0.2–1.2 m) stocks of plant-available P were shown to provide major portions of soil P supply (*Brédoire* et al., 2016). For other countries, such as Germany, a nationwide quantification of top- and subsoil P resources has not yet been performed, although this is crucial for our understanding of P pool dimensions as a function of various site conditions like major reference soil group, texture, parent material and further soil chemical and geophysical properties. Such a P inventory may also further support the identification of sites suitable for including subsoil into sustainable management strategies, which aim at extending nutrient resources accessible to crop roots, and thus to minimize the overuse of P fertilizers in near future (*Rejnders*, 2014).

The objective of the current study was to provide a survey of the P supply of German cropland from topsoil to 1 m depth. We hypothesized that major portions of German arable land contain sufficient amount of P in the plow layer, but that significant stocks of plant-available P are additionally found in the subsoil, with the size of these stocks depending mainly on soil texture, major reference soil group and parent material.

## 2 Material and methods

### 2.1 The German Agricultural Soil Inventory

The German Agricultural Soil Inventory was conducted by the Thünen Institute of Climate-Smart Agriculture, Germany. Agricultural soils were sampled in a time period between 2011 and 2018 down to 1 m depth, as described by *Vos* et al. (2019), on a grid of 8 × 8 km for whole Germany, resulting in a total of ca. 3,100 sampling points. Over all sampling points, plowing depth averaged at 30 cm. For each sampling point, standard parameters were documented, including type of soil parent material and its stratigraphic context, sequence of soil horizons and major reference soil group (see below), as well as current and historic land use. In soil pits, soil samples were obtained from at minimum five depth intervals (0–0.1, 0.1–0.3, 0.3–0.5, 0.5–0.7, and 0.7–1 m). If horizon borders were located in between the depth interval borders additional samples were obtained to account for the different horizons. After drying at 40°C, basic physical and chemical characteristics of fine soil < 2 mm were determined including texture, electrical conductivity, pH measured in $CaCl_2$, organic and inorganic carbon (OC, IC), as well as total nitrogen (N) content and stone content (> 2 mm). Dry bulk density of the fine earth fraction (< 2 mm) was determined in volumetrically collected samples dried at 105°C. The soils were classified according to the German classification system (*Ad-hoc-Arbeitsgruppe Boden*, 2005), and translated here into the international soil classification system of the World Soil Reference Base (*IUSS Working Group WRB*, 2015). Samples had been archived at Thünen Institute of Climate-Smart Agriculture, Germany, and basic data are described by *Poeplau* et al. (2020).

### 2.2 Subsample set

For the current study, using a selection algorithm (Kennard-Stone algorithm; *Kennard* and *Stone*, 1969), a subsample set of 96 sites was chosen from the German Agricultural Soil Inventory, which represents the proportions of the various soil groups, textures, soil parent materials as well as land use types in German cropland. As these sites were sampled at different depth intervals (see above), the analyses finally comprised 517 individual soil samples (for location of the study sites see Fig. 1). For this study we selected sites in

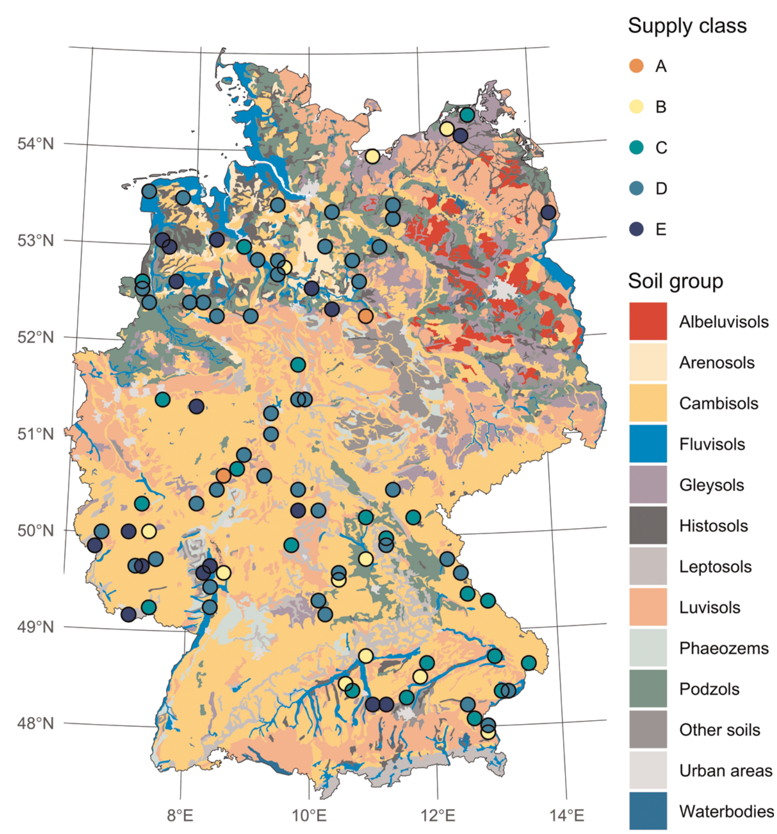


**Figure 1:** Map of Germany showing the major reference soil groups according to *IUSS Working Group WRB* (2015) and location of the 96 agricultural sites analyzed for the current study as well as their topsoil P supply class.

 

order to obtain representative subsets of all relevant major reference soil groups. The comparison to unpublished data show that this is not necessarily the same as when taking area-representative samples. However, our subset allows to understand P accrual in different soils of different origin. Further, *Zicker* et al. (2018) showed that changes in soil P availability due to different P management practices generally occur slowly due to the high P binding capacity in soils, therefore we did not include management factors, like, *e.g.*, fertilization regime and crop type, in our study.

## 2.3 Chemical analyses

For the following analyses, the fine earth fraction < 2 mm was used.

For determination of total phosphorus ($P_t$) contents, 1 g of soil was digested with 14 mL of hot *aqua regia* [conc. hydrochloric acid / conc. nitric acid 3:1 (v:v)] for 4 hours (DigiPREP MS Digestion System, SCP Science, Germany). After cooling, extracts were diluted to a volume of 50 mL, filtered and measured by inductively coupled plasma optical emission spectroscopy (ICP-OES; Ultima 2, HORIBA Jobin Yvon, Longjumeau, France).

Calcium acetate lactate-extractable phosphorus ($P_{CAL}$) is considered as a proxy for plant-available P in German soils and was measured according to *Schüller* (1969). An aliquot of 5 g of soil was shaken with 100 mL of a buffered extraction solution containing calcium lactate, calcium acetate and acetic acid (pH 3.7–4.1), then filtered over a paper filter. Extracts were reacted with molybdenum blue solution and ascorbic acid (*Murphy* and *Riley*, 1962), then measured photometrically (Specord 205, AnalytikJena, Germany). This method is well established in Germany, although plant-available P is underestimated in neutral and alkaline soils (*Schüller*, 1969). Therefore, the measured $P_{CAL}$ ($mP_{CAL}$) was corrected [$cP_{CAL}$; Eq. (1)] as proposed by VDLUFA for soil samples with a $pH_{CaCl_2} \geq 7.1$, using pH of the filtrated CAL extraction solution ($pH_{CAL}$) in case that the latter shows values ≥ 4.3:

$$cP_{CAL} = mP_{CAL} \times [1 + 0.83 \times (pH_{CAL} - 4.1)]. \quad (1)$$

Every 5th sample was measured in replicate for $P_t$ and $P_{CAL}$ to determine measurement precision, which was 8 mg $kg^{-1}$ and 0.3 mg $kg^{-1}$, respectively.

## 2.4 Site categorization

The 96 arable sites investigated in the current study were categorized in the following ways to assess differences in P supply and P stocks: For soil texture, each site was attributed to one of four groups (sand, loam, silt, clay; *Ad-hoc-Arbeitsgruppe Boden*, 2005), depending on the most prominent grain size distribution in subsoil (0.3–1 m). The German soil class (Bodenklasse) was translated into major reference soil groups (*IUSS Working Group WRB*, 2015) according to Supplementary Tab. S1. Soil parent material was categorized by rock solidness (bedrock vs. sedimentary rock), by transport record (relocated, formed by transport or formed *in situ*), by deposition process (*e.g.* marine, aeolian) and by pH class. For the latter, we complied with the soil pH classification according to U.S. Department of Agriculture (Supplementary Tab. S2).

For a uniform handling, always the material and its properties from the lowest depth increment was used for the categorization *via* parent material.

## 2.5 P supply in topsoil

The supply of topsoil (0–0.3 m) with plant-available P was calculated by converting $P_{CAL}$ contents into mg $P_{CAL}$ per 100 g soil and the values were grouped into supply classes A–E according to the updated recommendation of the Association of German Agricultural Analytic and Research Institutes (VDLUFA; *Wiesler* et al., 2018; Supplementary Tab. S3). The classes A and B indicate P deficiency, C is the class that should be targeted by cropland management, and the classes D and E indicate over-fertilization.

## 2.6 Calculation of $P_t$ and $P_{CAL}$ stocks

Stocks of $P_t$ and $P_{CAL}$ were calculated for the topsoil (0–0.3 m) and subsoil (0.3–0.5 m, 0.5–1 m), as well as for the whole uppermost 1 m according to *Poeplau* et al. [2017; Eq. (2)], using the respective values from the fine earth fraction (FE):

$$P\ stock_{FE} = c_P \times \rho_{FE} \times d \times (1 - X), \quad (2)$$

with $c_P$ as the contents of either $P_t$ or $P_{CAL}$ of fine earth in mg $kg^{-1}$, $\rho_{FE}$ as the dry bulk density of fine earth in g $cm^{-3}$, d as thickness of the respective depth interval in m, and X as the volume percentage of the coarse fraction in vol.-%.

Soil carbon and nutrient element stocks are often calculated with an equivalent soil mass approach rather than with fixed depths to account for soil compaction of arable land, caused by changes in land use or tillage regime (*Ellert* and *Bettany*, 1995; *Wendt* and *Hauser*, 2013). It was shown for SOC that stocks are affected by tillage only in the top 30 cm (*Meurer* et al., 2018). We calculated mass-corrected P stocks for topsoil additionally to the fixed-depth stocks for the complete uppermost meter. For this, the site with highest dry bulk density of either fine earth or total sample, respectively, in top 30 cm was chosen as a reference. We did not choose the site with lowest bulk density as a reference for two reasons: first, all sites were trafficked and, thus, we assume that no 'zero compaction site' is available in our set of study sites. Second, at the site with strongest compaction, both organic remains and fertilizer P have been introduced into the top 30 cm of soil (the average plowing depth), so that this complete depth interval has to be considered as topsoil rather than partly being subsoil that has to be subtracted from the lowermost topsoil of the other sites. Mass-corrected P stocks in topsoil were calculated in the following way: soil mass per hectar (M) was calculated for the top 30 cm of each site [Eq. (3)].

$$M = \rho \times d. \quad (3)$$

For each individual site, the soil mass missing for the mass-fixed P stock calculation ($M_m$) was calculated as the difference between M from the reference site and M of the individual site. From $M_m$, the depth interval that has to be added below the top 30 cm ($d_m$) was calculated, using average dry bulk density of the underlying depth interval [0.3–0.5 m; Eq. (4)].

$$d_m = M_m/\rho. \quad (4)$$

Using the respective depth interval $d_m$, average dry bulk density from 0.3–0.5 m and average P content from 0.3–0.5 m, the additional P stock was calculated according to Eq. (2). Afterwards, the additional P stock was added to the respective P stock calculated for the top 30 cm.

## 2.7 Presentation of data and statistics

For easier comparison, all $P_t$ and $P_{CAL}$ data from the top 30 cm (average plowing depth) as well as for those depth increments taken additionally to the above-mentioned scheme were merged, respectively, to obtain values for four depth intervals (0–0.3, 0.3–0.5, 0.5–0.7, and 0.7–1 m) at each site.

In Figures showing P stocks, only those stocks are displayed, which were not corrected for equivalent soil mass. Topsoil P stocks corrected for equivalent soil mass are given in Tab. 1 in parentheses.

Bar charts show mean values and, if applicable, standard error of the mean, box plots were created using SigmaPlot 13.0 (Systat).

Prior to statistical analyses, data were tested for normal distribution by Kolmogorow–Smirnow–Lilliefors test and, if necessary, transformed by natural logarithm [ln(x+1)]. Differences between groups within each category (soil texture, major reference soil group or parent material, see above) were tested for significance by one-way ANOVA with a significance level of 0.05 and 0.01 (highly significant), followed by post hoc Scheffé test using STATISTICA 7.0 (StatSoft).

**Table 1**: Stocks of plant-available P ($P_{CAL}$), total P ($P_t$) and portion of $P_{CAL}$ from $P_t$ in topsoil (0–0.3 m), shallow subsoil (0.3–0.5 m) and deep subsoil (0.5–1 m), sorted by groundwater influence, major soil group (*IUSS Working Group WRB*, 2015), predominant texture of each study site and various properties of the parent material. All values are based on fine earth data [see Eq. (1)]. Topsoil values that were corrected for equivalent soil mass are written in parentheses. Data are given as mean ± standard error.

| | $P_{CAL}$ stock (kg ha$^{-1}$) | | | $P_t$ stock (kg ha$^{-1}$) | | | $P_{CAL}$ stock (% of $P_t$ stock) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Depth interval** | **0–0.3 m** | **0.3–0.5 m** | **0.5–1 m** | **0–0.3 m** | **0.3–0.5 m** | **0.5–1 m** | **0–0.3 m** | **0.3–0.5 m** | **0.5–1 m** |
| **total** | | | | | | | | | |
| Arable sites (*n* = 96) | 339 ± 29 (362 ± 31) | 71 ± 11 | 101 ± 15 | 3,621 ± 179 (4,059 ± 206) | 1,301 ± 113 | 3,388 ± 474 | 10.4 ± 0.8 | 7.5 ± 1.0 | 6.4 ± 1.0 |
| Terrestrial (*n* = 84) | 329 ± 25 (348 ± 26) | 64 ± 10 | 81 ± 13 | 3,598 ± 191 (4,013 ± 218) | 1,286 ± 123 | 3,328 ± 527 | 10.5 ± 0.8 | 7.4 ± 1.1 | 6.2 ± 1.1 |
| Semi-terrestrial (*n* = 12) | 411 ± 158 (452 ± 174) | 123 ± 50 | 237 ± 66 | 3,783 ± 535 (4,378 ± 648) | 1,408 ± 291 | 3,797 ± 951 | 10.0 ± 2.0 | 8.8 ± 2.6 | 8.1 ± 2.8 |
| **Major soil group** | | | | | | | | | |
| Regosol, Leptosol (*n* = 13) | 299 ± 39 (309 ± 39) | 30 ± 9 | 44 ± 11 | 4,651 ± 753 (5,320 ± 813) | 1,790 ± 531 | 5,119 ± 2,236 | 7.2 ± 1.0 | 3.9 ± 1.9 | 3.2 ± 1.4 |
| Chernozem (*n* = 1) | 1,515 (1,612) | 294 | 140 | 5,024 (5,704) | 2,075 | 2,692 | 30.2 | 14.2 | 5.2 |
| Vertisol (*n* = 3) | 442 ± 47 (445 ± 48) | 10 ± 2 | 57 ± 13 | 5,251 ± 1,667 (5,887 ± 1,981) | 2,231 ± 1,221 | 16,825 ± 14,548 | 10.4 ± 3.3 | 0.9 ± 0.4 | 1.6 ± 1.5 |
| Cambisol (*n* = 25) | 339 ± 33 (359 ± 35) | 68 ± 15 | 69 ± 17 | 3,577 ± 245 (3,997 ± 293) | 1,205 ± 142 | 2,357 ± 393 | 9.8 ± 0.7 | 6.9 ± 1.5 | 4.8 ± 1.5 |
| Luvisol (*n* = 12) | 230 ± 48 (233 ± 48) | 22 ± 6 | 53 ± 17 | 3,375 ± 258 (3,694 ± 309) | 1,296 ± 120 | 3,183 ± 491 | 7.0 ± 1.3 | 1.8 ± 0.6 | 1.6 ± 0.4 |
| Podzol (*n* = 7) | 405 ± 122 (433 ± 121) | 82 ± 28 | 40 ± 7 | 2,345 ± 519 (2,518 ± 512) | 576 ± 136 | 435 ± 97 | 16.6 ± 2.1 | 12.5 ± 2.8 | 10.9 ± 2.2 |
| Stagnosol, Planosol (*n* = 14) | 233 ± 51 (246 ± 53) | 46 ± 20 | 98 ± 48 | 3,478 ± 358 (3,841 ± 430) | 1,146 ± 250 | 4,045 ± 678 | 7.1 ± 1.4 | 3.2 ± 1.1 | 2.6 ± 1.1 |
| Anthrosol (*n* = 9) | 398 ± 63 (449 ± 64) | 165 ± 51 | 206 ± 72 | 2,882 ± 622 (3,216 ± 715) | 1,134 ± 474 | 2,033 ± 790 | 20.3 ± 4.3 | 24.9 ± 5.1 | 23.0 ± 5.5 |

 

**Table 1.** Continued.

| | $P_{CAL}$ stock (kg $ha^{-1}$) | | | $P_t$ stock (kg $ha^{-1}$) | | | $P_{CAL}$ stock (% of $P_t$ stock) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Depth interval** | **0–0.3 m** | **0.3–0.5 m** | **0.5–1 m** | **0–0.3 m** | **0.3–0.5 m** | **0.5–1 m** | **0–0.3 m** | **0.3–0.5 m** | **0.5–1 m** |
| Fluvisol (*n* = 5) | 282 ± 23 (310 ± 27) | 71 ± 25 | 63 ± 24 | 3,906 ± 610 (4,653 ± 860) | 1,631 ± 387 | 3,036 ± 1,162 | 7.6 ± 0.7 | 5.0 ± 1.6 | 3.5 ± 1.2 |
| Gleysol (*n* = 5) | 591 ± 386 (646 ± 425) | 179 ± 120 | 307 ± 112 | 3,503 ± 1,201 (4,002 ± 1,402) | 1,236 ± 587 | 2,894 ± 1,025 | 13.4 ± 4.5 | 12.1 ± 5.8 | 12.5 ± 6.1 |
| Salic Fluvisol (*n* = 2) | 282 ± 88 (320 ± 106) | 111 ± 34 | 496 ± 27 | 4,174 ± 573 (4,631 ± 284) | 1,279 ± 646 | 7,955 ± 3,862 | 7.2 ± 3.1 | 9.8 ± 2.3 | 8.4 ± 4.4 |
| **Texture** | | | | | | | | | |
| Sand (*n* = 35) | 350 ± 33 (376 ± 34) | 90 ± 18 | 110 ± 25 | 2,851 ± 238 (3,130 ± 275) | 869 ± 148 | 1,420 ± 274 | 14.3 ± 1.4 | 14.0 ± 2.2 | 12.8 ± 2.2 |
| Loam (*n* = 23) | 337 ± 86 (360 ± 95) | 62 ± 29 | 69 ± 17 | 3,660 ± 344 (4,240 ± 423) | 1,290 ± 197 | 4,100 ± 1,017 | 8.6 ± 1.1 | 3.5 ± 0.9 | 2.3 ± 0.5 |
| Silt (*n* = 15) | 352 ± 92 (371 ± 98) | 73 ± 23 | 71± 17 | 3,903 ± 159 (4,314 ± 210) | 1,403 ± 126 | 2,951 ± 325 | 8.6 ± 1.8 | 5.0 ± 1.2 | 3.1 ± 0.8 |
| Clay (*n* = 23) | 292 ± 38 (309 ± 41) | 44 ± 12 | 101 ± 38 | 4,456 ± 495 (5,010 ± 546) | 1,890 ± 326 | 5,915 ± 1,490 | 7.2 ± 1.0 | 2.9 ± 0.8 | 2.3 ± 0.7 |
| **Parent material[a] type** | | | | | | | | | |
| Bedrock (*n* = 10) | 283 ± 49 (292 ± 48) | 28 ± 7 | 69 ± 21 | 4,759 ± 1,013 (5,238 ± 1,085) | 1,907 ± 707 | 8,454 ± 3,627 | 6.9 ± 1.2 | 2.7 ± 0.6 | 2.4 ± 0.7 |
| Sedimentary rock (*n* = 86) | 346 ± 32 (369 ± 34) | 76 ± 12 | 104 ± 17 | 3,488 ± 159 (3,922 ± 191) | 1,231 ± 97 | 2,851 ± 327 | 10.8 ± 0.8 | 8.1 ± 1.1 | 6.8 ± 1.1 |
| **Parent material type** | | | | | | | | | |
| Relocated (*n* = 4) | 374 ± 109 (392 ± 106) | 67 ± 25 | 59 ± 21 | 3,336 ± 730 (3,779 ± 750) | 1,489 ± 631 | 2,502 ± 847 | 12.0 ± 2.5 | 4.8 ± 1.1 | 3.9 ± 1.6 |
| Formed by transport (*n* = 43) | 389 ± 52 (419 ± 56) | 106 ± 19 | 158 ± 30 | 3,167 ± 235 (3,513 ± 274) | 1,105 ± 142 | 2,302 ± 365 | 13.6 ± 1.3 | 13.0 ± 1.9 | 11.5 ± 1.9 |
| Formed in situ (*n* = 49) | 292 ± 33 (308 ± 35) | 41 ± 10 | 53 ± 9 | 4,042 ± 267 (4,561 ± 306) | 1,458 ± 176 | 4,456 ± 863 | 7.6 ± 0.7 | 2.9 ± 0.5 | 2.0 ± 0.3 |
| **Parent material type** | | | | | | | | | |
| Glacial sediments (*n* = 41) | 311 ± 29 (330 ± 31) | 61 ± 12 | 76 ± 19 | 3,486 ± 217 (3,865 ± 262) | 1,158 ± 130 | 2,524 ± 317 | 9.4 ± 0.8 | 6.8 ± 1.5 | 5.0 ± 1.4 |
| Marine sediments (*n* = 3) | 308 ± 82 (335 ± 86) | 59 ± 43 | 278 ± 245 | 3,520 ± 189 (4,008 ± 223) | 1,064 ± 446 | 2,309 ± 1,783 | 8.6 ± 2.0 | 4.4 ± 1.8 | 9.5 ± 3.3 |
| Aeolian sediments (*n* = 8) | 343 ± 50 (371 ± 54) | 82 ± 28 | 112 ± 64 | 2,056 ± 389 (2,214 ± 405) | 682 ± 203 | 1,322 ± 566 | 22.1 ± 4.4 | 20.1 ± 5.0 | 18.7 ± 4.9 |
| Fluvial sediments (*n* = 19) | 445 ± 106 (480 ± 115) | 122 ± 39 | 183 ± 47 | 3,898 ± 390 (4,442 ± 458) | 1,442 ± 275 | 3,069 ± 688 | 11.4 ± 1.7 | 10.0 ± 2.4 | 9.5 ± 2.4 |

 

**Table 1.** Continued.

| | $P_{CAL}$ stock (kg ha$^{-1}$) | | | $P_t$ stock (kg ha$^{-1}$) | | | $P_{CAL}$ stock (% of $P_t$ stock) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Depth interval** | **0–0.3 m** | **0.3–0.5 m** | **0.5–1 m** | **0–0.3 m** | **0.3–0.5 m** | **0.5–1 m** | **0–0.3 m** | **0.3–0.5 m** | **0.5–1 m** |
| Weathered/ relocated sediments (*n* = 23) | 308 ± 64 (323 ± 67) | 52 ± 16 | 64 ± 14 | 3,876 ± 447 (4,336 ± 477) | 1,499 ± 290 | 4,486 ± 1,183 | 8.2 ± 132 | 3.5 ± 0.8 | 2.3 ± 0.5 |
| Other, multi-origin[b] (*n* = 2) | 292 ± 89 (294 ± 88) | 5 ± 1 | 28 ± 16 | 7,217 ± 1,360 (8,673 ± 1,171) | 3,450 ± 1,215 | 20,389 ± 10,985 | 3.9 ± 0.5 | 0.2 ± 0.0 | 0.1 ± 0.0 |
| **Parent material age** | | | | | | | | | |
| Holocene (*n* = 17) | 317 ± 42 (349 ± 44) | 90 ± 30 | 192 ± 53 | 3,782 ± 378 (4,4308 ± 476) | 1,514 ± 277 | 4,103 ± 784 | 11.4 ± 2.7 | 10.8 ± 3.5 | 10.4 ± 3.5 |
| Pleistocene (*n* = 67) | 357 ± 40 (379 ± 43) | 75 ± 13 | 83 ± 16 | 3,469 ± 176 (3,852 ± 208) | 1,182 ± 100 | 2,583 ± 360 | 10.7 ± 0.8 | 7.5 ± 1.1 | 5.9 ± 1.1 |
| Tertiary (*n* = 2) | 198 ± 68 (211 ± 78) | 16 ± 1 | 56 ± 31 | 1,625 ± 12 (1,923 ± 198) | 464 ± 115 | 1,059 ± 755 | 12.2 ± 4.3 | 3.7 ± 0.7 | 6.5 ± 1.8 |
| Jurassic (*n* = 2) | 117 ± 28 (131 ± 33) | 24 ± 6 | 37 ± 5 | 3,161 ± 2 (3,473 ± 115) | 571 ± 137 | 864 ± 338 | 3.7 ± 0.9 | 4.2 ± 0.0 | 4.8 ± 1.3 |
| Triassic (*n* = 7) | 326 ± 58 (335 ± 58) | 32 ± 10 | 54 ± 11 | 5,244 ± 1,427 (5,762 ± 1,525) | 2,380 ± 969 | 11,167 ± 5,120 | 7.8 ± 1.6 | 2.5 ± 0.8 | 1.6 ± 0.8 |
| Permian (*n* = 1) | 314 (319) | 12 | 224 | 4,562 (5,094) | 1,259 | 7,355 | 6.9 | 0.9 | 3.1 |
| **Parent material (composition)** | | | | | | | | | |
| Ultra-, extremely acidic (*n* = 13) | 382 ± 53 (431 ± 57) | 127 ± 28 | 139 ± 45 | 2,730 ± 509 (3,034 ± 582) | 757 ± 169 | 1,789 ± 695 | 19.4 ± 3.1 | 22.0 ± 4.0 | 19.3 ± 4.3 |
| Very strongly, strongly acidic (*n* = 15) | 319 ± 62 (333 ± 63) | 56 ± 16 | 123 ± 49 | 3,381 ± 322 (3,712 ± 364) | 922 ± 133 | 2,149 ± 585 | 9.9 ± 1.5 | 8.0 ± 2.5 | 7.6 ± 2.4 |
| Moderately, slightly acidic (*n* = 31) | 291 ± 25 (309 ± 26) | 64 ± 18 | 97 ± 24 | 3,632 ± 239 (4,130 ± 296) | 1,273 ± 187 | 3,466 ± 779 | 8.6 ± 0.7 | 5.6 ± 1.2 | 4.8 ± 1.2 |
| Neutral (*n* = 12) | 422 ± 167 (448 ± 183) | 87 ± 52 | 60 ± 21 | 3,968 ± 504 (4,448 ± 623) | 1,515 ± 289 | 3,445 ± 646 | 9.0 ± 2.1 | 4.0 ± 1.6 | 2.0 ± 0.6 |
| Alkaline (*n* = 25) | 349 ± 59 (364 ± 62) | 53 ± 14 | 92 ± 33 | 4,047 ± 458 (4,525 ± 503) | 1,743 ± 300 | 4,900 ± 1,428 | 9.1 ± 1.2 | 3.8 ± 0.8 | 3.0 ± 0.8 |

[a]Material in depth 0.7–1 m.
[b]Deckton, Tonmergel.

## 3 Results

### 3.1 $P_{CAL}$ contents in top- and subsoils

The $P_{CAL}$ contents throughout the sample set showed a wide range from less than 0.3 to 600 mg kg$^{-1}$, with topsoil contents mostly between 50 and 100 mg kg$^{-1}$ and the lowermost depth interval mostly between 3 and 15 mg kg$^{-1}$ (interquartile ranges, Supplementary Fig. S1). At most sites, values showed an abrupt decrease of $P_{CAL}$ below the plow layer, which further decreased with depth in the subsoils, and were lower by at least one order of magnitude in 0.7–1 m depth compared to the topsoils. In contrast, a different depth distribution of $P_{CAL}$ was found in some Anthrosols, Stagnosols/Planosols, Gleysols, Fluvisols, and in all Salic Fluvisols (Fig. 2). As a special case, $P_{CAL}$ contents in clayey Gleysols and in Salic Fluvisols strongly increased from shallow to deep subsoil and therein they even exceeded top-

 

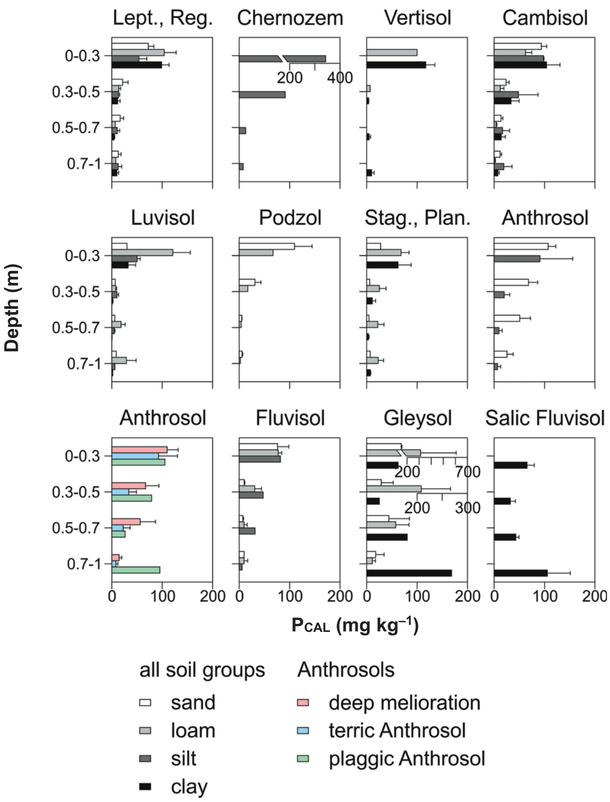


**Figure 2:** Depth distribution of $P_{CAL}$ contents for each of the 11 major soil groups, divided into the dominant soil texture group and, in case of Anthrosols, into classes of soil profile modification. Error bars are shown for all groups with $n \geq 2$ and represent standard error of the mean.

soil values. Also, the Chernozem showed a less steep decrease of $P_{CAL}$ contents with depth.

### 3.2 $P_{CAL}$ and $P_t$ stocks

German arable soils stored on average more than 500 kg ha$^{-1}$ of plant-available P. About one third of these $P_{CAL}$ stocks was located below the plow layer (0.3–1 m) and 20% even at depths below 0.5 m (data not shown here; for an overview of the magnitude of P stocks see Fig. 5). Intriguingly, sandy sites exhibited the largest subsoil $P_{CAL}$ stocks of 200 kg ha$^{-1}$ (36% of total $P_{CAL}$ stock) followed by silty, loamy and clayey sites with *ca*. 150 kg ha$^{-1}$ $P_{CAL}$ in subsoil (34% of total $P_{CAL}$ stock). Subsoil (0.3–1 m) $P_{CAL}$ stocks, as percentage of the uppermost 1 meter, were lowest in Vertisols (13%) and highest in Gleysols (45%), Anthrosols (48%) and Salic Fluvisols (68%; data not shown here).

Concerning total P stocks, an average of about 8 t ha$^{-1}$ was found in the soils down to 1 m depth. Respective stocks of total P in the subsoil exhibited even larger portions of the total soil profile P stocks than those of $P_{CAL}$; 56% of $P_t$ stocks were found below the plow layer and 41% below 0.5 m soil depth, respectively. Contrary to available P, sandy soils exhibited lowest relative subsoil $P_t$ stocks (45% of total $P_t$ stock), while largest subsoil $P_t$ stocks occurred in clayey soils (64% of total $P_t$ stock; Tab. 1). Relative portions of subsoil $P_t$ stocks from the uppermost meter were less contrasting between major reference soil groups than found for $P_{CAL}$ stocks, with percentages between 30% and 78% of total P in the subsoil of Podzols and Vertisols, respectively.

Among major reference soil groups, the Chernozem site showed largest $P_{CAL}$ and $P_t$ stocks throughout the uppermost meter. For the other soil groups the picture was more diverse. For instance, compared with the average of all terrestrial sites, Podzols and Anthrosols—both of which comprise mainly sandy sites—showed elevated $P_{CAL}$ stocks but lower ones of $P_t$ (Tab. 1). Significantly elevated $P_{CAL}$ stocks were also found in Gleysols and Salic Fluvisols compared to all other major reference soil groups, although at least of the latter topsoil $P_{CAL}$ stocks were in a similar range as the other major reference soil groups (between 230 and 440 kg ha$^{-1}$).

## 4 Discussion

### 4.1 Plant-available P supply in German arable topsoil

Taking the recently recommended German classification system of P supply in topsoils ('Versorgungsklasse'; *Wiesler* et al., 2018; see Supplementary Tab. S3) as a basis, almost 90% of the investigated sites were either ideally supplied with plant-available P (supply class C, 23%) or even over-supplied (supply classes D and E, 65%; Fig. 3).

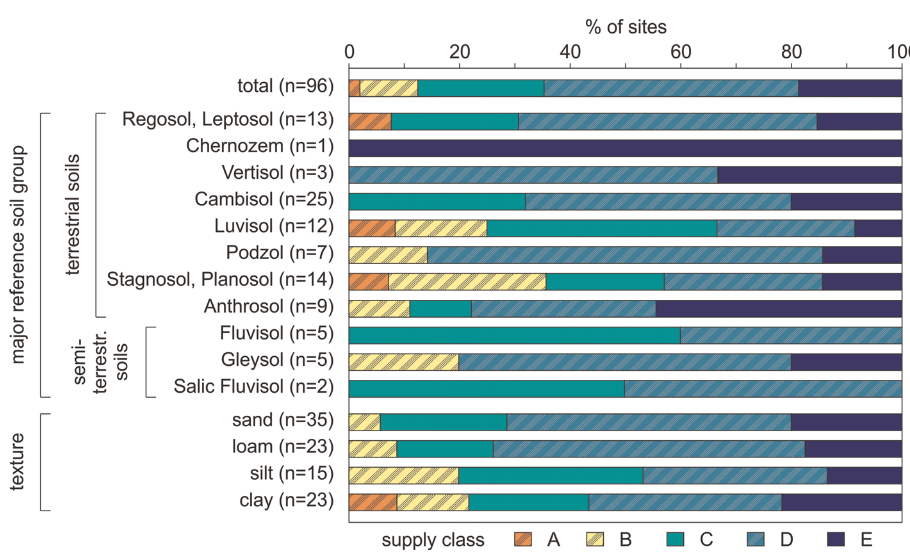


**Figure 3:** Relative portion of the five P supply classes in total sample set, among major reference soil groups and among soil texture groups.

Sandy sites, followed by loamy sites, comprised the highest portion of over-supplied topsoil (supply classes D and E; 71% and 74%, respectively), whereas sites with predominantly silty texture showed the highest portion of optimum P supply in topsoil (supply class C; 33% of the sites; Fig. 3). The only texture groups where 20% or more of the sites had sub-optimum P status (supply classes A and B) were silty and clayey sites. This agrees with many previous studies that showed a negative correlation of plant-available (labile) P with clay content (*e.g.*, *Lata Verma* and *Marschner*, 2013; *Wuenscher* et al., 2015). Thus, lower contents of labile P are commonly found in fine-textured topsoils, whereas a larger portion of applied fertilizer P remains in plant-available form in coarse-textured topsoils (*Lata Verma* and *Marschner*, 2013). In general, there is a stronger P binding to the clay fraction (*Hinsinger*, 2001), potentially enforced by predominant occurrence of P-binding Al and Fe oxides in the clay fraction (*Achat* et al., 2016). In the current study, this was reflected in a negative correlation of topsoil $P_{CAL}$ with clay contents both for the mainly fine-textured Vertisols (clay contents ca. 40–70%; $R^2$ = 0.27) and for mostly coarse-textured Luvisols and Anthrosols (clay contents ca. 10–30% and 0–30%; $R^2$ = 0.28 and 0.13, respectively).

Luvisols, Stagnosols/Planosols and Gleysols were the only major reference soil groups where 20% or more of the sites had sub-optimum P status (supply classes A and B), and these had a major overlap with the above mentioned silty and clayey sites with P deficiency: 66% of undersupplied sites of these major reference soil groups had a predominantly silty or clayey texture, only 11% had a sandy texture. Among the different soils studied, highest portions of optimum-supplied sites (40–60% supply class C) were found in Salic Fluvisols, Luvisols and Fluvisols. In contrast, the Chernozem site showed highest over-supply of P (100% supply class E), followed by Vertisols, Podzols, Gleysols and Anthrosols (> 75% supply class D and/or E). High contents of plant-available P often correlate with high OC contents (*Hinsinger*, 2001; *Hou* et al., 2018a, 2018b), and a positive correlation of $P_{CAL}$ with OC in topsoil was found for Vertisols ($R^2$ = 0.82), whereas the correlation was considerably lower for Anthrosols ($R^2$ = 0.25) and Gleysols ($R^2$ = 0.19). We assume that the predominant over-supply of P in Gleysols is related mainly to the location of these sites, as 3 over-supplied Gleysols were located in Northern Germany and one in Bavaria, both being regions with intense livestock production and high degree of P saturation in soil (*Fischer* et al., 2017). This is similar to, *e.g.*, Denmark, where livestock production occurs mainly on sandy soils and arable farming predominantly on heavier soils (*Rubæk* et al., 2013). Accordingly, our whole data set showed a positive, yet not significant, correlation of $P_{CAL}$ contents in 0–30 cm depth with livestock density on the farm level (see Supplementary Fig. S2).

In total, an ideal to high P supply was found for most German arable topsoils, thus providing good crop growth conditions: At least under Central European climate and soil conditions, deficient or even absent P fertilization had hardly altered crop yields, as shown by up to 100 years of fertilization history in various German long-term field experiments (*e.g.*, *Ellmer* et al., 2000; *Zicker* et al., 2018). Even if P acquisition strategies of plants might change in the near future, *e.g.*, by advanced breeding or novel crops, thus necessitating intensified P nutrition for crops, our data indicate that at least for the next several decades there will be sufficient P supply in most German arable soils, especially in those soils with low clay and carbonate contents as well as high organic carbon contents (*Prakash* et al., 2017). Organic and inorganic fertilization can also significantly influence P availability (*e.g.*, *Miner* et al., 2020). Unfortunately, such data are not available for the sampling sites. In our study we showed the strong influence of pedogenic properties and bedrock on plant-available P that is not blurred by fertilization effects.

## 4.2 Depth distribution of plant-available P

Elevated $P_{CAL}$ contents and large variations in the topsoil are mainly attributed to excessive P accumulation by fertilization (*Bauke* et al., 2018) and in part also to low solubility of P and subsequently minimum translocation of available P into the arable subsoil (*Amelung* et al., 2018). This entails the depth distribution commonly observed in most soils, with strong decrease of $P_{CAL}$ contents towards deeper parts. The contrasting depth distribution of $P_{CAL}$ in certain sites suggested that anthropogenic deep soil profile modifications (Anthrosols) and backwater, groundwater or marine water (Stagnosols/Planosols, Gleysols, Fluvisols, and Salic Fluvisols; Fig. 2) strongly affect the depth distribution of plant-available P. In the Chernozem, $P_{CAL}$ contents up to 0.5 m depth were relatively high as a result of soil organic matter accumulation until larger depth, as common for this major reference soil group.

Figure 2 shows that for most soils without deep soil profile modifications (*i.e.*, excluding Anthrosols), texture did, within each major reference soil group, affect $P_{CAL}$ contents in topsoil, but not or only to a minor degree below the plow layer. This means that for a given major reference soil group, depth curves of $P_{CAL}$ were similar at sites of different texture in 0.3–1 m depth. In contrast, texture effects on subsoil $P_{CAL}$ contents were more pronounced for Anthrosols and Gleysols than for other major reference soil groups. In deepest parts (0.7–1 m) of Gleysols the $P_{CAL}$ contents at the clayey site strongly exceeded those of the sandy and the loamy sites, *i.e.*, the negative correlation of labile P with clay contents, as described above for topsoil, did not apply for subsoil of Gleysols. *Beauchemin* et al. (1998) pointed to a potential translocation of P in clayey soils with back- or groundwater-influence through cracks and macropores. In addition, there may be elevated P mobilization in these soils by microorganisms under reduced conditions (*Thiele-Bruhn*, 2006), as well as any effects related to low P saturation at elevated topsoil P loads under intensive livestock production on Gleysols, as indicated above.

For Anthrosols in turn, subsoil $P_{CAL}$ contents were larger at sandy than at silty sites for the complete subsoil (Fig. 2), reflecting that particularly these sandy sites comprised Anthrosols with strong human impact, *i.e.*, deep melioration sites and plaggic Anthrosols, known to be rich in P and even prone to P leaching (*Siemens* et al., 2004). In contrast, the silty sites coincided with terric Anthrosols developed on colluvial material. Generally, texture thus exhibited even contrasting effects on subsoil $P_{CAL}$ contents in different major reference soil groups, depending on human impact and water regime, but supporting us in the assumption that soil formation has a stronger effect on the depth distribution of plant-available P than texture or parent material.

## 4.3 Stocks of total and plant-available P

### 4.3.1 General remarks on calculation methods

As described in chapter 2.6, P stocks were calculated under the assumption that solely fine earth (< 2 mm) contains $P_t$ and $P_{CAL}$. This approach is considered optimal to calculate soil organic carbon (SOC) stocks (*Poeplau* et al., 2017), as the coarse fraction is assumed not to contain OC. The coarse fraction may, however, contain considerable amounts of $P_t$ as minerals like apatite, while it is not relevant for $P_{CAL}$. We calculated $P_t$ stocks additionally under the assumption that $P_t$ contents are equal in fine earth and coarse fraction as the coarse fraction was not available for $P_t$ analysis (data not shown, if needed, see raw data in Supplement). When doing so, we obtain on average 5.6% larger $P_t$ stocks in topsoil and 18.9% higher $P_t$ stocks in subsoil (median values 2.7% and 2.9%), respectively. Because of the speculative assumption behind this, however, we present and discuss only $P_t$ and $P_{CAL}$ stocks calculated based on fine earth.

Mass-corrected $P_{CAL}$ and $P_t$ stocks exceeded the uncorrected stocks at average by 6.5% and 12.1%, respectively. Especially semi-terrestrial and anthropogenic soils ($P_{CAL}$) or semi-terrestrial and loamy soils ($P_t$) showed a high relative increase by mass correction, but there were no significant differences between both values neither for the whole sample set, nor for the eleven major reference soil groups or for the four texture groups (Supplementary Fig. S3). In our opinion, mass correction is not necessary for the current study, because compaction during sampling was avoided by collecting the samples in soil pits instead of using an auger, and because of limited variability in bulk density within plowed arable topsoils of given texture (see Supplement; *Poeplau* et al., 2020). Further arguments against mass correction are that (1) bulk density depends largely on texture and SOC and less on tillage-induced compaction (*Schneider* and *Don*, 2019), (2) tillage intensity of the individual sites just before sampling is unknown, and (3) we assume that plant roots explore the same maximum depth everywhere (as long as there is no rooting barrier in the soil) and thus depth of P storage being the main factor for P availability in soil. Application of the equivalent mass correction would thus rather lead to biased comparisons of P stocks when comparing sites over whole Germany.

### 4.3.2 P stocks

The average of 8 t $ha^{-1}$ of total P found in the soils down to 1 m depth is in the same order of magnitude like other selected reports on P storage in soils [see *Brédoire* et al. (2016) and references therein]. However, we have to keep in mind that total P stocks in our study relate to *aqua regia* digestion only. It may dissolve all P in soil, but does not necessarily have to, whereas a wet-chemical extraction with concentrated hydrofluoric acid, as performed in the cited study, may give a larger yield for total P. Moreover, a gap in total P balance of long-term agricultural sites might also be attributed to very stable P escaping the common wet-chemical extraction window (pers.comm. S. Bauke). A comparison of P yield of different analytical methods was beyond the scope of this study.

Also, the relative distribution of $P_t$ throughout the soil profile, with 56% located below the plow layer and 41% below 0.5 m, reflected global averages (*Jobbágy* and *Jackson*, 2001). The finding of lowest relative subsoil $P_t$ stocks in sandy soils and largest relative subsoil $P_t$ stocks in clayey soils (Tab. 1) is in agreement with other representative data sets on soil P, *e.g.*, from Belgium (*Renneson* et al., 2013). The finding of lowest relative subsoil $P_t$ stocks in Podzols and highest ones in Vertisols is thus in good accordance with texture-assorted $P_t$ stocks, as Podzols predominantly developed on sandy parent material and Vertisols on clayey parent material.

Total P thus did not necessarily coincide with elevated contents of available P. Indeed, soil $P_t$ and $P_{CAL}$ stocks were only weakly correlated with each other in topsoils ($R^2$ = 0.15) and did not show any significant correlation for the subsoils ($R^2$ = 0.01; not shown here). The picture that elevated stocks of $P_t$ did not coincide with elevated contents of $P_{CAL}$ held true also at the level of individual soil groups, as mentioned above for Podzols and Anthrosols (section 3.2), giving support to the assumption that particularly soils poor in P receive elevated amounts of plant-available fertilizer P. Especially the predominantly sandy sites in Northwestern Germany, which comprise mainly Podzols and Anthrosols, experience large P inputs *via* organic fertilization due to intensive livestock farming (*Fischer* et al., 2017).

The high relative subsoil $P_{CAL}$ stocks found in Gleysols, Anthrosols and Salic Fluvisols (see section 3.2) reflect the potential influence of land use, such as plaggen agriculture in Anthrosols and former grassland use in Gleysols (documented for 60% of the here shown Gleysols, whereas land use history is unknown for 2 of the 5 sites), on the accumulation of subsurface plant-available P. Overall in Germany, the percentage of sites where former grassland use is documented is highest for bogs (88%), followed by Salic Fluvisols and Gleysols (64 and 59%; *Poeplau* et al., 2020).

### 4.3.3 Percentage of plant-available P from total P

To better understand the delivery of $P_{CAL}$ from total P, we calculated $P_{CAL}$ stocks as percentage of those of $P_t$. We found a wide variety for the three investigated depth intervals, amounting from 0% to 50%, and usually decreasing from topsoil (0–0.3 m) towards the lowest depth increment (0.7–1 m) except again for the Anthrosols, Gleysols and Salic Fluvisols, as well as for sites with ultra- and extremely acidic soil parent materials (Tab. 1; for classification see also Supplementary Tab. S2). Contrary to the very low or absent correlation between $P_t$ and $P_{CAL}$ stocks for individual depth increments (see section 3.3.2), $P_{CAL}$ stocks as percentage from $P_t$ stocks for the whole upper 1 meter differed with the following study site criteria: percentages tended to be slightly higher in semi-terrestrial sites (median 7.7) than in terrestrial sites (median

 

5.5; Fig. 4A), and percentages in Anthrosols exceeded those values in shallow soils, Luvisols and backwater-affected soils significantly (Fig. 4B). Moreover, $P_{CAL}$ percentages were significantly higher in sandy sites than in finer grained sites (Fig. 4C). We attribute this finding, on the one hand, to the pH value, as a large portion of the sandy sites overlapped with ultra- and extremely acidic sites (see below). On the other hand, this finding also results from the opposing sizes of $P_{CAL}$ and $P_t$ stocks within certain soil texture categories (see section 3.3.2). Accordingly, increasing clay contents of soil parent material entail an increasing P fixation and therefore lower P availability (*Kamprath* and *Watson*, 1980; *Brédoire* et al., 2016; Fig. 4D).

## 4.4 Effects of other soil and soil parent material characteristics on P status

Based on a global data set, *Hou* et al. (2018a, 2018b) showed that after soil organic carbon content, climatic factors, parent material type and pH, the soil group is one of the main factors affecting soil available P, whereas texture (or sand content in the respective study) had a considerably lower impact on plant-available P. In the following, we thus focus on effect of major soil and soil parent material characteristics on P availability in German cropland.

It is well established that pH exerts a major influence on P availability in soil, with optimum availability in the pH range of 5.5 to 6.5 (*Ullrich-Eberius* et al., 1984; *Amelung* et al., 2018; *Niederberger* et al., 2019). Hence, we expected rising $P_{CAL}$ portions (in percent of $P_t$) with increasing pH up to this range, and dropping $P_{CAL}$ portions above. This was not shown by our complete sample set, but confirmed solely by topsoils of certain major reference soil groups: Podzols (pH 4.0–5.5) showed exponentially increasing $P_{CAL}$ percentages of $P_t$ with increasing pH value ($R^2$ = 0.34), whereas Vertisols (pH 7.0–7.5) showed exponentially decreasing $P_{CAL}$ percentages with increasing pH values ($R^2$ = 0.41; see Supplementary Fig. S4). The trend was represented neither by sites with wider pH spectrum like Anthrosols and Fluvisols nor by subsoil data.

In contrast to the relationship between pH and P availability described above, percentages of $P_{CAL}$ stocks out of total P stocks showed a completely different picture when referring the whole profile to the pH class of soil parent material: The contributions of $P_{CAL}$ to total P at sites with ultra- and extremely acidic soil parent material showed highly significantly elevated values relative to those sites with less acidic, neutral and alkaline soil parent material (Fig. 4E). As mentioned above, this is due to the large overlap between sandy and ultra- and extremely acidic sites ($n$ = 9). From the chemical point of view, P is immobilized at low pH value by fixation as Fe or Al phosphates (*Stevenson* and *Cole*, 1999); however, a certain maintenance of available P by fertilization and organic matter turnover may maintain elevated $P_{CAL}$ percentages if the overall stock of $P_t$ is low.

Besides pH, the proportions of available P are also controlled by SOC content: (1) the input of organic matter usually also goes along with an input of organic P, (2) dissolved organic matter species can inhibit P sorption on soil mineral surfaces (*Antelo* et al., 2007), increasing the plant-availability of P, and (3) OM increases P accessibility by improving soil structure in general (*Schröder* et al., 2011), whereas stimulations of microbial activity additionally promote P cycling and mineralization, particularly in topsoils (*Brédoire* et al., 2016). In contrast to earlier studies in forest soils (*Johnson* et al., 2003; *Niederberger* et al., 2019), however, our total sample set did not show a clear increase in labile inorganic P ($P_{CAL}$) contents with increasing OC contents, only three major reference soil groups showed this positive relationship for the topsoils (Vertisols, Anthrosols, Gleysols; see chapter 3.1). This finding supports the observation that P availability is strongly linked to SOC in forest and grassland soils, but less in croplands (*Achat* et al., 2016). However, over the whole sample set and calculated for the complete uppermost meter, relative portions of $P_{CAL}$ from $P_t$ revealed a weak positive correlation with OC stocks ($R^2$ = 0.33; see Supplementary Fig. S5).

The type of soil parent material also had a significant influence on $P_{CAL}$ percentages (Fig. 4F), with values being significantly larger for soils developed from aeolian material (including loess soils) than for those developed from glacial and weathered/relocated material. Seventy-five percent of sites with aeolian parent material developed on windborne sand, and sandy material showed highest percentages of plant-available P (see chapter 3.3.3). This is probably mainly caused by major reference soil groups on windborne sand, which comprise solely Podzols and Anthrosols, *i.e.*, soils with strong P input (see chapter 3.3.2). The remaining sites with aeolian parent material comprise Luvisols developed on loess deposits. At these sites, $P_{CAL}$ percentages were significantly lower than at sandy aeolian sites, and in the range of sites with weathered/relocated material. This can be ascribed to comparably low $P_t$ contents in sandy aeolian sediments and high $P_t$ contents from P-containing minerals usually present in loess.

## 4.5 Subsoil P stocks and their role for future P supply

The P stocks in top- and subsoils correlated positively, with higher determination coefficients for $P_t$ ($R^2$ = 0.44) than for $P_{CAL}$ ($R^2$ = 0.21; Fig. 5). The relationships between $P_t$ stocks in top- and subsoil reached especially high coefficients of determination ($R^2$ > 0.5) for Vertisols, Cambisols and Stagnosols / Planosols, whereas $P_{CAL}$ showed high determination coefficients ($R^2 \geq 0.75$) for Fluvisols, Anthrosols and Vertisols. We attribute this finding for $P_t$ to soil parent material: $P_t$ stocks are largely determined by soil parent material, and the large majority (≥ 90%) of this P is present in forms that are not available for direct plant uptake and are thus also mostly immobile throughout the soil profile. Intriguingly, most sites showed that $P_t$ stocks in the top- and subsoil were in a similar range, thus the regression was close to the 1:1 line (Fig. 5). Hence, and if surface P stocks were not predominantly affected by fertilization, the P stock in the subsoil largely reflects that of the surface soil. On the one hand, this is due to the influence of parent material as described above. On the other hand, it might well also reflect an intensive P cycling by roots from the sub- to the topsoil during the past hundreds to thousands of years of agricultural use, and eventually even back to the sub-

 

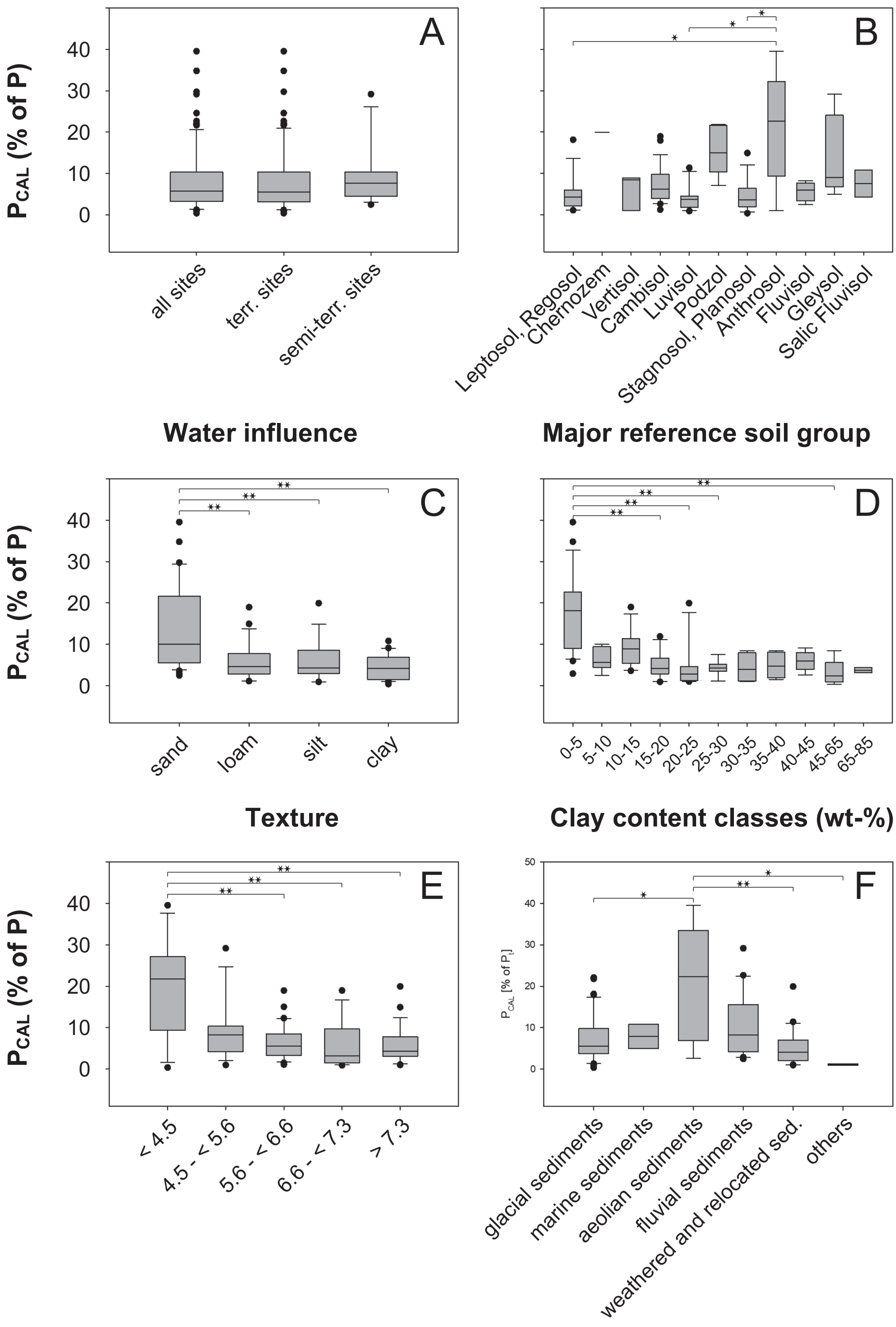


**Figure 4:** $P_{CAL}$ stocks as percentage of $P_t$ stocks, calculated for the complete uppermost 1 m, sorted by (A) water influence, (B) major reference soil group, (C) dominant soil texture, (D) clay contents of soil parent material, (E) pH classes, (F) type of soil parent material. Asterisks denote significant (level 0.05, one asterisk) and highly significant differences (level 0.01, two asterisks).

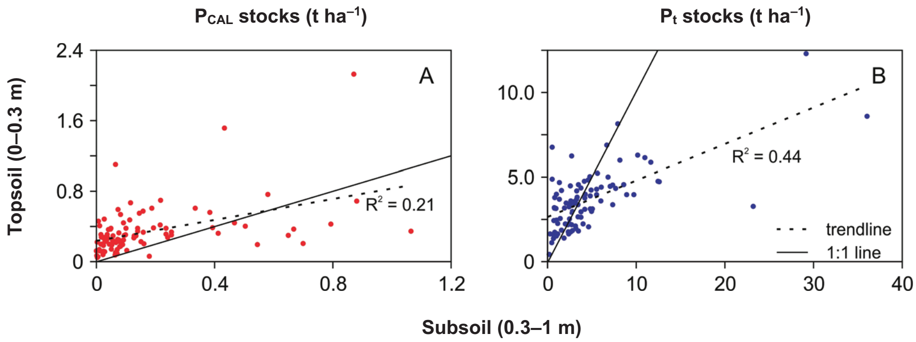


**Figure 5:** Subsoil vs. topsoil P stocks for (A) $P_{CAL}$ and (B) $P_t$. The solid lines represent the 1:1 lines, the dashed lines represent the linear trends, respectively.

soil *via* P translocations in the plants to the root tips (*Bauke* et al., 2017).

In contrast to $P_t$, most data points for $P_{CAL}$ lied above the 1:1 line of top- and subsoil $P_{CAL}$ stocks (Fig. 5), likely reflecting recent fertilizer P inputs. The coefficient of determination was slightly higher when correlating topsoil $P_{CAL}$ stocks with those in shallow subsoil (0.3–0.5 m; $R^2$ = 0.44; not shown here). This argues for the relocation of at least small amounts of fertilizer P into the shallow subsoil, *e.g.*, by leaching, as reported by, *e.g.*, *Sims* et al. (1998) and *Werner* et al. (2006), or *via* translocation of topsoil P into subsoil root tips as indicated above (*Bauke* et al., 2017). Additional reasons for the overall weak correlation can be attributed to specific major reference soil groups, such as Anthrosols, in which unknown amounts of topsoil P were translocated into the deeper subsoil (*Siemens* et al., 2004), and particularly by permanent delivery from more stable soil P pools due to organic matter mineralization (*e.g.*, *Bünemann*, 2015).

In summary, the positive relationships show that the topsoils contain more P when also the subsoils are rich in P. Many points follow a 1:1 line, but the average regression slope is below this line. Hence, on an average relative basis, subsoil contributes particularly to overall P stock in the upper 1 m when the overall P supply is small, whereas P-rich soils benefit from larger portions of P that are allocated in the topsoil. Particularly P-poor sites might benefit from access to subsoil P. On an absolute basis, however, these P-poor sites are also those where subsoil P stocks are lower than at other sites. Therefore, it remains questionable if the subsoil of German cropland could help to improve P status at under-supplied sites in terms of P supply class, as these sites store low amounts of plant-available P in subsoil as well.

On a quantitative basis, we may calculate that a crop utilization of 10% from $P_{CAL}$ stocks from shallow subsoil (0.3–0.5 m depth) and of 3% from deeper subsoil (0.5–1 m depth) would account for a P fertilizer requirement of 10 kg P $ha^{-1}$ (Tab. 1). Depending on the P supply class (Tab. S3; Supplementary Materials) and crop grown, this could already account for 25–50% of a fertilizer recommendation set between 20 and 40 kg P ha. To which extent such subsoil resource utilization could contribute to reducing the P fertilizer demand would then depend on the replenishment rate of available P in the subsoil. According to *Newman* (1995), a release of up to 5 kg P $ha^{-1}$ $y^{-1}$ is possible by weathering. For our sites, $P_t$ stocks between 30 and 50 cm depth—the transition zone at which biological P cycling is still enhanced relative to deeper subsoil (*Amelung* et al., 2015)—ranged between 0.5 and 2.2 t $ha^{-1}$ in the different soil groups (Tab. 1). Assuming an annual transformation of about 0.1% of these subsoil $P_t$ stocks would then account for an additional annual P provision of 0.5 to 2.2 kg $ha^{-1}$, which is in a similar range like the P release suggested by *Newman* (1995). This is clearly too low to sustain subsoil P nutrition of current agricultural cultivars in the long-term. Nothing is yet known, however, on the re-equilibration of plant-available P in the subsoil if the current pool would be heavily depleted by P-utilizing deeper roots. This replenishment rate, which so far has been determined only under controlled conditions and solely for surface bulk and rhizosphere soil (*e.g.*, *Morel* and *Hinsinger*, 1999), will likely be decisive in determining to which degree the subsoil may compensate for P needs from the surface soil. Determination for subsoil is, however, complicated by larger heterogeneity of P pools (*e.g.*, *Kautz* et al., 2013; *Barej* et al., 2014). The considerable amounts of plant-available and plant-unavailable P in subsoil could, nonetheless, clearly act as an 'insurance' system for crops, as far as these resources are not inaccessible due to compaction or other root-restricting properties of subsoil (*Schneider* and *Don*, 2019). Crops might utilize P from subsoil hotspots, *e.g.*, when needed by deep roots for any rapid physiological action.

## 5 Conclusions

The current study provides a first insight in P availability and stocks in German cropland, and this is overall in satisfactory to good condition, with considerable stocks of total and plant-available P not only in topsoil but also in subsurface. Our study thus adds to recent surveys on soil P status in EU cropland topsoils, which lacked an inventory of the soil profile down to 1 m depth so far. Here, we found that the subsoil (0.3–1 m depth) stores considerable amounts of total P, even of plant-available P, the latter averaging to 150–200 kg $P_{CAL}$ $ha^{-1}$. Usually plants consume only a minor portion of subsoil P, although this may exceed 50% in extreme cases, the utilization of which being promoted by optimum nutrient supply in topsoil. In this regard, the available P resources in the subsoil could theoretically contribute to the maintenance of yields for almost one decade, assuming a minimum fertilizer demand of 10 kg P $ha^{-1}$ $y^{-1}$, and likely longer, given that also for subsoils there is a re-supply from less available bonding forms. Our hypothesis of soil texture, major reference soil group and parent material as main control factors for P status in German farmland was partially confirmed: Variation of this supply is related to major reference soil group and less to soil texture and parent material properties. Noteworthy, it is mainly soils with large subsoil P stocks that also maintain larger P stocks in the surface soil.

 

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## Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

## References

*Achat, D. L.*, *Pousse, N.*, *Nicolas, M.*, *Brédoire, F.*, *Augusto, L.* (2016): Soil properties controlling inorganic phosphorus availability: general results from a national forest network and a global compilation of the literature. *Biogeochemistry* 127, 255–272.

*Ad-hoc-Arbeitsgruppe Boden* (2005): Bodenkundliche Kartieranleitung. Schweitzerbart, Stuttgart, Germany.

*Amelung, W.*, *Antar, P.*, *Kleeberg, I.*, *Oelmann, Y.*, *Lücke, A.*, *Alt, F.*, *Lewandowski, H.*, *Pätzold, S.*, *Barej, J. A. M.* (2015): The $\delta^{18}O$ signatures of HCl-extractable soil phosphates – methodological challenges and evidence of the cycling of biological P in arable soil. *Eur. J. Soil Sci.* 66, 965–972.

*Amelung, W.*, *Blume, H.-P.*, *Fleige, H.*, *Horn, R.*, *Kandeler, E.*, *Kögel-Knabner, I.*, *Kretzschmar, R.*, *Stahr, K.*, *Wilke, B.-M.* (2018): Böden als Pflanzenstandorte, in Amelung, W., Blume, H.-P., Fleige, H., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., Wilke, B.-M. (eds.): Scheffer/Schachtschabel Lehrbuch der Bodenkunde. Springer Spektrum, Berlin, Germany, pp. 491–581.

*Antelo, J.*, *Arce, F.*, *Avena, M.*, *Fiol, S.*, *López, R.*, *Macías, F.* (2007): Adsorption of a soil humic acid at the surface of goethite and its competitive interaction with phosphate. *Geoderma* 138, 12–19.

*Barej, J. A. M.*, *Pätzold, S.*, *Perkons, U.*, *Amelung, W.* (2014): Phosphorus fractions in bulk subsoil and its biopore systems. *Eur. J. Soil Sci.* 65, 553–561.

*Bauke, S. L.*, *Landl, M.*, *Koch, M.*, *Hofmann, D.*, *Nagel, K. A.*, *Siebers, N.*, *Schnepf, A.*, *Amelung, W.* (2017): Macropore effects on phosphorus acquisition by wheat roots—a rhizotron study. *Plant Soil* 416, 67–82.

*Bauke, S. L.*, *von Sperber, C.*, *Gocke, M. I.*, *Sandhage-Hofmann, A.*, *Honermeier, B.*, *Schweitzer, K.*, *Baumecker, M.*, *Don, A.*, *Tamburini, F.*, *Amelung, W.* (2018): Subsoil phosphorus is affected by fertilization regime in long-term agricultural experimental trials. *Eur. J. Soil Sci.* 69, 103–112.

*Beauchemin, S.*, *Simard, R. R.*, *Cluis, D.* (1998): Forms and concentrations of phosphorus in drainage water of twenty-seven tile-drained soils. *J. Environ. Qual.* 27, 721–728.

*Brédoire, F.*, *Bakker, M. R.*, *Augusto, L.*, *Barsukov, P. A.*, *Derrien, D.*, *Nikitich, P.*, *Rusalimova, O.*, *Zeller, B.*, *Achat, D. L.* (2016): What is the P value of Siberian soils? Soil phosphorus status in south-western Siberia and comparison with a global data set. *Biogeoscience* 13, 2493–2509.

*Bünemann, E. K.* (2015): Assessment of gross and net mineralization rates of soil organic phosphorus—A review. *Soil Biol. Biochem.* 89, 82–98.

*Canadell, J.*, *Jackson, R. B.*, *Ehleringer, J. R.*, *Mooney, H. A.*, *Sala, O. E.*, *Schulze, E. D.* (1996): Maximum rooting depth of vegetation types at the global scale. *Oecologia* 108, 583–595.

*Ellert, B. H.*, *Bettany, J. R.* (1995): Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Can. J. Soil Sci.* 75, 529–538.

*Ellmer, F.*, *Peschke, H.*, *Kohn, W.*, *Chmielewski, F. M.*, *Baumecker, M.* (2000): Tillage and fertilizing effects on sandy soils. Review and selected results of long-term experiments at Humboldt-University Berlin. *J. Plant Nutr. Soil Sci.* 163, 267–272.

*Fischer, P.*, *Pöthig, R.*, *Venohr, M.* (2017): The degree of phosphorus saturation of agricultural soils in Germany: Current and future risk of diffuse P loss and implications for soil P management in Europe. *Sci. Total Environ.* 599–600, 1130–1139.

*Godlinski, F.*, *Leinweber, P.*, *Meissner, R.*, *Seeger, J.* (2004): Phosphorus status of soil and leaching losses: results from operating and dismantled lysimeters after 15 experimental years. *Nutr. Cycl. Agroecosyst.* 68, 47–57.

*Gransee, A.*, *Merbach, W.* (2000): Phosphorus dynamics in a long-term P fertilization trial on Luvic Phaeozem at Halle. *J. Plant Nutr. Soil Sci.* 163, 353–357.

*Hinsinger, P.* (2001): Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant Soil* 237, 173–195.

*Horrigan, L.*, *Lawrence, R. S.*, *Walker, P.* (2002): How sustainable agriculture can address the environmental and human health harms of industrial agriculture. *Environ. Health Perspect.* 110, 445–456.

*Hou, E.*, *Chen, C.*, *Luo, Y.*, *Zhou, G.*, *Kuang, Y.*, *Zhang, Y.*, *Heenan, M.*, *Lu, X.*, *Wen, D.* (2018a): Effects of climate on soil phosphorus cycle and availability in natural terrestrial ecosystems. *Global Change Biol.* 24, 3344–3356.

*Hou, E.*, *Tan, X.*, *Heenan, M.*, *Wen, D.* (2018b): Data Descriptor: A global dataset of plant available and unavailable phosphorus in natural soils derived by Hedley method. *Nature Scient. Data* 5. DOI: https://doi.org/10.1038/sdata.2018.166.

*IUSS Working Group WRB* (2015): World Reference Base for Soil Resources, World Soil Resources Reports No. 106. FAO, Rome, Italy.

*Jobbágy, E. G.*, *Jackson, R. B.* (2001): The distribution of soil nutrients with depth: Global patterns and the imprint of plants. *Biogeochemistry* 53, 51–77.

*Johnson, A. H.*, *Frizano, J.*, *Vann, D. R.* (2003): Biogeochemical implications of labile phosphorus in forest soils determined by the Hedley fractionation procedure. *Oecologia* 135, 487–499.

 

*Kamprath, E. J.*, *Watson, M. E.* (1980): Conventional Soil and Tissue Tests for Assessing the Phosphorus Status of Soils, in Sample, E. C., Khasawneh, F. E. (eds.): The Role of Phosphorus in Agriculture. ASA, Madison, WI, USA, pp. 433–469.

*Kautz, T.*, *Amelung, W.*, *Ewert, F.*, *Gaiser, T.*, *Horn, R.*, *Jahn, R.*, *Jjavaux, M*, *Kemna, A.*, *Kuzyakov, Y.*, *Munch, J.-C.*, *Pätzold, S.*, *Peth, S.*, *Scherer, H. W.*, *Schloter, M.*, *Schneider, H.*, *Vanderborght, J.*, *Vetterlein, D.*, *Walter, A.*, *Wiesenberg, G. L. B.*, *Köpke, U.* (2013): Nutrient acquisition from arable subsoils in temperate climates: a review. *Soil Biol. Biochem.* 57, 1003–1022.

*Kennard, R. W.*, *Stone, L. A.* (1969): Computer aided design of experiments. *Technometrics* 11, 137–148.

*Kruse, J.*, *Abraham, M.*, *Amelung, W.*, *Baum, C.*, *Bol, R.*, *Kuhn, O.*, *Lewandowski, H.*, *Niederberger, J.*, *Oelmann, Y.*, *Ruger, C.*, *Santner, J.*, *Siebers, M.*, *Siebers, N.*, *Spohn, M.*, *Vestergren, J.*, *Vogts, A.*, *Leinweber, P.* (2015): Innovative methods in soil phosphorus research: a review. *J. Plant Nutr. Soil Sci.* 178, 43–88.

*Kuhlmann, H.*, *Baumgärtel, G.* (1991): Potential importance of the subsoil for the P and Mg nutrition of wheat. *Plant Soil* 137, 259–266.

*Kvakić, M.*, *Pellerin, S.*, *Ciais, P.*, *Achat, D. L.*, *Augusto, L.*, *Denoroy, P.*, *Gerber, J. S.*, *Goll, D.*, *Mollier, A.*, *Mueller, N. D.*, *Wang, X.*, *Ringeval, B.* (2018): Quantifying the limitation to world cereal production due to soil phosphorus status. *Global Biogeochem. Cy.* 32, 143–157.

*Lata Verma, S.*, *Marschner, P.* (2013): Compost effects on microbial biomass and soil P pools as affected by particle size and soil properties. *J. Soil Sci. Plant Nutr.* 13, 313–328.

*Meurer, K. H. E.*, *Haddaway, N. R.*, *Bolinder, M. A.*, *Kätterer, T.* (2018): Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach. *Earth-Sci. Rev.* 177, 613–622.

*Miner, G. L.*, *Delgado, J. A.*, *Ippolito, J. A.*, *Stewart, C. E.*, *Manter, D. K.*, *Del Grosso, S. J.*, *Floyd, B. A.*, *D'Adamo, R. E.* (2020): Assessing manure and inorganic nitrogen fertilization impacts on soil health, crop productivity, and crop quality in a continuous maize agroecosystem. *J. Soil Water Conserv.* 75, 481–498.

*Morel, C.*, *Hinsinger, P.* (1999): Root-induced modifications of the exchange of phosphate ion between soil solution and soil solid phase. *Plant Soil* 211, 103–110.

*Murphy, J.*, *Riley, J. P.* (1962): A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta* 27, 31–36.

*Newman, E. I.* (1995): Phosphorus inputs to terrestrial ecosystems. *J. Ecol.* 83, 713–726.

*Niederberger, J.*, *Kohler, M.*, *Bauhus, J.* (2019): Distribution of phosphorus fractions with different plant availability in German forest soils and their relationship with common soil properties and foliar P contents. *Soil* 5, 189–204.

*Poeplau, C.*, *Vos, C.*, *Don, A.* (2017): Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. *Soil* 3, 61–66.

*Poeplau, C.*, *Don, A.*, *Flessa, H.*, *Heidkamp, A.*, *Jacobs, A.*, *Prietz, R.* (2020): Erste Bodenzustandserhebung Landwirtschaft—Kerndatensatz. OpenAgrar. DOI: https://doi.org/10.3220/DATA20200203151139.

*Prakash, D.*, *Benbi, D. K.*, *Saroa, G. S.* (2017): Clay, organic carbon, available P and calcium carbonate effects on phosphorus release and sorption–desorption kinetics in alluvial soils. *Comm. Soil Sci. Plant Anal.* 48, 92–106.

*Rejnders, L.* (2014): Phosphorus resources, their depletion and conservation, a review. *Resour. Conserv. Recycl.* 93, 32–49.

*Renneson, M.*, *Dufey, J.*, *Legrain, X.*, *Genot, V.*, *Bock, L.*, *Colinet, G.* (2013): Relationships between the P status of surface and deep horizons of agricultural soils under various cropping systems and for different soil types: a case study in Belgium. *Soil Use Manage.* 29, 103–113.

*Rubæk, G. H.*, *Kristensen, K.*, *Olesen, S. E.*, *Østergaard, H. S.*, *Heckrath, G.* (2013): Phosphorus accumulation and spatial distribution in agricultural soils in Denmark. *Geoderma* 209, 241–250.

*Schneider, F.*, *Don, A.* (2019): Root-restricting layers in German agricultural soils. Part I: extent and cause. *Plant Soil* 442, 433–451.

*Schneider, F.*, *Don, A.*, *Hennings, I.*, *Schmittmann, O.*, *Seidel, S. J.* (2017): The effect of deep tillage on crop yield—What do we really know? *Soil Tillage Res.* 174, 193–204.

*Schröder, J. J.*, *Smit, A. L.*, *Cordell, D.*, *Rosemarin, A.* (2011): Improved phosphorus use efficiency in agriculture: A key requirement for its sustainable use. *Chemosphere* 84, 822–831.

*Schüller, H.* (1969): Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. *Z. Pflanz. Bodenkunde.* 123, 48–63.

*Siemens, J.*, *Ilg, K.*, *Lang, F.*, *Kaupenjohann, M.* (2004): Adsorption controls mobilization of colloids and leaching of dissolved phosphorus. *Eur. J. Soil Sci.* 55, 253–263.

*Sims, J. T.*, *Simard, R. R.*, *Joern, B. C.* (1998): Phosphorus loss in agricultural drainage: Historical perspective and current research. *J. Environ. Qual.* 27, 277–293.

*Stevenson, F. J.*, *Cole, M. A.* (1999): Cycles of Soils: Carbon, Nitrogen, Phosphorous, Sulfur, Micronutrients. Wiley and Sons, Hoboken, NJ, USA.

*Thiele-Bruhn, S.* (2006): Assessment of the soil phosphorus–mobilization potential by microbial reduction using the Fe(III)-reduction test. *J. Plant Nutr. Soil Sci.* 169, 784–791.

*Tóth, G.*, *Guicharnaud, R.-A.*, *Tóth, B.*, *Hermann, T.* (2014): Phosphorus levels in croplands of the European Union with implications for P fertilizer use. *Eur. J. Agron.* 55, 42–52.

*Ullrich-Eberius, C. I.*, *Novacky, A.*, *van Bel, A. J. E.* (1984): Phosphate uptake in *Lemna gibba* G1: energetics and kinetics. *Planta* 161, 46–52.

*Vos, C.*, *Don, A.*, *Hobley, E. U.*, *Prietz, R.*, *Heidkamp, A.*, *Freibauer, A.* (2019): Factors controlling the variation in organic carbon stocks in agricultural soils of Germany. *Eur. J. Soil Sci.* 70, 550–564.

*Wendt, J. W.*, *Hauser, S.* (2013): An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *Eur. J. Soil Sci.* 64, 58–65.

*Werner, W.*, *Trimborn, M.*, *Pihl, U.* (2006): Prediction of the P-leaching potential of arable soils in areas with high livestock densities. *J. Zhejiang Univ. Sci. B* 7, 515–520.

*Wiesler, F.*, *Appel, T.*, *Dittert, K.*, *Ebertseder, T.*, *Müller, T.*, *Nätscher, L.*, *Olfs, H.-W.*, *Rex, M.*, *Schweitzer, K.*, *Steffens, D.*, *Taube, F.*, *Zorn, W.* (2018): Phosphordüngung nach Bodenuntersuchung und Pflanzenbedarf. VDLUFA-Standpunkt. VDLUFA, Speyer, Germany. Available at: https://www.vdlufa.de/Dokumente/Veroeffentlichungen/Standpunkte/2018_Standpunkt_P-Duengung.pdf.

*Withers, P. J. A.*, *Neal, C.*, *Jarvie, H. P.*, *Doody, D. G.* (2014): Agriculture and eutrophication: where do we go from here? *Sustainability* 6, 5853–5875.

*Wuenscher, R.*, *Unterfrauner, H.*, *Peticzka, R.*, *Zehetner, F.* (2015): A comparison of 14 soil phosphorus extraction methods applied to 50 agricultural soils from Central Europe. *Plant Soil Environ.* 61, 86–96.

*Zicker, T.*, *von Tucher, S.*, *Kavka, M.*, *Eichler-Löbermann, B.* (2018): Soil test phosphorus as affected by phosphorus budgets in two long-term field experiments in Germany. *Field Crop. Res.* 218, 158–170.

 