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Soil available phosphorous and potassium stocks related to environmental properties, land uses and soils

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Abstract

Soil available phosphorus (SAP) and potassium (SAK) are indispensable for crops, and their stocks are important for food production needed for a growing global population. This study analysed 991 soil profiles across a large part of Romania covering forestland, grassland and cropland in almost all ecological regions. This study investigated SAP and SAK stocks for different soil depths and characterized their magnitude and variability within land uses under different environmental ecosystems, soil classes and soil types, for a better soil and land management under a temperate-continental climate. Cropland soils present the highest SAP and SAK stocks. Chernozems, Phaeozems and Vertosols possess the highest SAP and SAK stocks in Romania, representing the largest country's pool. Both SAP stocks and SAK stocks are significantly correlated with basic environmental properties, existing direct correlations between SAP, SAK, soil organic carbon (SOC) and total nitrogen (TN) stocks. For all land uses, SAP and SAK stocks correlated significantly and directly with each other, as well as with annual temperature, clay content, pH and sum of base cations, and inversely with altitude, slope and annual precipitation. The best predictive values using multiple regression models and basic environmental driving factors were found for forestland stocks of SAP and SAK, followed by grassland stocks, while the lowest prediction occurred for cropland stocks, probably due to the long-term additional nutrient input performed by farmers in cropland that changed the natural conditions otherwise present in grassland, and especially in forestland. Based on these results some management measures are discussed.

Introduction

Modern agriculture essentially depends on phosphorus and potassium fertilizers in addition to nitrogen and other nutrients (Borlan *et al.*, 1994; Lacatusu, 2000; Potter *et al.*, 2010; Ballabio *et al.*, 2019; Muntwyler *et al.*, 2024). Recent studies (Ballabio *et al.*, 2019; Muntwyler *et al.*, 2024) have reported soil maps of both P and K nutrients for much of Europe. Soil P drives soil organic matter (Somavilla *et al.*, 2022) and food production which is needed for a growing global population, but knowledge of soil available phosphorus (SAP) stocks for plants on a global scale is poor (McDowell *et al.*, 2023). Soil available potassium (SAK) is also an important nutrient for plants. Akbas *et al.* (2017) have investigated the spatial distribution of SAK related to different land uses and parent materials in a watershed in Turkey, emphasizing their influence on SAK. P is a non-renewable and finite resource, and there is an increasing need to sustainably use P in agriculture; on one hand, soil P deficiency negatively affects plant growth, while on the other hand, soil P surplus can leach into aquatic systems, affecting water quality and causing eutrophication with subsequent negative effects upon ecosystems' structure and functioning (Smith *et al.*, 1999; Özbek *et al.*, 2016).

Potter *et al.* (2010) revealed worldwide differences for soil nutrients between various regions, countries or continents. There are regions where soil nutrients were depleted through intense agriculture relative to nutrient additions, as well as regions where application of fertilizers led to rich-in-nutrient soils, the so-called hot spots, where there are also water quality problems due to leaching and runoff, as in the Northern Hemisphere.

Continuous extraction of SAP and SAK by crops and biomass harvesting can lead, in addition to soil stock depletion, to a drop in crop yields, and ultimately to a decrease in organic matter input to the soil (Borlan *et al.*, 1994; Somavilla *et al.*, 2022). Luna *et al.* (2022) investigated both SAP and soil total phosphorous (STP) stocks at various depths and compared their values for more soil classes, while Panagos *et al.* (2022) estimated STP and SAP in agricultural 0.2 m depth topsoil in EU and UK. In Germany, Gocke *et al.* (2021) have quantified STP and SAP stocks down to 1 m depth.

Soil depth where nutrient stocks are generally quantified depends primarily on the development of the main root system mass. The role of plant root systems and depth in the magnitude of soil organic matter, nutrient uptake, and soil content has been documented by different scientists: Jobbagy and Jackson (2000), Gerzabek *et al.* (2005), Dodd *et al.* (2011), Fan *et al.* (2016), Paltineanu *et al.* (2016, 2017, 2020), Wang *et al.* (2018), Dhillon and Van Rees (2017), Wehr *et al.* (2020), Yang *et al.* (2020), and Fernandez-Ugalde *et al.* (2022).

An important European Project-LUCAS was carried out to stress the importance of the main soil nutrients` resources through a topsoil survey mostly during the last decade (Orgiazzi *et al.*, 2018; Ballabio *et al.*, 2019; Fernandez-Ugalde *et al.*, 2022), showing the present-day situation in Europe. Soil P and K stocks are mainly controlled by soil, climatic, plant and management factors (McBeath *et al.*, 2012; Ye *et al.*, 2014; Meyer *et al.*, 2020).

While synthesizing the knowledge about soil fertility and fertilizer application in Romania, Borlan *et al.* (1994) and Lacatusu (2000) emphasized the low SAP and moderate SAK contents soils. More recently, Mărin *et al.* (2022) have reported that about two-thirds of cropland areas in Romania are characterized by low, very low and extremely low SAP content values.

The objectives of this paper are to: (1) investigate the current SAP and SAK stocks for different soil depths and characterize their magnitude and variability within land uses under different environmental ecosystems, (2) test the existence of significant differences for SAP and SAK stocks between land uses, soil classes and soil types, (3) test the significance of relationships between SAP and SAK stocks as a function of the main environmental variables, aiming to thoroughly understand the size of their stocks within land uses and landforms, for a better soil and land management under a temperate-continental climate.

Materials and methods

Environmental conditions and soil profiles

Romania's landforms are diverse, consisting of high-elevation up to more than 2500 m altitude (A) in the Carpathian Mountains in the central part, followed by lower hills and tablelands towards the country's borders, and then followed by river plains such as Tisa Plain, Danube Plain, and Dobrogea Plateau towards the borders and ending with the Black Sea to the south-east.

The climate is also diverse due to the mountains and hills occurring over a temperate-continental climate pattern according to Köppen-Geiger climate classification (Peel *et al.*, 2007), with Bsk in the south-eastern parts of the country to Dfa in the southern parts and Dfb and Dfc in the central and northern parts. The Black Sea also exerts a drying influence in the south-eastern part of the country. The main climate variables, such as long-term mean annual air temperature (T) and precipitation (Pr) values, were assessed for the soil profiles using the Climate Adapt Program, with its interpolation technique and climate data grid (New *et al.*, 2002). The aridity index proposed by de Martonne (1926) (Iar, with $Iar = Pr/(T + 10)$ was calculated with the above data.

Due to the diverse surface topography and climate categories, the country has specific flora zones as a function of major landforms, from steppes and silvo-steppes in the Danube Plain and Dobrogea region to deciduous trees (oak trees, beech trees) in the high tablelands and hills, as well as coniferous trees and specific shrubs and grasses in the mountains. Across the country, there are forestland (28%), grassland (20%), and cropland (41%), and all these land uses cover about 89% of the country's surface area, being under continuous dynamics (Andrei, 2015). Croplands consist of arable crops, permanent crops such as vineyards and orchards, and vegetable crops. The most used arable crops are cereals such as wheat (27% from cropland area), maize (30%), barley (5.3%), sunflower (14%), brassica (6%), potatoes (1%), and sugar beet (<1%) (https://insse.ro/cms/ro/tags/anuarul-statistic-al-romaniei); as fruit trees there are apple trees, plum trees, peach trees and cherry trees (all about 2% of cropland's area, mainly with plum trees, 0.9% and apple trees, 0.8%), and there are many vineyard cultivars (2% of the cropland area), especially in the sunny hills and tableland regions. Lacatusu *et al.* (2024) have recently presented a detailed situation of the specific wild flora in Romania.

The present study analyses 991 soil profiles from across a large part of Romania during 2012–2022, mainly across the western, southern and south-eastern parts, covering forestland, grassland and cropland in almost all ecological regions (Archive of ICPA Bucharest). Soil profile locations are depicted on a Shuttle Radar Topography Model map (Farr and Kobrick, 2000), Fig. 1.

The Romanian Taxonomic Soil System (Florea and Munteanu, 2012) was used to characterize the soil classes (in a number of 10) and soil types (in a number of 22), close to but not identical to WRB (IUSS, 2022). These soil classes and types are: (a) Antrisols (number 1 soil type-Anthrosol) with 15 soil profiles evolved on various deposits; (b) Cambisols, with 255 profiles, on calcic or acid ferro-magnesian deposits (2-Eutricambosols, 3-Districambosols); (c) Chernisols, 188 profiles, mainly on loess and loam deposits (4-Chernozems, 5-Phaeozems, 6-Kastanozems, 7-Rendzina); (d) Hydrisols, 31 profiles (8-Gleysols, 9-Stagnosols) on various-textured unconsolidated materials especially found in or near rivers or other water bodies; (e) Luvisols, 259 profiles (10-Preluvosols, 11-Luvosols, 12-Alosols) on various unconsolidated materials or alluvial and colluvial deposits, (f) Protisols, 174 profiles (various less-fertile soil types with shallow rock bed or lower thickness (13-Aluviosols, 14-Psamosols, 15-Regosols, 16-Lithosols); (g) Salsodisols, 18 profiles (17-Solonchaks/Solonetzes) over sodium-rich deposits; (h) Spodisols, 38 profiles (18-Prepodzols, 19-Podzols) on acid coarse-grained rocks under wet and cold mountain conditions showing migration and accumulation of organic acids and amorphous mixtures of organic matter and aluminium and/or iron; (i) Umbrisols, 2 profiles (20-Humosiosols); and (j) Vertisols, 11 profiles (21-Pelosols, 22-Vertosols), over swell-shrink clayey or loamy-clayey Pleistocene materials.

Almost all soil classes and soil types that are specific for Romania were analysed in this study, except Andisols (andosols) and Histisols (Histosols) that were assimilated to the Umbrisols from the viewpoint of SAP and SAK stocks (Borlan *et al.*, 1994).

Soil sampling and processing of data

Soil samples, both disturbed and undisturbed, were taken from the soil horizons identified in the profiles. Soil chemical and physical properties were determined in the ICPA-Bucharest laboratories. Standardized methods described below and reported by Florea *et al.* (1987) were used: particle-size distribution (sieving and sedimentation method, PTL 44), bulk density (BD) (method SR EN ISO 11272: 2014) determined on 100 cm^3 metal cylinders in five replications for each layer, soil organic carbon content (SOC, modified Walkley-Black method, STAS 7184/21–82 standard), total soil N content (TN) content, (Kjeldahl method, STAS 7184/2-85 standard), pH (glass electrode in 1:2.5 water suspension, SR 7184-13:2001), sum of exchangeable base cations (SB) (STAS 7184/12-88, 2.2.2; PTL 15), soil carbonates content using

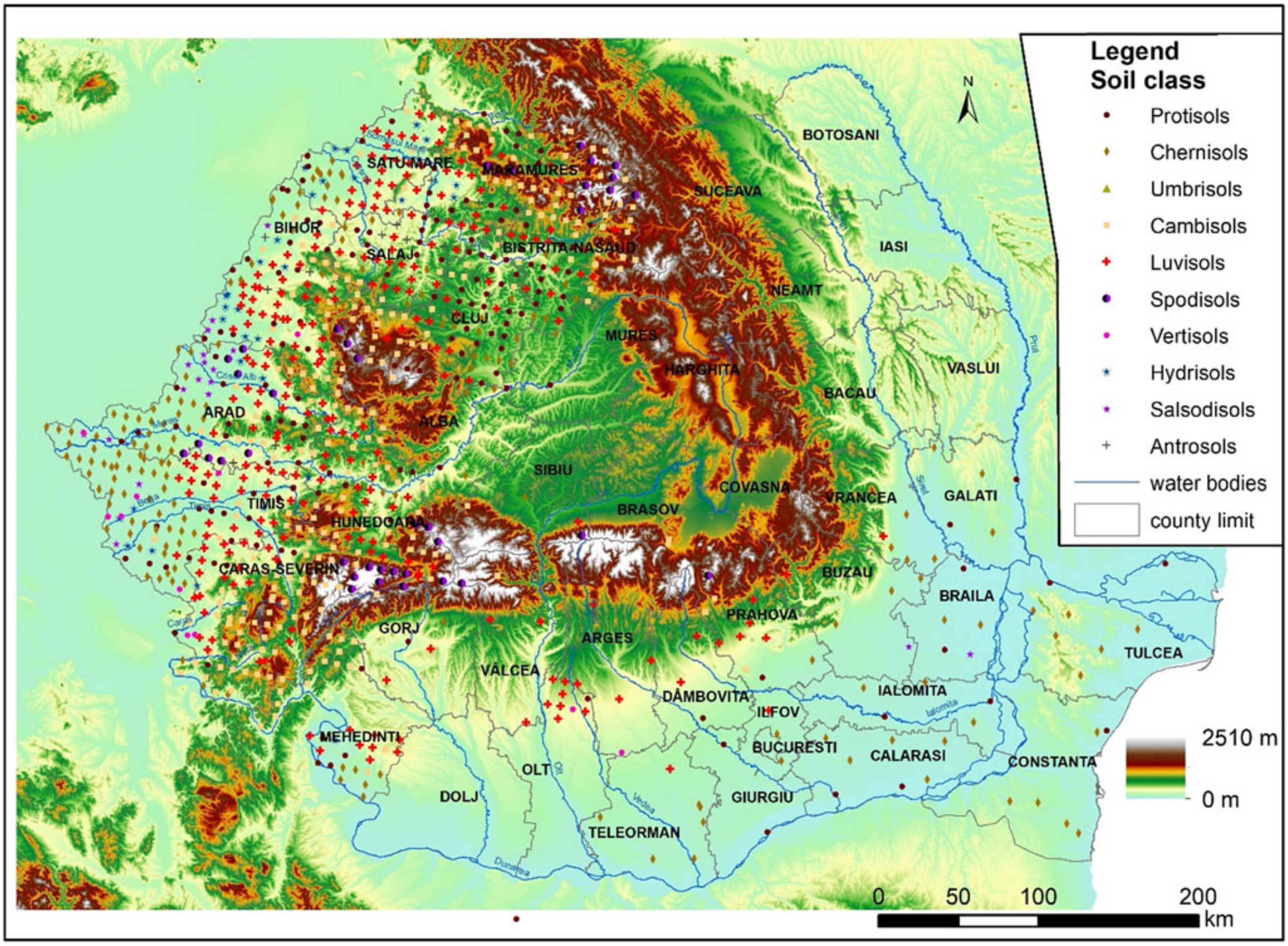

Figure 1. Spatial distribution of the studied soil profiles belonging to soil classes across Romanian landscape and counties.

the gas-volumetric method (Scheibler, STAS 7184/16-80; PTL-43), SAP and SAK (Egner-Riehm-Domingo method using ammonium acetate and lactic acid, STAS 7184/19-82; PTL 19 and STAS 7184/18-80; PTL 22, respectively). The determined soil content values (% or mg/kg) of SOC, TN, SAP and SAK were used to calculate their soil stocks (Mg/ha) by multiplying these per cent values with BD (kg/dm) and layer thickness (cm), and subtracting the skeleton (particles >2 mm) where the case. Control of data quality was performed for their reliability before calculations.

Three soil thickness values were used for weighted average calculation in order to determine and process the above stocks: 0–0.2, 0–0.3 and 0–0.5 m layers. We primarily used the maximum depth based on the prevailing depth of plant roots of about 0.5 m (Gerzabek *et al*., 2005; Paltineanu *et al*., 2016; 2017; Dhillon and Van Rees, 2017; Wehr *et al*., 2020; Yang *et al*., 2020), and on their role in crops' activity.

Microsoft Excel and SPSS Version 21 were used for data processing for normality testing, analysis of variance (ANOVA), simple and multiple stepwise regressions, and significance testing for correlation coefficients (r) and adjusted determination coefficients (r^2). The mean data of SAP and SAK stocks for 0.5 m depth were processed through ANOVA as a function of various driving factors and based on a split-plot design. The means of the investigated design groupings were compared and tested for significance using Duncan's multiple range test. The tabled values followed by different letters are significantly different. The classical symbols were used for different significance thresholds using t test: symbol * or significant for probability $P \leqslant 0.05$; symbol ** or distinctly significant for $P \leqslant 0.01$; symbol *** or highly significant for $P \leqslant 0.001$.

In order to create maps of SAP and SAK stocks, soil profiles' representativity was tested using the 52 000 soil units from Romania (the Soil Association Map of Romania, scale 1: 2 00 000, Archive of ICPA Bucharest). This was done by applying Cochran's sample size formula after taking 1.96 as 'z' critical value of the normal distribution for the required confidence level of 95%. The obtained result enables soil class generalization for SAP stock and SAK stock representation. The maps of SAP stocks and SAK stocks were done by assigning the obtained mean values after statistical processing to the soil units. SAP and SAK stocks were assessed by multiplying their mean values with the corresponding surface areas for each soil class.

Factors influencing soil available phosphorus and potassium

Land uses and environmental variables

Forestland represents circa 28% of the total surface area of Romania (Andrei, 2015). The forests are found especially in rugged high-altitude hills, plateaus, and mountains, where the climate is wet and cold. Small forestland areas are also found within low-altitude plains. Most of the forestland areas are found between ca. 280 and 1040 m a.s.l., and their slope are between 10 and 42%, with all slope aspects. There is a trend of increasing land slope with A. Pr amounts to 744 ± 71 mm, while T to 8.3 ± 1.8°C, and the mean annual Iar is 41.5 ± 8.4. The soils occurring within forestlands have a mean clay (CL) content of 19.1 ± 10.1%, and this is a sandy-loamy texture, a mean value of SB of 9.0 ± 6.8 cmol (+)/kg, while the pH mean is 4.9 ± 0.9, characterized as strongly acid.

Grasslands consisting of meadows, pastures, shrubland, etc. represent ca. 20% of the country's area (Andrei, 2015). Most of the grassland area occurs between 20 and 730 m a.s.l., showing a lower mean slope than the forestland's one, i.e. between 0 and 22.5%, with all aspects. The climate variables indicate warmer and dryer areas, with Pr of 658 ± 100 mm and T of 9.4 ± 1.9°C, while Iar is 35 ± 9.7. The mean CL content is around 27.3 ± 12.6% characterizing a loamy texture, while pH and SB reach as much as 6.1 ± 1.3, slightly acid, and 14.7 ± 8.1 cmol (+)/kg, respectively.

The land of arable field crops, orchards, and vineyards, generically called cropland (agroforestry systems), represents about 41% of the total area of Romania (Andrei, 2015). Cropland benefits the lowest lands, mainly having A values between 60 and 330 m a.s.l. and the lowest slopes from about 0 to 12%. The mean annual Pr and T reach at 621 ± 40 mm and 10.1 ± 0.9°C, respectively, while Iar is 31 ± 3.2. The mean CL content is 29.8 ± 11.4%, also being a loamy texture, and the mean pH is slightly acid (6.3 ± 1.0), while the mean SB is 17.0 ± 6.8 cmol (+)/kg.

Grouping the environmental factors for soil available phosphorus and potassium data processing

The environmental factors, both qualitative and quantitative, were grouped for SPSS data processing as follows:

i) land uses (three: forestland, grassland and cropland),
ii) soil classes (10: Antrisols, Cambisols, Chernisols, Hydrisols, Luvisols, Protisols, Salsodisols, Spodisols, Umbrisols and Vertisols),
iii) soil types (22: Alosol, Aluviosol, Anthrosol, Chernozem, Districambosol, Eutricambosol, Phaeozem, Gleysol, Humosiosol, Kastanoziom, Lithosol, Luvosol, Pelosol, Podzol, Preluvosol, Prepodzol, Psamosol, Regosol, Rendzina, Solonet, Stagnosol and Vertosol); additionally,
iv) altitude (A) with a (1) subalpine and alpine zone, 1600–2200 m a.s.l., (2) *Picea abies* (European spruce) floor with A between 1400 and 1600 m, (3) *Picea abies* and mixed forest floor, 1200–1400 m a.s.l., (4) *Fagus sylvatica* floor between 500 and 1200, (5) *Quercus petraea, Q. frainetto and Q. cerris floor,* 200–500 m a.s.l., as (6) silvo-steppe + steppe zone floor, the same A values;
v) CL content (particles of size <0.002 mm) characterizing soil texture: (1) sandy texture (<5.9% CL content), (2) loamy-sandy texture (between 6 and 12.9% CL content), (3) sandy-loamy texture (13–20.9% CL), (4) loamy texture (21–32.9% CL), (5) clayey-loamy texture (33–45.9% CL), (6) loamy-clayey texture (46–60.9% CL), (7) clayey texture (>61% CL content);
vi) soil chemical reaction, pH: (1) strongly acid (pH values <5 units, (2) moderately acid (pH between 5.01 and 5.8), (3) slightly acid (pH = 5.81–6.8), (4) neutral (pH = 6.81–7.2), (5) slightly alkaline (pH = 7.21–8.4), (6) moderately-strongly alkaline (8.5–9.0);
vii) land slope (Sl), with the intervals: (1) flat (Sl = 0–2%), (2) very gently sloping (2–5%), (3) gently sloping (5–10%), (4) moderately sloping (10–25%), (5) steeply sloping (25–50%), (6) extremely sloping (50–100%);
viii) slope aspect, with the exposures of: (1) northern, (2) eastern, (3) southern, (4) western, and (5) flat areas, no exposure. The soil profiles were not uniformly carried out among the slope aspects. The flat land occurs in about a third of the cases studied; the other four aspects are relatively uniformly distributed across the lands.

Results

Comparison between the stocks' means of soil available phosphorus and potassium depending on environmental variables

Current SAP stocks for 0.2 m and 0.3 m depth layers represented about 54–57% and 71–75% from the 0.5 m depth layer SAP stock for the forestland, grassland and cropland, respectively, even if the 0.2 m SAP stocks were expected to be around 40% compared to 0.5 m stocks, and the 0.3 m depth stocks around 60%, as are the ratios between these depths, if the nutrient stocks would have been homogeneously distributed across the soil profiles, Fig. 2. Similarly, the same graph shows the values of SAK stocks for the same depths` layers representing about 49–53% and 67–70% for forestland and grassland, respectively, and only 45% and 65% for cropland, again much more than the theoretical 40% and 60%, respectively.

For all land uses, SAP and SAK stocks for 0.2 m depth were linearly and highly significantly correlated with the same stocks for 0.5 m depth ($r^2 = 0.927^{***}$ and $r^2 = 0.917^{***}$), respectively, while the coefficient of determination between SAP and SAK stocks for 0.3 m depth and those for 0.5 m were even higher ($r^2 = 0.960^{***}$ and $r^2 = 0.966^{***}$). Similarly, SAP and SAK stocks

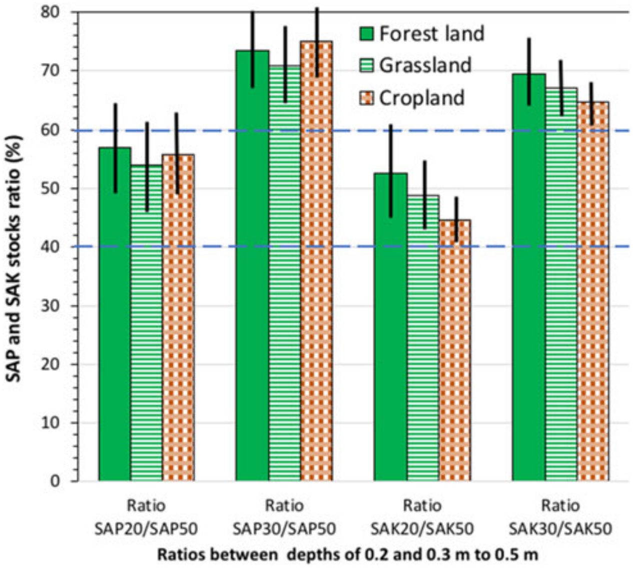

Figure 2. Percentage of the current soil available phosphorous (SAP) stocks and soil available potassium (SAK) stocks for 0.2 m and 0.3 m depth layers versus the 0.5 m depth layer SAP stocks and SAK stocks, respectively, in the three studied land uses; horizontal dash lines of 40% and 60% represent theoretical percentage ratios between the 0.2 and 0.3 m depths to 0.5 m depth, while vertical bars represent standard deviation values.

for 0.2 m depth were linearly and highly significantly correlated with the same stocks for 0.3 m depth ($r^2 = 0.958$*** and $r^2 = 0.973$***), respectively. Additionally, Table 1 also presents all relationships between SAP and SAK stocks for these three soil depths: 0.2 m, 0.3 m and 0.5 m, having in turn as an independent variable each one of these three. These relationships can be considered as pedo-transfer functions between these three soil depths for each of SAP and SAK stocks.

Figure 3 presents SAP and SAK stocks for 0.2, 0.3 and 0.5 m depth layers in the three land uses. Cropland presented the maximum values of SAP and SAK stocks, significantly higher than grassland, which in turn presented significantly higher values than forestland, for each soil depth. For the 0.5 m depth, SAP stocks reached as much as 31.5 kg/ha in cropland, 14.6 kg/ha in grassland, and 5.2 kg/ha in forestland, while SAK stocks were 158 kg/ha, 116 kg/ha and 78 kg/ha, in the above land uses, respectively. The stocks for 0.2 and 0.3 m depths were

The lowest plains, with A values from 0 to 200 m a.s.l., possessed the highest SAP stock values, significantly different from almost any other A-value landforms, for any soil depth, Fig. 4. For the 0.5 m depth, SAP stock was 33.2 kg/ha; the SAK stocks for the same depth, considerably higher (154 kg/ha) than SAP stock, were maximum in the 0–200 m and 200–500 m landforms, generally decreasing with increasing A.

Table 1. Regression equations for soil available phosphorous (SAP) and soil available potassium (SAK) stocks (kg/ha) between the depths of 0.2 m, 0.3 m and 0.5 m, respectively, the determination coefficients (r^2) with their significance degree; the depth values (m) are attached to their stock symbols

Regression equations between SAP stocks and SAK stocks, respectively	r^2	Significance
For SAP stocks: 0.2 m and 0.3 m depths as a function of 0.5 m depth		
SAP 0.2 = 0.5263 × SAP 0.5 + 0.0142	0.927	***
SAP 0.3 = 0.7585 × SAP 0.5 − 0.5125	0.960	***
For SAP stocks: 0.3 m and 0.5 m depths as a function of 0.2 m depth		
SAP 0.3 = 1.386 × SAP 0.2 − 0.0365	0.958	***
SAP 0.5 = 1.7618 × SAP 0.2 + 1.2187	0.927	***
For SAP stocks: 0.2 m and 0.5 m depths as a function of 0.3 m depth		
SAP 0.2 = 0.6908 × SAP 0.3 + 0.4083	0.958	***
SAP 0.5 = 1.2655 × SAP 0.3 + 1.3357	0.960	***
For SAK stocks: 0.2 m and 0.3 m depths as a function of 0.5 m depth		
SAK 0.2 = 0.440 × SAK 0.5 + 2.7831	0.917	***
SAK 0.3 = 0.6741 × SAK 0.5 − 1.5216	0.966	***
For SAK stocks: 0.3 m and 0.5 m depths as a function of 0.2 m depth		
SAK 0.3 = 1.4716 × SAK 0.2 − 2.4721	0.973	***
SAK 0.5 = 2.0829 × SAK 0.2 + 4.0856	0.917	***
For SAK stocks: 0.2 m and 0.5 m depths as a function of 0.3 m depth		
SAK 0.2 = 0.6609 × SAK 0.3 + 3.1397	0.973	***
SAK 0.5 = 1.433 × SAK 0.3 + 6.2042	0.966	***

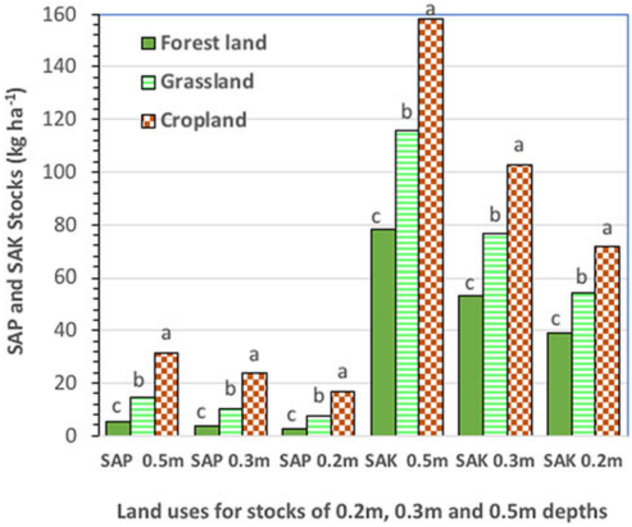

Figure 3. Soil available phosphorous (SAP) stocks and soil available potassium (SAK) stocks for 0.2, 0.3 and 0.5 m depth layers in the three land uses; different letters in a grouping mean significantly different using Duncan's multiple range test.

Generally, the finer the soil texture the higher the SAP and SAK stocks (Fig. 5). The loamy, clayey-loamy, loamy-clayey and clayey textures showed the highest values, in general significantly different from the coarser textures in the case of SAK stocks. Even if there was the same trend for SAP stocks, due to large inside variation the differences were not statistically significant.

Soil available phosphorus and potassium stocks within 0.5 m depth presented maximum values within the flat areas, over 30 k/ha for SAP stock and over 150 kg/ha for SAK stock, Fig. 6. The four slope categories (0–25%) showed the highest SAP and SAK stocks' values that in general were significantly different from the steepest ones (25–100%), regardless the soil depth.

The aspect of flat areas with no sun exposure presented the highest SAP and SAK stock values, with over 30 kg/ha and over

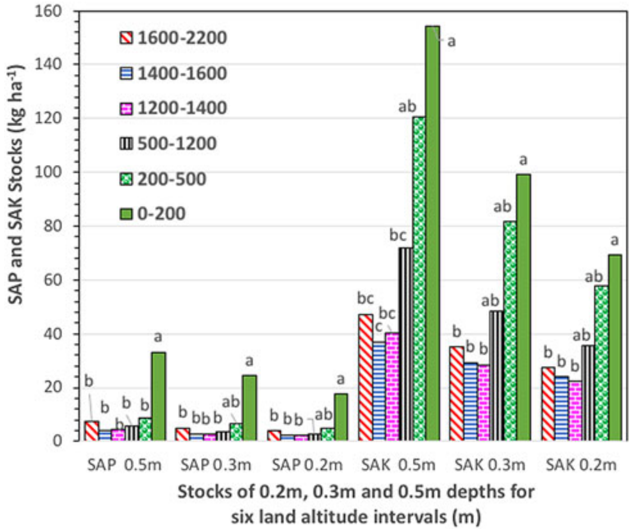

Figure 4. Soil available phosphorous (SAP) stocks and soil available potassium (SAK) stocks for 0.2, 0.3 and 0.5 m depth layers depending on altitude: 0–200, 200–500, 500–1200, 1200–1400, 1400–1600 and 1600–2200 m.

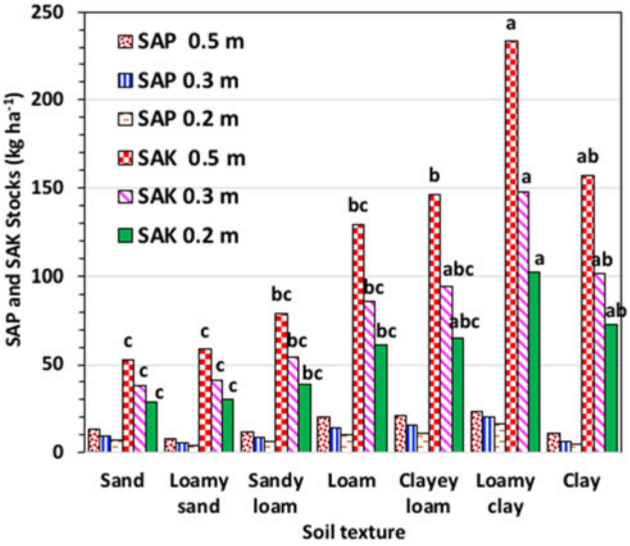

Figure 5. Soil available phosphorous (SAP) stocks and soil available potassium (SAK) stocks for 0.2, 0.3 and 0.5 m depth layers depending on soil texture.

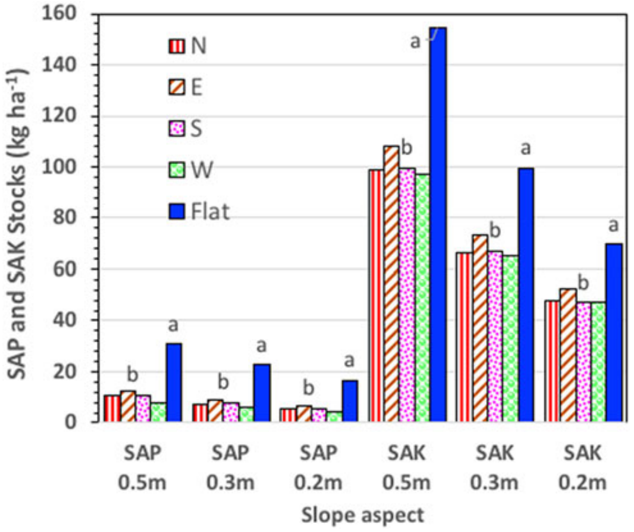

Figure 7. Soil available phosphorous (SAP) stocks and soil available potassium (SAK) stocks for 0.2, 0.3 and 0.5 m depth layers depending on slope aspect.

155 kg/ha within 0.5 m depth, respectively, Fig. 7. The above values were significantly different from all the other slope aspects: northern, eastern, southern and western ones. This pattern was similar for the other two soil depths, 0.2 and 0.3 m.

Soil available phosphorus stocks (ca. 50 kg/ha) presented significantly highest values in neutral pH soils for 0.5 m depth, and correspondingly lower values for the other two soil depths, Fig. 8. The next in row were the SAP stocks from the neighbour pH categories, slightly alkaline and slightly acid. The lowest SAP stock values were within the extreme pH categories: strongly acid and moderately-strongly alkaline. Soil available potassium stock pattern differed from the SAP stock one regarding pH. Thus, the neutral, slightly alkaline and moderately-strongly alkaline (about 176–200 kg/ha) SAK stocks showed the highest values, while the minimum ones were within the slightly-, the moderately- and the strongly-acid ones, Fig. 8. The highest SAK stock values generally differed significantly from the lowest ones. There were similar patterns for the other two soil depths.

Vertisols, Chernisols and Hydrisols had the highest SAP stocks, with about 35 to 42 kg/ha within the 0.5 m depth, while the lowest SAP stocks were for Umbrisols, Cambisols and Luvisols (ca. 4–10 kg/ha) (Table 2). Even if the differences were considerable between soil classes, up to about 10 times, they were not significant due to the large SAP stocks variation. On the other hand, SAK stock variation between soil classes was also large, from about 175–200 kg/ha within Salsodisols, Chernisols and Antrisols, to about 25–90 kg/ha for Umbrisols, Spodisols, Cambisols and Luvisols, for the same 0.5 m soil depth. However, Salsodisols had significantly higher SAK stocks than Umbrisols, Spodisols and Cambisols (Table 2).

There was a somewhat similar situation regarding the soil types, Table 2, last section. Phaeozems, Gleysols, Vertosols and

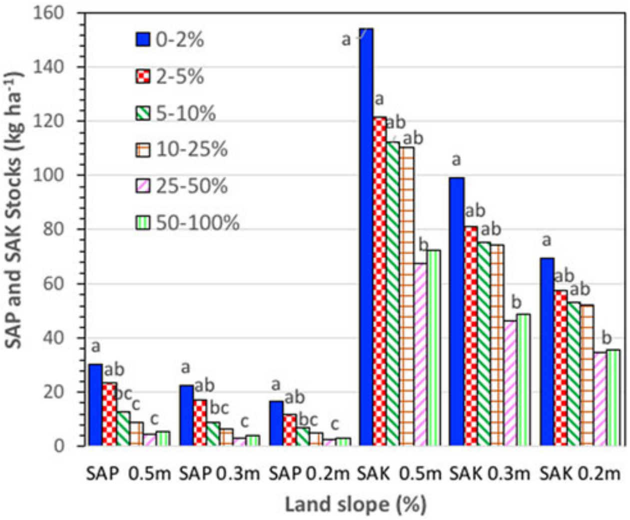

Figure 6. Soil available phosphorous (SAP) stocks and soil available potassium (SAK) stocks for 0.2, 0.3 and 0.5 m depth layers depending on land slope.

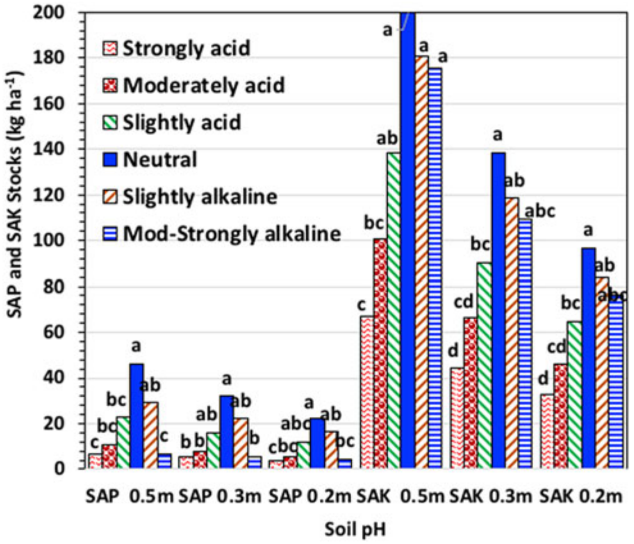

Figure 8. Soil available phosphorous (SAP) stocks and soil available potassium (SAK) stocks for 0.2, 0.3 and 0.5 m depth layers depending on soil pH.

Table 2. Soil available phosphorous (SAP) and potassium (SAK) stocks (kg/ha) for three soil depths (0.2, 0.3 and 0.5 m) within the studied soil classes and soil types

Soil attribute	N	SAP 0.5 m		SAP 0.3 m		SAP 0.2 m		SAK 0.5 m		SAK 0.3 m		SAK 0.2 m	
Soil class													
Salsodisols	18	20.7	a	14.8	a	10.5	a	200.8	a	124.3	a	84.5	a
Chernisols	188	40.3	a	30.0	a	22.0	a	191.5	ab	126.9	a	87.5	a
Antrisols	15	13.8	a	11.2	a	7.6	a	174.6	abc	110.1	a	77.4	ab
Hydrisols	31	34.6	a	24.7	a	17.9	a	171.0	abc	106.1	ab	72.4	ab
Vertisols	11	42.3	a	26.6	a	18.0	a	159.1	abc	102.7	ab	70.3	ab
Protisols	174	15.0	a	11.4	a	8.4	a	137.3	abcd	94.0	ab	68.1	ab
Luvisols	259	9.7	a	7.0	a	4.9	a	90.6	abcd	57.4	ab	40.0	ab
Cambisols	255	6.3	a	4.3	a	3.1	a	71.7	bcd	49.0	ab	34.4	ab
Spodisols	38	13.4	a	9.1	a	6.4	a	59.1	cd	40.1	ab	44.0	ab
Umbrisols	2	3.7	a	2.5	a	1.9	a	27.0	d	22.3	b	19.2	b
Soil type													
Phaeozem	85	33.4	a	24.5	a	17.6	a	226	a	150	a	104.2	a
Regosol	51	11.4	a	8.8	a	6.5	a	205	ab	138	ab	98.2	ab
Solonetz	18	20.7	a	14.8	a	10.5	a	201	ab	124	ab	84.5	ab
Kastanoziom	3	16.6	a	12.9	a	10.4	a	180	abc	119	ab	86.0	ab
Gleysol	28	35.8	a	25.5	a	18.5	a	175	abc	107	ab	72.9	ab
Anthrosol	15	13.8	a	11.2	a	7.6	a	175	abc	110	ab	77.4	ab
Vertosol	9	50.8	a	31.8	a	21.4	a	171	abc	110	ab	74.8	ab
Chernozem	91	51.0	a	38.2	a	28.3	a	165	abc	108	ab	73.6	ab
Rendzina	9	5.1	a	4.1	a	3.2	a	141	abc	98	ab	71.6	ab
Stagnosol	3	23.2	a	16.9	a	12.3	a	135	abc	94	ab	67.8	ab
Aluviosol	90	17.3	a	13.1	a	9.5	a	122	abc	82	ab	58.5	ab
Preluvosol	107	11.4	a	8.2	a	5.8	a	111	abc	70	ab	48.2	ab
Pelosol	2	3.9	a	3.0	a	2.3	a	106	abc	69	ab	50.0	ab
Eutricambosol	110	9.0	a	6.1	a	4.4	a	96	abc	65	ab	43.6	ab
Psamosol	14	28.3	a	20.3	a	14.4	a	93	abc	61	ab	43.1	ab
Luvosol	150	8.6	a	6.2	a	4.4	a	77	abc	49	ab	34.4	ab
Lithosol	19	4.5	a	4.0	a	3.6	a	60	abc	56	ab	51.7	ab
Prepodzol	32	14.5	a	9.8	a	6.9	a	60	abc	40	ab	46.4	ab
Podzol	6	8.0	a	5.3	a	3.9	a	56	abc	40	ab	31.6	ab
Districambosol	145	4.3	a	2.9	a	2.2	a	53	abc	37	ab	27.4	ab
Alosol	2	2.4	a	2.2	a	2.0	a	44	bc	31	ab	20.8	ab
Humosiosol	2	3.7	a	2.5	a	1.9	a	27	c	22	b	19.2	b

N – number of soil profiles, the means followed by different letters are significantly different within the same soil nutrient content (table columns) between both soil classes and soil types, respectively, according to Duncan's multiple range test.

Chernozems had the highest SAP stock values for 0.5 m soil depth (33–51 kg/ha), while Rendzinas, Pelosols, Eutricambosols, Luvosols, Lithosols, Podzols, Districambosols, Alosols and Humosiosols presented the lowest SAP stocks (4–9 kg/ha). There were no significant differences between soil types either for 0.5 m depth or for the other two soil depths. SAK stocks were maximum within Phaeozems, Regosols and Solonetzs with over 200 kg/ha, while Pelosols, Eutricambosols, Psamosols, Luvosols, Lithosols, Prepodzols, Podzols, Districambosols, Alosols and Humosiosols presented the lowest SAK stocks, between 27 and 96 kg/ha. Most of these great differences were not significant, except between Phaeozems and Humosiosols.

Soil available phosphorus and potassium stocks were directly and highly significantly correlated with each other, either linearly or curvilinearly (power functions) for all the three studied land uses (Table 3). Inverse, curvilinear and highly significant correlations existed between A, SAP stocks and SAK stocks for forestland, grassland and cropland, except between SAK stock and A for cropland (not-significant) (Table 3). There was a similar correlation pattern for Sl, SAP stocks and SAK stocks. From the

Table 3. Relationships of 0.5 m depth soil available phosphorous (SAP) and potassium (SAK) stocks (kg/ha) versus some single environmental variables (weighted averages over the same 0.5 m depth) and stepwise multiple regression models with SAP and SAK stocks as independent variables

	SAP stocks relationships			SAK stocks relationships		
Land use	Regression equations	*r*	Sign	Regression equations	*r*	Sign
Forestland	$SAP = 0.029 \times SAK + 2.94$	0.522	***	$SAK = 9.47 \times SAP + 29.2$	0.522	***
Grassland	$SAP = 0.1049 \times SAK + 2.497$	0.374	***	$SAK = 1.33 \times SAP + 96.1$	0.374	***
Cropland	$SAP = 0.0496 \times SAK^{1.1264}$	0.495	***	$SAK = 71.24 \times SAP^{0.2178}$	0.495	***
All land uses combined	$SAP = 0.1671 \times SAK^{0.8021}$	0.455	***	$SAK = 52.9 \times SAP^{0.2578}$	0.455	***
Forestland	$SAP = -3.286 \times \ln(A) + 25.9$	−0.315	***	$SAK = 87.7 \times e^{-7E-04 \times A}$	−0.371	***
Grassland	$SAP = 36.94 \times A^{-0.353}$	−0.309	***	$SAK = 112.4 \times e^{-8E-04 \times A}$	−0.361	***
Cropland	$SAP = 987.13 \times A^{-0.888}$	−0.352	***	$SAK = 0.0139 \times A + 155.4$	0.001	NS
All land uses combined	$SAP = 111.6 \times A^{-0.532}$	−0.388	***	$SAK = 121.0 \times e^{-1E-03 \times A}$	−0.432	***
Forestland	$SAP = -3.208 \times \ln(Sl) + 14.82$	−0.460	***	$SAK = -49.6 \times \ln(Sl) + 227.2$	−0.392	***
Grassland	$SAP = 8.08 \times Sl^{-0.27}$	−0.317	***	$SAK = 100.8 \times e^{-0.017 \times Sl}$	−0.266	***
Cropland	$SAP = 15.61 \times e^{-0.077 \times Sl}$	−0.347	***	$SAK = 0.3451 \times Sl + 156.5$	0.001	NS
All land uses combined	$SAP = 10.63 \times Sl^{-0.365}$	−0.417	***	$SAK = 111.1 \times Sl^{-0.174}$	−0.351	***
Forestland	$SAP = -18.74 \times \ln(Pr) + 129$	−0.274	***	$SAK = 2E + 11 \times Pr^{-3.346}$	−0.428	***
Grassland	$SAP = 1E + 08 \times Pr^{-2.612}$	−0.300	***	$SAK = 688.5e^{-0.003 \times Pr}$	−0.419	***
Cropland	$SAP = 8E + 29 \times Pr^{-10.33}$	−0.434	***	$SAK = 1018.3 \times e^{-0.003 \times Pr}$	−0.209	***
All land uses combined	$SAP = 8E + 11 \times Pr^{-3.949}$	−0.388	***	$SAK = 5E + 09 \times Pr^{-2.77}$	−0.480	***
Forestland	$SAP = 0.6204 \times T + 0.0614$	0.172	***	$SAK = 21.56 \times e^{0.1112 \times T}$	0.270	***
Grassland	$SAP = 1.3039 \times e^{0.1516 \times T}$	0.213	***	$SAK = 27.29 \times e^{0.1201 \times T}$	0.293	***
Cropland	$SAP = 0.1469 \times e^{0.4265 \times T}$	0.247	***	$SAK = -8.92 \times T + 248.2$	0.002	NS
All land uses combined	$SAP = 0.7376 \times e^{0.2218 \times T}$	0.281	***	$SAK = 20.1 \times e^{0.153 \times T}$	0.341	***
Forestland	$SAP = -8.349 \times \ln(Iar) + 36.15$	−0.234	***	$SAK = 16682 \times Iar-1.546$	−0.380	***
Grassland	$SAP = 1050.5 \times Iar^{-1.497}$	−0.280	***	$SAK = 6082.5 \times Iar^{-1.216}$	−0.386	***
Cropland	$SAP = 1E + 10 \times Iar^{-6.065}$	−0.393	***	$SAK = 1495.7 \times Iar^{-0.736}$	−0.110	NS
All land uses combined	$SAP = 16808 \times Iar^{-2.251}$	−0.358	***	$SAK = 24137 \times Iar^{-1.601}$	−0.449	***
Forestland	$SAP = 0.1089 \times CL + 3.1074$	0.168	**	$SAK = 26.13 \times e^{0.038 \times CL}$	0.514	***
Grassland	$SAP = 0.1752 \times CL + 9.833$	0.004	NS	$SAK = 34.02 \times e^{0.0331 \times CL}$	0.546	***
Cropland	$SAP = 18.32 \times e^{-0.017 \times CL}$	−0.132	*	$SAK = 86.91 \times e^{0.0108 \times CL}$	0.185	**
All land uses combined	$SAP = 4.29 \times e^{0.0116 \times CL}$	0.103	**	$SAK = 35.9 \times e^{0.0324 \times CL}$	0.508	***
Forestland	$SAP = 0.25 \times pH^{1.6263}$	0.273	***	$SAK = 12.23 \times e^{0.3037 \times pH}$	0.363	***
Grassland	$SAP = 0.668 \times e^{0.3399 \times pH}$	0.327	***	$SAK = 5.838 \times pH^{1.4868}$	0.413	***
Cropland	$SAP = 0.033 \times pH^{3.1665}$	0.337	***	$SAK = 22.275 \times pH^{0.9188}$	0.222	***
All land uses combined	$SAP = 0.0707 \times pH^{2.5214}$	0.390	***	$SAK = 4.499 \times pH^{1.6691}$	0.456	***
Forestland	$SAP = 0.299 \times SB + 2.503$	0.312	***	$SAK = 34.37 \times e^{0.0504 \times SB}$	0.461	***
Grassland	$SAP = 3.106 \times e^{0.0374 \times SB}$	0.228	***	$SAK = 18.56 \times SB^{0.6014}$	0.512	***
Cropland	$SAP = 7.39 \times e^{0.0228 \times SB}$	0.103	NS	$SAK = 48.14 \times SB^{0.3336}$	0.242	***
All land uses combined	$SAP = 1.499 \times SB^{0.5577}$	0.284	***	$SAK = 19.86 \times SB^{0.5907}$	0.530	***
Grassland	$SAP = 0.4485 \times SOC^{0.5375}$	0.194	***	$SAK = 25.8 \times \ln(SOC)-3.83$	0.100	*
Cropland	$SAP = 0.4014 \times SOC^{0.7225}$	0.205	***	$SAK = 99.24e^{0.0018 \times SOC}$	0.115	*

Stepwise multiple regression models with SAP and SAK stocks as independent variables

Equation	r	Adjust. r^2	Sign.	Land use
$\text{SAP stock} = 5.22 + 0.028 \times \text{SAK} - 0.066 \times \text{Sl} + 0.190 \times \text{SB} - 0.114 \times \text{CL}$	0.573	0.318	***	Forestland
$\text{SAK stock} = 466.6 \times 7.72 \times \text{SAP} + 2.98 \times \text{CL} + 2.83 \times \text{TN} - 0.787 \times \text{Pr} + 0.103 \times \text{A}$	0.646	0.406	***	Forestland
$\text{SAP stock} = 7.88 + 0.099 \times \text{SAK} + 0.121 \times \text{SOC} - 0.856 \times \text{CL} + 0.898 \times \text{SB} - 0.022 \times \text{A}$	0.455	0.198	***	Grassland
$\text{SAK stock} = 300 + 1.08 \times \text{SAP} + 2.44 \times \text{CL} - 0.366 \times \text{Pr} - 13.5 \times \text{T} + 2.82 \times \text{TN} + 11.4 \times \text{pH}$	0.541	0.283	***	Grassland
$\text{SAP stock} = -147.7 + 0.164 \times \text{SAK} + 15.2 \times \text{T}$	0.450	0.197	***	Cropland
$\text{SAK stock} = 36.1 + 1.071 \times \text{SAP} + 10.11 \times \text{TN}$	0.462	0.208	***	Cropland
$\text{SAPstock} = -12.6 + 0.125 \times \text{SAK} + 2.68 \times \text{T} - 0.706 \times \text{CL} + 0.764 \times \text{SB} + 0.116 \times \text{SOC} - 1.202 \times \text{TN} - 0.292 \times \text{Sl}$	0.454	0.201	***	All land uses combined
$\text{SAKstock} = 310.1 + 1.104 \times \text{SAP} + 2.05 \times \text{CL} - 0.375 \times \text{Pr} + 5.51 \times \text{TN} - 11.8 \times \text{T} + 10.6 \times \text{pH} - 0.184 \times \text{SOC}$	0.527	0.273	***	All land uses combined

Sl, slope (%); CL, clay content (%); SB, sum of base cations (cmol (+) kg^{-1}); Pr, annual precipitation (mm); T, mean annual temperature (°C); Iar, de Martonne aridity index (mm °C^{-1}); for these relationships, SAP, soil available phosphorous stock (kg/ha); SAK, soil available potassium stock (kg/ha); SOC stock and TN stocks (Mg ha^{-1}); r, coefficient of correlation; NS, not significant, E-as in Excel notation.

investigated climatic variables, both Pr and Iar were inversely and highly significantly correlated with SAP and SAK stocks, curvilinearly in most of the cases, for all land uses (Table 3). There were direct correlations between the other climatic variable considered, T, *v.* SAP and SAK stocks, also as curvilinear in most of the cases.

The soil properties, CL, pH and SB, had also been correlated with SAP and SAK stocks. There were weak correlations between CL and SAP stock, directly, linearly and distinctly significant for forestland, not-significant for grassland, and inversely and significant for cropland, Table 3. In contrast to the latter, there were direct, curvilinearly and highly or distinctly significant correlations between SAK stock and CL. SAP and SAK stocks and pH were correlated directly, curvilinearly and highly significantly.

In most of the cases the correlations between the studied environmental variables and SAP and SAK stocks were weaker for cropland than for forestland and grassland. However, there were curvilinear, direct and highly significant correlations between SAP stock and SOC stock, as well as direct, weak and significant correlations between SAK stocks and SOC stock (Table 3).

The most appropriate predictive models for SAP and SAK stocks obtained using stepwise multiple regression method excluded some of the proposed variables suggested by the simple regressions and retained certain explanatory variables. For forest, the best performing models retained SAK stock, Sl, SB and CL as predictors for SAP stocks ($r = 0.573$), and SAP stock, CL, TN stock, Pr and A as predictors for SAK stocks ($r = 0.646$) (Table 3, last part). In the case of grassland, for SAP stock the retained explanatory variables are: SAK stock, SOC stock, CL, SB and A ($r = 0.455$), and for SAK stock: SAP stock, CL, Pr, T, TN stock and pH ($r = 0.541$). The explanatory variables for cropland SAP stock were only SAK stock and T ($r = 0.450$), while for cropland SAK stock the variables were SAP stock and TN stock ($r = 0.462$). For all land uses combined, the retained explanatory variables for SAP stock were: SAK stock, T, CL, SB, SOC stock, TN stock and Sl ($r = 0.454$), and for SAK stock they were SAP, CL, Pr, TN stock, T, pH and SOC stock ($r = 0.527$).

Figure 9a presents the spatial distribution of the 0.5 m depth SAP stocks (kg/ha) within soil classes in Romania. The largest circle-like area situated somewhat in the central hilly and mountainous parts of the country had low (0–15 kg/ha) SAP stocks. The lowest (<5 kg/ha) SAP stocks occurred for mountain soils (Umbrisols, Histosols and Andisols) with a total of 1440 Mg, covering an area of 3891 km^2. Luvisols and Cambisols also had a low (5–10 kg/ha) SAP stock magnitude, totalling 88 179 Mg within an area of 1 10 619 km^2 from low-elevation mountains, hills and high plains. The next SAP stock category (10–15 kg/ha) was represented by Protisols, Spodisols and Antrisols, from mountains and high-altitude regions and also from river flood plains, with a total stock of 65 578 Mg from a 44 432 km^2 area. The 15–25 and 25–35 kg/ha SAP stock categories represented by Hydrisols and Salsodisols occupied relatively small areas, 5 791 km^2 and 1734. Km^2, respectively, showing total SAP stocks of 20 044 Mg and 3592 Mg. There were higher SAP stocks (>35 kg/ha) for the low-altitude plains and hills from the marginal parts of the country, within the western and eastern regions where cropland, especially arable land prevailed, and where annual P application was carried out. The soil classes from the above category were Chernisols and Vertisols, with a total SAP stock of 2 80 746 Mg, from an area of 69 509 km^2.

Figure 9b shows the spatial distribution of the 0.5 m depth SAK stocks (kg/ha) within soil classes. The high-altitude landforms were within the lowest SAK stock categories, specifically 0–30 kg/ha, i.e. Umbrisols, Histosols and Andisols, with a total amount of 10 506 Mg from an area of 3891 km^2; the Spodisols belonged to the 30–60 kg/ha SAK stock category, with a total of 43 996 Mg covering 7443 km^2 from high mountainous regions. Other mountainous areas represented by Cambisols formed the 60–90 kg/ha category, with a total SAK stock of 4 02 862 Mg from 56 163 km^2. Luvisols (category 90–120 kg/ha) had an area of 54 457 km^2, mainly in hilly, plateaus and high plains, and a total SAK stock of 4 93 217 Mg, while Protisols (120–150 kg/ha) were usually found in low-altitude plains, totalling 5 01 065 Mg SAK stocks, and an area of 36 488 km^2. Antrisols, Hydrisols and Vertisols formed the 150–180 kg/ha SAK stock category and occupied relatively small areas of 9567 km^2 in plains and river flood plains, with a total amount of 1 59 865 Mg. Chernisols occupied the largest (66 234 km^2) area, and combined with Salsodisols (67 969 km^2 together), were in the highest (180–210 kg/ha) category, with a total of 13 03 304 Mg SAK stocks. They were generally situated in cropland area from the

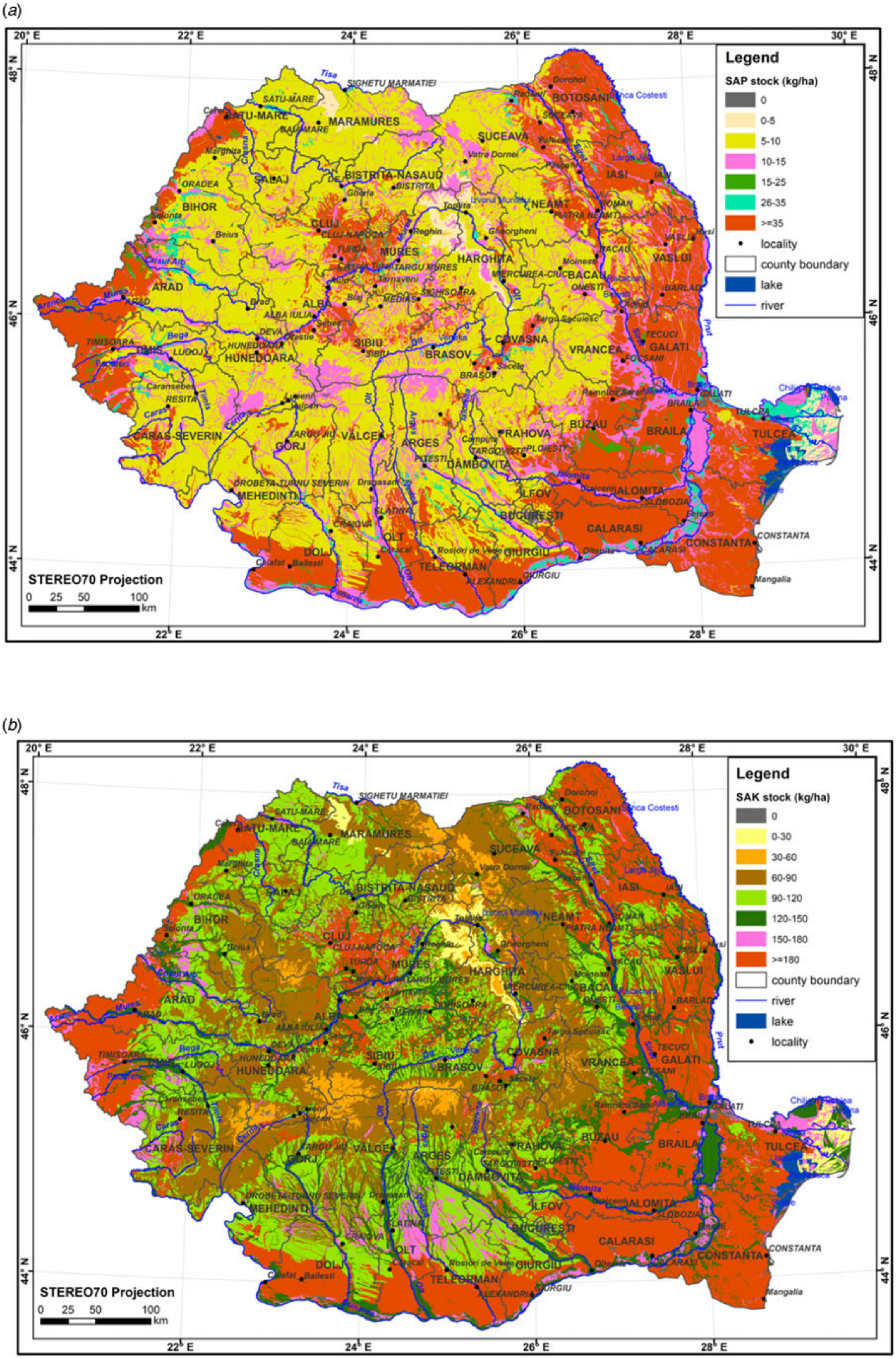

Figure 9. (a) Spatial distribution of the 0.5 m depth soil available phosphorous (SAP) stocks (kg/ha) within soil classes. (b) Spatial distribution of the 0.5 m depth soil available potassium (SAK) stocks (kg/ha) within soil classes.

low hilly regions and mainly from the plains in the eastern, south-eastern, southern and western parts of Romania.

Discussion

Soil available phosphorus and potassium stocks and their depth and spatial distribution

The mountain soils have the lowest 0.5 m depth SAP and SAK stocks, while the low-altitude plains and hills from the arable land zone, where there generally are Chernisols and Vertisols, show the maximum stocks. Romanian soils possess low 0.5 m depth SAP stock mean values among European countries, with 5.2 kg/ha for forestland, 14.6 kg/ha for grassland, 31.5 kg/ha for cropland, and 17.1 kg/ha for all land uses combined, *v.* e.g. German soils that present about 500 kg/ha for a larger soil depth (1 m) in cropland, with one third within the plough layer and one fifth below 0.5 m depth Gocke *et al.* (2021). Even after subtracting one fifth from 500 kg/ha to standardize to 0.5 m depth for comparison, the difference remains substantial. Nevertheless, similar to German soils, Romanian Chernozem SAP stocks are the highest *v.* the stocks of the other soil types in the country. The average 0.5 m depth SAK stock across all land uses combined presents moderate values rising to 118.3 kg/ha, while forestland has the lowest stock (78.3 kg/ha), increasingly followed by grassland (115.5 kg/ha) and cropland (158.1 kg/ha).

The current SAP stock data are consistent with the world map representing topsoil Olsen P content (McDowell *et al.*, 2023), where SAP content in Romania is generally shown as being lower than that of western European countries, e.g. between 10 and 15 mg kg^{-1} in Carpathian Mountains, and somewhat higher, 20–30 mg kg^{-1} in the rest of area, essentially in cropland (McDowell *et al.*, 2023). Panagos *et al.* (2022) estimated a STP stock for 0.2 m depth agricultural topsoil at a large mean of 1412 kg ha^{-1} and the SAP stock at a mean value of 83 kg ha^{-1} in EU and UK, with considerable difference between North and South, while the SAP to STP ratio at 1:17 for the whole study area. Compared to our results, even though the methods of analysis are different (Egner-Riehm-Domingo method *versus* Olsen P), this European 0.2 m depth SAP mean value is much higher than the highest 0.5 m depth SAP stock mean values occurring in Romania (Figs 3–8, Table 2). The difference between the higher SAP stocks occurred in the countries from western Europe and the stocks from Romania might be explained through the larger amounts of fertilizers applied in time in those countries. Such differences are generally common among various regions and countries (Potter *et al.*, 2010).

The spatial distribution of SAP and SAK stocks of our results is generally consistent with the study made by Ballabio *et al.* (2019), specifically as regional variation, even if the latter showed SAP and SAK contents for only 0.2 m depth across Europe; thus, the lowest SAP content values for Romania reported by Ballabio *et al.* (2019) occurred within the forests of the Carpathian Mountains and in south-eastern cropland part of the country, where pH was also high, determining its low plant availability. There are also differences resulted probably from the sampling sites and laboratory method. The same similarity trend between the data of Ballabio *et al.* (2019) was noted for SAK stocks, where the SAK contents in Romania reported by Ballabio *et al.* (2019) showed the highest values in most of the country, similar to many regions from southern Europe, such as Italy and Spain.

Thus, the present paper brings an additional contribution to the SAP and SAK stocks knowledge in the EU. For the 0.2 m depth (meaning 40% from the 0.5 m studied depth size), SAP stocks generally exceed 50% of the corresponding 0.5 m stocks in all land uses, and for the 0.3 m depth (representing 60% from the 0.5 m depth) SAP stocks exceed 70% of the 0.5 m stocks (Fig. 2, horizontal lines). The same percentage kind of SAK stocks is also higher than the corresponding depth percentage for 0.5 m depth. In other words, SAP and SAK stocks fall in magnitude with depth, and the soil pedo-transfer functions from Table 1 might be used to convert the stocks between depths. This depth stock distribution seems to be normal and has also been noted in other countries, e.g. by Dhillon *et al.* (2020), who have stressed that the concentration of SAP and SAK is significantly higher in the surface soil, decreasing with soil depth.

Environmental conditions for soil available phosphorus and potassium stocks in soils and their correlations

For the ecological conditions of Romania, both SAP stocks and SAK stocks are significantly correlated with basic environmental properties for all three studied land uses, according to single and multiple relationships (Table 3). Similar correlations have also been obtained under different environmental conditions in various regions and countries. Somavilla *et al.* (2022) have reported that cropland soils export higher SAP amounts than grassland soils in Brazil and that the mowing grasslands led to a change in the labile (available) P pool from inorganic to organic forms as well as to an increase in SOC and TN stocks. This suggests existing direct correlations between SAP, SOC and TN stock, confirming our multiple relationships, which additionally quantify the contribution of each environmental factor.

In calcareous soils showing high pH values, P availability is generally low (Fig. 8), presumably attributed to chemical precipitation of P nutrient as Ca-P minerals, as has been also found earlier by Borlan *et al.* (1994), Lacatusu (2000) and Meyer *et al.* (2020). The highest SAP stocks occur in neutral soils; thus, pH is critical in determining SAP stock values because SAP are minimal in strongly acid soils, due probably to chemical precipitation of Al- and Fe-P minerals. Unlike Meyer *et al.* (2020) who have found an indirect correlation between K and P availability, a direct correlation, irrespective of the land use, was found in this work and might be considered a novelty for this part of the continent.

Luna *et al.* (2022) have found higher STP contents in some fine-textured soils suggesting a direct correlation between P and CL, similar to our findings regarding SAP and CL. They have also reported higher contents of SAP and STP in 0.2 m depth topsoil correlated with fertilizer application, and have also stressed that topsoil P is the most important P source for plants (McBeath *et al.*, 2012). P availability for crops directly depends also on rainfall (McBeath *et al.*, 2012), and so does leaching (Paltineanu *et al.*, 2021), and this finding partly explains why the soils from the high-elevation wet landforms (mountains and high hills) have lower SAP stocks, while cropland soils mainly occurring in lower and dryer plains with limited leaching have higher SAP and SAK stocks. SAP was also found to be directly correlated with SOC, TN stock and salinity content (Ye *et al.*, 2014). While Jakšić *et al.* (2021) presented similar findings concerning SAK stock and SOC stock in Serbia, Wu *et al.* (2022) and Zhang *et al.* (2022) reported correlations between SAP and SOC in soils of China.

In Turkey, a country in close proximity to Romania, SAK stock was maximum in grassland, different from our case, and was directly correlated with CL, as in our study; parental material and land use type are the main factors responsible for the spatial SAK variability (Akbas *et al.*, 2017). According to Borlan *et al.* (1994) and Hillel (2008), the main sources of K in soils are the geological deposits of feldspars and micas that release K through weathering.

The predictive models using stepwise multiple regression revealed that SAP and SAK had the greatest contribution in predicting their reciprocal stocks (Table 3), and at the same time, other proposed variables by simple regression have been excluded. Thus, SAP stock and SAK stock have the greatest contribution in predicting their reciprocal stocks, and vice versa. From the other soil properties, CL has been retained in six cases, TN stock in five cases, showing their great influence, while SB and SOC stock in three, and pH in two cases. The climate variables T and Pr have been retained in four and three cases, respectively, while A and Sl, which are strongly correlated, have been retained in two cases each.

These mentioned environmental driving factors, along with land uses, have thus the highest predictive values. Generally, the r values obtained with single regression equations (Table 3) have increased when using multiple regression equations (Table 3). However, the rise in r values is not high, due probably to the fact that linear regression equations are used in the multiple regression equation model, while the simple regression equation model has employed the best fit of equation type, mostly as non-linear functions.

From all land uses, the best predictive values using multiple regression models and basic environmental driving factors were found for the forestland stocks of SAP and SAK, followed by grassland stocks, while the lowest prediction occurred for cropland stocks. This may probably be attributed to the long-term additional nutrient input performed by farmers in cropland that changed the natural conditions otherwise present in grassland, and especially in forestland.

The obtained results also emphasized the major role played by land use in the occurrence of SAP and SAK stocks. As Ballabio *et al.* (2019) reported, the land use has a strong influence on SAP and SAK contents and stocks, and is the main driver for SAP, because cropland benefits of higher fertilizer application. On the other hand, land cover areas of permanent crops have lower levels of P. Thus, our results bring additional information *v.* the data existing in literature, especially for the larger soil depths considered.

As described in a previous section, these three land uses have specific altitude and slope values, which in turn exert some influence on SAP and SAK stocks as was shown by the statistics tests. Concerning the altitude, this variable primarily acts as climate, not only as Pr, T and Iar that were dealt with here, but also as cloudiness, air humidity, wind speed, etc.

Management considerations

As McDowell *et al.* (2023) reported, quantification of SAP stocks might help farmers find better solutions for using P fertilizers more efficiently, minimizing leaching that usually occurs within coarse-textured soils and wet environments (Paltineanu *et al.*, 2021; 2022), typical of higher hills and mountains, and preventing phosphorus and potassium loss and degradation of water quality. This finding is particularly important under different environmental conditions, i.e. in north-western European countries, where P leaching from rich-in-P soils is one of the major causes of diffuse P losses (Panagos *et al.*, 2022), and where there are also recommendations to reduce P fertilizer input (Vandermoere *et al.*, 2021).

As already mentioned, cropland presents the highest SAP and SAK stock values, due both to natural and man-made conditions. Because Pr increases with A in hills and mountains, so does leaching and erosion, while most of the cropland areas are within flat plains, where chemical fertilizers are usually applied annually. Measures to diminish nutrient leaching specifically from sandy and loamy-sandy soils and wet regions are welcome to preserve SAP and SAK stocks (Lacatusu *et al.*, 2019; Domnariu *et al.*, 2020; Paltineanu *et al.*, 2021; 2022).

Cropland is spread over most Chernozems, Phaeozems and Vertosols possessing the highest SAP and SAK stocks in Romania and representing the country's largest pool of fertile soils. However, under these poor SAP conditions of Romanian soils, the obtained correlations between SAP, SAK, TN and SOC stocks suggest annual applications of various amounts of P, depending on the existing stocks and crop needs, which would increase SAP stocks; the crops would thus better use N-based fertilizers and K-based fertilizers (Mărin *et al.*, 2022) in cropland, while integrating manures with fertilizers could be a viable nutrient management practice of increasing SAP stock in less fertile sandy soils (Sharma *et al.*, 2023). Management recommendations on fertilizer application have also been done by Zhang *et al.* (2022), Grigatti *et al.* (2023), and Muntwyler *et al.* (2024) for cropland, also recommending crop rotation, conservation tillage, straw return, raw and composted agro- and bio-waste, and green manure application to improve carbon sequestration and phosphorus and potassium availability.

Human intervention in grassland is generally scanty. In order to prevent the worsening of soil physical properties that could implicitly increase runoff, leaching and erosion, reasonable grazing and avoidance of unreasonable wild tourism with off-road vehicles are recommended for grassland (Bogunovic *et al.*, 2022; Centeri, 2022; Lacatusu *et al.*, 2024). This measure would also help increase SAP stock, SAK stock and SOC sequestration.

Conclusions

Soil available phosphorus and potassium stocks strongly decrease with depth; soil relationships were obtained between the SAP and SAK stocks of 0.2 m, 0.3 m and 0.5 m depths, and these pedotransfer functions might be used to convert these stocks between the above depths.

Land use exerts a considerable influence on SAP and SAK stocks. Cropland soils present the highest SAP and SAK. Chernozems, Phaeozems and Vertosols possess the highest SAP and SAK stocks in Romania representing the largest country's pool.

For the studied ecological conditions that can also be encountered in other European countries, e.g. in neighbouring countries, both SAP stocks and SAK stocks are significantly correlated with basic environmental properties for all three studied land uses, with existing direct correlations between SAP, SAK, SOC and TN stocks. The best predictive values using multiple regression models and basic environmental driving factors were found for the forestland stocks of SAP and SAK, followed by grassland stocks, while the lowest prediction occurred for cropland stocks.

The results and conclusions obtained in this study, where Romanian ecosystems were a case study, might be useful for other land uses, regions and countries with similar environmental conditions.

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