Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-23

DOI: *10.15244/pjoes/215760* ONLINE PUBLICATION DATE: 2026-02-18

Original Research

Soil Characterization in a Silvoarable Ecosystem from Romania: *Populus deltoides* (Bartram ex Marshall) x *P. nigra* (L.) and *Brassica napus* (L.)

Romina Mazăre[1], Mădălina Iordache[1, 2]°*

[1]University of Life Sciences ”King Mihai I” of Timișoara, Department of Sustainable Development and Environmental Engineering, 119 Calea Aradului, Timișoara, Romania
[2]Research Centre of Bioresources, Environment and Geospatial Data, University of Life Sciences ”King Mihai I” of Timișoara, 119 Calea Aradului, Timișoara, Romania

Received: 25 May 2025
Accepted: 17 December 2025

Abstract

A silvoarable ecosystem was studied in the western part of Romania (Timiș County). This agricultural system was established by associating two plant species: a rapeseed crop (the hybrid LG Architect of *Brassica napus* L.) and a hybrid poplar plantation (*Populus deltoides* Bartram ex Marshall × *Populus nigra* L.). The study aimed to assess several physical (particle size composition (coarse sand (2.0-0.2 mm), fine sand (0.2-0.02 mm), silt (0.02-0.002 mm), colloidal clay (<0.002 mm), physical clay (<0.01 mm)) and bulk density) and chemical (pH, humus, total nitrogen, plant-available phosphorus, and plant-available potassium) parameters of soil during two seasonal periods: autumn and spring. Different soil depths were considered: 0-30 cm in the poplar plantation and 0-10 cm in the rapeseed crop. Generally, higher values were observed for the chemical soil parameters in the rapeseed soil than in the poplar soil in the spring season, after winter exposure. This effect emphasizes the enhancement of the potential of the rapeseed crop by combining it with the woody plant (hybrid poplar) within the silvoarable system, and shows the effectiveness of this type of plant association as an agricultural alternative, as well as the contribution of the woody plant (hybrid poplar) to improving the soil conditions for the herbaceous crop (rapeseed). This study shows that edging crops with trees can be a sustainable agricultural strategy.

Keywords: agroforestry, poplar clones, soil texture, winter exposure, crop bordering, tree bordering, intercropping, depth-wise

*e-mail: madalina.borca@usvt.ro
°ORCID iD: 0000-0002-5302-7261

Introduction

The associations between trees and herbaceous plants within silvopastoral and silvoarable systems are sustainable tools for exploiting the food-producing agricultural systems [1-3]. Bordering agricultural crops with woody plantations, such as hybrid poplar, has several benefits for soil sustainability and crop efficiency. These benefits are sometimes related to the protection and improvement of the general growing conditions for the agricultural crop [4], rather than to a direct increase in soil fertility. Among the main advantages, it is remarkable that trees act as a protective shelterbelt against strong winds, reducing water evaporation from the soil and protecting plants from mechanical stress [5, 6]. Strong winds can dry out the soil and reduce the efficiency of photosynthesis in the herbaceous crop [5]. Among the structural and morphological traits of the woody plants which border the monoculture in order to ensure a favorable microclimate for the crop, important to be mentioned are the crown morphology as an aboveground characteristic [7] and the roots as an underground characteristic [8]. The tree crown impacts the local microenvironment of the agricultural crop by influencing the light access, the wind direction, soil moisture, and even by controlling some plant diseases due to the antimicrobial flavonoids from its twigs and leaves [9]. Tree roots stabilize the soil and prevent the loss of the fertile layer through aeolian (wind) or water (precipitation) erosion. Field crops are more exposed to erosion if there is no natural barrier. Trees help regulate temperature and humidity in the agricultural field, protecting plants from temperature extremes. Wood plantations offer protection and can help with natural pest control. Although tree plantations may have less fertile soil than agricultural crops, they bring important benefits by protecting against wind and erosion, creating a more favorable microclimate, supporting biodiversity and even gradually recycling nutrients. These advantages make edging crops with trees a sustainable agricultural strategy.

The hybrid poplar (*Populus deltoides* Bartram ex Marshall × *Populus nigra* L.) has been largely described in the field literature [10-12] for its potential in rapid biomass production, but it also represents a useful option to be included in temperate silvoarable ecosystems due to several important morphological and functional characteristics which contribute both economically and ecologically to the efficient and sustainable exploitation of the agricultural crops. This plant is able to grow on bare soils or on those subjected to flooding waterlogging [13] and is an excellent water manager, being considered an isohydric woody plant [14] because it is able to maintain a relatively constant hydric potential during the drought seasons by stomatal mechanisms activated to avoid water loss and to regulate the evapotranspiration. To reach this goal, for this hybrid species, very important are the water availability and the accessibility to groundwater [15], and also the ability to avoid heat stress, thus gaining high biomass and performing the expected ecophysiological roles in the silvoarable associations. Other important contributions of the *Populus* x *euramericana* (*Populus deltoides* Bartram ex Marshall × *Populus nigra* L.) are provided in ecosystems by its phytoremediation capacity of soils polluted with heavy metals [16, 17], while several studies emphasized the potential of this plant to exhibit soil salt tolerance [18]. The current context of resource scarcity and the alteration of the environmental factors determined new approaches and alternatives of crop growing to better use the local land conditions and to mitigate issues like soil degradation and nutrient loss. Thus, integrating the woody plants in the yield strategies by intercropping or crop bordering was proven to be an efficient choice to mix species to gain reciprocal advantages in expressing their maximal productive potential.

Generally, most of the scientific literature has focused on highlighting the biomass and yield gain or carbon sequestration in the agroforestry systems for the mixed or associated plant species. Most frequently, the studies have addressed aspects regarding the chemical properties of the soil and their dynamics, while studies related to the physical structure of the soil were rare [19, 20]. Even rarer are the studies that address the subject of the vertical, depth-wise distribution of soil physical and chemical properties in agroecosystems. This research aims to contribute to clarifying the vertical distribution of several physical and chemical soil properties across the soil profile in a temperate silvoarable ecosystem established by associating a herbaceous crop species and a woody one, and also to highlight the relationships between the analyzed soil factors. The aim was also to reveal the seasonal variation of soil parameters and to find whether differences exist regarding the soil parameters in the associated plants, in attempting to emphasize the role of the woody plant on the bordered monoculture.

Materials and Methods

Research Site

A silvoarable ecosystem was studied in the western part of Romania (Timis County) (45.45418°N, 20.90334°E). This agricultural system was established by associating two plant species: a rapeseed crop (the hybrid LG Architect of *Brassica napus* L.) and a hybrid poplar plantation (*Populus deltoides* Bartram ex Marshall × *Populus nigra* L.). The rapeseed field was bordered on both sides by a hybrid poplar plantation. One of the hybrid poplar flanks covered an area of 6962 m^2 and had a width of approximately 80 m, while the other spanned 64,807 m^2 and had a width of approximately 190 m. The rapeseed crop area covered 9918 m^2 and had a width of approximately 55 m (Fig. 1).

Fig. 1. The research site (45.45418°N, 20.90334°E) (Google Maps capture).

Research Objectives

The study aimed to assess the evolution of several physical and chemical parameters of soil (Vertisol, World Reference Base for Soil Resources 2022) during two seasonal periods: autumn (November 2022 [21]) and spring (May 2023). Although the general perception is that soil properties, particularly physical structure and organic matter content, change slowly, there are studies showing that freeze–thaw processes can induce both physical (in terms of soil aggregate stability and particle size distribution) and chemical (soil organic carbon, salinity, and others) transformations in the topsoil even within a very short time, after a single natural cycle, or in even shorter periods when certain soil parameters were analyzed under freeze-thaw cycles conducted in laboratory conditions [22]. Thus, the analysis of a 0-40 cm soil layer cultivated with cotton in an agricultural area of China (Xinjiang), within a study aimed at capturing the effects of a single seasonal freeze–thaw cycle (from the end of 2022 to the end of 2023), showed that after just one freeze–thaw cycle, when the distribution of soil aggregates before and after freezing and thawing was analyzed, regardless of the size of soil aggregates, the content of different fractions significantly changed (the proportion increased or decreased).

The analyzed physical soil parameters were: particle size composition (coarse sand (2.0-0.2 mm), fine sand (0.2-0.02 mm), silt (0.02-0.002 mm), colloidal clay (<0.002 mm), physical clay (<0.01 mm)) and bulk density. The analyzed chemical soil parameters were: pH, humus (stable, organic component of the soil that results from the decomposition of plant and animal matter), total nitrogen, plant-available phosphorus, and plant-available potassium. Different soil depths were considered: 0-30 cm in the poplar plantation and 0-10 cm in the rapeseed crop. When different soil depths were chosen for analysis, the following factors were considered: the root systems and the soil disturbance and management associated with the two plants constituting the silvoarable system. Thus, the poplar trees have deep, extensive root systems that can influence soil properties at greater depths. Studying the 0-30 cm layer allows a better understanding of how the trees impact the soil particle size distribution and nutrient distribution across layers. The rapeseed has a shallower root system that mainly interacts with the topsoil (0-10 cm). This is where most nutrient uptake occurs and where physical and chemical changes due to crop management (e.g., fertilization, tillage) are most pronounced. Within the studied silvoarable system, the rapeseed crop was cultivated in conventional tillage and fertilization, making the top 10 cm the most relevant for analysis. The poplar plantation, being a perennial woody system, experienced no soil disturbance in the studied system for 8 years, so a deeper profile (0-30 cm) was selected for analysis. Additionally, the different inputs of organic matter and nutrients in the two plant systems (from fallen leaves and from crop residues, respectively) was also a reason for choosing different soil depths of analysis. By selecting different depths, this study aimed to capture the most relevant soil interactions for each plant sub-system, ensuring a meaningful comparison of how different land uses affect soil properties.

Research Methodology

The physical soil parameters were determined as follows: particle size distribution was established by the gravimetric method according to the Atterberg scale for interpretation [23], and the bulk density was determined through the core method according to the international standard SR ISO 11272:2000. The chemical parameters of the soil were established using the following research standardized methodologies: pH through the potentiometric method in aqueous suspension (soil:water ratio – 1:2.5); determination of humus according to the Walkley wet combustion method [24]; determination of the total N using the Kjeldahl method [25]; determination of plant-available P and plant-available K was performed using the Egner-Riehm-Domingo method [26] and the spectrophotometry. The statistical interpretation of data was performed using the IBM SPSS 28.0.0.0 software.

Soil Sampling

In the poplar, the soil samples were collected from the smaller flank, and the sampling was conducted between rows (Fig. 2). In the rapeseed, the soil was sampled after harvesting (November 2022) and before harvesting (May 2023). The soil sampling points were marked during the initial sampling (autumn), and the subsequent sampling (in spring) was conducted at the same locations. In the poplar, the soil samples were collected only from one flank, and both in the rapeseed and the poplar, the soil samples were collected from three sample points with three repetitions.

Considerations on Selecting Soil Sampling Depth

For this study, the upper soil layers were of interest because studies have shown that the freeze–thaw effect on the soil horizon decreases with increasing depth until the maximum freezing depth is reached [27, 28]. The soil surface tends to exchange material most closely with the atmospheric environment, so the physical and chemical weathering gradually decrease as the depth of the soil horizon increases, and the size and content of soil particles can be used to some extent as indicators of the degree of weathering [28]. The main argument for choosing different soil sampling depths for the two plants was represented by the differences in soil management systems. Also, differences between rapeseed and poplar soils regarding the root system and organic matter inputs determined different sampling depths for analysis. Rapeseed is an annual crop with fine, dense roots concentrated in the surface 0-10 cm of soil. Studies show that the rhizosphere area (roots, along with crop residues, rhizodeposits, and biological community) is the one that contributes to greater aggregate turnover and breakdown, particularly in the topsoil [29]. Poplar, as a perennial woody plant, has a coarser, deeper root system, with a more stable structure, which provides a higher degree of soil consolidation, and studies have shown that it involves a lower interaction with weathering and freeze–thaw factors [30]. In poplar stands, tree canopy and litter cover can buffer soil against strong freeze-thaw dynamics at the surface. The rapeseed crop, being more exposed, experiences greater thermal fluctuations and physical weathering at the soil surface. Based on these arguments, we considered that a 1:3 ratio (10 cm versus 30 cm) is appropriate to highlight the results aimed at the two plant systems. Also, other studies have shown that the contribution of poplar litter helps mitigate the rate at which changes (destructuration) in particle size distribution occur in the first centimeters of the surface soil [31].

In the case of rapeseed, the 0-10 cm soil layer was analyzed because this is directly affected by agricultural practices (plowing, disc harrowing, seedbed preparation). These operations disturb approximately the first 30 cm of soil, therefore, sampling beyond this depth was considered irrelevant, as soil layers are mixed through these practices. Under these conditions, changes

Fig. 2. View of the researched silvoarable ecosystem.

in soil particle size distribution are best represented by analyzing only the 0-10 cm surface horizon. In contrast, in the case of hybrid poplar (a perennial, no-tillage system), the 0-30 cm layer reflects the main zone of root activity and organic matter accumulation, influenced by biological processes and unaffected by mechanical disturbance. Thus, the differentiation of sampling depths was intended both to allow a direct quantitative comparison of particle size values between the two plant systems in homologous horizons and to highlight how soil management and vegetation type (annual cultivation with mechanical practices vs. perennial no-tillage) affect particle size distribution. A 0-10 cm layer in the case of poplar would not be representative, as it would only capture the surface layer covered by litter, without considering that the hybrid poplar has an extensive and deep root system, along with fine roots distributed vertically, especially within the first 20-30 cm of soil. In tree plantations, the near-surface fine roots can strongly influence soil aggregation because of their high biomass and extensive contact area with the soil, and both large and small aggregates were found to be associated with fine-root biomass [32]. A study conducted on six artificial afforestation tree species, including *Populus* L., showed that more than 50% of fine root length is found within the first 40 cm of soil [33]. Other studies that have investigated the physico-chemical characteristics of the soil in woody biocoenoses (coniferous evergreen forest patches and broadleaf deciduous forest patches in urban ecosystems) have sampled the first 0-30 cm of soil [34], while others sampled the 0-20 cm and 20-40 cm soil layers to study the soil texture in agroforestry systems where the woody species was *Terminalia brownie* [35]. However, there are also studies that carried out soil sampling in *Populus* L. plantations only in the 0-10 cm layer [32]. In contrast, for rapeseed it would not have been justified to sample down to 30 cm, because mechanical interventions alter the structure and modify the soil within the first 30 cm, and the effect of mechanical disturbance caused by agricultural practices cannot be compensated by the effect of the roots over the short period between these operations. Other agroforestry studies (agroforestry intercropping systems, agroforestry fallow systems, agroforestry grazing systems) also have monitored only the 0-10 cm soil layer, regardless of the type of plant, whether woody plantation or annual cropland [36, 37].

The choice of these depth intervals was also inspired by other studies that exploit different depth intervals in soil analyses by disseminating the results as averages of these intervals belonging to a single soil profile. For example, Poeplau et al. (2023) [38] provided values for soil organic carbon and clay contents by mass-weighted averaging the values obtained for 2 depths: 0-10 and 10-30 cm.

Also, in one of its reports, IPCC (Intergovernmental Panel on Climate Change) [39, 40] showed that many soil indicators undergo transformations in the upper profile where they are often the most directly exposed to natural and anthropogenic disturbances. Changes in certain chemical soil parameters (for example, soil carbon stocks) are detected below 20-30 cm, although the rooting zones of trees extend considerably deeper than 30 cm. Compared to the conventional practices, the no-till management increases soil carbon in the first 5-10 cm of topsoil [41], which could result in an overestimation of values in surface soil samples in these ecosystems; therefore, it would not have been relevant to remain at the same 0-10 cm sampling depth as for rapeseed. And, for consistency, both physical and chemical indicators at the same depth intervals were measured. The Food and Agriculture Organization of the United Nations (2020) [42] also showed that the 0-10 cm and 10-30 cm soil layers are the most relevant for, for example, the analysis of soil organic carbon and bulk density, while the 0-10 cm layer is the most relevant for the analysis of particulate organic carbon.

In conclusion, the sampling depths were selected according to the specificity of each land use system, in order to capture the most representative pedological layer, as demonstrated by the arguments above in the specialized literature.

Results and Discussion

The physical and chemical parameters of the soil determined for the two component plants of the silvoarable system are shown in Table 1 and Table 2. The soil properties recorded in May 2023 were compared with the previously published [21, 43] soil properties recorded in November 2022 for the same silvoarable ecosystem. Seasonal comparisons of the soil parameters were performed for all soil depths established in the study.

Physical Properties of Soil

Particle Size Distribution

For the soil depth 0-10 cm, a decrease in the content was found for coarse sand both in the poplar soil and in the rapeseed soil in May 2023, as compared with November 2022, by 39.35% in the poplar soil (Fig. 3) and by 51.67% in the rapeseed crop (Fig. 4).

The fine sand content remained unchanged in poplar soil and slightly decreased (by 13.71%) in the rapeseed soil. The silt content was lower in spring than in autumn in the poplar soil, and it was slightly higher (by 5.69%) in the rapeseed soil. In other cases, there was reported an increase in soil silt in the agroforestry systems [44, 45]. These results could be explained by a combination of multiple factors, either natural or agricultural, which determine changes in the soil structure over the seasons. The decrease in the soil coarse sand both in the poplar plantation and in the rapeseed crop after the winter

Table 1. Evolution of the physical soil parameters in the silvoarable ecosystem (autumn versus spring).

Populus spp. (hybrid poplar) plantation (mean values)												
Soil parameter	Coarse sand (2.0-0.2 mm) (%)		Fine sand (0.2-0.02 mm) (%)		Silt (0.02-0.002 mm) (%)		Colloidal clay (<0.002 mm) (%)		Physical clay (<0.1 mm) (%)		Bulk density (g/cm^3)	
Soil depth (cm)	0-10 cm											
Sampling period	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023
Measured value	6.10±2.90	3.70±0.75	41.93±1.77	41.93±9.72	23.93±1.45	23.16±5.08	28.03±2.77	31.20±5.63	41.00±3.67	46.23±8.31	1.470±0.026	1.32±0.10
Soil depth (cm)	10-20 cm											
Sampling period	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023
Measured value	6.36±2.59	3.66±0.11	42.10±1.70	43.40±8.00	23.33±1.92	22.23±3.29	28.20±2.26	30.70±4.77	41.00±3.24	44.76±5.50	-	-
Soil depth (cm)	20-30 cm											
Sampling period	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023
Measured value	6.06±3.09	3.33±0.05	35.06±9.93	42.13±6.93	30.00±10.05	21.76±4.10	28.86±2.82	32.76±2.88	41.93±2.91	47.46±5.74	1.47±0.05	1.54±0.22
Brassica napus (rapeseed) crop (mean values)												
Soil parameter	Coarse sand (2.0-0.2 mm) (%)		Fine sand (0.2-0.02 mm) (%)		Silt (0.02-0.002 mm) (%)		Colloidal clay (<0.002 mm) (%)		Physical clay (<0.1 mm) (%)		Bulk density (g/cm^3)	
Soil depth (cm)	0-10 cm											
Sampling period	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023	November 2022 [26]	May 2023
Measured value	4.20±2.51	2.03±1.01	40.63±5.70	35.06±2.09	25.10±2.98	26.53±0.96	30.06±5.20	36.36±1.91	43.46±6.67	52.50±3.08	-	-

Table 2. Evolution of the chemical soil parameters in the silvoarable ecosystem (autumn versus spring).

Populus spp. (hybrid poplar) plantation (mean values)										
Soil parameter	pH (units)		Humus (%)		Total N (%)		Plant-available P (mg/kg)		Plant-available K (mg/kg)	
Soil depth (cm)	0-10 cm									
Sampling period	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023
Measured value	6.55±0.32	6.36±0.10	2.33±0.54	1.44±0.17	0.14±0.01	0.15±0.02	4.38±2.61	35.45±13.42	125.66±22.50	119.33±47.54
Soil depth (cm)	10-20 cm									
Sampling period	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023
Measured value	6.26±0.18	6.25±0.12	1.76±0.16	1.20±0.05	0.12±0.005	0.12±0.01	4.04±2.51	31.71±15.60	90.66±12.74	77.33±16.92
Soil depth (cm)	20-30 cm									
Sampling period	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023
Measured value	6.27±0.10	6.60±0.15	1.06±0.18	0.65±0.08	0.12±0.005	0.12±0.02	5.65±2.98	37.19±6.29	96.66±5.68	70.66±8.50
Brassica napus (rapeseed) crop (mean values)										
Soil parameter	pH (units)		Humus (%)		Total N (%)		Plant available P (mg/kg)		Plant available K (mg/kg)	
Soil depth (cm)	0-10 cm									
Sampling period	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023	November 2022 [21]	May 2023
Measured value	6.42± 0.24	6.23±0.08	2.07±0.65	2.15±0.29	0.12±0.005	0.19±0.02	18.78±15.61	53.85±17.54	124±15.87	143.66±39.46

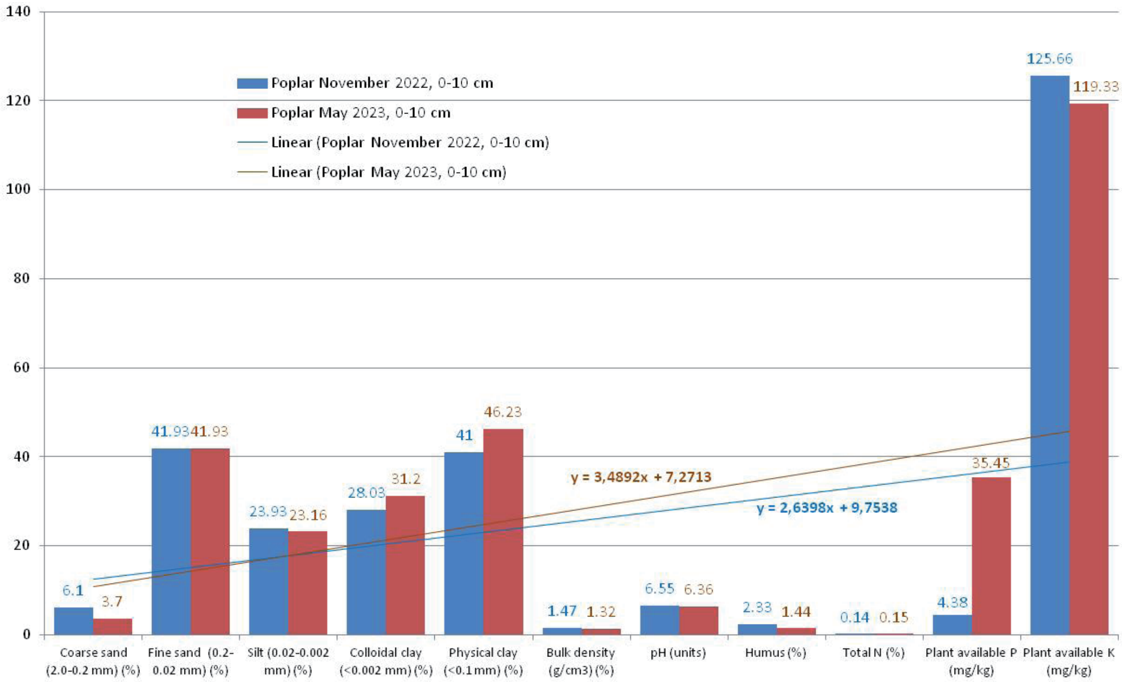

Fig. 3. Seasonal variation of soil physical and chemical parameters in the poplar plantation, 0-10 cm soil depth.

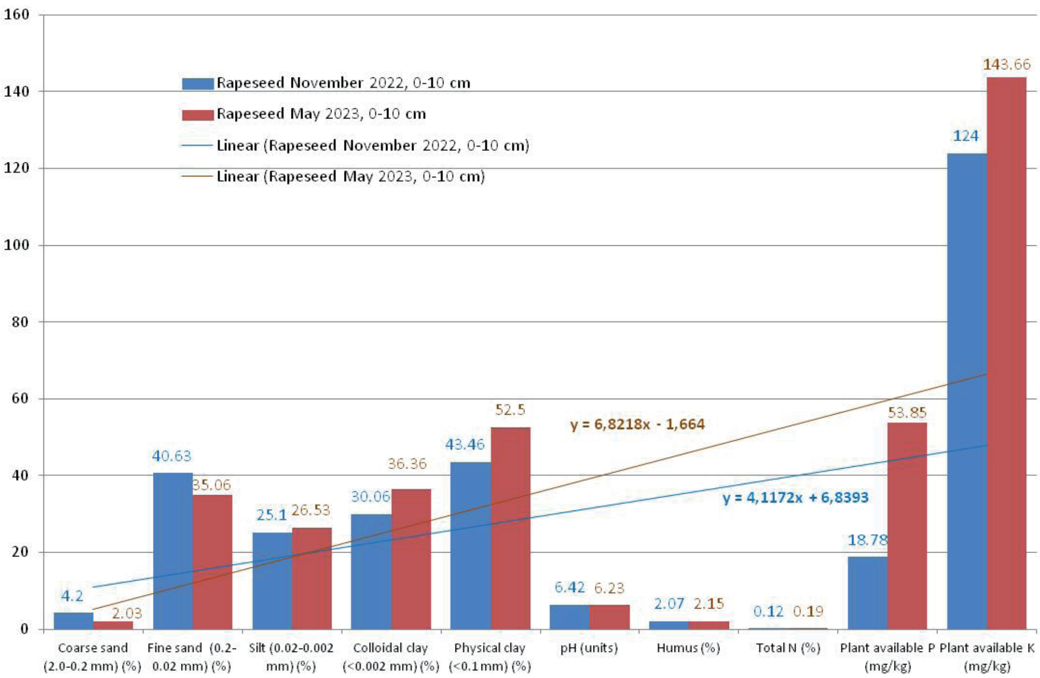

Fig. 4. Seasonal variation of soil physical and chemical parameters in the rapeseed crop, 0-10 cm soil depth.

passed could be the result of the freeze-thaw processes combined with erosion processes and particle transport, because the coarse sand fraction of soil is more susceptible to erosion by runoff than other fractions [46]. The freeze-thaw cycles during the winter may cause differentiated particle migration and redistribution in the soil profile, depending on particle size. Thus, the silt is more easily transported deeper in the soil profile, or even washed out, which may explain why its content has decreased in the poplar soil (Figs 3 and 5), both for the 0-10 cm and 10-20 cm depths, but slightly increased for the depth 20-30 cm (Fig. 6).

The contents of soil clay (colloidal, physical) increased at the 0-10 cm depth of soil in May 2023 as compared to November 2022, after the winter exposure, both in the rapeseed crop and the poplar plantation (Figs 3 and 4). Also, for the same soil depth, the contents of colloidal and physical clay recorded in spring were

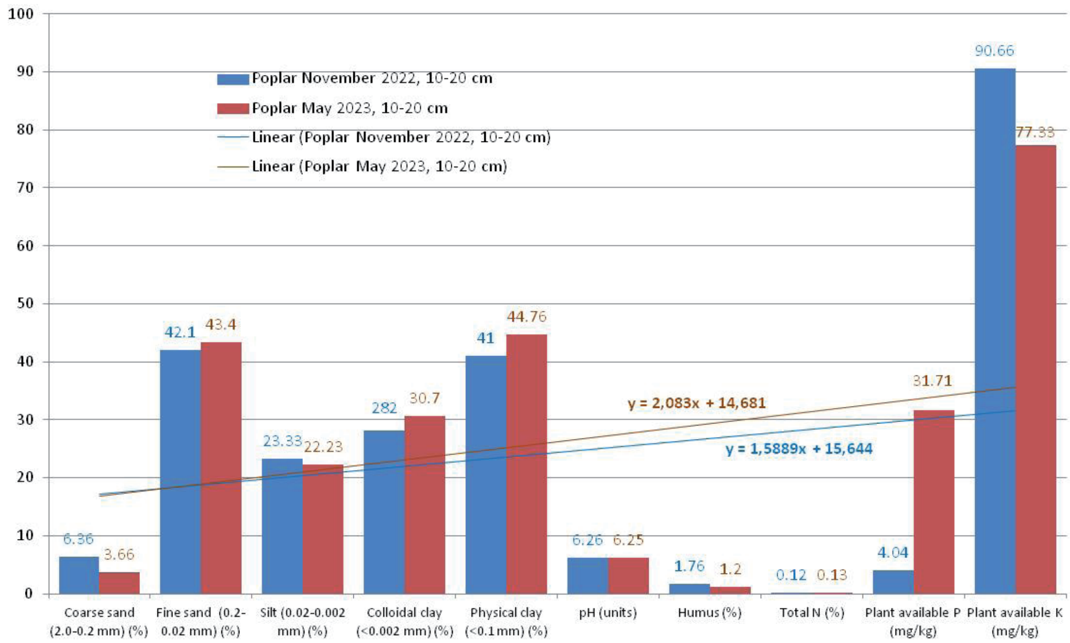

Fig. 5. Seasonal variation of soil physical and chemical parameters in the poplar plantation, 10-20 cm soil depth.

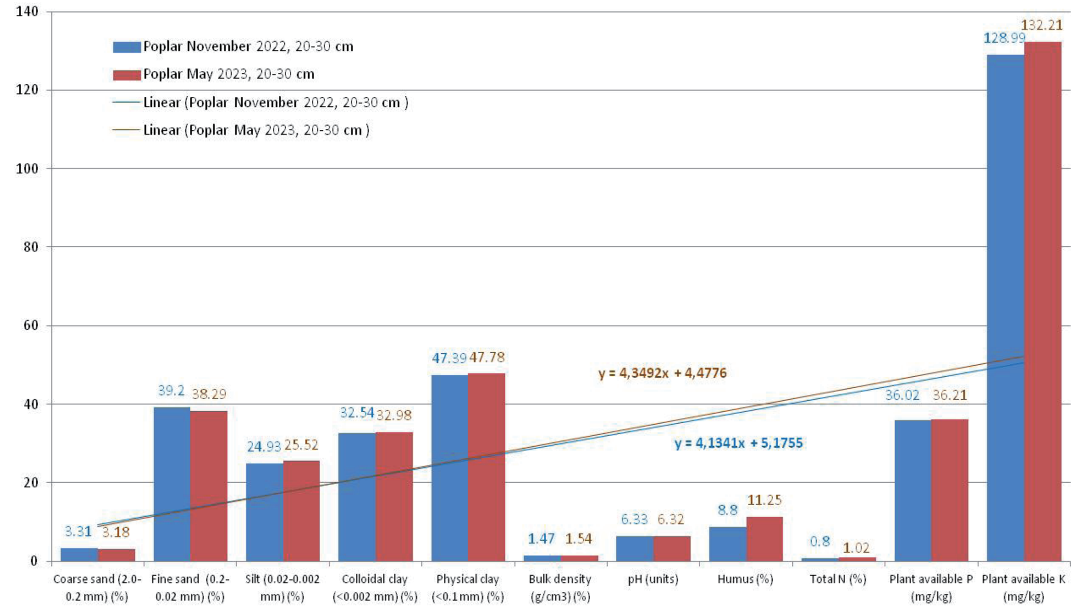

Fig. 6. Seasonal variation of soil physical and chemical parameters in the poplar plantation, 20-30 cm soil depth.

higher in the rapeseed soil than in the poplar soil, by 16.53% and 13.56%, respectively (Fig. 7).

The differences between the autumn values and spring values of colloidal and physical clay in the 0-10 cm soil layer were statistically significant for the rapeseed crop (Table 3).

The increase of the content of clay fractions in the first 10 cm of soil after winter could be possible due to the freeze-thaw cycles during the winter. This explanation is based on certain specific features that characterize Vertisols, mainly related to their texture and clay dynamics, as these soils have a very high clay content, which swells upon wetting and strongly contracts upon drying. During these contraction-expansion movements, soil particles rub against each other, leading to a soil profile with horizons that are difficult to be differentiated, since the material is heavily mixed through "self-mixing" (a process known as pedoturbation). Clay is characterized by fine particles and a large specific surface area, which gives it strong water adsorption capacity, and it contains small, densely distributed pores that make it very susceptible to the phase transitions of water during freeze–thaw processes. Therefore, soils with high clay content are extremely

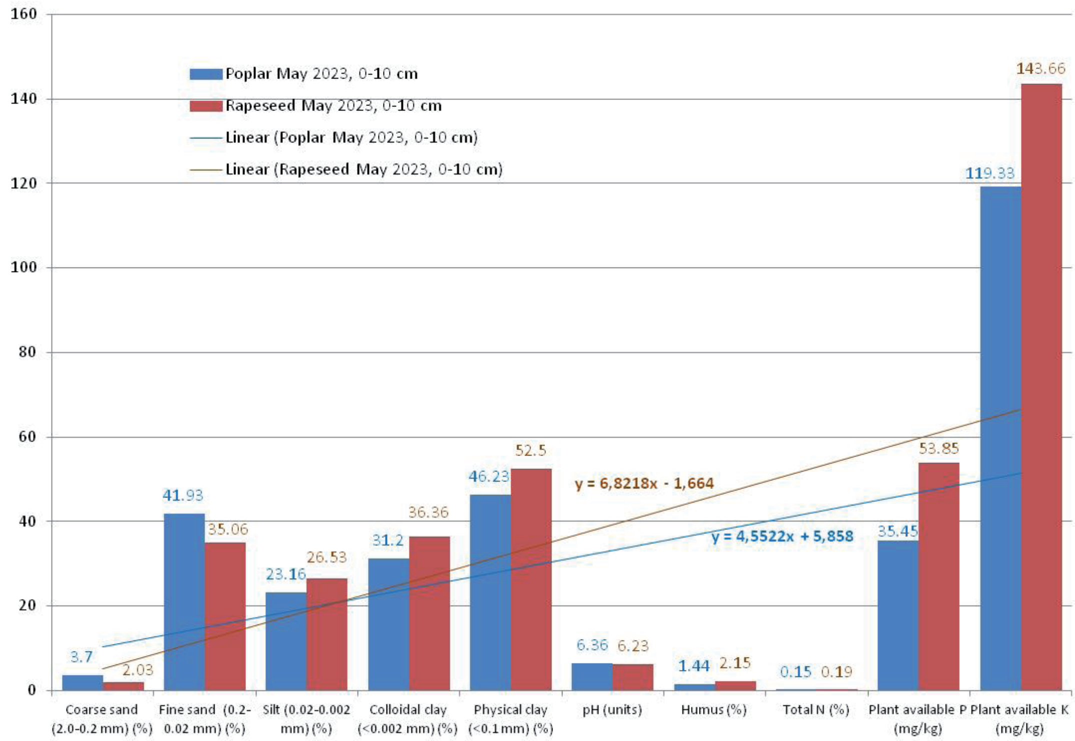

Fig. 7. Comparison of soil physical and chemical parameters (poplar plantation versus rapeseed crop), 0-10 cm soil depth, spring season.

Table 3. Seasonal evolution of soil parameters (Paired Samples t-test) in the silvoarable ecosystem.

No.	Category of soil parameter	Soil parameter	Soil depth (cm)	Seasonal comparison of soil parameters (autumn/spring)	t	df	Significance ($p<0.05$)
1	Physical parameters	Colloidal clay (%)	0-10 cm	Rapeseed November – Rapeseed May	-2.972	2	0.049
			20-30 cm	Poplar November – Poplar May	-8.253	2	0.007
2		Physical clay (%)	0-10 cm	Rapeseed November – Rapeseed May	-3.570	2	0.035
			20-30 cm	Poplar November – Poplar May	-3.183	2	0.043
3		Bulk density (g/cm^3)	0-10 cm	Poplar November – Poplar May	3.279	2	0.041
4	Chemical parameters	pH (units)	20-30 cm	Poplar November – Poplar May	-3.728	2	0.033
5		Humus (%)	0-10 cm	Poplar May – Rapeseed May	-3.019	2	0.047
			10-20 cm	Poplar November – Poplar May	4.494	2	0.023
			20-30 cm	Poplar November – Poplar May	5.707	2	0.015
6		Total N (%)	0-10 cm	Rapeseed November – Rapeseed May	-5.000	2	0.019
7		Plant-available P (mg/kg)	0-10 cm	Poplar November – Poplar May	-4.743	2	0.021
			20-30 cm	Poplar November – Poplar May	-6.389	2	0.012
8		Plant-available K (mg/kg)	20-30 cm	Poplar November – Poplar May	6.433	2	0.012

sensitive to freeze–thaw cycles [47], hence the water content at the moment of freezing-thawing is important, because studies have shown that higher water content reduces soil aggregate stability [48]. The higher clay content measured in our study can increase not because new clay is formed, but because aggregates are broken down and finer fractions are more easily dispersed during particle size distribution. The clay particles tend to form smaller aggregates than sand or silt particles [49]. Another factor explaining the higher content of the clay in the superior soil layer after winter exposure could be the physical fragmentation of the larger soil aggregates [50], a phenomenon more encountered in winter at the soil surface than deeper, which releases finer colloidal and physical clay particles, which are less mobile than other larger soil textural particles and end up accumulating in the upper soil layer. The explanation is largely based on the fact that the loss or reduction of aggregate stability has been proven to occur during freeze–thaw cycles and that it depends on soil type, the initial aggregate size and stability, soil moisture content at freezing [51], the number of freezing and thawing cycles and the freezing temperature [48]. Our study addresses only one freeze–thaw cycle, whereas other studies have investigated several cycles (starting from three) [48], but even after short periods of freeze–thaw cycles conducted under laboratory conditions, effects of decreased aggregate stability have been observed. The effects of a single laboratory-applied freeze–thaw cycle on soil have shown a dispersive action on soil aggregates, increasing the proportion of small and medium aggregates (<0.5 mm). The increase in the number of freeze–thaw cycles applied in the laboratory within the same study resulted in a significant increase in the proportion of soil aggregates <0.5 mm [52]. Other studies have shown that the amount of dispersible clay increased after short freeze–thaw cycles of 12 hours [53]. Dagesse (2011) [53] showed that the destructive effect of freeze–thaw was due to ice crystals that grew in the inter-aggregate pore spaces and their subsequent sublimation, an effect enhanced by the absence of vegetation cover on the soil. He also demonstrated, through a short-term laboratory experiment, that soil aggregate stability measured in spring can reflect the effects of the freeze–thaw process. A study [54] revealed that the mean weight diameter of soil particles of thawed soil was smaller than that measured in the frozen soil. This has also been confirmed in studies conducted very recently [28] for soil particles such as clay and silt. This study showed that freeze-thaw cycles determined the enrichment of soil in silt and clay particles in the soil profile, both fractions increasing with the reduction of size and of the content of sand. Its results were recorded under open-field conditions, but were also confirmed by a short-term laboratory experiment, showing that the freeze-thaw process was always accompanied by the fragmentation and aggregation of soil particles regardless of the freeze-thaw duration, and that the clay content increases alongside with the fractal dimension. The same study revealed that the increase in silt content occurred progressively closer to the soil surface (12 cm) as the number of freeze–thaw cycles increased and that silt increased while sand decreased, showing a reciprocal relationship. The researchers also reported that most sand particles were transformed into silt particles, but also into clay particles during the freeze–thaw process, as a result of freeze–thaw breakdown, which explains the significant reduction in sand content. The same study showed that both fragmentation of the large particles and aggregation of the small particles occur simultaneously during freezing–thawing, which explains why their contents differ compared to the initial state before freeze–thaw. Moreover, the number of freeze–thaw cycles causes fragmentation and aggregation to continue occurring, so that particle size distribution remains dynamic according to a bidirectional pattern [55]. Consequently, the content of small particles (such as clay and silt) does not always increase or decrease after a certain number of freeze–thaw cycles, but rather fluctuates with the cycles, even within the same cycle [28]. Another study showed that the coarse particles of 45-200 μm are broken down after freeze-thaw into particles of <20 μm and, with the increase of freeze-thaw cycles, fine particles of <20 μm aggregate into particles of 45-200 μm [55]. So, the number of freeze–thaw cycles matters, but it does not cancel the phenomenon. Moreover, other studies have also shown that positive and negative temperature changes can act as a catalyst for soil particle movement [56], which can modify the soil particle morphology. Doetterl et al. (2018) [57] showed that secondary minerals in the soil most likely derive from the freeze–thaw weathering of primary minerals. In our study, the rapeseed plot, being more exposed, experiences greater thermal fluctuations and physical weathering, enhancing aggregate breakdown and clay release. Poplar canopies can mitigate temperature variations and reduce the direct effects of freeze–thaw processes on the surface soil, compared to rapeseed fields, which are more exposed and therefore more severely affected. Studies on the changes in erodibility experienced by soil clay fractions as a result of aggregate breakdown through freeze–thaw have shown that even after a single freeze–thaw cycle, resistance to erosion decreases due to the reduction of critical shear stress, variations in the micropores between clay aggregates, interactions between clay minerals and electrolytes, as well as changes in the internal structures of the aggregates [58]. Another indoor laboratory experiment showed that, after controlled freeze–thaw cycles, the proportion of aggregates smaller than 0.25 mm increased with the rising number of freeze–thaw cycles [59]. A 2025 study showed that the frequency of freeze–thaw cycles was negatively correlated with the clay percentage and that these cycles have high sensitivity in determining both the clay content and the proportion of soil aggregates >0.25 mm [60]. As freeze–thaw cycles progress, the soil structure undergoes an increase in the proportion of large pores and the formation of cracks and penetrating voids, which leads to reduced strength [47, 55]. Other studies have shown that, in the short term (from October to June), in freezing regions of China, on orchard-cultivated land compared with uncultivated land, seasonal freeze–thaw exerted severe effects on water-stable aggregates in orchards, which consequently led to a reduction in aggregate stability [61].

Also, as the degree of soil compaction increases, structural changes due to weathering are less likely to occur and tend to take place closer to the surface [28, 55]. A study conducted on this topic showed that the silt and clay contents increased more in the upper part than in the lower part of the soil, indicating an enrichment in the 0.002-0.02 mm particles [28]. Another study showed that after 5 freeze–thaw cycles, more coarse particles of 45-200 μm were broken down into fine particles of <20 μm [55]. This latter finding could explain why, in the poplar-planted soil, where soil management had been no-tillage for 8 years, the increase in clay content after one winter season was only half of that observed in the rapeseed-planted soil. Since rapeseed was subjected to agricultural practices, while the poplar plantation was not, the loosening of the upper soil horizon also led to a higher presence of pores that hold water, which is exposed to freeze–thaw processes. This, combined with the absence of a protective surface layer such as the litter in the poplar plantation, may explain why in rapeseed soil the clay content was higher even before winter, as well as why the increase in clay proportion after the winter season occurred at a higher rate in rapeseed (approximately 20%) compared to the poplar plantation (approximately 12%), for both clay fractions (physical and colloidal). Also, the poplar litter, being woody, decomposes more slowly and stabilizes aggregates, which may limit clay dispersion in the short term. The increase in clay fraction after winter is largely due to freeze–thaw–induced breakdown of soil structure, while the higher values in rapeseed compared to poplar likely reflect greater root-induced disturbance, residue turnover, and surface exposure in cropland, versus the stabilizing effects of tree cover and slower litter decomposition in the poplar plantation. Oztas and Fayetorbay (2003) have found that as the number of freeze-thaw cycles increases, there is a significant change in the distribution of aggregates with different particle sizes. The proportion of >1 mm aggregates significantly decreases, and the proportion of the aggregates with sizes <0.5 mm gradually increased [48]. The phenomenon of soil destructuring through the reduction of particle size after freeze–thaw is particularly important, since studies have demonstrated that wind-driven sediment flux from thawed soil exceeds that from frozen soil, even at identical soil moisture levels [54]. Against the backdrop of the continuously projected global warming, the decrease in the number of soil freezing days, especially when combined with reduced soil moisture, may pose a threat of soil erosion through deflation, and from this perspective, the association of crops with tree plantations may represent

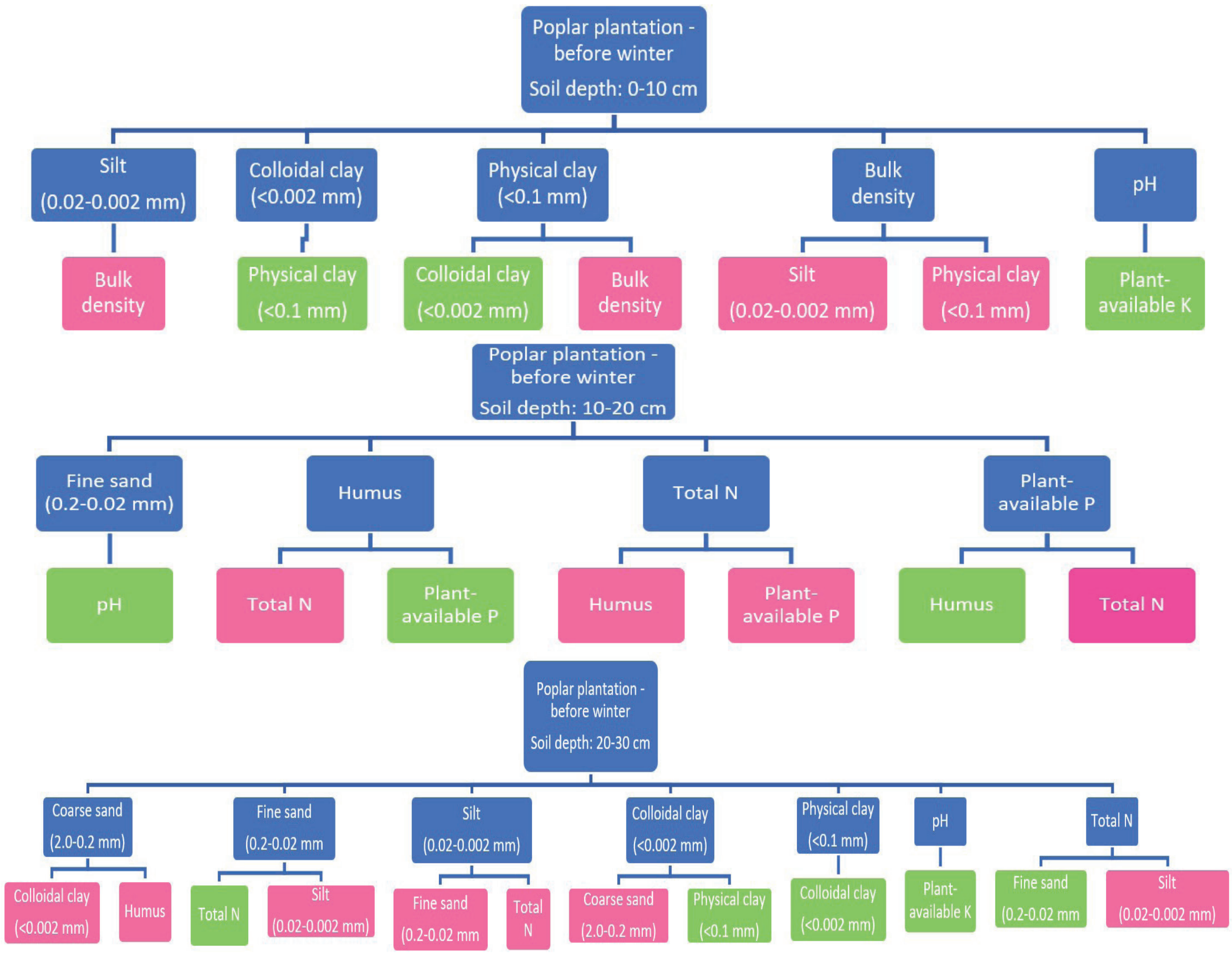

Fig. 8. Significant correlations (Pearson correlation, p<0.5) between soil parameters in the poplar plantation, in autumn (before winter). Red boxes = negative correlations; Green boxes = positive correlations.

an option to counteract this effect.

Higher contents of colloidal and physical clay were recorded in May 2023 as compared to November 2022 for the rest of the studied depths in the poplar soil: 10-20 cm and 20-30 cm (Figs 5 and 6). Although obvious, these seasonal increases were statistically significant only for the depth 20-30 cm (Table 3). The higher content of clay in the deeper soil layers after winter exposure can be attributed to clay leaching by vertical translocation in the soil profile [19, 62], a water-mediated eluviation process that occurs in springtime. Additionally, water migration from the bottom to the upper part is possible during the freeze-thaw process and is facilitated by factors such as self-weight stress (static load stress) and temperature gradient [63]. The vertical migration of water may determine changes in the distribution of the soil particles [64]. Another study [20] showed that the fine particles of soil (clay, silt) could be transported by water erosion, leaving behind the coarser soil particles. Also, the bioturbation activity during the spring may contribute to the redistribution of the clay particles across the soil layers, mediating the clay aggregation in the deeper soil layers [62].

The possibility of particle migration within the soil profile seems plausible also because it was observed that, after winter, the decrease in coarse sand content in the 0-10 cm layer of poplar soil coincided with an increase in silt content in the immediately deeper 10-20 cm layer (Pearson correlation, $p<0.05$) (Figs 8 and 9).

The fact that more statistically significant correlations were found in the poplar plantation soil, both between physical and chemical soil factors, compared to rapeseed soil, may be due to the conventional agricultural practices of the rapeseed crop, which involve disturbing the soil layers. Thus, in Fig. 10, it can be observed that in the rapeseed soil during the autumn season, the fine-sized physical

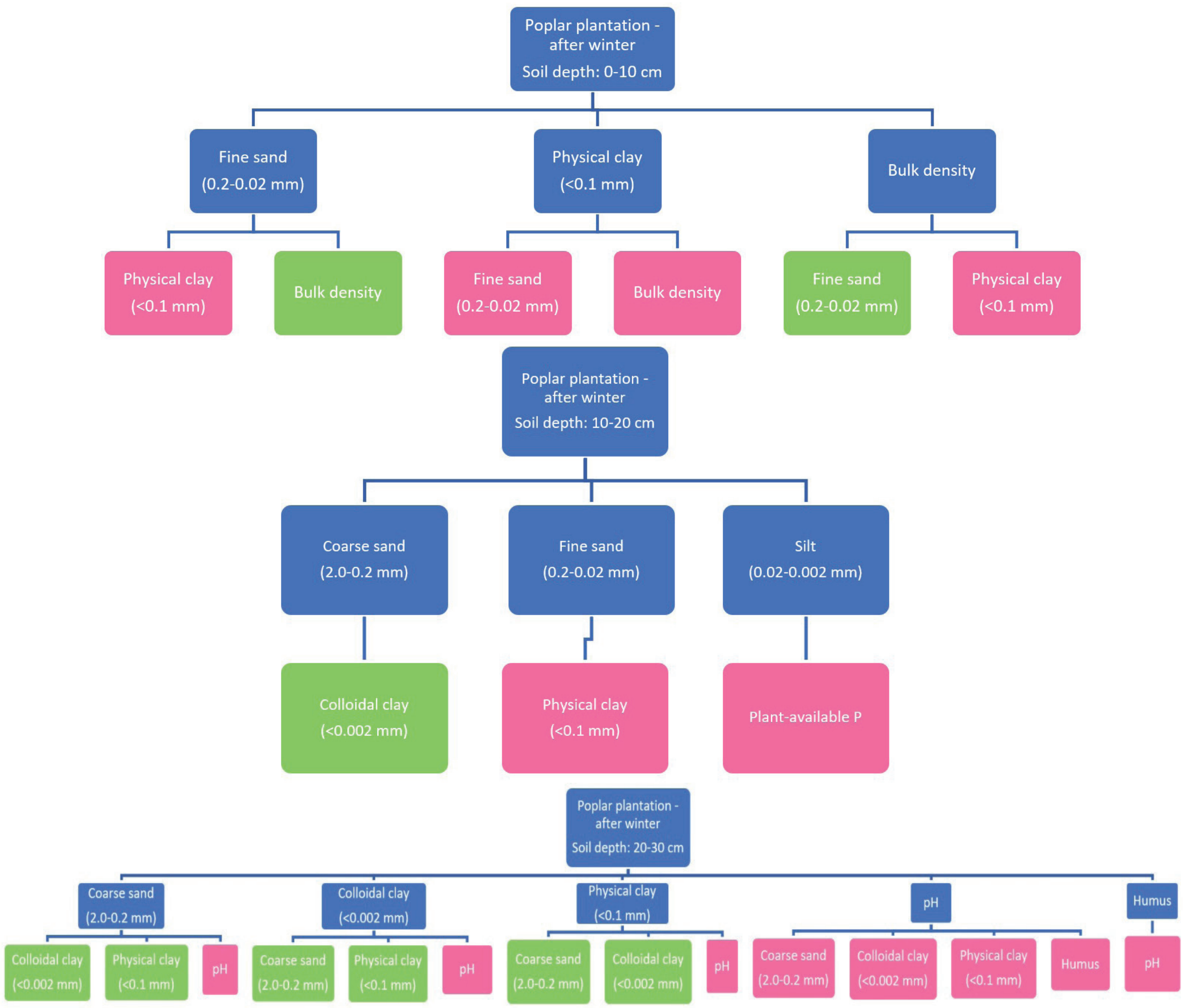

Fig. 9. Significant correlations (Pearson correlation, $p<0.5$) between soil parameters in the poplar plantation, in spring (after winter). Red boxes = negative correlations; Green boxes = positive correlations.

particles are the ones that show statistically significant correlations (fine sand with silt). This relationship may be explained by their presence in the 0-10 cm soil layer as a result of soil aggregate fragmentation caused by agricultural technologies. Additionally, both fine sand and silt showed a relationship with plant-available P, but in different ways. Fine sand correlated negatively with plant-available P, whereas silt correlated positively (Fig. 10).

In rapeseed, after winter, the inverse relationship between coarse sand content at the 0-10 cm soil depth and silt content in the immediately deeper soil layer (10-20 cm) was not maintained (Fig. 11), but a positive correlation was found between the two types of studied clay, indicating that the colloidal clay content increased with the increase in physical clay content (Fig. 4), i.e. similar to the trend observed in poplar soil but before winter (Fig. 3).

These results show that in the upper 10 cm layer of rapeseed soil, the two clay fractions are interdependent, and this relationship was not affected over the winter. In contrast, in poplar soil, a positive correlation between the 2 clay fractions was observed only in autumn in the first 10 cm, but this correlation was no longer present after winter. However, after winter, a change occurred in poplar soil that could explain the decrease in coarse sand content at the surface – namely, in the immediately deeper layer (10-20 cm), the content of colloidal clay correlates positively with the coarse sand content (Fig. 9), the same as it happens for the 20-30 cm depth, where both clay fractions correlate positively with the coarse sand content. These correlations can justify why the decrease in the amount of coarse sand is very small at the 10-20 cm depth compared to the 20-30 cm depth, probably due to the correlation with the colloidal clay (Figs 5 and 6). Thus, based on this last analysis, it can be concluded that clay plays a crucial role not only in the 0-10 cm soil horizon but also in the deeper horizons (10-20 cm and 20-30 cm) after winter, in both poplar and rapeseed soils.

The higher value of the silt content in the 0-10 cm layer of rapeseed soil (5.69%) (Fig. 4), in contrast

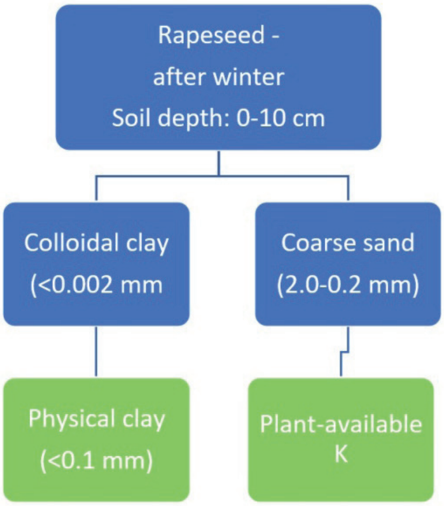

Fig. 11. Significant correlations (Pearson correlation, p<0.5) between soil parameters in the rapeseed crop, in spring (after winter).
Red boxes = negative correlations; Green boxes = positive correlations.

with the decreasing value found in the poplar soil (Fig. 3), could be influenced by other factors such as the plant root factors [65], land use management [66] or microbiological activity at soil level [67]. The rapeseed root system could contribute to the physical stabilization of the fine particles of the soil texture, and the microbiome established around the root system of rapeseed may develop relationships with the organic matter in the upper layers of soil, which can stabilize the silt fraction [68]. This is a microbiological stabilization, but the organic matter can also sustain a physical stabilization of the silt particles of the soil, which is supported by the findings of this study, because a statistically significant difference regarding the content of organic matter (humus) was observed between the poplar soil and rapeseed soil (Table 3) when the spring values were compared in the first 10 cm of the soil profile. Thus, in the first 0-10 cm,

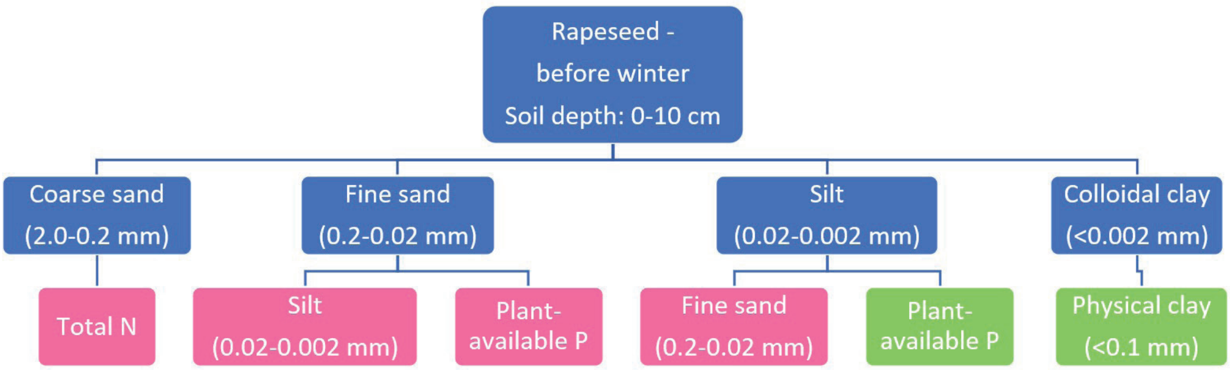

Fig. 10. Significant correlations (Pearson correlation, p<0.5) between soil parameters in the rapeseed crop, in autumn (before winter).
Red boxes = negative correlations; Green boxes = positive correlations.

the humus content of rapeseed soil was 49.30% higher than that of the poplar soil, which may explain why at this depth the silt content was higher in the rapeseed soil than in the poplar soil. This situation was contrary to initial expectations, which were based on the significant contribution of organic residues resulting from leaf fall [69], but it is in line with the results of other studies that showed significantly higher soil pH values in forest plantations than in monocultures [70]. However, positive correlations between soil silt and organic matter in agroforestry systems were previously reported [44] and explained as a result of organic matter increasing the silt content at the expense of soil sand.

The coarse sand content decreased more in the rapeseed soil (51.67%) than in the poplar soil (39.35%) in the 0-10 cm depth of soil, in May 2023, as compared to November 2022. The larger decrease observed in the rapeseed soil may also be influenced by the autumn agricultural practices from the rapeseed crop, which can alter the distribution of soil particle fractions [71].

Soil Bulk Density

The bulk density was determined only for the poplar soil, for 2 depths: 0-10 cm and 20-30 cm (Table 1). There was observed a statistically significant (Table 3) low decrease (10.21%) of the soil bulk density recorded in May 2023 as compared to that recorded in November 2022 for the soil depth 0-10 cm (Fig. 3), and a slight increase (4.76%) of the soil bulk density (Fig. 6) recorded in May 2023 as compared to that recorded in November 2022 for the depth 20-30 cm in the poplar soil. Several factors could explain these seasonal variations. Thus, the spring thawing and the moisture variations at soil level could determine the soil loosening and expansion [72] in the surface soil, which could explain the decrease in the bulk density in the upper (0-10 cm) soil layer, processes that are less significant in the deeper soil. Also, in the springtime, the soil biological activity was intensified, leading to soil loosening. As well, a contribution to the decrease in bulk density in the first 0-10 cm of soil could be brought by the input of organic matter through leaf litter in the poplar plantation. The increase of the bulk density in the 20-30 cm layer of poplar soil could be due to the seasonal hydrological regime [73] at the soil level and also to the natural compaction of the soil through the poplar roots contribution. Only for the 0-10 cm poplar soil were found statistically significant correlations of the bulk density with other physical soil fractions, after winter exposure. Thus, a statistically significant (Pearson correlation, $p<0.05$) positive correlation was found between soil bulk density and soil content of fine sand, respectively, a negative correlation between bulk density and the content of physical clay (Fig. 9). This correlation is further supported by the negative relationship between fine sand and physical clay in the first 10 cm of poplar soil after winter. Thus, the decrease in soil bulk density in spring compared to fall occurred against the background of an increase in physical clay content at this level. It is possible that, due to their small size, fine sand particles form less porous structures in the soil, leading to a higher bulk density in the first 10 cm of poplar soil. Additionally, the fact that the poplar soil has remained uncultivated for the past 8 years may have contributed to this effect. On the other hand, the negative correlation between soil bulk density and physical clay may be attributed to the latter's high capacity to form more stable aggregates in soil through its association with organic matter. These aggregates contribute to a looser soil structure by retaining more water, which is a plausible upper soil effect in an undisturbed ecosystem such as the studied poplar plantation, because this plantation benefits from litter input as a source of organic matter, as well as other factors known to increase soil organic matter content in undisturbed poplar plantations, such as soil microbiology and soil mesofauna factors [74, 75]. A negative relationship between soil bulk density and silt content was also found by Muche and Molla (2024).

Chemical Properties of Soil

In the rapeseed crop, a statistically significant seasonal difference was found for the parameter total N in the 0-10 cm soil layer (Fig. 4, Table 3). Thus, the content of the total N in the rapeseed soil has increased by 58.33% in the first 10 cm in May 2023 versus November 2022. Generally, there were observed higher values of the chemical parameters of soil in the rapeseed soil than in the poplar soil in the spring season (May 2023) (Fig. 7), in contrast to other studies [76]. For example, the content of humus was significantly higher (49.30%) in the first 10 cm of the soil in the rapeseed crop than in the poplar plantation in May 2023 (Fig. 7, Table 3), the total N increased by 26.66% in the rapeseed soil compared with the poplar soil, the plant-available P increased by 51.90%, and plant-available K increased by 20.38%. Lower values of the chemical soil parameters were previously observed in the soil of poplar shelterbelts [77] which border farmlands. This effect of enhancing the potential of the rapeseed crop by combining it with the woody plant (hybrid poplar) is precisely the one pursued by establishing the silvoarable system, in attempting to reach the effectiveness of this type of plant association and the contribution of the woody plant in improving the soil conditions of the herbaceous crop. Excluding the rapeseed fertilization, the higher values of soil parameters in the rapeseed crop compared to the soil of the hybrid poplar plantation can be explained by the different nutrient absorption due to the distinct positioning of the roots of these plants within the soil layers. Also, due to the maintenance workings of soil and agricultural crop, the competition of weeds is eliminated, which means that, in the first years after the planting of poplar plantations, the level of nutrients remains higher in crops than in woody plantations, until the plantation is stabilized, some studies indicate for this a necessary period of up to 10 years [78]. Long-term hybrid poplar plantations are the ones capable of increasing soil pH, SOC, total N and moisture contents compared to those on the cropland [79]. Hybrid poplars grow rapidly and have an extensive root system, which allows them to extract large amounts of nutrients from the soil, particularly nitrogen, phosphorus, and potassium. In the poplar plantation, this constant extraction can reduce the concentration of nutrients compared to the adjacent agricultural land. Additionally, differences in soil coverage are also important [80], as in the poplar plantation, the shade created by the trees and the thick layer of fallen leaves can retain moisture and increase humidity, which favours soil acidification processes (lowering of pH). As well, plants that grow on nutrient-poor soils possess physiological traits that favor nutrient recycling. In the case of phosphorus, the relationships between the traits that influence its recycling appear to be more complex in roots than in leaves. It has been observed that, in general, at the whole-plant level, as the growth rate increases and tissues have a longer lifespan, phosphorus resorption becomes less important for meeting the plant needs. However, roots may be an exception to this rule, as their lifespan does not seem to be influenced in the same way. It has been found that long-lived roots may not be adaptive in soils with very low phosphorus availability; but this may be compensated by the fact that plants recycle significant amounts of phosphorus from senescing tissues, thereby reducing the need to absorb P from the soil [81].

A reason why the soil of the rapeseed crop registered higher values of the nutrient concentrations may result from the silvoarable association: the hybrid poplars consume more nutrients, especially in the first years of vegetation, depleting the soil. This should not be seen as a limitation because, although hybrid poplars consume nutrients from the soil, in the long term, they can recycle nutrients through fallen leaves, gradually contributing to soil fertilization [82]. It has been shown that agroforestry plantations, although they have lower biodiversity compared to natural forests, still share the beneficial contributions of litter, which may be one of the reasons they are associated with agricultural crops. Thus, it has been found that the microclimate and especially the litter provided by agroforestry plantations sometimes explain soil chemical properties better than tree diversity in forests, and the phosphorus content in agroforestry plantations compared to that in cultivated, fertilized areas, could be explained by the return of phosphorus from the litter [83]. The poplar leaves decompose more slowly, slowing down the nutrient recycling. In this study, the poplar plantation was undisturbed or minimally disturbed for 8 years, while the rapeseed crop benefited from fertilizers and had a faster decomposition of organic matter. Other factors have also been found to influence the relationship between trees and soil phosphorus. Under certain conditions, trees are able to maintain high growth rates even in phosphorus-deficient soils, through physiological mechanisms that remain incompletely understood. These mechanisms are believed to have evolved in response to limited phosphorus availability and are associated with enhanced phosphorus uptake and utilization efficiency [84, 85]. Such adaptations include the synthesis of galactolipids as substitutes for phospholipids, reduced genome size, preferential and flexible allocation of phosphorus to leaves, efficient remobilization of phosphorus from senescing leaves and woody tissues, and extended tissue longevity. Additional tree strategies that enhance phosphorus acquisition involve the production of root phosphatases to access organic phosphorus from phosphodiesters and phytate, symbiotic associations with mycorrhizal fungi specialized in phosphorus uptake, secretion of organic anions from roots to mobilize soil-bound phosphorus, increased mass flow, and modifications in root architecture and depth distribution [84]. Woody twigs, branches, and coarse roots can represent substantial phosphorus reservoirs in high-biomass ecosystems such as forests, acting as storage pools that support the growth of new organs following the leafless period in deciduous trees [86]. Root length and lifespan [85] are key adaptive factors for species growing in phosphorus-deficient soils. In the case of the studied poplar plantation, the lower soil nutrient concentrations compared to the rapeseed field may be explained by the greater root length of poplars, which allows them to explore a larger soil volume and provides a greater surface area for phosphorus uptake and storage. A limitation of this mechanism emerges in long-term plantation systems. Studies have shown that once a root has depleted the available phosphorus in its rhizosphere, it no longer has easy or rapid access to new reserves, even if it remains alive [81, 87]. Therefore, unlike an agricultural crop such as rapeseed, which is fertilized and has a shorter plant-soil cycle with plants harvested annually, forest plantations continuously exploit soil resources but without a rapid return of phosphorus to the soil, except possibly through litterfall, which decomposes slowly. However, as agroforestry systems mature, they become more functional, improving nutrient cycling and the soil's water retention capacity. Certain essential soil characteristics tend to stabilize over time [88], so even after many years of use, the introduction of agroforestry systems gradually contributes to the restoration of the soil's chemical and physical properties. This supports the sustainable long-term use of land and shows that the age of the agroforestry system is an important factor in relation to soil parameters [44, 89].

Regarding the seasonal variation of the chemical parameters of soil (Figs 3 and 6), statistically significant differences were observed between the soil content of plant-available P recorded in the poplar soil in May 2023 versus that recorded in November 2022 at the 0-10 cm soil depth (Fig. 3, Table 3). Thus, the content of plant-available P was approximately 8 times higher in May 2023 than in November 2023 in the poplar topsoil (0-10 cm). Another seasonal statistically significant variation was observed for the parameter humus recorded in May 2023 versus that recorded in November 2022 in the poplar soil at the depth 10-20 cm (Fig. 5, Table 3). Thus, the humus content decreased by 31.82% in May 2023 versus November 2022 in the 10-20 cm poplar soil. The content of humus decreased by 38.20% also in the poplar soil in the 0-10 cm layer (Fig. 3) after winter exposure. Since our expectations were that the carbon content in the poplar soil would increase (based on the contribution of litter and that of the no-tillage system, which favor microbiological activity and soil fauna activity, increasing the concentration of organic carbon), this result represented a challenge in finding explanations for its occurrence, especially since in rapeseed there was found a slight increase in the content of soil organic carbon. It seems that the decrease in soil carbon content in poplar-planted soils was also observed during the first (5) years after planting [78] and is associated with high planting density and short rotation cycles ranging from 2 to 8 years, which involve a high rate of organic matter decomposition due to favorable factors such as higher temperature, higher moisture, and increased microbiological activity as a result of litter presence, but at the same time with inefficiency in subsequently capturing carbon in stable organo-mineral complexes [22]. This inefficiency was found to be caused by soil particle disruption during freeze-thaw water phase transitions (volume expansion and contraction), as this process exposes the resulting smaller soil particles to rapid mineralization and carbon loss [22]. Also, after freeze-thaw, the soil stability and soil organic carbon decreased. Vertisols are soils with high clay content that make these soils vulnerable in the superior horizons to physical modifications occurring during the water transition between the liquid or solid state, and even gaseous by sublimation, the soil aggregate disruption being susceptible to occur [47]. Also, the soil salinity could be a factor for clay dispersion and flocculation, and this may lead to loss of soil organic matter and subsequently to loss of soil organic carbon. There is also evidence that soil compaction (to which the analyzed poplar plantation is also susceptible because of the 8-year no-till system and of woody roots) decreases its water infiltration rate and alters its hydraulic properties [51], leading to soil drying in the upper horizon, and these are phenomena associated with soil carbon loss. In the no-tillage management systems of hybrid poplar plantations, especially in long-term ones (15 years, which is rare, because usually the cycles are short to reach the interest of harvesting biomass), the specialized literature reported that lower soil respiration takes place, which leads to lower soil carbon loss [90].

At the 20-30 cm depth, statistically significant seasonal variations were observed in the poplar soil for pH, humus, plant-available P and plant-available K (Fig. 6, Table 3). Thus, in the 20-30 cm poplar soil, the pH slightly decreased in May 2023 versus November 2022, the plant-available P slightly increased, the humus increased by 27.84%, and the plant-available K slightly increased by 2.49%.

The results of our study showed a 50% higher amount of humus (the stable fraction of SOC) in the rapeseed soil compared to poplar, but with a lower pH than in the poplar in the first 10 cm of soil. The pH values were slightly higher under poplar than under rapeseed in both seasons, contrary to other studies that have shown a reduction in soil pH under agroforestry compared to open fields [91].

An inverse relationship between the amount of soil organic matter and pH value has also been reported in other studies. For example, one study found that soil pH showed a strong negative correlation with organic matter when investigating soil physicochemical property variations depending on plant fine-root distribution [34]. Other studies [35] that investigated agroforestry systems where the woody species bordering the cropland was *Terminalia brownii* showed that soil pH did not record significant differences between the tree canopy and open fields. Manjur et al. (2014) [92], studying agroforestry systems in Ethiopia with tree species *Faidherbia albida* and *Croton macrostachyus* scattered on *Zea mays* farmland, found that soil pH tended to rise with increasing distance from the tree base, being lower beneath the canopy and slightly higher in adjacent cultivated open areas. It is not unusual for soils with organic matter content to have lower pH values, because the microbiological decomposition of organic matter releases organic acids (humic, fulvic, acetic, etc.) which donate protons (H^+) to the soil solution, lowering the soil pH. The higher pH level in poplar soil could be related to its increased moisture at this depth, which leads to a higher cation exchange rate, as previously reported [93]. Other processes like chelation and cation (calcium, magnesium, potassium, or sodium) binding by organic matter determine the release of H^+ into the soil solution and this exchange process increases the soil acidity. Organic matter has many carboxyl and phenolic groups that can hold onto cations. The decrease in the humus content in the first 20 cm of the soil and its increase in the 20-30 cm layer, in the poplar plantation soil, after exposure to winter, may be the result of the differentiated phenomena of microbiological and biological activity (bioturbation) [94-96] at the depth of the soil, against the background of the differences in humidity and temperature in deeper layers of soil compared to the surface layer exposed to freezing-thawing phenomena during the winter. These factors may also explain the seasonally significant variations of the soil chemical parameters in the poplar soil, at different depths. Another explanation for the lower pH value observed in the arable soil, despite its higher organic matter content compared to poplar, could be the enhanced microbial respiration and CO_2 release in the rapeseed soil associated with the soil management system that results in greater loosening of the rapeseed soil compared to the poplar soil. Studies have shown that soil aeration is associated with increased microbial activity, which can enhance the amount of CO_2 in soil pores, and its dissolution in soil water may form carbonic acid (H_2CO_3), which lowers pH. Nevertheless, for the present study, we consider that nitrogen fertilization of rapeseed is a more important factor in explaining why the pH was lower in rapeseed cultivation than in poplar, even though the amount of organic matter was found to be higher. Studies have shown that in soils with high organic matter and microbial activity, ammonium (NH_4^+) resulting from its decomposition or fertilizers can be oxidized to nitrate (NO_3^-) through nitrification. This process releases H^+ ions, acidifying the soil. Also, the soils rich in organic matter often retain more moisture, which can enhance the leaching of Ca^{2+}, Mg^{2+}, K^+, and Na^+, leaving behind H^+, Fe^{2+}, Mn^{2+}, and Al^{3+} ions, which lowers pH. Ngaba et al. (2023) [97] showed that soil acidification increased by more than 100% in temperate soils due to agroforestry practices as a result of soil NO_3^- increase and Ca^{2+} leaching, alongside an increase in Fe^{2+} and Al^{3+}. The same study revealed that N mineralization, soil nitrogen content, and dissolved organic nitrogen content are increased, particularly in temperate agroforestry soils compared to tropical or Mediterranean systems. However, the same study also demonstrated that, in agroforestry, trees may reduce soil acidity by decreasing water drainage as well as through deep capture and recycling of nutrients, an aspect which we believe also explains why, in our study, the pH of the poplar-planted soil was slightly higher than that of the rapeseed-cultivated soil. This suggests rather an effect of improved water management mediated by poplar roots than an effect of litter, considering that under poplar, the organic matter (humus) content was lower. However, we consider that the relationship between litter contribution and organic carbon content in the 0-10 cm soil horizon of the poplar plantation is important to elucidate. What was surprising in our study was the fact that the organic matter content was lower in poplar soil than in rapeseed soil, although the expectation was that litter input from the poplar plantation would produce the opposite situation. This is because it can be observed that organic matter content decreased considerably after the winter season, being lower in May than in November across all three studied depths in poplar soil. Wolde and Desalegn (2025), studying the relationship between soil organic matter and litter in agroforestry systems [98], showed that organic matter is added to the soil when litter fall decomposes; therefore, in our study, we consider that the decrease in organic matter content in the poplar plantation during the unfavorable season was also due to the fact that litter input did not occur or was very limited as a result of the winter freeze, which did not favor its decomposition. One possible explanation could be that the 8-year no-tillage system caused much of the organic matter to stay on the surface as litter, not always incorporated into the soil profile, and therefore less mineralization in poplar soil, while better soil aeration in rapeseed and, consequently, higher microbial activity, may have led to a faster nitrogen cycle in rapeseed than in poplar, and thus to greater soil acidification in rapeseed. Current research has further indicated that crop residues (roots, stubble) decompose rapidly in annual systems, producing organic acids and CO_2, both of which lower the soil pH [99]. Annual crops usually have shallow roots and do not recycle base cations from deeper layers, resulting in less buffering against the acidifying effects of organic matter decomposition. In the perennial deep-rooted systems, base cycling from deep roots can help neutralize acidity [97]. Also, the poplar plantation was unfertilized with synthetic N fertilizers and therefore nitrification had less substrate available, which determined less acidification. In addition, the deep-rooted poplars may recycle base cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) from deeper soil layers, buffering its acidity. It could also be relevant, in explaining the results of our study, that annual cropping cycles create pulses of organic inputs that increase the content of organic matter in the annually cropped soil. This could explain why, in rapeseed, after the freeze season, the amount of soil organic carbon slightly increased compared to the value recorded before the unfavorable season (Table 2). In croplands, organic matter inputs are seasonal and decomposition is accelerated by tillage (more aeration, larger porosity), and the transient accumulation of organic matter often coincides with short-term acidification before organic matter is stabilized. This can also explain why the soils with higher organic matter in annual croplands are often the more acidic ones.

A negative correlation was also found between soil silt content and plant-available P in the poplar soil after winter, but at a greater depth, specifically at 10-20 cm (Fig. 9). Positive correlations between soil silt content and phosphorus in the upper 30 cm of soil have also been reported in other studies, which have highlighted the complex interactions between phosphorus fractions and silt. These studies have identified silt as one of the main drivers, along with total soil N content, in determining the availability of phosphorus fractions in soil [100], mainly due to its smaller particle size, which facilitates its binding to organic matter, thereby retaining more phosphorus that can later become available through the influence of other factors, such as pH and clay content. These findings may explain why, in our study, fine silt particles were positively correlated with plant-available P, while as the size of the physical soil particles increased (fine sand), their presence in the soil was negatively correlated with plant-available P content. Our findings support that the size of the physical particles of soil is important in nutrient availability. It was also observed that plant-available P interactions occurring in the top 10 cm of soil are mainly with the physical soil factors (physical particles), whereas at greater depths, it establishes correlations with chemical elements. For instance, in the poplar soil during autumn, at the depth of 10-20 cm, plant-available P was negatively correlated with total N and positively correlated with humus content (Fig. 8), supporting the research of Muche and Molla (2024), who found that P availability in the upper 30 cm of soil is significantly influenced both by the total N and organic matter. Also, after winter, in the poplar soil, the importance of pH was observed in the 20-30 cm soil layer. This chemical factor established negative correlations with coarse sand, clay, and humus at this depth.

Conclusions

The most obvious seasonal changes in soil physical parameters were observed in the 0-10 cm horizon, followed by the 10-20 cm layer, in both rapeseed and poplar soils. After winter, coarse sand increased in the first 10 cm soil layer of both plants, while silt decreased in poplar but increased in rapeseed; both physical and colloidal clay fractions increased in both soils at all studied depths. Bulk density showed seasonal variation in the poplar plantation, decreasing in the 0–10 cm horizon but increasing in the 20-30 cm layer after winter. Soil organic carbon dynamics differed between systems: poplar soil experienced an unexpected decrease after winter, while rapeseed soil showed a slight increase. The humus content was higher in rapeseed, mainly as a result of nutrient cycling, whereas poplar maintained a slightly higher soil pH, explained by root-mediated deep water capture and recycling of nutrients rather than by litter input. Freeze–thaw cycles induced soil aggregate breakdown and clay fraction increase, with stronger effects in rapeseed due to greater surface exposure, mechanical disturbance, and absence of protective litter. Sampling depths (0-10 cm in rapeseed, 0-30 cm in poplar) captured the representative processes in each system, reflecting differences in root activity, litter cover, and soil management.

Overall, higher chemical parameter values were found in rapeseed soil than in poplar soil after winter, underscoring the potential of integrating rapeseed with woody plants such as hybrid poplar within silvoarable systems, where the woody plant (hybrid poplar) contributes to improved soil conditions for the adjacent herbaceous crop (rapeseed). This highlights the effectiveness of silvoarable systems as a sustainable agricultural alternative, where trees contribute to improved soil conditions for adjacent crops.

To verify the validity of the results over time, future studies should focus on long-term monitoring of multiple freeze–thaw cycles to better understand cumulative effects on soil structure, as well as nutrient and organic matter dynamics in agroforestry systems, the role of litter quality, and decomposition rates in shaping nutrient cycling and organic matter stability, the assessment of how root systems (depth, distribution, turnover) mediate soil chemical and physical characteristics in perennial vs. annual components of the agroforestry system and deeper monitoring depths for soil parameters.

Funding

The article publishing charge is supported by the University of Life Sciences "King Mihai I" from Timisoara, Romania.

Conflict of Interest

The authors declare no conflict of interest.

References

1. DASH U., GUPTA B., BHARDWAJ D.R., SHARMA P., KUMAR D., CHAUHAN A., KEPRATE A., DAS J. Tree spacings and nutrient sources effect on turmeric yield, quality, bio-economics and soil fertility in a poplar-based agroforestry system in Indian Himalayas. Agroforestry Systems, **98** (4), 911, **2024**.
2. LIU P., CHENG F., HU J., LI M., WANG X., YOU S., TONG W., CHENG L., ZHANG J., KOU L. Effects of silvopastoral systems on soil nutrient properties in the low hilly area of western Henan province, China. Agricultural and Forest Meteorology, **98** (6), 1343, **2024**.
3. RIVEST D., MARTIN-GUAY M. Nitrogen leaching and soil nutrient supply vary spatially within a temperate tree-based intercropping system. Nutrient Cycling in Agroecosystems, **128** (2), 217, **2024**.
4. JACOBS S., WEBBER H., NIETHER W., GRAHMANN K., LUETTSCHWAGER D., SCHWARTZ C., BREUER L., BELLINGRATH-KIMURA S. Modification of the microclimate and water balance through the integration of trees into temperate cropping systems. Agricultural and Forest Meteorology, **323**, 109065, **2022**.
5. WEI W., LIU T., ZHANG S., SHEN L., WANG X., LI L., ZHU Y., ZHANG W. Root spatial distribution and belowground competition in an apple/ryegrass agroforestry system. Agricultural Systems, **215**, 103869, **2024**.
6. BAKER T., ENGLAND J., BROOKS S., STEWART S., MENDHAM D. Effect of silvopasture, paddock trees and linear agroforestry systems on agricultural productivity: A global quantitative analysis. Agricultural Systems, **224**, 104240, **2025**.
7. THOMAS A., PRIAULT P., PIUTTI S., DALLÉ E., MARRON N. Crown morphology of *Populus deltoides* x *P. nigra* and *Alnus glutinosa* growing in agroforestry and forest mixture plantations. Agroforestry Systems, **97**, 673, **2023**.
8. GAGNE G., LORENZETTI F., COGLIASTRO A., RIVEST D. Soybean performance under moisture limitation in a temperate tree-based intercropping system. Agricultural Systems, **201**, 103460, **2022**.
9. ZHONG L., ZHOU L., ZHOU Y., CHEN Y., SUI P., WANG J., WANG M. Antimicrobial flavonoids from the twigs of *Populus nigra* x *Populus deltoides*. Natural Product Research, **26** (4), 307, **2012**.
10. DOWELL R., GIBBINS D., RHOADS J., PALLARDY S. Biomass production physiology and soil carbon dynamics in short-rotation-grown *Populus deltoides* and *P. deltoides* x *P. nigra* hybrids. Forest Ecology and Management, **257** (1), 134, **2009**.
11. TOILLON J., PRIAULT P., DALLÉ E., BODINEAU G., BASTIEN J., BRIGNOLAS F., MARRON N. Early effects

of two planting densities on growth dynamics and water-use efficiency in *Robinia pseudoacacia* (L.) and *Populus deltoides* (Bartr. ex Marsh.) x *P. nigra* (L.) short rotation plantations. Annals of Forest Science, **78** (3), 73, **2021**.
12. NDIAYE A., PRIAULT P., DALLÉ E., LAFLOTTE A., MARRON N. N_2-fixing species benefit biomass production in agroforestry mixtures depending on spatial scale and plantation age but not in the mixed forestry system. Forest Ecology and Management, **579**, 122508, **2025**.
13. BÉJAOUI Z., ALBOUCHI A., LAMHAMEDI M., ABASSI M., EL AOUNI M. Adaptation and morpho-physiology of three *Populus deltoides* Marsh. x *P-nigra* L. clones after preconditioning to prolonged waterlogging. Agroforestry Systems, **86** (3), 433, **2012**.
14. DAVIDSON K.J., LAMOUR J., ROGERS A., SERBIN S.P. Late-day measurement of excised branches results in uncertainty in the estimation of two stomatal parameters derived from response curves in *Populus deltoides* Bartr. × *Populus nigra* L. Tree Physiology, **42** (7), 1377, **2022**.
15. FONTENLA-RAZZETTO G., WAHREN F., HEILIG D., HEIL B., KOVACS G., FEGER K., JULICH S. Water Use of Hybrid Poplar (*Populus deltoides* Bart. ex Marsh x *P. nigra* L.“AF2“) Growing Across Contrasting Site and Groundwater Conditions in Western Slovakia. Bioenergy Research, **16** (1), 379, **2023**.
16. ZALESNY R., WIESE A., BAUER E., RIEMENSCHNEIDER D. Sapflow of hybrid poplar (*Populus nigra* L. x *P-maximowiczii* A.!Henry ‚NM6‘) during phytoremediation of landfill leachate. Biomass and Bioenergy, **30** (8-9), 784, **2006**.
17. YI L., WU M., YU F., SONG Q., ZHAO Z., LIAO L., TONG J. Enhanced cadmium phytoremediation capacity of poplar is associated with increased biomass and Cd accumulation under nitrogen deposition conditions. Ecotoxicology and Environmental Safety, **246**, 114154, **2022**.
18. GALOVIC V., KEBERT M., POPOVIC B., KOVACEVIC B., VASIC V., JOSEPH M.P., ORLOVIC S., SZABADOS L. Biochemical and gene expression analyses in different poplar clones: The selection tools for afforestation of halomorphic environments. Forests, **12** (5), 636, **2021**.
19. QUÉNARD L., SAMOUËLIAN A., LAROCHE B., CORNU S. Lessivage as a major process of soil formation: A revisitation of existing data. Geoderma, **167**, 135, **2011**.
20. MUCHE K., MOLLA E. Assessing the impacts of soil water conservation activities and slope position on the soil properties of the Gelda Watershed, Northwest Ethiopia. Applied and Environmental Soil Science, **2024**, 6858460, **2024**.
21. MAZĂRE R., IORDACHE M. Characterization of an agroforestry system from west of Romania through sustainability indicators of soil. Scientific Papers-Series A-Agronomy, **66** (1), 765, **2023**.
22. LUO P., ZHAO L., CHEN R., CHEN P., DHITAL Y.P., LI H., WANG D., YANG J., CHEN Y., LIU Q., WANG Z. Leaching salinity and mulching straws during freeze-thaw period enhance post-thawing cotton yield and quality by optimizing soil aggregates stability. Soil & Tillage Research, **250**, 106:506, **2025**.
23. ATTERBERG A. Die rationelle klassifikation der sande und kiese. Chemiker Zeitung, **190529**, 195, **1905** [in German].
24. WALKLEY A. A critical examination of a rapid method for determining organic carbon in soils. Effect of variations in digestion conditions and of inorganic soil constituents. Soil Science, **63**, 251, **1947**.
25. KJELDAHL J. Neue Methode zur Bestimmung des Stickstoffs in organischen Körpern. Zeitschrift für analytische Chemie, **22**, 366, **1883** [In German].
26. EGNER H., RIEHM H., DOMINGO W.R. Studies concerning the chemical analysis of soils as background for soil nutrient assessment. II. Chemical extracting methods to determinate the phosphorous and potassium content of soil. Kungliga Lantubrukshögskolans Annaler, **26**, 199, **1960** [In German].
27. WANG Y., LIU X., LV M., ZHANG Z. Mechanisms and influencing factors of hydrothermal processes in active layer soils on the Qinghai-Tibet Plateau under freeze–thaw action. Catena, **220**(A), 106694, **2023**.
28. XU C., ZHANG Z., ZHANG S., JIN D., YANG C, MELNIKOV A., ZHAI J. Self-weighting of the overlying soil horizon catalyzed by freeze-thaw cycles leads to silt particle enrichment in the soil profile. Catena, **237**, 107815, **2024**.
29. KOJIMA Y., TODA T., HAMAMOTO S., OHTAKE Y., KAMIYA K. Segmentation of Plant Roots and Soil Constituents Through X-Ray Computed Tomography and Image Analysis to Reveal Plant Root Impacts on Soil Structure. Agriculture-Basel, **15** (13), 1437, **2025**.
30. ZHOU M.X., LI Y.B., WANG S.L., XU C.J., GAO T.Y., CUI J.X. Interspecific variation and threshold dynamics of soil separation capacity in shrub root-soil complexes under sequential freeze-thaw cycles and controlled hydrodynamic conditions. Applied Ecology and Environmental Research, **23** (4), 6177, **2025**.
31. WU G.-L., JIA C., HUANG Z., LÓPEZ-VICENTE M., LIU Y. Plant litter crust appear as a promising measure to combat desertification in sandy land ecosystem. Catena, **206**, 105573, **2021**.
32. GE Z., FANG S., CHEN H.Y.H., ZHU R., PENG S., RUAN H. Soil Aggregation and Organic Carbon Dynamics in Poplar Plantations. Forests, **9** (9), 508, **2021**.
33. JIAN S., ZHAO C., FANG S., YU K. The distribution of fine root length density for six artificial afforestation tree species in Loess Plateau of Northwest China. Forest Systems, **24** (1), e003, **2015**.
34. TRAN L.T.N., AN J.Y., CARAYUGAN M.B., HERNANDEZ J.O., RAHMAN S.K.A., YOUN W.B., CARVALHO J.I., JO M.S., HAN S.H., NGUYEN H.-H., PARK B.B. Fine-Root Distribution and Soil Physicochemical Property Variations in Four Contrasting Urban Land-Use Types in South Korea. Plants-Basel, **13** (2), 164 ,**2024**.
35. HANDISO M.A., LEMMA B., ASFAW Z., BROMM T., MELLISSE B.T., GLASER B. Farmers‘ perceptions of *Terminalia brownii* management in agroforestry Parklands and its impact on soil physicochemical properties in the South Ari District, Southern Ethiopia. Agroforestry systems, **99** (2), 35, **2025**.
36. ZOUNGRANA A., CISSÉ M., TRAORÉ M., DE CANNIÈRE C., BATIONO B.A., VISSER M., TRAORÉ S. Influence of agroforestry systems on earthworm diversity and soil properties in a Sudano-Sahelian landscape. Geoderma Regional, **37**, e00786, **2024**.
37. FONKENG E.E., CHEVALLIER T., SAUVADET M., ENOCK S., RAKOTONDRAZAFY N., CHAPUIS-LARDY L., TAKOUTSING B., FRITZ O.T., HARMABD J.-M. Dynamics of soil organic carbon pools following conversion of savannah to cocoa agroforestry systems in the Centre region of Cameroon. Geoderma Regional, **36**, e00758, **2024**.

38. POEPLAU C., DON A. *A simple soil organic carbon level metric beyond the organic carbon-to-clay ratio.* Soil Use and Management, **39** (3), 1057, **2023**.
39. Intergovernmental Panel on Climate Change - 2019 Refinement to the 2006 IPPC Guidelines for National Greenhouse Gas Inventories. Volume 4 – Agriculture, Forestry and Other Land Use, **2019**. Available online: https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html.
40. Intergovernmental Panel on Climate Change - 2019 Refinement to the 2006 IPPC Guidelines for National Greenhouse Gas Inventories. Volume 4 – Agriculture, Forestry and Other Land Use. Chapter 4: Forest land – Corrected on July 2023, **2023**. Available online: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch04_Forest%20Land.pdf.
41. SLESSAREV E., ZELIKOVA J., HAMMAN J., CULLENWARD D., FREEMAN J. Depth matters for soil carbon accounting. CarbonPlan, **2021**. Available online: https://carbonplan.org/research/soil-depth-sampling.
42. FAO - A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes – GSOC-MRV Protocol. Rome, p. 28, **2020**. Available online: https://doi.org/10.4060/cb0509en.
43. IORDACHE M., MAZĂRE R., BORZA I. Using the bulk density and particle size composition of soil as sustainability indicators to characterize a silvoarable ecosystem of Romania. Scientific Papers-Series A-Agronomy, **67** (2), 37, **2024**.
44. KINYILI B., NDUNDA E., KITUR E. Agroforestry stand age influence physical and chemical soil parameters. Trees Forests and People, **18**, 100694, **2024**.
45. DHALIWAL S., NARESH R., WALIA M., GUPTA R., MANDAL A., SINGH R. Long-term effects of intensive rice-wheat and agroforestry based cropping systems on build-up of nutrients and budgets in alluvial soils of Punjab, India. Archives of Agronomy and Soil Science, **66** (3), 330, **2020**.
46. LV M., WANG Y., MA Z., GAO Z., WANG X. Relationship between soil structure and hydrological properties of the active layer in the permafrost region of the Qinghai-Tibet Plateau based on fractal theory. Catena, **247**, 108518, **2024**.
47. LU R., YANG J., WU Y. Study on the Influence of Clay Content on the Freeze–Thaw Characteristics and Mechanisms of Solidified Low-Liquid-Limit Clay. Applied Sciences-Basel, **15** (6), 3005, **2025**.
48. OZTAS T., FAYETORBAY F. Effect of freezing and thawing processes on soil aggregate stability. Catena, **52** (1), 1, **2003**.
49. WHISLER K., ROWE H., DUKES J. Relationships among land use, soil texture, species richness, and soil carbon in Midwestern tallgrass prairie, CRP and crop lands. Agriculture Ecosystems and Environment, **216**, 237, **2016**.
50. ZHAI J., ZHANG Z., MELNIKOV A., ZHANG M., YANG L., JIN D. Experimental Study on the Effect of Freeze-Thaw Cycles on the Mineral Particle Fragmentation and Aggregation with Different Soil Types. Minerals, **11** (9), 913, **2021**.
51. ROY D., JIA X., STEELE D.D., CHU X., LIN Z. Infiltration into Frozen Silty Clay Loam Soil with Different Soil Water Contents in the Red River of the North Basin in the USA. Water, **12** (2), 321, **2020**.
52. ZHANG H., CAO T., GUO Z., WANG Y., HOU X. Response of soft rock and sand compound soil structure to freeze-thaw cycles in Mu Us Sandy Land, China. Frontiers in Environmental Science, **12**, 1405203, **2024**.
53. DAGESSE D. Effect of Freeze-Drying on Soil Aggregate Stability. Soil Science Society of America Journal, **75** (6), 2111, **2011**.
54. WANG L., SHI Z.,H., WU G.L., FANG N.F. Freeze/thaw and soil moisture effects on wind erosion. Geomorphology, **207**, 141, **2014**.
55. SHEN J., WANG Q., CHEN Y., HAN Y., ZHANG X., LIU Y. Evolution process of the microstructure of saline soil with different compaction degrees during freeze-thaw cycles. Engineering Geology, **304**, 106699, **2022**.
56. SUN B., REN F., DING W., ZHANG G., HUANG J., LI J., ZHANG L. Effects of freeze-thaw on soil properties and water erosion. Soil and Water Research, **16** (4), 205, **2021**.
57. DOETTERL S., BERHE A.A., ARNOLD C., BODÉ S., FIENER P., FINKE P., FUCHSLUEGER L., GRIEPENTROG M., HARDEN J.W., NADEU E., SCHNECKER J., SIX J., TRUMBORE S., VAN OOST K., VOGEL C., BOECKX P. Links among warming, carbon and microbial dynamics mediated by soil mineral weathering. Nature Geoscience, **11** (8), 589, **2018**.
58. GUO Y., XIAO J., WEN S., LIN C. Experimental Study on Clay Erodibility Subjected to Freeze-Thaw and Varying Temperature Conditions through Hole Erosion Tests. Journal of Cold Regions Engineering, **39** (3), 04025023, **2025**.
59. LI H., ZHANG X., LI M., HU W., GUO M. Impact of Freeze-Thaw Action to Wind Erosion: An Indoor Simulated Experiment. Land Degradation & Development, **36** (17), 6025, **2025**.
60. WANG Z., LIU X., SUN F., JIANG Q., SHANG H., ZHENG C. Effect of biochar and cyanobacteria crust incorporation on soil wind erosion in arid mining area under freeze-thaw action. Scientific Reports, **15** (1), 16363, **2025**.
61. LIANG Y., DENG X., SONG T., CHEN G., WANG Y., ZHANG Q., LU X. Influences of Seasonal Freezing and Thawing on Soil Water-stable Aggregates in Orchard in High Cold Region, Northeast China. Chinese Geographical Science, **31** (2), 234, **2021**.
62. SAUZET O., CAMMAS C., GILLIOT J., MONTAGNE D. Long-term quantification of the intensity of clay-sized particles transfers due to earthworm bioturbation and eluviation/illuviation in a cultivated Luvisol. Geoderma, **429**, 116251, **2023**.
63. WANG Q., LIU F., ZHONG X., GAO Z., LIANG S., LIANG Y. Dynamic Characteristics and Mechanism of the Saturated Compacted Loess under Freeze-Thaw Cycles. Geofluids, **2021**, 6296578, **2021**.
64. XU G., ZHENG Q., YANG X., YU R., YU Y. Freeze-thaw cycles promote vertical migration of metal oxide nanoparticles in soils. Science of The Total Environment, **795**, 148894, **2021**.
65. KAUSHAL R., KUMAR A., PATRA S., ISLAM S., TOMAR J.M.S., SINGH D.V., MANDAL D., RAJKUMAR MEHTA H., CHATURVEDI O.P., DURAI J. In-situ soil moisture conservation in bamboos for the rehabilitation of degraded lands in the Himalayan foothills. Ecological Engineers, **173**, 106437, **2021**.
66. LUO T., LIU W., XIA D., XIA L., GUO T., MA Y., XU W., HU Y. Effects of land use types on soil erodibility in a small karst watershed in western Hubei. PeerJ, **10**, e14423, **2022**.
67. TIAN C., WU X., BAHETHAN B., YANG X., YANG Q., WANG X. Soil bacterial community characteristics and influencing factors in different types of farmland

shelterbelts in the Alaer reclamation area. Frontiers in Plant Science, **15**, 1488089, **2024**.
68. SIX J., CONANT R., PAUL E., PAUSTIAN K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil, **241** (2): 155, **2002**.
69. SALES E., BARRETO-GARCIA P., MONROE P., PEREIRA M., MARTINS K., DOS SANTOS T., DA SILVA C.F., SANTOS L.D., NUNES M. Do coffee agroforestry systems favor carbon and glomalin input in soil biogenic aggregates? Catena, **249**, 108685, **2025**.
70. CAO X., ZHANG Z., WANG J., DAI H., ZHANG A., XU X. Evaluation of soil quality in different *Bletilla striata* agroforestry systems in Eastern China. Horticulturae, **10** (12), Article 1308, **2024**.
71. PHEFADU K., MUNJONJI L. Assessing the impact of no-tillage duration on soil aggregate size distribution, stability and aggregate associated organic Carbon. Agronomy, **14** (11), 2482, **2024**.
72. LU C., SUGIHARA S., NOMA S., TANAKA H., TAJIMA R., MATSUMOTO S., HIROSE D., ZHANG X., WANG N., BAN T. Phosphorus Dynamics in Managed and Natural Soils: SEM-PLS Analysis of *Vaccinium*, Forest, and Grassland Ecosystems. Plants, **14** (2), 189, **2025**.
73. XUE B., JIANG Y., WANG Q., MA B., LIANG X., HOU Z., LI. F., CUI Y. Quantification of the water exchange in an agroforestry system under the background of film-mulching drip irrigation of farmland. Agricultural Water Management, **290**, 108597, **2023**.
74. SALEHI A., GHORBANZADEH N., KAHNEH E. Earthworm biomass and abundance, soil chemical and physical properties under different poplar plantations in the north of Iran. Journal of Forest Science, **59** (6), 223, **2013**.
75. HEYN N.; JOERGENSEN R.G.; WACHENDORF C. Soil organic C and N stocks in the first rotation of poplar plantations in Germany. Geoderma Regional, **16**, e00211, **2019**.
76. CHAUDHARY V., GHALEY B. Insights into beneficial effects of an agroforestry system on soil properties and crop yields: A case study from the experimental farm at University of Copenhagen, Denmark. Sustainability, **17** (4), **2025**.
77. ZHU M., CHENG G., ZHANG X., GUO Y., WU Y., WANG Q., WANG H., WANG W. Shelterbelts increased soil inorganic carbon but decreased nitrate nitrogen, total phosphorus, and bulk density relative to neighbor farmlands depending on tree growth, geoclimate, and soil microbes in the Northeast China Plain. Catena, **231**, 107344, **2023**.
78. ANTONIELLA G., KUMAR A., CHIARABAGLIO P.M., MUGNOZZA G.S., CHITI T. Do poplar plantations enhance organic carbon stocks in arable soils? A comprehensive study from Northern Italy. Journal of Environmental Management, **370**, 122882, **2024**.
79. ZHENG J., CHEN J., PAN G., WANG G., LIU X., ZHANG X., LI L., BIAN R., CHENG K., ZHENG J. A long-term hybrid poplar plantation on cropland reduces soil organic carbon mineralization and shifts microbial community abundance and composition. Applied Soil Ecology, **111**, 94, **2017**.
80. PILON L., AMBUS J., BLUME E., JACQUES R., REICHERT J. Integrated analysis of agroecosystems with citrus orchards in organic, agroforestry, and conventional systems. Agroecology and Sustainable Food Systems, **50** (1), 46, **2025**.
81. VENEKLAAS E. Phosphorus resorption and tissue longevity of roots and leaves - importance for phosphorus use efficiency and ecosystem phosphorus cycles. Plant and Soil, **476** (1-2), 627, **2022**.
82. ERICSSON T. Nutrient cycling in energy forest plantations. Biomass and Bioenergy, **6** (1-2), 115, **1994**.
83. MARTIN A., MUON R., LY N., JOUQUET P. Examining the key roles of reforestation and termite mounds on soil properties and biodiversity in an agroforestry system in Cambodia. Agroforestry Systems, **99** (5), **2025**.
84. AOYAGI R., KITAYAMA K., TURNER B. How do tropical tree species maintain high growth rates on low-phosphorus soils? Plant and Soil, **480** (1-2), 31, **2022**.
85. WEEMSTRA M., KIORAPOSTOLOU N., VAN RUIJVEN J., MOMMER L., DE VRIES J., STERCK F. The role of fine-root mass, specific root length and life span in tree performance: A whole-tree exploration. Functional Ecology,: **34** (3), 575, **2020**.
86. ACHAT D., POUSSE N., NICOLAS M., AUGUSTO L. Nutrient remobilization in tree foliage as affected by soil nutrients and leaf life span. Ecological Monographs, **88** (3), 408, **2018**.
87. WEN Z., WHITE P., SHEN J., LAMBERS H. Linking root exudation to belowground economic traits for resource acquisition. New Phytologist, **233** (4), 1620, **2020**.
88. DE SOUZA F., OLIVEIRA J., DOS SANTOS C., FERREIRA E., DA SILVA R., DE PAULA M., ALVES J.D.N., DE OLIVEIRA J.S.R., RODRIGUES J.I.D., MARTINS W. Physical and chemical soil quality and litter stock in agroforestry systems in the Eastern Amazonia. Agriculture Ecosystems and Environment, **382**, **2025**.
89. HANKE D., NASCIMENTO S., DICK D., VIEIRA R., DEBLE L. Variables related to soil fertility in successional agroforestry systems: Serras do Sudeste, RS, Brazil. Agroforestry Systems, **98** (7), 2547, **2024**.
90. GONG J., GE Z., AN R., DUAN Q., YOU X., HUANG Y. Soil respiration in poplar plantations in northern China at different forest ages. Plant and Soil, **360** (1-2), 109, **2012**.
91. BHATIA A.K., PANT K.S., PRAKASH P., KUMAR P., SHARMA H., SAAKSHI, PRAKASH, KUMARI B. Fruit and pulse synergy: evaluating *Vigna mungo* performance in Himalayan wild pomegranate based agroforestry systems. Agroforestry Systems, **99** (2), **2025**.
92. MANJUR B., ABEBE T., ABDULKADIR A. Effects of scattered *F. albida* (Del) and *C. macrostachyus* (Lam) tree species on key soil physicochemical properties and grain yield of maize (*Zea mays*): a case study at Umbulo Wacho watershed, southern Ethiopia. Wudpecker Journal of Agricultural Research, **3** (3), 63, **2014**.
93. DOS RAMOS A., DE LIMA S., FERREIRA C., PINTO L., FERREIRA R., DIAS A., MATOS P.S., PEREIRA M.G. Macrofauna and soil properties in agroforestry system and secondary forest. Revista Brasileira de Ciencia do Solo, **49**, **2025**.
94. IORDACHE M. Abundance of earthworms under fertilization with organo-mineral fertilizers in a chernozem from west of Romania. Journal of Food, Agriculture and Environment, **10** (3-4), 1103, **2012**.
95. PHILLIPS H., GUERRA C., BARTZ M., BRIONES J., BROWN G., CROWTHER T., EISENHAUER N. Global distribution of earthworm diversity. Science, **369** (6464), 480, **2020**.

96. IORDACHE M. Chemical composition of earthworm casts as a tool in understanding the earthworm contribution to ecosystem sustainability-a review. Plant Soil and Environment, **69** (6), 247, **2023**.
97. NGABA M.J.Y., MGELWA A.S., GURMESA G.A., UWIRAGIYE Y., ZHU F., QIU Q., FANG Y., HU B., RENNENBERG H. Meta-analysis unveils differential effects of agroforestry on soil properties in different zonobiomes. Plant and Soil, **496** (1-2), 589, **2023**.
98. WOLDE A., DESALEGN S. Impact of nitrogen-fixing trees in agroforestry on soil physicochemical properties and crop productivity in Ethiopia: a systematic review. Archives of Agronomy and Soil Science, **71** (1), 1, **2025**.
99. ZONG M., ABALOS D., CHEN J., LIANG Z., LI Y., ELSGAARD L., POEPLAU C., SCHIEDUNG M., JORGENSEN U. Ten-year effects of perennial cropping systems on soil organic carbon stock and stability in sandy soils: Mechanisms and biochemical drivers. European Journal of Agronomy, **168**, 127639, **2025**.
100. LU J., ZHANG M., ZHANG X., PEI W., BI J. Experimental study on the freezing-thawing deformation of a silty clay. Cold Regions Science and Technology, **151**, 19, **2018**.