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Effect of pine afforestation on soil physicochemical properties compared to pasture land: A case study in Kosovo

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Abstract: This study investigates the long-term effects of pine (*Pinus nigra*) afforestation on soil characteristics in comparison to adjacent pastureland in central Kosovo. Soil samples (n = 24) were collected from two land-use types, pine plantations and grassland, over three topographic positions (lower, medium, upper) and two depths (0–10 cm and 10–20 cm). Standard laboratory techniques were used to determine soil organic matter (SOM), organic carbon (SOC), total nitrogen (TN), pH (H_2O and $CaCl_2$), available phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and bulk density (*BD*). The data were analysed using principal component analysis (PCA) and correlation matrices. The top soils (0–10 cm) beneath pine had higher soil organic matter (mean 2.45%) compared to the pasture lane (1.59%). The SOC and TN levels increased by 43% and 36%, respectively. Soil pH was lower under pine (mean pH_H_2O = 6.3) than under pasture land (pH_H_2O = 6.81), particularly on middle and lower slopes. Exchangeable calcium and magnesium declined by up to 20% under pine plantations, and bulk density also decreased (for example, 1.15 $g \cdot cm^{-3}$ under pine land compared to 1.29 $g \cdot cm^{-3}$ under pasture land), signifying reduced compaction. Phosphorus concentrations were slightly higher under pasture at a depth of 0–10 cm (mean 12.4 $mg \cdot 100\ g^{-1}$), but under pine, they increased at a depth of 10–20 cm on top slopes. PCA showed differentiation based on land use, with the initial two components representing 70.1% of the overall variance.

Keywords: bulk density dynamics; land use change; soil acidification; soil carbon sequestration

Soils constitute intricate ecosystems that serve as habitats for almost fifty percent of the Earth's biodiversity (Anthony et al. 2023). Approximately 75% of Earth's surface area has been altered into ecosystems affected by human activity (Luyssaert et al. 2014). Afforestation of previously cultivated, abandoned, or degraded agricultural land is a crucial land management approach for improving carbon (C) accumulation and supporting biodiversity (Post, Kwon 2000; Survila et al. 2022). Numerous studies have shown that long-term afforestation increases the total carbon (C) in the ecosystem (Paul et al. 2002; Nave et al. 2013; Bárcena et al. 2014). Paul et al. (2002) observed that afforestation considerably affects soil carbon stores, with variations depending on tree type and

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environmental conditions. Berthrong et al. (2009) also noted that the conversion of grasslands to forests typically enhances soil carbon while simultaneously modifying pH and exchangeable base cations. Hiltbrunner et al. (2013) observed minor alterations in soil carbon stocks following conifer afforestation, alongside significant shifts in carbon dynamics attributed to increased litter accumulation. A meta-analysis by Don et al. (2011) supports that alterations in tropical and subtropical land use, particularly the conversion of grassland to forest, frequently result in significant enhancements in soil organic carbon and associated soil quality metrics. This rise is mostly attributed to the expansion of aboveground biomass and the gradual accumulation of soil organic carbon over time. These modifications highlight the significance of afforestation as an effective strategy for augmenting carbon sequestration and promoting overall ecosystem functionality (Jandl et al. 2007; Pan et al. 2013).

Land-use type, organic input quantity and quality, and the decomposition rate of the materials that create soil organic carbon (SOC) determine the SOC in a given soil. Plant communities provide litter and roots, while microbes act on these materials to create organic matter (OM) in forms of SOC, which are protected and stabilised within soil aggregates (Bresilla et al. 2023). When land uses change, the amount of organic residues being added will change, as well as the amount of biological activity that processes those organic residues into SOC, ultimately impacting how SOC changes over time. SOC decline causes a decrease in aggregate stability, increasing the susceptibility of soils to degrading and eroding structurally (Spain et al. 1983). Declines in organic content can also increase *BD*, creating fewer pores and less total pore volume and thus limiting water infiltration into the soil (Haghighi et al. 2010). Ultimately, land-use conversion results in changes to the organic carbon pool and many associated hydraulic properties and *BD*, impacting how the soil physically works and the soil's ability to support vegetation. This research examines the long-term effects of over 55 years of afforestation with pine trees compared to pasture land use on soil physicochemical properties, particularly in the topsoil (0–10 cm) and subsoil layers (10–20 cm). The purpose of this research is to assess the effect of pine cultivation on important soil properties by comparing long-term pine forest stands to adjacent non-forest, pasture reference sites. The research directly assesses changes in soil nutrient status, organic carbon sequestration, acidity, and additional physicochemical properties to determine the overall impact of afforestation with pine on soil function and quality. The findings contribute to advancing knowledge of the ecological impacts of pine-dominated landscapes and provide valuable information for forest management and soil conservation strategies.

MATERIAL AND METHODS

Study area. This study was conducted in the Malisheva Municipality, in Llazica village, and Drenasi Municipality, Krivova village, both locations being situated on a slope in the central part of Kosovo (Figure 1). Due to the influence of various soil formation factors and the diverse geographic areas of the Dukagjini Plain, the soils in Malisheva and Drenasi Municipality, both in agricultural and non-agricultural lands, exhibit significant diversity.

According to Schad et al. (2015) classification system, both locations of the study areas were identified as Luvisols across all sampling points.

The study focused on two different land uses: planted pine forest (42°33'35.49"N, 20°46'42.22"E in Llazica and 42°38'55.25"N, 20°58'40.31"E in Krivova) and pasture land use (42°33'36.79"N, 20°46'40.70"E in Llazica and 42°35'53.23"N, 20°58'35.15"E in Krivova).

Over 55 years ago, in certain regions of Kosovo, the state organisation implemented afforestation on designated state-owned sloped terrain. The primary objective of planting pine trees (*Pinus nigra*) in Kosovo throughout the 1960s and 1970s, particularly in regions characterised by steep topography and unproductive soil, was to enhance ecological conditions and mitigate soil erosion. This was a component of a comprehensive afforestation project executed in numerous parts of Kosovo.

According to L. Hyseni (personal communication, 2025), the majority of the planting materials in Kosovo came from the state-run forest nursery at Istog, Forest Institute, which currently operates under the Forest Agency, Ministry of Agriculture, Forestry, and Rural Development. This nursery was usually responsible for producing seedlings. Typically, bare-root seedlings that were one to two years old were used for afforestation; later on, container seedlings were also used on occasion.

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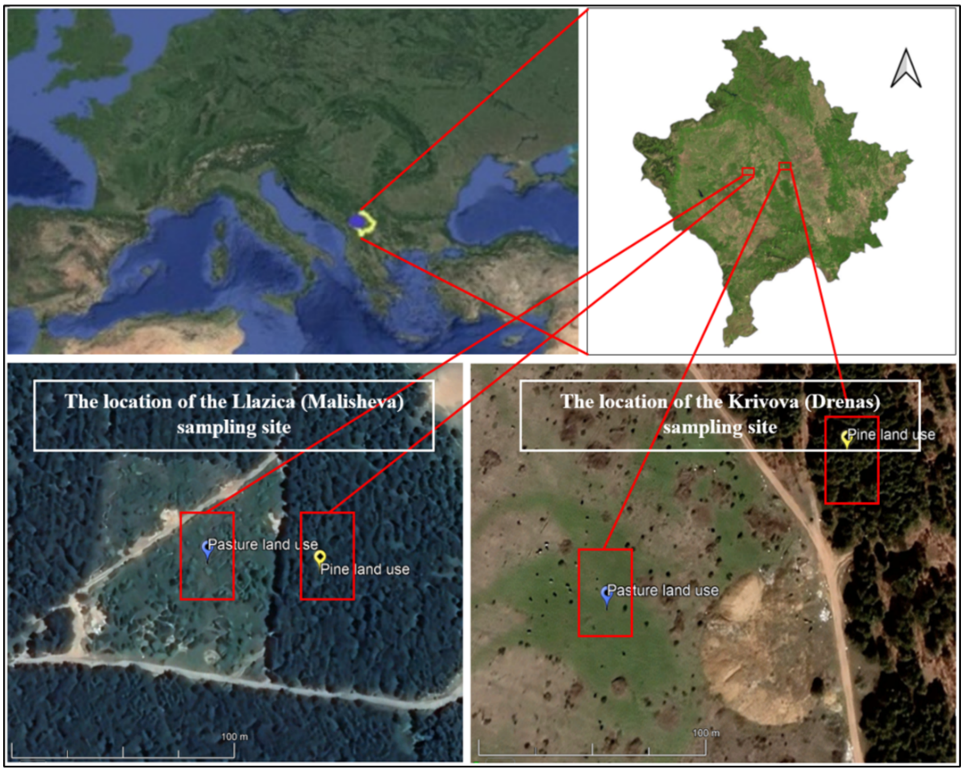

Figure 1. Location of the sampling sites

Depending on site conditions and management goals, the typical planting density during this time was between 2 000 and 3 500 seedlings per ha. Stand tending activities followed the then-standard silvicultural procedures, which included early cleanings in the first five to ten years and moderately intense pre-commercial thinnings at intervals of about eight to twelve years.

According to the Hydrometeorological Institute of Kosovo, the nation's climate is primarily continental. The climate of the study region is defined by warm to hot summers and cold winters, with an annual precipitation of approximately 700 mm. Additionally, air temperatures exhibit an average yearly temperature of 10.8 °C, with fluctuations ranging from –11.8 °C in winter to +37.6 °C in summer (KEPA 2020; Regional Development Agency – West 2022).

Soil sampling. This study involved the collection of soil samples from both planted pine forest and pasture land uses, with both locations situated on the same slope. Soil samples were collected from two depths (0–10 cm and 10–20 cm) in a total of twenty-four samples. Twelve samples were composite samples, created from subsamples collected from many different locations to make a representative sample. The other twelve samples were core samples, collected in an undisturbed manner using metal cylinders.

There were standard protocols used for field sampling, while all tools, containers and cylinders had been appropriately cleaned and calibrated prior to their utilisation (quality assurance – QA). The soil samples were dried at room temperature, crushed, homogenised, and sifted with a 2-mm sieve (Tan 1995).

Soil physical and chemical analyses. To ensure the precision and reproducibility of the analytical results, standard quality assurance (QA) and quality control (QC) practices were implemented during sampling and laboratory analysis.

The chemical analyses included soil reaction (pH-H_2O and $CaCl_2$) according to ISO 10390:2005 (Soil quality – Determination of pH), soil organic matter using the 'Walkley-Black' method (FAO 2019), soil organic carbon and total nitrogen; available phosphorus was measured following Olsen (1982), whereas potassium, calcium, and magnesium were measured according to Mehlich (1984). Soil bulk density was determined with Kopecky metallic rings on over-dried samples, following the protocol established by Blake and Hartge (1986), reported in $g \cdot cm^{-3}$.

https://doi.org/10.17221/73/2025-JFS

Statistical analyses. PCA was carried out on *Z*-score standardised soil data, including *BD*, pH, P, Ca, K, Mg, TN, SOC, and SOM. Analyses were conducted using R (Version 4.3.2, 2023), employing the 'prcomp()' function. Visualisation was performed using 'ggbiplot' and 'factoextra', with 95% confidence ellipses around land-use groups to illustrate multivariate clustering. The first two PCs were interpreted based on variable loadings and eigenvalues explaining variance.

RESULTS AND DISCUSSION

Effects of afforestation on soil physicochemical properties. Our results (Figure 2) indicate that, in general, pine plantations have higher levels of soil organic matter, soil organic carbon, and total nitrogen, particularly in the 0–10 cm layer, than pastureland. This is consistent with paired-site studies from South Africa, which documented changes in carbon and nitrogen stocks with afforestation of sub-humid grassland with *Pinus* spp. that was dependent on their drainage class and species; for example, *P. patula* in well-drained soils during paired-site studies resulted in slight increases in soil organic carbon (Lebenya et al. 2018). The accumulation of soil organic carbon under pine in the upper slope positions is likely attributed to higher litter inputs, reduced surface disturbances, and improved drainage before degradation, among other factors, which all allow for a buildup of stable organic matter on the surface soil. Long-term studies from temperate Europe that compare pine forests support these trends, with generally higher soil organic carbon in the organic layer for pine, but often lower soil organic carbon in the mineral layer, and conditions were most pronounced at sandy or weakly developed soils (Ražauskaitė et al. 2020). Our results showed that the 0–10 cm layer at most pine plantation sites had higher concentrations of soil organic matter and total nitrogen than the pasture, particularly at middle and upper positions on the landscape, which is suggestive of successful stabilisation of organic matter in the surface horizons.

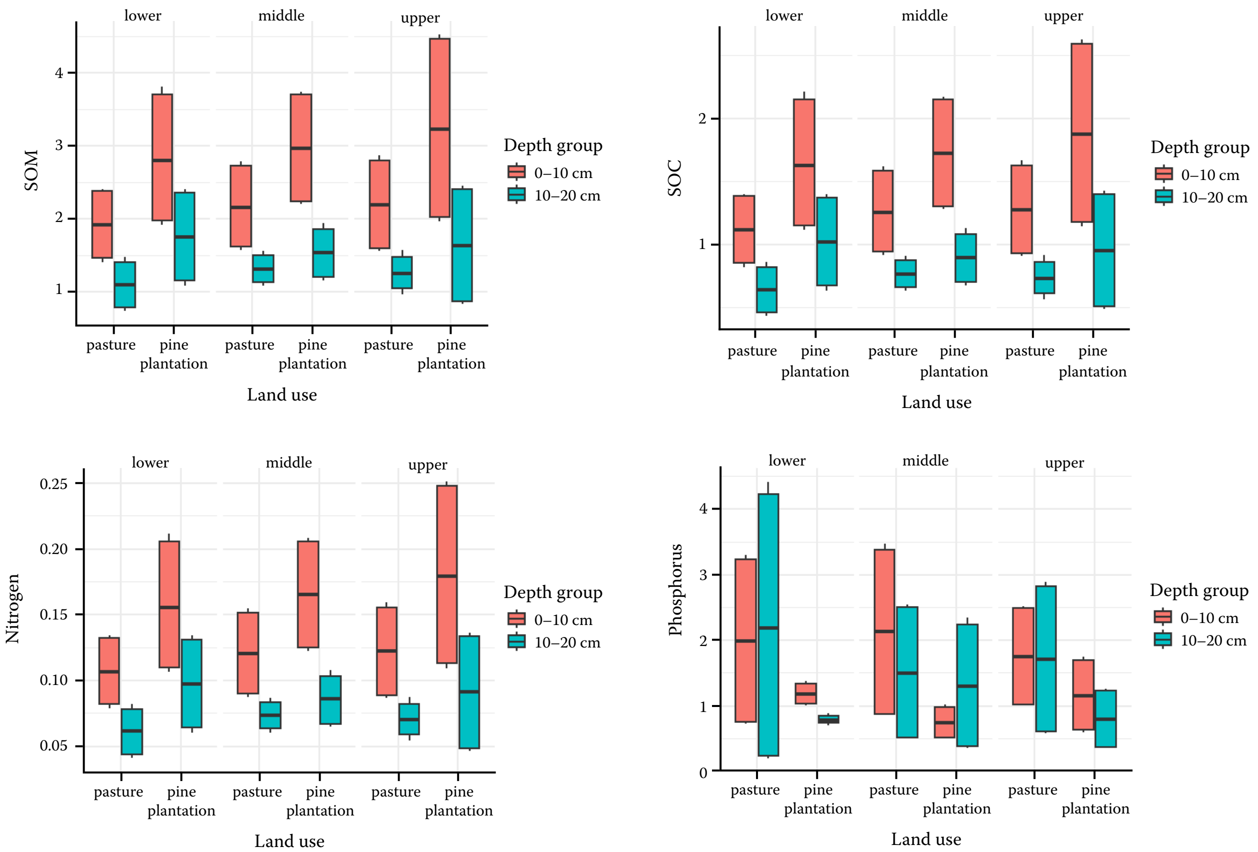

Figure 2. Boxplots showing soil organic matter (SOM), soil organic carbon (SOC), total nitrogen (N), and available phosphorus (P) across two land uses (pasture vs. pine plantation), two soil depths (0–10 cm and 10–20 cm), and three slope positions (lower, middle, upper)

https://doi.org/10.17221/73/2025-JFS

In contrast, phosphorus levels were slightly higher under pasture for lower-slope position samples from the top 10 cm. Pine sites had more phosphorus in the 10–20 cm layer of upper slope positions, which may represent the vertical reallocation of phosphorus, or phosphorus retention, in relation to organic input and microbial cycling.

Literature indicates that soil organic carbon and total nitrogen responses to afforestation are time-dependent, often resulting in an initial decline over the first decade after planting, followed by a gradual recovery period and accumulation. Further literature from studies regarding SOC accumulation over 130 years after afforestation of Alpine pasture with *Picea abies* L. indicates that even 130 years later, SOC stocks in the mineral soil layers could be lower than for native grassland, thus reflecting the importance of the prolonged recovery process and the original use of the land (Egli et al. 2023). In fact, a meta-analysis across Europe indicates that pine species frequently add SOC stocks to the forest floor but can decrease or have no effect on SOC stocks at the sub-soil depth, unless conducive conditions exist (Ražauskaitė et al. 2020).

The changes in nutrient status as a result of afforestation can be seen in Figure 3. This figure shows differences in the quantity of exchangeable potassium, calcium, magnesium and soil pH levels between pasture and pine plantation land uses, at two different soil depth levels (0–10 cm and 10–20 cm), and at three different elevation levels (lower position, middle position, upper position). Recent juxtapositional empirical studies in paired pine and pasture landscapes validated our findings: afforestation with conifer species, especially *Pinus*, generally results in a loss of exchangeable cation nutrients, including potassium, calcium, and magnesium, and reduced but small soil pH losses (Berthrong et al. 2009).

In our results, pine plantation locations consistently had higher potassium values at the 0–10 cm depth in upper slope positions, but lower relative values compared to pasture in deeper layers or lower positions. This could represent higher levels of cation uptake into biomass, typically in older plantations,

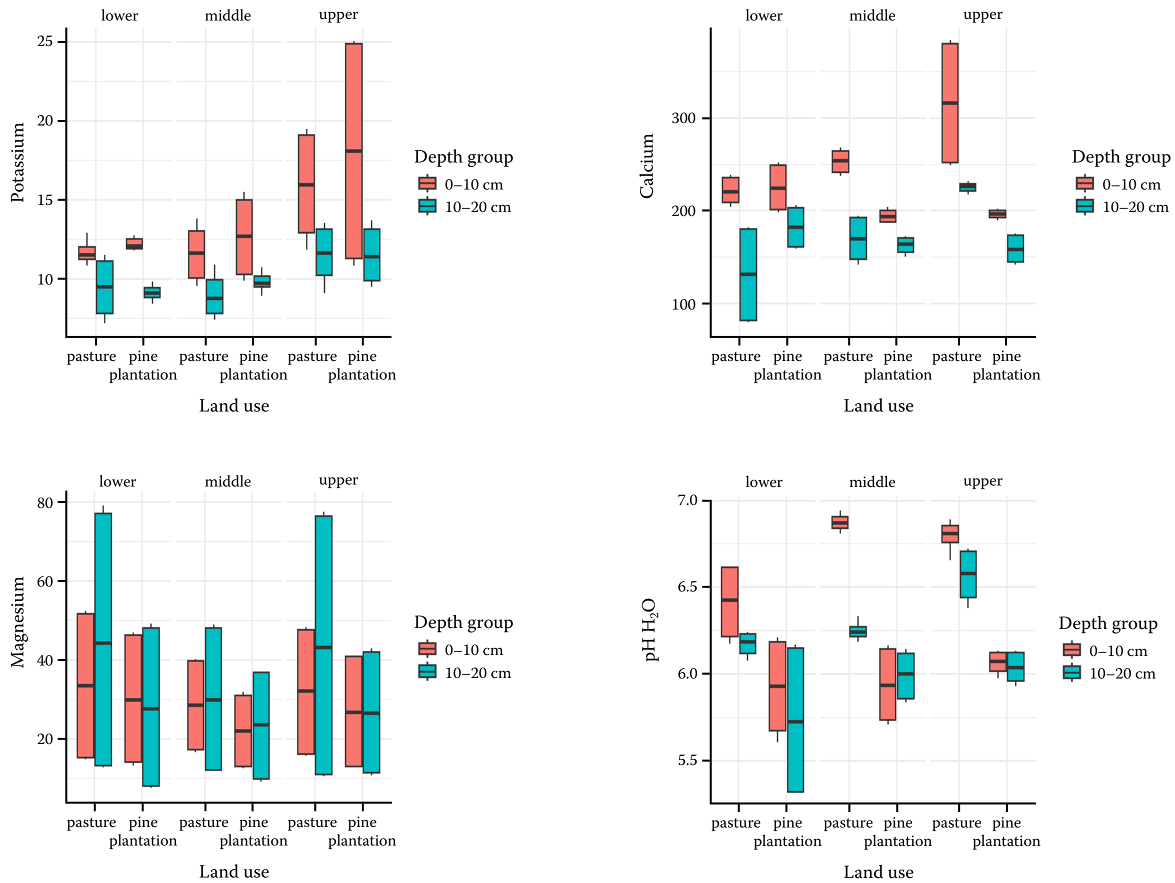

Figure 3. Boxplots showing potassium (K), calcium (Ca), magnesium (Mg) and pH (H_2O) across two land uses (pasture vs. pine plantation), two soil depths (0–10 cm and 10–20 cm), and three slope positions (lower, middle, upper)

https://doi.org/10.17221/73/2025-JFS

in addition to reduced levels of cation leaching that may have occurred from intact canopy systems.

Calcium and magnesium show similar patterns: pine soils tend to have less exchangeable calcium and magnesium than pasture soils, especially in the surface mineral horizon, which is consistent with evidence that calcium and magnesium were depleted after grassland afforestation and conversion to managed pine forestry (Berthrong et al. 2009; Diers et al. 2021).

Soil pH in afforestation sites is often lower than in pasture sites. The literature shows that the average pH was lower by about 0.3–0.8 units on average after pine percentage values, with most evidence coming from studies with initially neutral to alkaline soils with pH decreases following acidifying processes such as organic acid deposition and cation uptake into biomass (Novák 2022; Berthrong et al. 2009). Pine plantation soils on upper slopes had slightly lower pH at 0–10 cm, and a number of longleaf pine plantation studies demonstrated slightly lower pH in upper soil depths, consistent with this mechanism, whereas at the deeper depths of 10–20 cm, soils were at pH convergence.

A more recent paired-land use assessment (Puhlick et al. 2025) also confirmed that exchangeable potassium, calcium, and magnesium were lower in longleaf pine afforested soils compared to former agricultural sites, exemplifying nutrient depletion into tree biomass as a common result produced from management of plantation forests.

In Figure 4, the soil pH results reflect a similar pattern found in afforestation studies globally, with the data showing lower value for soil pH ($CaCl_2$) under pine plantation in the surface layer of the soil, especially at the lower and middle slope positions. The acidification observed corresponds to trends documented in long-term chronosequence studies, indicating that when subalpine pastures are afforested, the soil pH declines due to increased cation uptake into biomass and organic acid inputs from litter (Speckert et al. 2023). In these chronosequence typing studies, declining soil pH tends to be around 0.2–0.4 pH units in the topsoil mineral horizon following conversion to spruce or pine land uses (Speckert et al. 2023). Soil under cultivated pine trees had decreased pH level, both close to and between the trees, consistent with the metadata available for *Pinus* (Berthrong et al. 2009).

The bulk density results indicate the mean bulk density is lower under pine plantation at the 0–10 cm depth on the lower and middle slopes, while the upper slope also indicates a slightly higher bulk density under pine plantation compared to pasture. The observed patterns are consistent with the site and environmental factors outlined from the well-characterised site by Survila et al. (2022). In intact older stands, tree roots and increased organic matter loosen surface soil structure and decrease compaction (Hiltbrunner et al. 2013). Speckert et al. (2023) documented consistent mineral SOC stocks over a 130-year afforestation chronosequence on Swiss alpine pasture – meaning stable soil mass – though the organic horizons did accumulate carbon, resulting in a net increase in total SOC. The authors also documented that forested sites were more acidic than pastures and presented organic layering in soils below

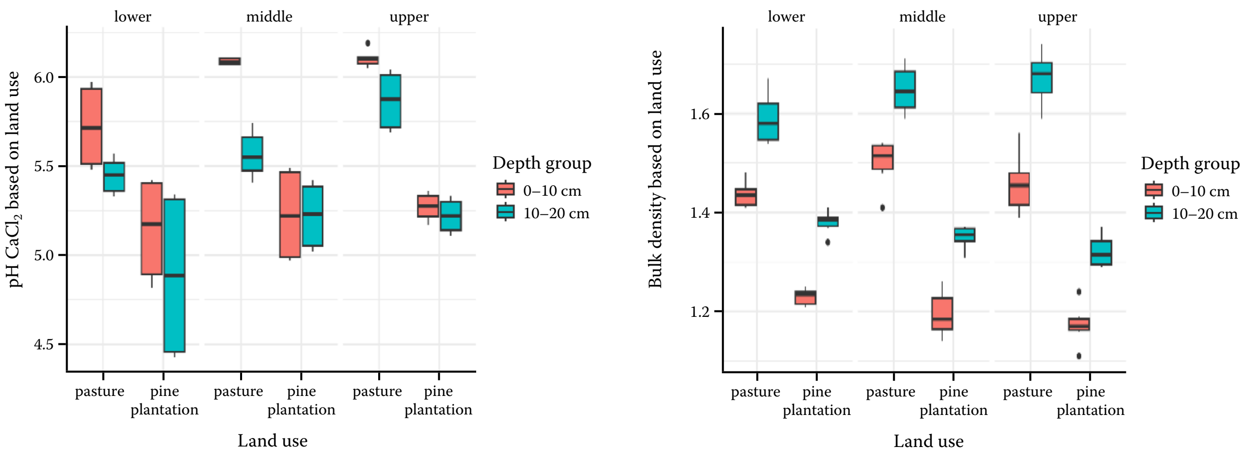

Figure 4. Boxplots showing pH ($CaCl_2$) and bulk density (*BD*) across two land uses (pasture vs. pine plantation), two soil depths (0–10 cm and 10–20 cm), and three slope positions (lower, middle, upper)

https://doi.org/10.17221/73/2025-JFS

forest sites, which is consistent with our findings of decreased pH, and variable bulk density at depth and by slope (Speckert et al. 2023).

Correlation between soil physicochemical properties. The correlation matrix in Figure 5 shows the relationships among different soil parameters for various land uses and depths. Several notable patterns are evident in the data.

The strongest positive correlations ($r \approx 1.00$) occur between soil organic matter, soil organic carbon, and total nitrogen. This aligns with their simultaneous presence and shared origin from organic residues and microbial activity. This finding highlights the connection between these properties in affecting soil fertility and structure Lal (2020).

Soil pH_H_2O has a moderate positive correlation with calcium ($r = 0.63$) and bulk density ($r = 0.48$). This indicates that higher pH values are linked to soils that contain more base cations like calcium, which help with buffering capacity. It is well known that soil pH can influence the availability of cationic nutrients such as calcium, magnesium, and potassium (Guo et al. 2010).

Interestingly, magnesium has a strong negative correlation with soil organic matter, soil organic carbon, and total nitrogen ($r \approx -0.62$). This may indicate that Mg is most likely leaching or forming complexes in soils with more organic matter, particularly in acidic conditions and forests (Augusto et al. 2017). Available phosphorus has low to moderate correlations with the other nutrients. The most obvious is with pH ($r = 0.32$) and Mg ($r = 0.64$); there are weaker correlations with potassium and bulk density. Because phosphorus is often tied up in acidic soils, the correlations may represent better phosphorus availability in neutral to slightly acidic conditions, as noted by Shen et al. (2011).

Potassium had a moderate positive correlation with soil organic matter and soil organic carbon ($r = 0.66$), which would support the idea that organic matter may hold K, likely due to higher cation exchange capacity in soils higher in humus (Tóth et al. 2016).

Lastly, bulk density had a negative correlation with soil organic matter, soil organic carbon, and total nitrogen ($r \approx -0.53$). This highlights that dense soils have become less organic matter-rich. This finding aligns with the generalised inverse correlation between organic matter content and soil compaction (Egli et al. 2023).

The principal component analysis (PCA) in Figure 6 illustrates the differences in soil characteristics across two land use categories, pasture and

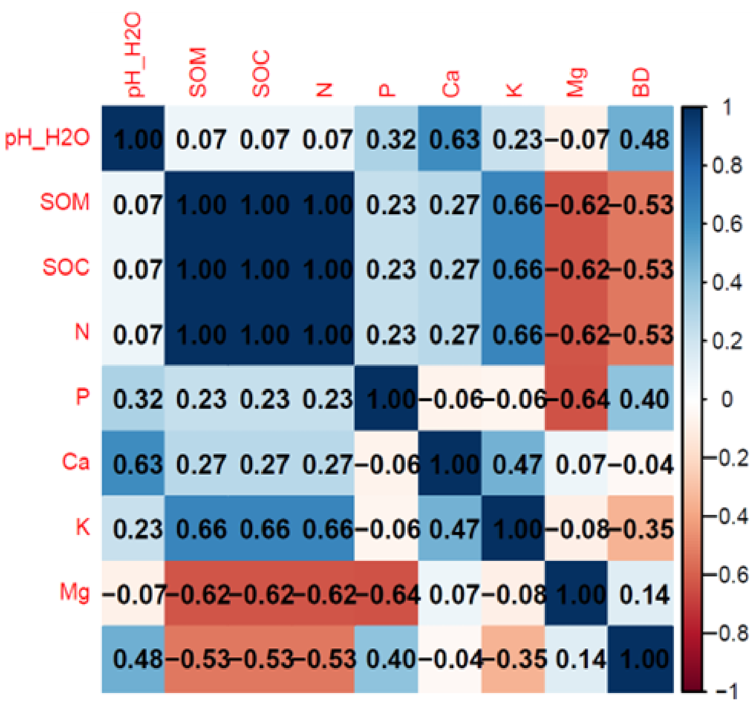

Figure 5. Pearson correlation matrix showing relationships among soil parameters (pH, SOM, SOC, N, P, Ca, K, Mg, *BD*)

SOM – soil organic matter; SOC – soil organic carbon; *BD* – bulk density

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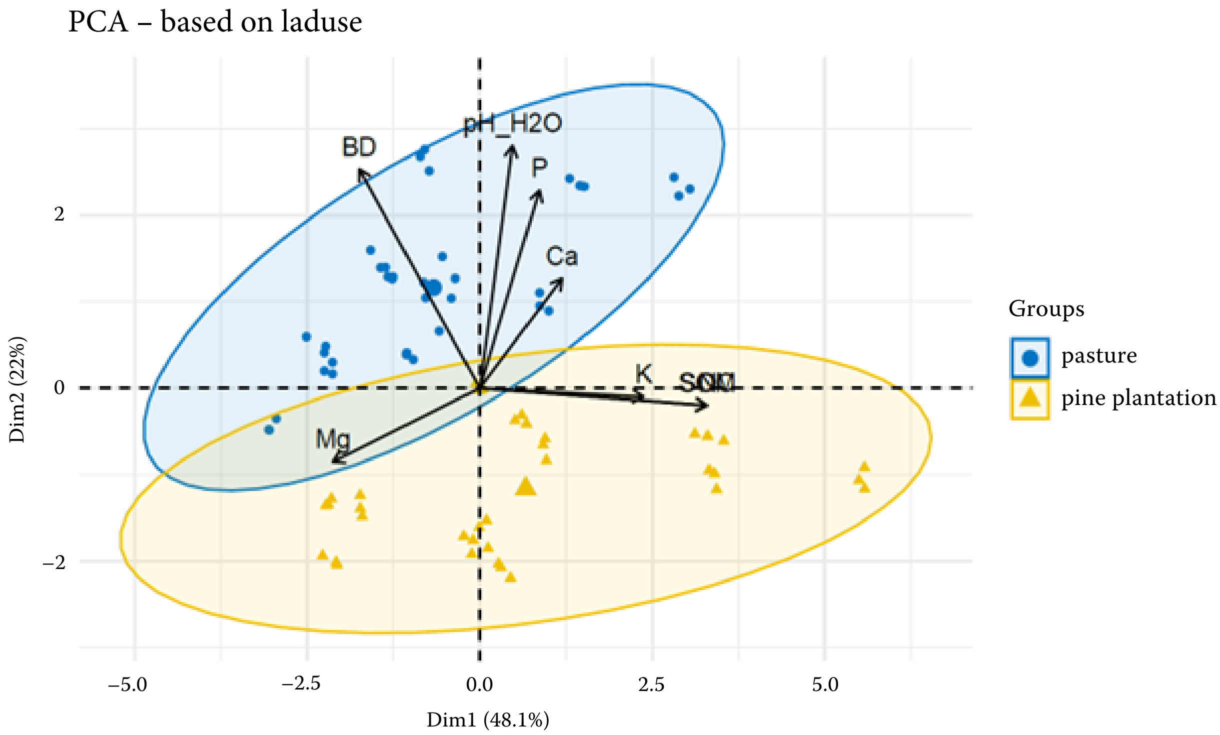

Figure 6. Principal Component Analysis (PCA) biplot showing separation of soil samples from pasture (blue circles) and pine plantation (yellow triangles) based on soil properties

pine plantation. The initial two primary components account for 48.1% and 22% of the overall variance, collectively representing 70.1% of the data's variability. This substantial quantity indicates that the primary distinctions in soil qualities associated with land use are represented by these two dimensions. The soil samples are distinctly categorised into two groups according to land use. Pasture soils, indicated by blue circles, predominantly occupy the left half of the plot and are associated with elevated levels of bulk density, pH, calcium, and phosphorus. This indicates that these soils possess a higher mineral-dominant composition. Grazing activities may affect this by causing soil compaction and introducing nutrients through animal manure (Berthrong et al. 2009).

Conversely, soils in pine plantations, indicated by yellow triangles, aggregate on the right side and correlate with elevated concentrations of potassium, soil organic carbon, and soil organic matter. These trends illustrate the impact of afforestation on soil chemistry, particularly the accumulation of organic matter resulting from increased litter inputs and less physical disturbance (Hiltbrunner et al. 2013). The cultivation of pine species frequently enhances soil organic matter and soil organic carbon via litterfall, hence augmenting carbon sequestration, however, potentially leading to soil acidification (Paul et al. 2002; Berthrong et al. 2009).

The initial main component (Dim1), accounting for 48.1% of the variance, distinctly differentiates soils with elevated organic matter content, characteristic of pine plantations, from those with increased mineral density and decreased organic content, typical of grazing systems. Dim2 (22%) accounts for greater variation, potentially associated with disparities in magnesium, indicating deeper soil processes or geochemical variations among locations.

CONCLUSION

This study's research results indicate extended duration of afforestation with pines leading to distinctive, long-lasting changes in soil properties for those afforested areas when compared to those of corresponding pasture land. The changes were seen at multiple depths and topographic positions, and include: differences in inputs of organic matter; impacts on the nitrogen cycle; differences in soil structure due to the transition from an herbaceous

https://doi.org/10.17221/73/2025-JFS

community to a pine community; and ultimately, the importance of pine plantings in soil carbon sequestration and nutrient availability and therefore, provide useful information for present and future afforestation efforts in Kosovo.

This study was conducted at only two sites and used a specified stand type, which limits the ability to make generalisations beyond these specific sites and types. Future studies will benefit from conducting more studies at additional sites, different species mixes, and including a greater number of soil indicators in order to improve the ability to understand the overall evolution of soils after afforestation, especially when incorporating soil microbiological and structural indicators. Future studies should also aim at capturing the evolution of soils over time more accurately to better understand the patterns of recovery and stabilisation after afforestation.

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