2024-05-09

Soil Organic Matter Components and Characteristics of Forest Soil in Spruce and Sycamore Plantations in the Temperate Region

Samuel Obeng Apori School of Food Science and Environmental Health
Technological University Dublin

Michelle Giltrap
Technological University Dublin

Julie Dunne
Technological University Dublin

See next page for additional authors

Authors

Samuel Obeng Apori School of Food Science and Environmental Health; Michelle Giltrap; Julie Dunne; and Furong Tian Nanolab Research Centre, FOCAS Research Institute

Discover Agriculture

Research

Soil organic matter components and characteristics of forest soil in spruce and sycamore plantations in the temperate region

Samuel Obeng Apori[1,2] · Michelle Giltrap[1,3] · Julie Dunne[1] · Furong Tian[1,2]

Received: 20 September 2023 / Accepted: 29 April 2024
Published online: 09 May 2024

Abstract
The stability of soil organic matter (SOM) that governs soil organic carbon (SOC) storage depends on its characteristics and components, but little is known about how tree species in forest ecosystems affect SOM components and characteristics. In this study, we used FTIR spectroscopy to investigate plantations of two ecologically and economically significant tree species—namely, spruce (*Picea* spp.) and sycamore (*Acer pseudoplatanus*)—in order to determine how the different litter inputs and root-microbe interactions of these two plantations affect the functional groups, components, and characteristics of their SOM. Soil samples were taken from the topsoil (0–10 cm) and subsoil (10–20 cm). In the 0–10 cm soil depth, the SOM's hydrophilic, hydrophobic, and aromatic components differ between the spruce and sycamore plantations. The hydrophobic components constitute the primary constituents of the SOM of the two forest plantations, in contrast to the expected predominance of the hydrophilic component of the SOM. Also, the high hydrophobicity (hydrophilic/hydrophobic) in the subsoil of the spruce plantations was attributed to a decrease in hydrophilic components and a subsequent increase in hydrophobic components of the SOM. The sycamore plantations exhibited a higher SOM aromaticity and a greater degree of decomposition than the spruce plantations. The aforementioned distinctions emphasise the contrasting mechanisms involved in transforming and turnover of the two-tree species' soil organic matter (SOM).

Keywords Hydrophobic · Hydrophilic · Hydrophobicity · Aromaticity

1 Introduction

Forest ecosystems possess a significant quantity of terrestrial carbon (C) stocks, with over 50% in soil [1–3]. Therefore, carbon accumulation in soil within forest ecosystems is considered a prospective approach to mitigate atmospheric carbon dioxide concentration [4, 5]. The stability of Soil Organic Matter (SOM), which governs the carbon reservoir in terrestrial ecosystems, is intricately linked to the composition of its constituent components (hydrophilic, aromatic, hydrophobic, etc.), their inherent attributes (hydrophobicity, aromaticity, and extent of decomposition), and their distinctive carbon chemistry signature [6, 7]. SOM characteristics such as the hydrophobicity primarily caused by aliphatic C–H units found in methyl, methylene, and methine groups[8, 9] regulate the water affinity, influencing the resistance to

✉ Samuel Obeng Apori, d21125192@mytudublin.ie | [1]School of Food Science Environmental Health, Technological University Dublin, City Campus, Grangegorman, Dublin D07ADY7, Ireland. [2]Nanolab, FOCAS Research Institute, Technological University Dublin, 11 Dublin D08 CKP1, Ireland. [3]FOCAS Research Institute, Radiation and Environmental Science Centre, Technological University Dublin, City Campus, Camden Row, 11 Dublin D08C KP1, Ireland.

microbial degradation, wetting rate, and adsorption processes [10]. The hydrophobic organic constituents are likely the main contributors to soil repellence, while the hydrophilic constituents impact soil wettability [11].

One major factor influencing the soil C pools in forest ecosystems is tree species [12]. The selection of tree species for afforestation or reforestation projects is a widely recognised tool utilised by foresters for management purposes, and in more recent years, it has been the subject of discourse as a potential method for enhancing carbon sequestration in soils [5].

Numerous studies have demonstrated the impact of tree species on soil organic carbon (SOC) sequestration (SOC) [13–15]. For instance, Díaz-Pinés et al. [13] demonstrated that Scot's pine soils exhibit a significantly higher carbon storage capacity as compared to Pyrenean oak soils in Central Spain, which was linked to the quality of the SOM. Nonetheless, despite the fact that the stability of SOM that governs SOC storage depends on the SOM characteristics and components, there is still a lack of research on the components and characteristics of soil organic matter (SOM) affected by tree species. Tree species have the potential to influence soil organic matter components and characteristics through variation in C inputs (that is, net primary production), litter quality and the release of root exudates, thereby affecting the SOM decomposition rate [16].

Among the tree species, sycamore (*Platanus spp.*) and spruce (*Picea spp.*) have gained considerable interest in the field of plantation forestry due to their unique growth patterns, litter characteristics, and potential influence on the accumulation of SOC [17–19]. Sycamore and spruce exemplify tree species that belong to the categories of deciduous and coniferous, respectively. Deciduous trees commonly undergo a seasonal shedding of their leaves, introducing a combination of labile and recalcitrant organic substances into the soil [20]. In contrast, coniferous trees generate needles that decompose slower, resulting in variations in litter composition and decomposition rates [21]. The dissimilarities in litterfall and decomposition patterns between these two tree species can consequently impact the SOM component and characteristics influencing carbon storage.

Fourier-transform infrared (FTIR) spectroscopy proves to be a cost-effective and efficient spectroscopic method, successfully used to examine the characteristics and the components of SOM in different types of ecosystems [6–8, 22–24]. Therefore, we used FTIR spectroscopy to investigate plantations of two ecologically and economically significant tree species—namely, spruce (*Picea spp*.) and sycamore (*Acer pseudoplatanus*)—in order to determine how the different litter inputs and root-microbe interactions of these two plantations affect the functional groups, components, and characteristics of their soil organic matter. We hypothesise that sycamore and spruce differ in SOM components and forest soil characteristics due to their distinct litterfall and decomposition rates.

2 Materials and methods

2.1 Study site and soil sampling

The study was conducted in forest plantations (spruce and sycamore plantations) located in Tullamore, Co-Offaly, Ireland. The annual air temperature in the county exhibits a range of 5.7 °C to 13.0 °C, with a mean precipitation of 819 mm [25]. The study area exhibits the presence of histosol soil, characterised by a drainage channel that effectively manages water flow. For the purpose of this study, fifteen forest plantations were chosen, comprising six sycamore plantations and nine spruce plantations. The criteria for selecting these forest plantations across the region included the consent of the landowners to take soil samples in their fields, and forest that adhere to contemporary Irish forestry best management practices as delineated by the Forest Service (2000). The age of the forest plantations selected for this study ranged from 12 to 15 years. The sycamore plantations exhibited a notable height ranging from approximately 8 to 14 m, with a well-established canopy whilst the spruce plantations exhibited a height range of 10 to 16 m. The thickness of the peat layer differs between 0.5 m and 7.5 m across the selected forest plantations. The average soil pH under the selected spruce forest plantations and the sycamore forest plantations was 5.6 and 6.1, respectively. The soil pH was measured in a soil-to-water suspension ratio of 1:2.5, using a glass electrode in a pH meter [26].

A total of 30 soil samples (15 topsoils and 15 subsoils) were collected from 15 forest plantations (six sycamore plantations and nine spruce plantations) between October 2021 and January 2022. Therefore, 12 and 18 soil samples (sub and topsoil) were collected from the six sycamore plantations and nine spruce plantations, respectively. Ten quadrants measuring 0.5 m × 0.5 m were strategically positioned at random distances along a diagonal line within 5 m × 50 m plots for each location. The collection of soil samples was carried out using a Russian peat corer with a diameter of 15 cm. The samples were taken up to 20 cm and subsequently divided into two layers: 0–10 cm and 10–20 cm. In each of the 15 forest plantations, one composite soil sample consisting of ten cores was collected from every quadrant and placed in self-sealing plastic bags. The soil samples were subjected to drying in an oven at a temperature of 45 °C within a laboratory environment. After the samples were dried, they underwent crushing and subsequent sieving using a 2 mm mesh to facilitate their preparation for Fourier Transform Infrared (FTIR) analysis.

2.2 ATR-FTIR measurements

To conduct a comparison of the SOM functional group in the two forest plantations systems, an analysis was performed on a dried soil sample using Fourier-transform infrared spectroscopy (FTIR) in attenuated total reflection (ATR) mode with DTGS detector (Perkin Elmer Spectrum One, PerkinElmer Inc., Waltham, MA, USA). The ATR crystal underwent a cleaning process using anhydrous ethanol after each sample. To maintain the integrity of the measurements and minimise the influence of atmospheric variations within the laboratory, the instrument was calibrated relative to the ambient air in the surrounding environment prior to each measurement. This precautionary step aimed to prevent any potential deviations in the results that could be attributed to fluctuations in the laboratory's atmosphere. The soil samples underwent spectral characterisation with a resolution of 4 cm^{-1} and a scan range of 4000–650 cm^{-1}. The processing of spectra data, including baseline correction (using the connecting line method), smoothing (employing the Savitzzky-Golay method), and normalisation, was conducted using the OriginPro 2023 software (OriginLab Corporation based in Northampton, MA, USA). The intensity of the peak (measured by height) was recorded to evaluate the extent of infrared absorption for the selected peak. The observed absorption bands have been attributed to their corresponding organic carbon assignments, as specified in Table 1.

The peaks at 2980 and 2920 cm^{-1} were integrated by aggregating their respective heights, thereby consolidating them into a singular peak representing hydrophobic soil organic matter (SOM) functional groups. The hydrophobicity was calculated by the ratio of hydrophobic (C–H) and hydrophilic (C = O) functional groups at 2920 + 2980 cm^{-1} and 1720 cm^{-1}, respectively [33, 34]. The decomposition of SOM has been conducted by examining the ratio of the hydrophilic functional group to the total sum of aromatic and aliphatic compounds [24, 35]. Therefore, the degree of decomposition index (DDI) of peat organic matter was calculated by dividing the intensity peak at 1720 cm^{-1}, indicative of hydrophilic components, by the sum of the peak height at 2980 + 2920 cm^{-1}, which corresponds to the hydrophobic component of SOM. The assessment of SOM aromaticity involved calculating the ratio between aromatic (1610 cm^{-1} + 1520 cm^{-1}) and aliphatic (2980 + 2920 cm^{-1}) groups.

2.3 Data analysis

A significance test using an Independent t-test was performed using OriginPro 2023 (OriginLab Corporation, Northampton, MA, USA) to determine if there is a significant difference in the functional groups, components, and characteristics of Soil Organic Matter (SOM) between the spruce and sycamore plantations. Additionally, Correlation and Principal Component Analysis (PCA) were utilized to examine the interconnections among the functional groups, components, and characteristics of SOM in both the spruce and sycamore plantations.

Table 1 Peak positions in the FT-IR spectra, as documented in the literature, along with their suggested assignments

Peak name	Wavenumber limits (cm^{-1})	Characterization	References
1050	1070–1040	O–H deformation and C–O Stretching	[27]
1110	1116–1080	Secondary alcohol	[28]
1410	1420–1410	O–H deformation and C–O stretching of phenolics group	[29]
1520	1535–1500	Aromatic rings, amides II vibration	[30]
1610	1620–1600	Aromatic C = C stretch, strong H-bond C = O of conjugated ketones	[30, 31]
1640	1660–1630	C = O stretching of amide groups	[32]
2920, 2980	3020–2800	Symmetric and asymmetric aliphatic C–H stretching vibrations or aliphatic methyl and methylene	[27]

3 Results

3.1 SOM functional groups

The FTIR spectra of the soil in the spruce and sycamore plantations displayed similarities, as shown in Fig. 1. Nevertheless, the differentiation in SOM functional groups of the soil originating from the two plantations was contingent upon the examination of peak intensity, specifically focusing on the height of specific peaks, as detailed in Table 2. In the two soil depths (0–10 and 10–20 cm), SOM functional groups such as secondary alcohols (peak, 1110), O–H deformation and C–O stretching of phenolics (peak, 1410) aromatic C = C, strong H-bond C = O of conjugated ketones (peak, 1610) and C = O stretching of amide groups (peak, 1640) did not differ significantly among the forest soil in the spruce and sycamore plantations. Nevertheless, the spruce plantations demonstrated a greater C–O stretching of polysaccharides (peak, 1050), aromatic rings in amides II vibration (peak, 1520) and aliphatic methyl and methylene (peaks, 2920 and 2980) than the sycamore plantations.

3.2 SOM components

The surface soil exhibited a greater hydrophilic component of the SOM compared to the subsoil. The hydrophilic component of the SOM of the spruce plantations was higher than the sycamore plantations in 0–10 cm (Fig. 2A). The hydrophilic components of the soil organic matter (SOM) in spruce and sycamore plantations showed no significant differences ($P > 0.05$) within the 10–20 cm depth range of the forest soil (Fig. 2A). Like the hydrophilic components, a significant difference ($P < 0.05$) in the hydrophobic component was exhibited on the surface soil (0–10 cm) such that the soil samples from the spruce plantations showed higher hydrophobic functional group than the soil samples from the sycamore plantations (Fig. 2B).

In the 10–20 cm soil depth, there was no significant difference ($P > 0.05$) observed in the hydrophobic components of the soil organic matter (SOM) between the spruce and sycamore plantations. In the 0–10 cm soil depth, there is a notable difference (statistically significant at $P < 0.05$) in the aromatic composition of the soil organic matter (SOM) between the spruce and sycamore plantations (Fig. 2C). In the case of the spruce plantations, there is a notably higher aromatic SOM component, reaching 24.15%, when compared to the sycamore plantations (Fig. 2C). However, for the 10–20 cm sample, there is no significant difference in aromatic components between the sycamore and spruce plantations (Fig. 2C).

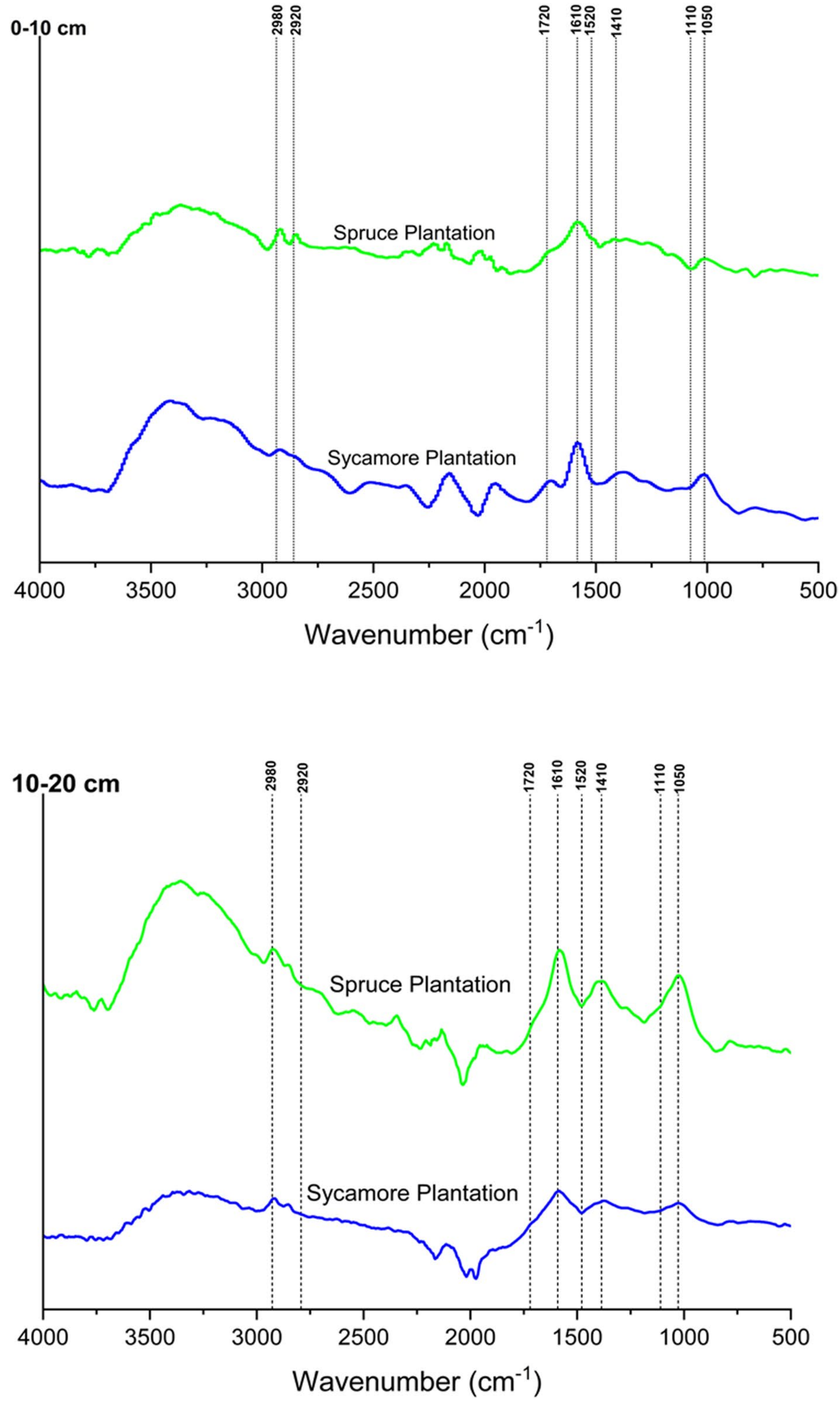
3.3 SOM characteristics

In the top 0–10 cm, greater aromaticity was observed in the sycamore plantations forest soil compared to the aromaticity of SOM in the spruce plantations (Fig. 3A) while the aromaticity levels of the SOM exhibited no substantial variance ($P > 0.05$) between sycamore and spruce plantations within the 10–20 cm depth (Fig. 3A). The hydrophobicity of the forest SOM was higher on the subsoil soil than on the surface soil (Fig. 3B). In the 0–10 cm layer, there was no significant difference in hydrophobicity ($P > 0.05$). However, the hydrophobicity of the soil in the spruce plantations showed a significant variance compared to that in the sycamore plantations within 10–20 cm (Fig. 3B). The sycamore plantations exhibited a greater DDI compared to the spruce plantations, although there was no significant difference observed at both depths (0–10 and 10–20 cm) (Fig. 3C).

3.4 Pearson correlation and principal component analysis

Two principal components (PC) were extracted from SOM functional groups, components, and characteristics of forest SOM (Fig. 4). In the 0–10 cm soil depth, the first PC (64.47% of total variance) comprises hydrophobicity, hydrophobic, aromatic, hydrophilic, O–H deformation and C– O stretching related to phenolics (peak, 1410), aromatic C = C, strong hydrogen bonding in C = O of conjugated ketones (peak, 1610) and C = O stretching associated with amide group (peak, 1640), C–O stretching linked to polysaccharides (peak, 1050) and aliphatic methyl and methylene features (peaks, 2920 and 2980). The grouping of aliphatic methyl and methylenes (peaks 2920 and 2980) with the hydrophobic functional group suggests that the changes in hydrophobic properties of SOM depend on the availability of the SOM's aliphatic methyl and methylene functional group at both peaks (2920 and 2980). The second PC accounted for a variance of 22.7%,

Fig. 1 FTIR spectra of forest soil in spruce and sycamore plantations established on a Histosols



indicating that the variation in the data was primarily influenced by the aromaticity, secondary alcohols (peak, 1110) and degree of decomposition (Fig. 4). In 10–20 cm, the first PC (51.8% of total variance) comprised variables characterising all the identified carbon chemistry signatures, aromatic, hydrophilic, hydrophobic and hydrophobicity. The grouping of aliphatic methyl and methylene (peak 2920) and hydrophobicity indicate that the decrease in aliphatic methyl and

Table 2 Peak intensity (×10^2) determined by ATP-FTIR of forest soil

Peak number (cm^1)	spruce plantation	sycamore plantation	t-test[a]	Significant[b]
0–10 cm				
1050	1.394 ± 0.014	0.344 ± 0.004	0.338	*
1110	0.073 ± 0.005	0.071 ± 0.003	0.431	ns
1410	1.449 ± 0.014	1.013 ± 0.002	0.521	ns
1520	1.329 ± 0.013	0.461 ± 0.003	0.879	*
1610	1.144 ± 0.011	0.948 ± 0.001	0.707	ns
1640	1.295 ± 0.012	0.843 ± 0.002	0.607	ns
2920	2.186 ± 0.018	0.457 ± 0.002	1.958	*
2980	2.220 ± 0.014	0.916 ± 0.004	0.921	*
10–20 cm				
1050	0.951 ± 0.009	0.429 ± 0.004	0.043	*
1110	1.106 ± 0.006	0.736 ± 0.004	0.968	ns
1410	1.086 ± 0.008	1.018 ± 0.002	0.142	ns
1520	1.467 ± 0.013	0.675 ± 0.003	1.036	*
1610	1.143 ± 0.008	0.980 ± 0.002	0.351	ns
1640	1.012 ± 0.007	0.920 ± 0.003	0.195	ns
2920	2.299 ± 0.009	0.459 ± 0.004	1.233	*
2980	1.353 ± 0.023	1.110 ± 0.004	0.478	*

The values are the mean ± SD

**Significant at the 0.05 level*

[a]*t-test and* [b]*Significant were obtained from Two-Sample t-test, ns, not significant*

methylene functional group during SOM decomposition will decrease the hydrophobicity of the SOM. The second PC (29.7% total variance) consisted of aromaticity and the DDI, occurring at the positive part of the second PC (Fig. 4).

The Pearson correlation was employed to assess the relationship among the characteristic components and functional groups of forest SOM (Fig. 5). All the identified carbon chemistry except for O–H deformation and C– O stretching related to phenolics (peak, 1410) showed a strong positive correlation with the aromatic, hydrophobic and hydrophilic components of the SOM in both soil depths (0–10 and 10–20 cm) (Fig. 5). Within the 0–10 cm depth, there was a strong negative relationship between the hydrophilic components and the aromatic and hydrophobic components of the soil organic matter (SOM) (Fig. 5a). However, at a depth of 10–20 cm, there was a weak negative relationship between the hydrophilic and aromatic components of the SOM, although this relationship was not statistically significant (Fig. 5b). The aromaticity correlated negatively with hydrophobicity and the DDI (Fig. 5). The DDI exhibited a negative correlation with hydrophobicity, indicating that the decrease in the hydrophobicity increases SOM decomposition, occurring at both the top and the subsoil (0–10 and 10–20 cm).

3.5 Discussion

In both the spruce and sycamore plantations, the results of the SOM functional groups indicate the presence of carbon compounds containing functional groups of the SOM, including the carbohydrate, lignin content and polyphenolics compounds, confirming the expected occurrence of these compounds within the soil organic matter in forest plantations. Interestingly, our results exhibit similarities with the functional groups identified in the SOM from diverse geographical regions and soil types, namely a tilled Mediterranean Semiarid soil [23], various soil types (automorphic, gleyic, and Gleysols) in Estonia [24], various peatland use types (grassland, forestry, cutaway and cutover) in Ireland [7] and regenerating cutover peatlands [22]. This convergence in the carbon compounds containing functional groups of the SOM across the diverse geographical regions, different soil management practices and soil types implies that the presence of the SOM functional groups in this study might not be limited to specific soil types or climate systems. Instead, it suggests a broader ecological relevance that transcends geographical boundaries [36, 37], while acknowledging this similarity, it is crucial to recognize that the quantity (intensity) of the SOM functional groups differs under different vegetation, soil type, and climatic conditions [23, 38].

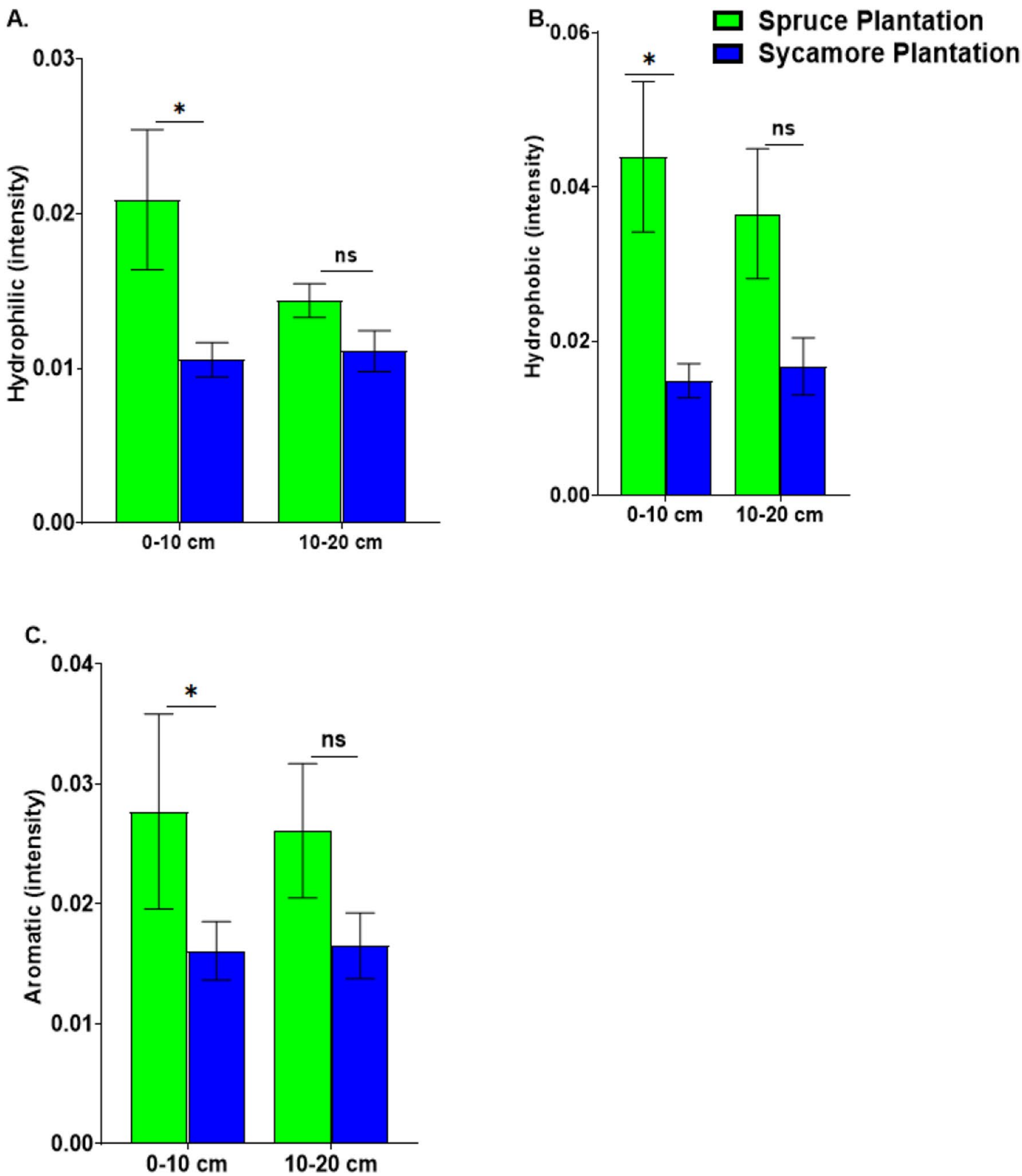


Fig. 2 Average content of (**A**), hydrophilic (**B**), hydrophobic and (**C**) aromatic components of forest soil. Error bars indicate the SD. "ns" represent not significant ($p > 0.05$), while "*$p \leq 0.05$" denotes significance

The SOM functional groups, components, and characteristics of forest soil of the studied forest plantations mainly depend on the plant litter input quality and quantity, turnover rate, and soil characteristics [13, 39, 40]. The higher C–O stretching of polysaccharides (peak, 1050) and aliphatic methyl and methylene (peaks, 2920 and 2980) functional group exhibited by the spruce plantations than the sycamore plantations may probably be assigned to the characteristics of higher litter C:N ratio and lower annual litterfall [41]. According to Verstraeten et al. [42], a higher C: N ratio of litter under the spruce plantations leads to the decrease of the decomposition rates of SOM, which could subsequently increase the polysaccharides components of the SOM. Litterfall, comprised of fallen leaves, plant debris, and organic material, serves as a primary source of plant-derived carbon compounds, such as cellulose, lignin, and other organic polymer inputs to the soil [43, 44]. A lower litterfall can result in decreased inputs of organic carbon, influencing microbial activity and decomposition rates. This, in turn, can impact the overall composition of soil organic matter (SOM), potentially causing

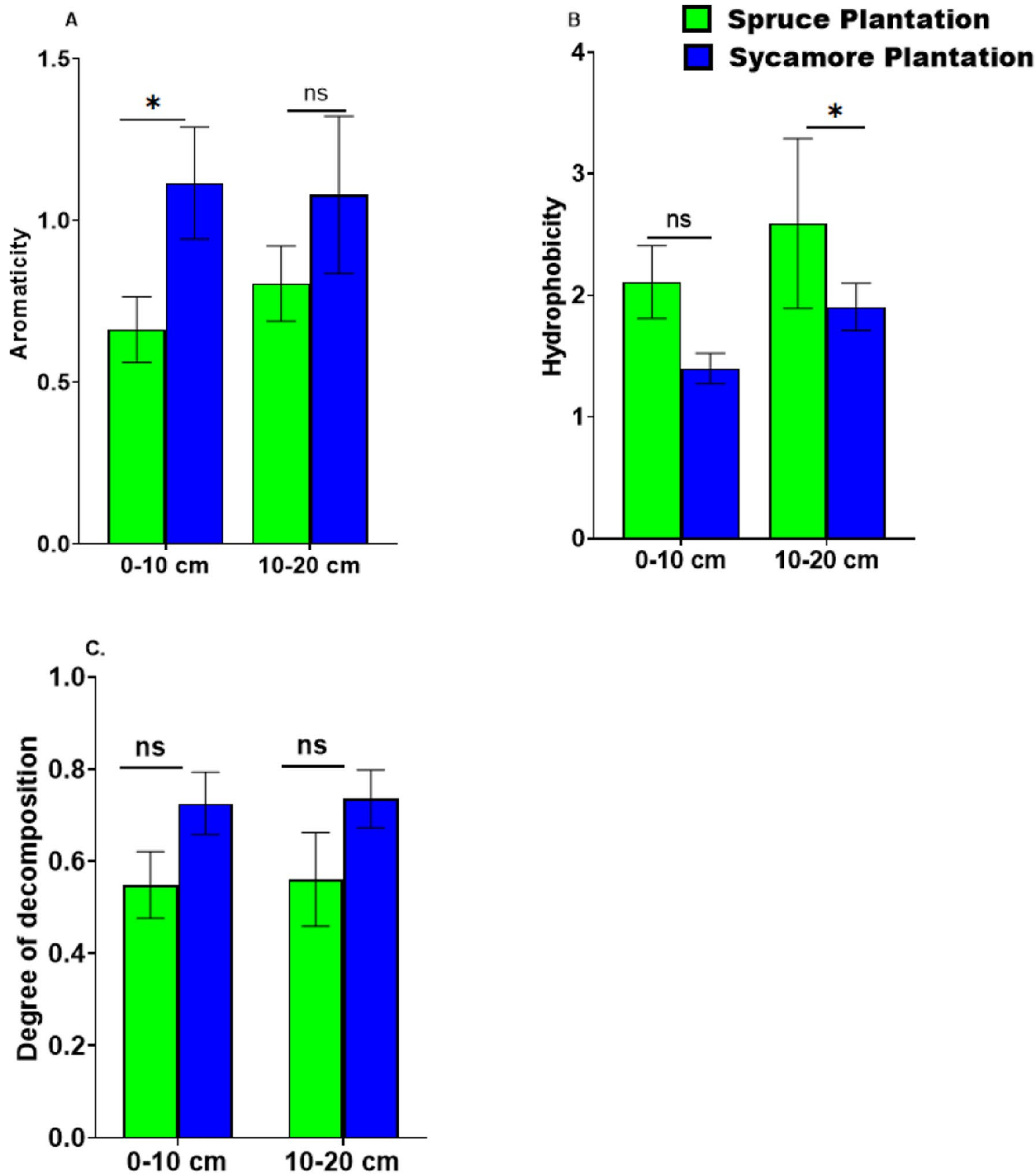


Fig. 3 Average content of (**A**), Aromaticity (**B**), hydrophobicity (**C**) Degree of decomposition of forest soil. Error bars indicate the SD. "ns" represent not significant ($p > 0.05$), while "$*p \le 0.05$" denotes significance

shifts in the relative abundance of various functional groups and chemical constituents within the soil. Hence, this could potentially account for the observed differences in aliphatic methyl and methylene (peaks, 2920 and 2980) as well as C-O stretching of polysaccharides (peak, 1050) constituents within the SOM between sycamore and spruce plantations.

The peaks at 2980 + 2920 and 1720 indicate the presence of C–H and C = O functional groups, which correspond to the hydrophilic and hydrophobic components of the soil, respectively. Generally, hydrophilic components dominate the composition of the SOM [23, 45]. Our study's results indicated that the hydrophobic components constitute the primary constituents of SOM, in contrast to the expected predominance of the hydrophilic component of the SOM occurring at 0–10 cm depth. The findings are consistent with the observations reported by [7, 10, 23, 46] for histosol (peatland). The prevalence of hydrophobic constituents in soil organic matter (SOM) within forested peat soils, as observed in our study, can be attributed to the presence of waterlogged conditions that limit microbial activity and

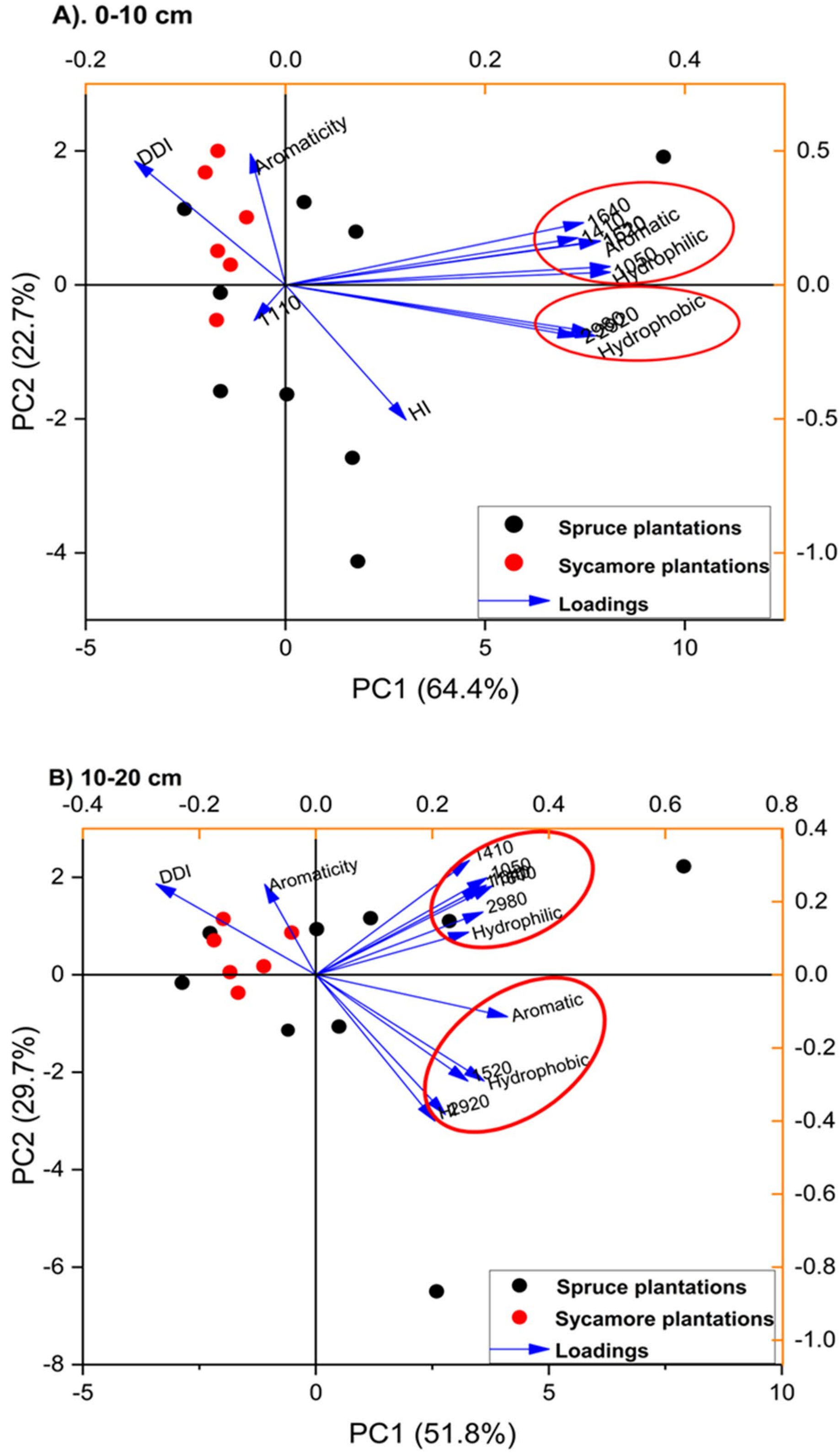


Fig. 4 Biplots of the SOM functional groups, characteristics, and components of SOM under spruce and sycamore plantations. DDI, Degree of decomposition index. The parameters within the circle signify their interconnectedness.HI, Hydrophobicity Index

reduce decomposition rates, which leads to the preservation of recalcitrant organic compounds possessing inherent hydrophobic properties [47, 48]. The forest canopy further contributes to hydrophobic constituents by depositing compounds like waxes and lipids from plant litter, creating a reservoir of water-insoluble substances as compared to other ecosystems such as field crops and grassland ecosystems [49]. This distinctive environment promotes the

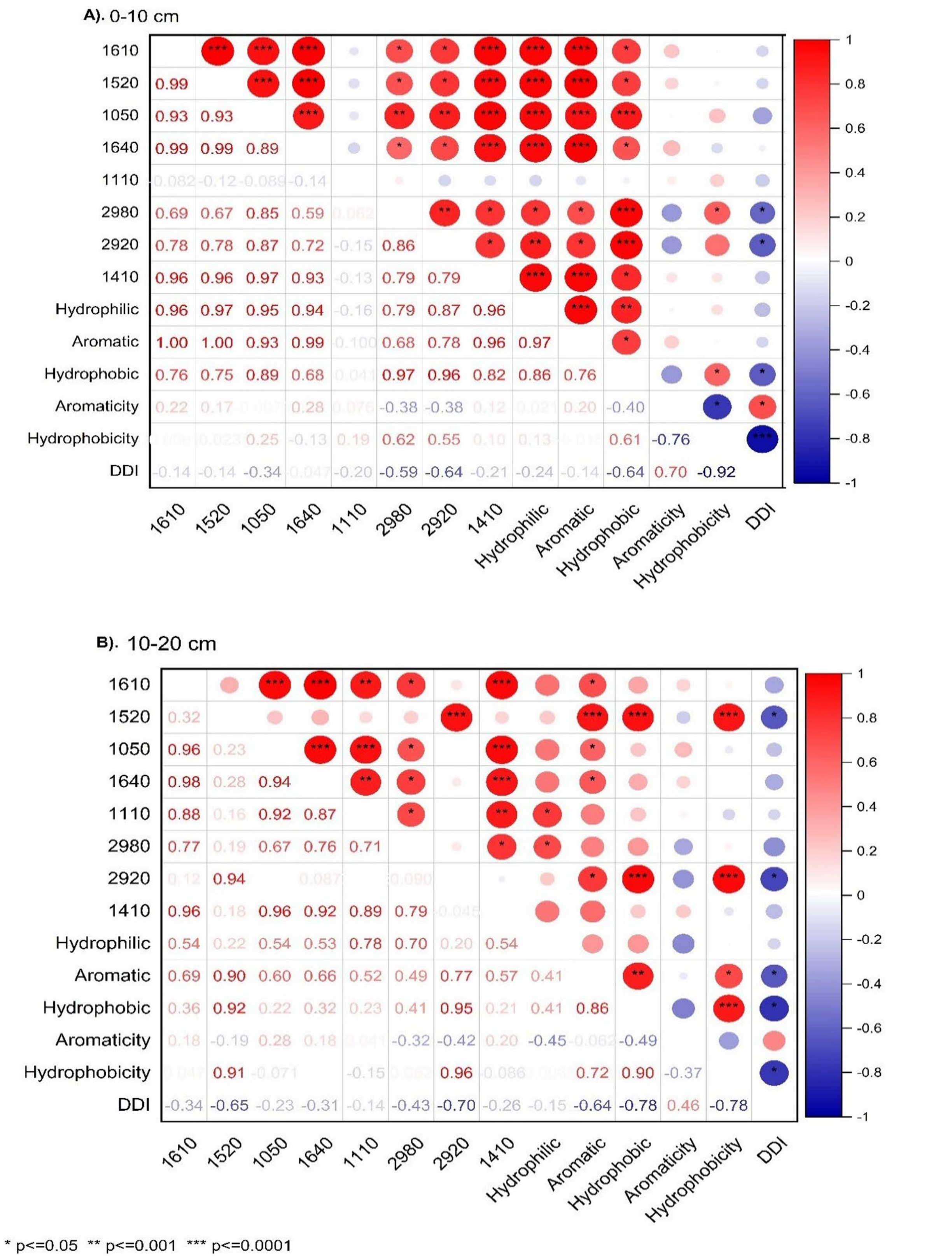


Fig. 5 Pearson's rank correlation carbon chemistry signature, characteristics, and components. DDI, degree of decomposition

persistence and accumulation of hydrophobic organic components, challenging the conventional expectation of hydrophilic dominance in SOM composition.

The lower hydrophobic components in the organic matter of the topsoil in the sycamore plantations suggest a higher decomposition rate of labile carbohydrates compared to the spruce plantations (as seen in Table 2 at peaks 2920 and 2980). The higher aromaticity observed in the sycamore plantations, in comparison to the spruce plantations, can be ascribed to the accelerated decomposition rate of aliphatic functional groups present in the SOM compared to the spruce plantations. The decomposition of aliphatic structures potentially results in an enrichment of aromatic compounds within the SOM [50]. Notably, the observed negative correlation between the hydrophobicity of SOM and its aromaticity, as illustrated in Fig. 5, suggests that the process of accelerated decomposition, leading to increased aromaticity, is particularly prominent in the subsoil layers (10–20 cm). This correlation implies that as the hydrophobicity of SOM decreases, there is a concurrent rise in aromaticity, indicating a dynamic interplay between decomposition processes, hydrophobic components, and aromatic structures in modifying the composition of SOM in the subsoil layers of the sycamore plantations.

The hydrophobicity is defined by the ratio of hydrophobic (C-H) groups to hydrophilic (C = O) functional groups [33]. The higher hydrophobicity in the subsoil of the spruce plantations than in the sycamore plantations (Fig. 3B) can be attributed to a decrease in hydrophilic components and a subsequent increase in hydrophobic components of the SOM. Such an effect is likely due to the higher C: N ratio and the wax coating characteristics of the litter of the spruce plantations as compared to the sycamore plantations [41]. A higher C:N ratio and wax coating have been linked to slower decomposition rates and higher tannin content compared to the litter in sycamore plantations [51]. Therefore, the litterfall in the spruce plantations, distinct from the sycamore plantations, introduces plant residues with a higher C:N ratio [52, 53]; subsequent microbial-driven decomposition preferentially breaks down hydrophilic compounds, reducing their abundance, while concurrently yielding recalcitrant organic materials with inherent hydrophobic properties [54, 55], thereby contributing to the observed increase in hydrophobic components. The observed low hydrophobicity of SOM at the sycamore plantations can potentially be ascribed to the heightened microbial activity involved in plant litter degradation [35]. This microbial activity may enhance the occurrence of C = O groups, thereby facilitating the formation of stable microbial carbohydrates. The similarity in the studied SOM functional group, components and characteristics between the 0–10 cm and 10–20 cm layers of the forested soil can be attributed to the uniform distribution of the functional groups (Table 2), microbial activity, and decomposition processes throughout the examined soil depths [7].

3.6 Conclusion

The study findings showed that sycamore and spruce affect the functional groups, characteristics and components of SOM. The SOM functional groups, such as the aliphatic methyl and methylene (peaks, 2920 and 2980) and C–O stretching of polysaccharides (peak, 1050) functional group, were higher in the soil from the spruce plantations than the sycamore plantations. Significant variations were observed in the hydrophilic, hydrophobic, and aromatic soil organic matter (SOM) components between the spruce and sycamore plantations. The SOM of the forest soil of the sycamore plantations exhibited higher aromaticity than the SOM from the spruce plantations. The noteworthy observation pertained to the unforeseen prevalence of hydrophobic components as the principal constituents of soil organic matter, deviating from the expected predominance of the hydrophilic component. The high hydrophobicity (hydrophilic/hydrophobic) in the subsoil of the spruce plantations can be linked to a decrease in hydrophilic components and a subsequent increase in hydrophobic components of the SOM. Also, the high degree of decomposition exhibited by the sycamore can be assigned to the low hydrophobic component of the SOM compared to the spruce plantations.

Author contribution A.S.O, M.G, and F.T were involved in the conceptualization and design of the experiments, implementation of the experiments, analysis and interpretation of the data, contribution of reagents, materials, analysis tools, or data, and the writing of the paper. J.D. contributed substantially to data analysis and interpretation and played a key role in revising the manuscript. All authors reviewed the manuscript.

Funding Not applicable.

Data availability All data generated or analyzed in the course of this study are incorporated within this manuscript.

Declarations

Competing interests The authors declare that they have no relevant financial or non-financial interests to disclose.

References

1. Lal R. Forest soils and carbon sequestration. For Ecol Manage. 2005;220(1–3):242–58.
2. Sierra CA, del Valle JI, Orrego SA, Moreno FH, Harmon ME, Zapata M, et al. Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. For Ecol Manag. 2007;243(2–3):299–309.
3. Wei X, Shao M, Gale W, Li L. Global pattern of soil carbon losses due to the conversion of forests to agricultural land. Sci Rep. 2014;4(1):4062.
4. Deshmukh CS, Julius D, Evans CD, Susanto AP, Page SE, Gauci V, et al. Impact of forest plantation on methane emissions from tropical peatland. Glob Change Biol. 2020;26(4):2477–95.
5. Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz R, Hagedorn F, et al. How strongly can forest management influence soil carbon sequestration? Geoderma. 2007;137(3–4):253–68.
6. Ellerbrock RH, Kaiser M. Stability and composition of different soluble soil organic matter fractions–evidence from δ13C and FTIR signatures. Geoderma. 2005;128(1–2):28–37.
7. Obeng AS, Dunne J, Giltrap M, Tian F. Soil organic matter carbon chemistry signatures, hydrophobicity and humification index following land use change in temperate peat soils. Heliyon. 2023;9: e19347.
8. Capriel P, Beck T, Borchert H, Gronholz J, Zachmann G. Hydrophobicity of the organic matter in arable soils. Soil Biol Biochem. 1995;27(11):1453–8.
9. Capriel P. Hydrophobicity of organic matter in arable soils: influence of management. Eur J Soil Sci. 1997;48(3):457–62.
10. Šimon T, Javuurek M, Mikanova O, Vach M. The influence of tillage systems on soil organic matter and soil hydrophobicity. Soil Tillage Res. 2009;105(1):44–8.
11. McKissock I, Gilkes RJ, Van Bronswijk W. The relationship of soil water repellency to aliphatic C and kaolin measured using DRIFT. Soil Research. 2003;41(2):251–65.
12. Dixon RK, Solomon AM, Brown S, Houghton RA, Trexier MC, Wisniewski J. Carbon pools and flux of global forest ecosystems. Science. 1994;263(5144):185–90.
13. Angst G, Mueller KE, Eissenstat DM, Trumbore S, Freeman KH, Hobbie SE, et al. Soil organic carbon stability in forests: distinct effects of tree species identity and traits. Glob Change Biol. 2019;25(4):1529–46.
14. Díaz-Pinés E, Rubio A, Van Miegroet H, Montes F, Benito M. Does tree species composition control soil organic carbon pools in Mediterranean mountain forests? For Ecol Manage. 2011;262(10):1895–904.
15. Wang H, Liu S, Wang J, Shi Z, Lu L, Zeng J, et al. Effects of tree species mixture on soil organic carbon stocks and greenhouse gas fluxes in subtropical plantations in China. For Ecol Manage. 2013;300:4–13.
16. Horwath W. Carbon cycling and formation of soil organic matter. In: Horwath W, editor. Soil microbiology, ecology and biochemistry. Amsterdam: Elsevier; 2007. p. 303–39.
17. Guidi C, Vesterdal L, Gianelle D, Rodeghiero M. Changes in soil organic carbon and nitrogen following forest expansion on grassland in the Southern Alps. For Ecol Manage. 2014;328:103–16.
18. Steffens C, Beer C, Schelfhout S, De Schrijver A, Pfeiffer EM, Vesterdal L. Do tree species affect decadal changes in soil organic carbon and total nitrogen stocks in Danish common garden experiments? Eur J Soil Sci. 2022;73(1): e13206.
19. Vesterdal L, Ritter E, Gundersen P. Change in soil organic carbon following afforestation of former arable land. For Ecol Manage. 2002;169(1–2):137–47.
20. Achilles F, Tischer A, Bernhardt-Römermann M, Heinze M, Reinhardt F, Makeschin F, et al. European beech leads to more bioactive humus forms but stronger mineral soil acidification as Norway spruce and Scots pine: results of a repeated site assessment after 63 and 82 years of forest conversion in Central Germany. For Ecol Manage. 2021;483: 118769.
21. Nicoll BC, Gardiner BA, Rayner B, Peace AJ. Anchorage of coniferous trees in relation to species, soil type, and rooting depth. Can J For Res. 2006;36(7):1871–83.
22. Artz RR, Chapman SJ, Robertson AJ, Potts JM, Laggoun-Défarge F, Gogo S, et al. FTIR spectroscopy can be used as a screening tool for organic matter quality in regenerating cutover peatlands. Soil Biol Biochem. 2008;40(2):515–27.
23. Laudicina VA, Novara A, Barbera V, Egli M, Badalucco L. Long-term tillage and cropping system effects on chemical and biochemical characteristics of soil organic matter in a Mediterranean semiarid environment. Land Degrad Dev. 2015;26(1):45–53.
24. Pärnpuu S, Astover A, Tõnutare T, Penu P, Kauer K. Soil organic matter qualification with FTIR spectroscopy under different soil types in Estonia. Geoderma Reg. 2022;28: e00483.
25. Hammond RF, Brennan LE. Soils of Co. Offaly. Soil Survey Bulletin 2003;43.
26. Sparks DL, Page AL, Helmke PA, Loeppert RH. Methods of soil analysis, part 3: Chemical methods, vol. 14. John Wiley & Sons. 2020.
27. Niemeyer J, Chen Y, Bollag JM. Characterization of humic acids, composts, and peat by diffuse reflectance Fourier-transform infrared spectroscopy. Soil Sci Soc Am J. 1992;56(1):135–40.
28. Gondar D, Lopez R, Fiol S, Antelo JM, Arce F. Characterization and acid–base properties of fulvic and humic acids isolated from two horizons of an ombrotrophic peat bog. Geoderma. 2005;126(3–4):367–74.
29. Senesi N, Loffredo E. The chemistry of soil organic matter. In: Sparks DL, editor. Soil physical chemistry. London: CRC Press; 2018. p. 239–370.
30. Francioso O, Sanchez-Cortes S, Bonora S, Roldán ML, Certini G. Structural characterization of charcoal size-fractions from a burnt Pinus pinea forest by FT-IR, Raman and surface-enhanced Raman spectroscopies. J Mol Struct. 2011;994(1–3):155–62.

31. Hladkỳ J, Pospíšilová L, Liptaj T. Spectroscopic characterization of natural humic substances. J Appl Spectrosc. 2013;80:8–14.
32. Zaccheo P, Cabassi G, Ricca G, Crippa L. Decomposition of organic residues in soil: experimental technique and spectroscopic approach. Org Geochem. 2002;33(3):327–45.
33. Ellerbrock RH, Gerke HH, Böhm C. In situ DRIFT characterization of organic matter composition on soil structural surfaces. Soil Sci Soc Am J. 2009;73(2):531–40.
34. Matějková Š, Šimon T. Application of FTIR spectroscopy for evaluation of hydrophobic/hydrophilic organic components in arable soil. Plant Soil Environ. 2012;58(4):192–5.
35. Chefetz B, Chen Y, Hadar Y. Purification and characterization of laccase from *Chaetomium thermophilium* and its role in humification. Appl Environ Microbiol. 1998;64(9):3175–9.
36. Lehmann J, Kleber M. The contentious nature of soil organic matter. Nature. 2015;528(7580):60–8.
37. Marín-Spiotta E, Gruley KE, Crawford J, Atkinson EE, Miesel JR, Greene S, et al. Paradigm shifts in soil organic matter research affect interpretations of aquatic carbon cycling: transcending disciplinary and ecosystem boundaries. Biogeochemistry. 2014;117:279–97.
38. Dick DP, Gonçalves CN, Dalmolin RS, Knicker H, Klamt E, Kögel-Knabner I, et al. Characteristics of soil organic matter of different Brazilian Ferralsols under native vegetation as a function of soil depth. Geoderma. 2005;124(3–4):319–33.
39. Kotroczó Z, Juhos K, Biró B, Kocsis T, Pabar SA, Varga C, et al. Effect of detritus manipulation on different organic matter decompositions in temperate deciduous forest soils. Forests. 2020;11(6):675.
40. Tang X, Wang YP, Zhou G, Zhang D, Liu S, Liu S, et al. Different patterns of ecosystem carbon accumulation between a young and an old-growth subtropical forest in Southern China. Plant Ecol. 2011;212:1385–95.
41. Huang YH, Li YL, Xiao Y, Wenigmann KO, Zhou GY, Zhang DQ, et al. Controls of litter quality on the carbon sink in soils through partitioning the products of decomposing litter in a forest succession series in South China. For Ecol Manage. 2011;261(7):1170–7.
42. Verstraeten G, Vancampenhout K, Desie E, De Schrijver A, Hlava J, Schelfhout S, et al. Tree species effects are amplified by clay content in acidic soils. Soil Biol Biochem. 2018;121:43–9.
43. Crow SE, Lajtha K, Filley TR, Swanston CW, Bowden RD, Caldwell BA. Sources of plant-derived carbon and stability of organic matter in soil: implications for global change. Glob Change Biol. 2009;15(8):2003–19.
44. Zech W, Guggenberger G, Haumaier L, Pöhhacker R, Schäfer D, Amelung W, et al. Organic matter dynamics in forest soils of temperate and tropical ecosystems. Humic Subst Terr Ecosyst. 1996. https://doi.org/10.1016/B978-044481516-3/50004-9.
45. Monreal CM, Schnitzer M, Schulten HR, Campbell CA, Anderson DW. Soil organic structures in macro and microaggregates of a cultivated brown chernozem. Soil Biol Biochem. 1995;27(6):845–53.
46. Perdana LR, Ratnasari NG, Ramadhan ML, Palamba P, Nugroho YS. Hydrophilic and hydrophobic characteristics of dry peat. IOP Conf Ser Earth Environ Sci. 2018;105: 012083.
47. Apori SO, Mcmillan D, Giltrap M, Tian F. Mapping the restoration of degraded peatland as a research area: a scientometric review. Front Environ Sci. 2022;10: 942788.
48. Liu W, Fritz C, van Belle J, Nonhebel S. Production in peatlands: Comparing ecosystem services of different land use options following conventional farming. Sci Total Environ. 2023;875: 162534.
49. Esperschütz J, Zimmermann C, Dümig A, Welzl G, Buegger F, Elmer M, et al. Dynamics of microbial communities during decomposition of litter from pioneering plants in initial soil ecosystems. Biogeosciences. 2013;10(7):5115–24.
50. Cuypers C, Grotenhuis T, Nierop KG, Franco EM, de Jager A, Rulkens W. Amorphous and condensed organic matter domains: the effect of persulfate oxidation on the composition of soil/sediment organic matter. Chemosphere. 2002;48(9):919–31.
51. Lorenz K, Preston CM, Raspe S, Morrison IK, Feger KH. Litter decomposition and humus characteristics in Canadian and German spruce ecosystems: information from tannin analysis and 13C CPMAS NMR. Soil Biol Biochem. 2000;32(6):779–92.
52. Špulák O, Kacálek D, Bartoš J, Leugner J. The early impact of mixed canopies with Norway spruce, European beech and silver fir on a new forest floor. Eur J Forest Res. 2023;142(4):851–63.
53. Uri V, Kukumägi M, Aosaar J, Varik M, Becker H, Aun K, et al. Litterfall dynamics in Scots pine (Pinus sylvestris), Norway spruce (Picea abies) and birch (Betula) stands in Estonia. For Ecol Manage. 2022;520: 120417.
54. Prescott CE, Vesterdal L. Decomposition and transformations along the continuum from litter to soil organic matter in forest soils. For Ecol Manage. 2021;498: 119522.
55. Yang J, Mu J, Zhang Y, Fu C, Dong Q, Yang Y, et al. Initial carbon quality of newly shed foliar litter in an Alpine forest from proximate analysis and 13C NMR spectroscopy perspectives. Forests. 2022;13(11):1886.