Impact of charcoal and tree species on forest soil recovery after fire disturbance

Thi Hong Van Tran
tran.thi.hong.van@student.urk.edu.pl

University of Agriculture in Krakow: Uniwersytet Rolniczy im Hugona Kollataja w Krakowie
https://orcid.org/0009-0006-4427-7089

Bartłomiej Woś
Tomasz Wanic
Marcin Pietrzykowski
Agnieszka Józefowska

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Abstract

Background and aims

Charcoal and tree species are among the main factors influencing forest soil recovery after fire disturbance. This study investigates the impact of charcoal on the podzolization process and examines the effects of different tree species on soil properties in post-fire sites.

Methods

Research plots were established in pure stands of Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), silver birch (*Betula pendula* Roth), and pedunculate oak (*Quercus robur* L.) in two variants: with and without charcoal removal before tree planting. Soil samples were collected from various horizons and analyzed for various physical and chemical soil properties. The study utilized principal component analysis, correlation, and graphical representations prepared with Canoco 5 and R software to analyze the data.

Results

The presence of charcoal significantly accelerated the podzolization process, particularly under pine and birch stands. Tree species were found to distinctly affect soil formation, with pine and birch promoting more acidic conditions conducive to podzolization, while oak and larch had a more neutral effect. The comparison of soil classification systems revealed that the World Reference Base for Soil Resources more effectively captured the variations in soil properties influenced by tree species and charcoal compared to the USDA Soil Taxonomy.

Conclusion

Charcoal and tree species play crucial roles in post-fire soil recovery. The retention of charcoal can accelerate podzolization, especially under specific tree species, impacting soil classification and management strategies in fire-prone areas.

Introduction

The study of post-fire forest ecosystems has garnered considerable interest due to the ecological and environmental implications of forest fires. Forest fires can significantly alter the composition and structure of forest soils, which, in turn, affects nutrient cycling, soil fertility, and vegetation regrowth (Agbeshie et al. 2022). One consideration of post-fire forest management is the decision to retain or remove charcoal from the affected areas. Charcoal, a byproduct of incomplete combustion, has been shown to affect soil properties and processes, including podzolization, which is the leaching of organic matter and metals from the upper soil horizons to lower layers (Pánik 2013; Soucémarianadin et al. 2014).

The effects of retaining charcoal in the soil post-fire have varying implications for soil recovery. On one hand, charcoal can enhance soil carbon content and stabilize soil structure, thereby promoting soil fertility and plant growth (Makoto et al. 2011). Charcoal can influence the retention of various substances, potentially affecting podzolization (Pluchon et al. 2014). Conversely, charcoal, due to its extensive structure, affects passively the retention of nutrients, maybe the availability of nutrients is lower. However, the question of how to remove or not to remove charcoal after forest fires affects the process of soil recovery remains open.

In this study, we focus on four tree species— Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), silver birch (*Betula pendula* Roth), and pedunculate oak (*Quercus robur* L.)—to better understand how charcoal retention or removal influences soil properties and forest recovery. Due to their significance in temperate forest ecosystems, both ecologically and economically, as well as their varying responses to fire and soil conditions, these species were selected for this study. Scots pine is notable for its resilience and ability to thrive in diverse soil conditions, including poor, sandy soils, quickly re-establishing to provide essential ground cover and prevent erosion. Its deep root system stabilizes the soil, and its fallen needles contribute organic matter, enhancing soil fertility (Durrant et al. 2016). European larch, a deciduous conifer, sheds its needles annually, accumulating organic matter on the forest floor to improve soil fertility and structure. Its rapid growth and extensive root system further stabilize soil and retain water (da Ronch et al. 2016). Silver birch, as a pioneer species, quickly colonizes open areas post-fire, thriving in poor soils and providing initial soil stabilization. The leaf litter from birch trees decomposes rapidly, enhancing nutrient cycling and soil structure (Beck et al. 2016). Although pedunculate oak establishes more slowly, it plays a crucial role in long-term soil recovery. Oak trees significantly contribute to soil organic content through leaf litter and deep-root systems, aiding in nutrient cycling, soil aeration, and enhancing soil stability and water infiltration (Eaton et al. 2016). However, fewer studies have assessed the influence of different forest tree species on the formation of forest soil after fire.

In this study, we use both the United States Department of Agriculture (USDA) Soil Taxonomy and the World Reference Base for Soil Resources (WRB) for soil classification. These systems provide a comprehensive framework for understanding soil characteristics and processes, with the USDA Soil Taxonomy system offering detailed criteria for soil classification based on soil properties, while the WRB system provides a global perspective, facilitating comparison across different regions and ecosystems (Sanjari et al. 2021).

Our research aims to elucidate the impacts of charcoal on soil properties and podzolization processes under different tree species, contributing to the broader understanding of post-fire forest management and soil conservation practices. By comparing the effects of charcoal retention and removal, we seek to inform forest management strategies that enhance soil health and forest resilience in fire-prone areas.

Materials and methods

Study area

The research study was carried out in the Rudziniec forest district, which was severely impacted by a forest fire in August 1992. This event was one of the largest fires in Central Europe after World War II and resulted in the death of over 75% of the trees and extensive exposure of mineral soil. The fire occurred near the village of Kuźnia Raciborska and affected a total of 9062 hectares of land, including 8461 hectares of forestland, primarily composed of moderately moist and humid mixed pine-oak forests. Specifically, 2154.3 hectares of forest were burned in the Rudziniec area. Following the fire, the remaining trees were cut, the wood/logs extracted, and the site was replanted. The research site is located at N50°17’28.69”; E18°25’3.554” and experiences an average annual temperature of 9.6°C and a mean annual precipitation of 567 mm, based on data collected from meteorological stations between 1990 and 2019 (Woś et al. 2023).

Experimental design and soil sampling

The research plots was located in four pure stands of tree species: Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), silver birch (*Betula pe*ndula Roth), and pedunculate oak (*Quercus robur* L.). Based on the data obtained from the Rudziniec Forest District, research areas were selected according to the treatments carried out after the fire and before afforestation. This approach allowed for the establishment of two treatment variants: plots with charcoal retained and plots with charcoal removed. Each variant was established in pure stands of the four tree species, resulting in eight distinct plot types.

The trees selected for this study were 30 years old. This work presents data from the surfaces where the soil pits were described, providing comprehensive insights into the effects of charcoal retention and tree species on soil properties. Soil pits were dug and described according to the FAO Guidelines (Jahn et al. 2006) and then were classified according to the United States Department of Agriculture Soil Taxonomy (Soil Survey Staff 2022) and the World Reference Base for Soil Resources (IUSS Working Group WRB 2022). Soil samples were collected from each horizon for detailed physical and chemical analyses.

Soil Sampling and Analysis: Soil samples were air-dried and sieved through a 2 mm mesh before analysis. Soil texture was analyzed using a Fritsch GmbH Laser Particle Sizer ANALYSETTE 22, which measures the distribution of soil particle sizes. Soil pH was measured potentiometrically in both H_2O and 1 M KCl solutions at a 1:2.5 soil-to-solution ratio. The content of total organic carbon (C%) was measured using the dry combustion method with a TruMAc®- CNS analyzer; samples containing carbonates were pre-treated with 10% HCl to remove inorganic carbon. Cation-exchange capacity (CEC) was determined by extracting the cations with 1M CH_3COONH_4 and measuring them using a spectrometer (CP OES ICAP 6000 Series). Iron forms were analyzed following the methods of Courchesne and Turmel (2007): total extractable iron (Fe^{3+}) was determined using a mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a ratio of 1:3; amorphous and poorly crystalline iron forms (free Fe^{3+}) were measured using the acid ammonium oxalate method; organically bound iron (active Fe^{3+}) was assessed using the sodium pyrophosphate method; and total extractable iron (Fe^{2+}) was determined using the dithionite-citrate method.

Data analysis

Data collected from the field and laboratory analyses were subjected to statistical analysis using R Statistical Software (version 4.3.2; R Core Team 2023) and Canoco (version 5.0; Ter Braak and Šmilauer 2012). Principal Component Analysis (PCA) was carried out to reduce the dimensionality of the data and to identify the main factors contributing to the variability in soil properties. Correlation analysis was conducted to examine the relationships between different soil parameters. Graphical representations were generated to visualize the results and to facilitate the interpretation of the data using the 'ggplot2' R package (version 3.5.1; Wickham 2016).

Results

Soil morphology

The horizons of the soilpits analyzed in this study exhibit no variation in the nomenclature of horizons when classified according to the USDA Soil Taxonomy (ST) and the World Reference Base for Soil Resources (WRB) (Fig. 1).

The soil surface is adorned with a layer of forest litter and humus (H horizon), collectively varying in total thickness from 1 to 5 cm (Table 1). At the surface, the soils exhibit an A horizon, characterized by varying degrees of organic matter accumulation and biological activity. All A horizons exhibit colors ranging from dark to very dark grayishbrown. In areas where charcoal was not removed after a fire, the A horizons are notably thicker, ranging from 8 to 15 cm, compared to those in areas where charcoal was removed, which range from 4 to 10 cm in thickness.

Table 1
Soil profile characteristics with and without charcoal removal across four tree species

	Tree species	Horizon ST/WRB	Depth (cm)	Color	Structure	Texture	Moisture	Root
Without charcoal removal	Pine	H	4 – 0	10YR 2/1	subangular moderate weak	sand	moderate	common
		A	0–12	10YR 5/2	single grain	sand	fresh	few
		AE	12–22	7.5YR 5/6	subangular weak	sand	fresh	few
		Bhs	22–34	10YR 6/8	single grain	sand	fresh	very few
		BC	34–65	5YR 4/8,	single grain/subangular weak-Fe)	sand	moderate	none
		C	65–160	10YR 6/8				
	Larch	H	3 – 0	10YR 2/1	subangular weak	sand	moderate	common
		A	0–15	10YR 4/1	single grain	sand	fresh	few
		E	15–30	5YR 2/3	pedogenic, formed by cementation from precipitates of iron	loamy sand	fresh	few
		Bh	30–40	5YR 2/3,	single grain	sand	fresh	none
		Bhs	40–85	10YR 6/3	single grain	sand	moderate	none
		C	85–150	10YR 6/3				
	Birch	H	3 – 0	7.5YR 1.7/1	subangular weak	loamy sand	fresh	common
		A	0–8	7.5YR 4/2	single grain	sand	fresh	few
		AE	8–16	5YR 4/6	subangular	sand	fresh	few
		Bhs	16–35	10YR 6/8	single grain	sand	moderate	very few
		BC	35–80	10YR 7/6	single grain	sand	moderate	none
		C	80–150					
	Oak	H	1 – 0	10YR 2/2	moderate subangular	sandy loam	moderate	common
		A	0–10	10YR 5/2	single grain	sand	moderate	few
		AE	10–18	5YR 3/4	moderate subangular	sand	moderate	common
		Bhs	18–35	10YR 6/6	single grain	sand	fresh	few
		BC				sand	moderate	very few

	Tree species	Horizon ST/WRB	Depth (cm)	Color	Structure	Texture	Moisture	Root
		C	35–85	10YR 7/3	single grain			
			85–150					
With charcoal removal	Pine	H	2 – 0	10YR 2/1	subangular weak	sand	moderate	many
		A	0–5	7.5YR 4/1	single grain	sand	moderate	few
		E	5–12	7.5YR 4/6	single grain	sand	fresh	common
		Bhs	12–25	10YR 6/8	single grain	sand	fresh	very few
		BC	25–80	10YR 7/3	single grain	sand	moderate	none
		C1	80–130	5YR 6/8	single grain	sand	moderate	none
		C2	130–180					
	Larch	H	5 – 0	10YR 2/1	weak	sand	fresh	many
		A	0–6	10YR 5/1,	weak	sand	fresh	common
		BE	6–32	7.5YR 5/8	weak	sand	fresh	few
		BC	32–70	10YR 6/8	single grain	sand	wet	none
		C	70–150	10YR 7/4				
	Birch	H	3 – 0	10YR 2/2	subangular weak	loamy sand	moderate	common
		A	0–4	10YR 5/2	single grain	sand	fresh	few
		E	4–12	7.5YR 4/6	subangular weak	sand	fresh	common
		Bhs	12–30	10YR 6/8	single grain	sand	fresh	few
		BC	30–60	10YR 7/4, 5YR 6/8	single grain	sand	moderate	very few
		C1	60–125	10YR7/3	single grain	sand	moderate	none
		C2	125–160			sand		
	Oak	H	5 – 0	7.5YR 3/1	subangular	sand	fresh	many
		A	0–10		subangular	sand	fresh	many

Tree species	Horizon ST/WRB	Depth (cm)	Color	Structure	Texture	Moisture	Root
	E	10–30	7.5YR 4/1	subangular/single grain	sand	fresh	common
	E2	30–62	7.5YR 6/1	subangular	sand	moisture	few
	Bh	62–77	7.5YR 4/3	subangular/single grain	sand	wet	very few
	Bhs	77–97	7.5YR 4/4	single grain	sand		none
	C	97–150	10YR 6/4				

Below the A horizon lies the eluvial horizon E, where leaching processes have resulted in the removal of clay, iron, and organic compounds, leading to a depletion of these materials from the soil matrix. E horizons, including AE and BE subhorizons, display hues ranging from brown-gray to gray. In regions with charcoal presence, the eluvial horizons range in thickness from 8 to 15 cm. Conversely, in areas without charcoal, there is considerable variability in the thickness of the E horizons, ranging from 7 to 52 cm. The profile collected under larch soil lacks an E horizon, featuring only an BE horizon that exhibits characteristics more akin to the B horizon than the E horizon. The determination of the E horizon is hindered by its limited presence, presenting challenges in delineation.

Following the eluvial horizon is the spodic horizon B, which is often associated with the translocation of these materials from the overlying layers. The spodic horizons occur within 100 cm from mineral soil surface, starting at depths ranging from 6 to 62 cm and having thicknesses measuring between 12 and 55 cm (including the Bh and Bhs horizons). The spodic horizon comprises a mixture of humic matter, such as decomposed plant material, as well as iron and aluminum oxides. These components contribute to the formation of distinctive color patterns, ranging from yellow-red hues (Hue 10YR, Hue 7.5YR, Hue 5YR, following the Munsell color system), indicative of iron oxides, in conjunction with organic richness. In areas featuring charcoal presence, coloration typically appears darker and more reddish, varying according to the tree species. Predominantly, a 5YR hue is prevalent across most profiles (birch, larch, and oak), while pine exhibits a light yellowish-red hue (Hue 7.5YR 5/6). Conversely, in regions devoid of charcoal, colors tend to be lighter and more yellowish, often with at least one subhorizon displaying a 7.5YR hue and a value of ≤ 5.

The transition horizon BC, situated between the spodic horizon and the mineral-rich C horizon, serves as an intermediary zone exhibiting characteristics of both the spodic (B) and mineral (C) horizons. This transitional layer facilitates the gradual shift from the distinct features of the spodic horizon to those of the underlying C horizon. However, the gradual transition inherent in the formation of spodic horizons, along with the presence of the transition horizon BC, introduces complexities that can hinder the precise determination of spodic horizon thickness.

Finally, the lowest layer is C horizon, characterized by the presence of parent material not involved in any soil-forming processes, lacking the distinct organic and mineral features observed in the overlying horizons. This horizon acts as a substrate for the growth of the upper horizons and is crucial for the formation of soil.

In the analyzed profiles, sand texture predominates across almost all horizons, with occasional occurrences of loamy sand or sandy loam observed, particularly in A or Bh horizons, especially in areas with charcoal presence. The formation of subangular structures, notably weak in A, Bh, and Bhs horizons, can be attributed to several factors, including the influence of organic matter decomposition, root activity, and soil disturbance (Fig. 2).

In the upper horizons (A), where organic matter accumulation is prevalent, decomposition processes contribute to the weakening of structural integrity, resulting in subangular structures. Additionally, the presence of roots further disrupts soil aggregates, leading to the formation of weaker structures (Table 1).

As soil depth increases, single grain structures become more prevalent, with fewer occurrences of aggregates observed in the E horizon. However, in the B horizon, where processes such as illuviation and organic matter accumulation are more pronounced, aggregate formation is more prevalent. Roots are commonly found in the A horizon, with their abundance decreasing from A to E, and then increasing from E to B, and becoming very few or absent from BC to C horizons.

In areas where larch is present alongside charcoal, the soil structure exhibits a pedogenic nature, formed by cementation from precipitates of iron. This process contributes to the development of aggregated structures, enhancing soil stability and resilience.The cation exchange capacity (CEC) of the studied soil profiles is relatively low, attributable to their sandy texture. There is a parallel trend observed between CEC and accumulated carbon content (C%), with higher values present in the A horizons. This is followed by a reduction in accumulation within the E horizons and a subsequent increase in the spodic horizons (Fig. 3).

The iron forms (Fe%) extracted by various methods reveals variability, indicating the intricate nature of iron in these soils. The near-perfect correlation coefficients (close to 1) suggest that the different extraction methods yield iron measurements that are highly interrelated. For instance, total Fe^{3+} has a correlation of 0.959 with free Fe^{3+}, indicating that these two forms of iron are likely to increase or decrease together in the soil samples. The high correlation of 0.968 between total Fe^{3+} and total Fe^{2+} supports the notion that these iron forms are influenced similarly by soil conditions and tree species. The strong correlations between different iron forms suggest that they could be used interchangeably as indicators of soil forming processes and soil quality in post-fire forest soils (Fig. 4).

The biplot analysis integrates soil property measurements from the spodic (_B) and albic (_E) horizons under pine, larch, birch, and oak trees in two distinct experimental areas: PFC, where char remains post-fire, and PF, where charcoal has been removed (Fig. 5).

The PCA biplot illustrates that the first principal component (PC1) accounts for 64.9% of the variance, while the second principal component (PC2) explains an additional 21.7%. PC1 captures the variance predominantly associated with soil texture (sand and clay content) and organic matter content (C%), which are critical factors in post-fire soil recovery. PC2 appears to reflect the acidity (pH_{H2O} and pH_{KCl}) and various iron forms extracted using different methods, indicating the chemical changes post-fire.

The soil profiles exhibit strong acidity throughout all horizons (Fig. 3). As shown in Fig. 5, vectors ending in _B or _E denote the horizon from which the soil sample was taken, with _E likely representing the albic horizon's higher acidity and lower nutrient content compared to the spodic horizon (_B). The direction and length of vectors such as 'Birch_PFC_E' suggest a strong influence of Birch in the albic horizon on the soil's sand content and pH levels in the PFC area.

Soil classification on the USDA Soil Taxonomy

The soil pedons that were analyzed all exhibited distinct characteristics of spodic horizons, where amorphous mixtures of organic matter and aluminum, along with iron and/or manganese, had accumulated. The properties described (depth, thickness, color, texture, etc.) of these spodic horizons were entirely consistent with the classification standards for the Spodosol order according to the USDA Soil Taxonomy.

The upper part of the soil profile consists of an eluvial horizon that lies above the spodic horizon, and it is not characterized by a plaggen epipedon/argillic/kandic horizon, permafrost, or both permafrost and gelic materials, which are common features of the Alfisols and Ultisols orders and the Gelisols order, respectively. The analyzed pedons meet the criteria for mineral soils and are classified as Spodosols, which is distinct from the Histosols order.

Among the eight pedons examined, the one located in the larch forest soil area that did not remove charcoal after fire has a spodic horizon that is 10 cm thick and contains 6.38% organic carbon. Consequently, this pedon is classified as Humods (suborder), Haplohumods (great group) and Typic Haplohumods (subgroup) (Fig. 6).

The remaining seven pedons have a moderate amount of organic carbon in their spodic horizons, which classifies them as Orthods (suborder). The pedon in the larch forest soil area that removed charcoal after fire is classified as Haplorthods (great group) and Aquentic Haplorthods (subgroup) due to its redoximorphic features within 75 cm of the mineral soil surface, aquic conditions, and coarse sand texture class in the upper 2.5 cm of Hue 10YR 5/1 according to Munsell.

The remaining pedons that have a spodic horizon with a texture class of coarse sand and either or both a moist color value or chroma of 4 or more in the upper 2.5 cm are classified into the great groups and subgroups of Haplorthods and Entic Haplorthods, respectively.

Soil classification on the World Reference Base for Soil Resources

According to the World Reference Base (WRB), the Reference Soil Group (RSG) Podzols are characterized by a spodic horizon. The soil layers in all the pedons exhibit strong acidity. These acidic conditions promote podzolization, as evidenced by lower pH values in the A and E horizons compared to the lower horizons. The shift in organic matter content and exchangeable cations between horizons clearly aligns with the traits of Podzols. Additionally, differences in iron content between eluvial and illuvial horizons suggest the occurrence of podzolization processes.

All eight analyzed pedons exhibit an albic horizon situated within the uppermost 100 cm of the mineral soil. They also comprise mineral material with a sandy or loamy sand texture in most layers, with a cumulative thickness surpassing 30 cm. Given these characteristics, all eight pedons are classified as principal qualifier Albic with the supplementary qualifier Arenic (Fig. 7).

The larch forest soil area pedon that did not remove charcoal after fire displays a spodic horizon with a subhorizon that is cemented ('ortstein') to a moderately cemented degree across at least 50% of its horizontal extent. As this subhorizon does not fulfill the Placic qualifier's diagnostic criteria, it is additionally classified as principal qualifier Ortsteinic.

The larch forest soil area pedon that removed charcoal after fire presents a layer at least 25 cm thick, beginning within 75 cm of the mineral soil surface. This layer does not form part of a hydragric horizon, exhibits stagnic properties, and possesses reducing conditions in certain parts of its volume containing reductimorphic features. As a result, it is classified as Stagnic with the principal qualifier.

Discussion

Charcoal affects the podzolization process

According to Barrett (1997), soil pedons under post-fire forests show strong development of spodic horizons, especially the Bhs horizon, where there is accumulation of organic compounds and sesquioxides (iron and aluminum). Litter from forest trees produces organic acids, which can promote the formation of ortstein and Bhs horizons. The presence of these acids from leaves and other organic matter may enhance podzolization by promoting the movement of iron and aluminum into the B horizons.

Pluchon et al. (2015) discovered evidence of charcoal's ability to act as a long-term but not entirely inert source of carbon. The study suggested that charcoal's presence could influence soil organic matter dynamics and nutrient availability, potentially enhancing the decomposition of organic matter and the mobilization of nutrients, which are crucial processes in podzolization. Podzolization is characterized by the leaching of organic matter, iron, and aluminum from the upper horizons and their accumulation in the lower horizons. In the studied profiles, soils with post-fire charcoal presence exhibited thicker A horizons and more pronounced spodic (B) horizons. This may be due to this horizons not being destroyed during charcoal removal. This reduction in depth was accompanied by a noticeable increase in the clarity and abruptness of horizon boundaries, suggesting a faster leaching of organic matter and mobilization of metal oxides. Charcoal residue, as discovered by Soucémarianadin et al. (2014), can positively impact soil horizon thickness by boosting organic carbon content, improving soil structure, and fostering microbial activity. Specifically, charcoal can raise the organic carbon content in soil horizons, especially in podzolic B horizons. This increased carbon content can lead to thicker soil layers because of an increase in organic matter, which enhances soil structure and stability. Charcoal has the ability to create organo-mineral complexes, which safeguard organic carbon from decomposition and improve the physical structure of the soil, making it more porous and better able to retain water. This can result in long-term accumulation of organic matter in the soil, causing soil layers to thicken over time, particularly in areas with high humidity. Additionally, the presence of charcoal can alter the podzolization process, affecting how nutrients and water move through the soil layers. This can result in the formation of new soil horizons or changes in the thickness of existing horizons. On the other hand, charcoal provides a habitat for microorganisms, helping to enhance decomposition and nutrient cycling in the soil. Elevated microbial activity can lead to the formation of thicker soil layers due to the accumulation of organic decomposition products.

Bekchanova et al. (2024) also found that biochar contributes to the improvement of the nutrient cycle in sandy-textured soils, which is consistent with the current study's results that show enhanced material translocation in soils containing charcoal. Furthermore, the data indicates that podzolization involves leaching carbon and iron from the uppermost soil horizons, rather than retaining them.. Soils with charcoal exhibited darker hues, primarily 5YR, indicative of higher concentrations of organic matter and iron oxides. These elements not only facilitate the translocation of materials within the soil profile but also contribute to the formation of distinct spodic horizons. The presence of darker and more reddish hues in the spodic horizons of birch, larch, and oak soils, compared to the lighter hues in pine soils without charcoal, further underscores charcoal's role in accelerating these processes.

Preston and Schmidt (2006) highlighted the role of charcoal in enhancing soil organic carbon content and its influence on soil chemical processes. Their research showed that charcoal could act as a persistent source of organic carbon, which stabilizes soil structure and promotes the formation of spodic horizons. This aligns with the current findings where charcoal-rich soils exhibited darker, more stable horizon profiles indicative of advanced podzolization.

Moreover, findings from the studies by Buurman et al. (2008) and Czimczik et al. (2005) support these observations. Buurman et al. (2008) highlighted that the presence of pyrogenic carbon, resulting from fire events, can significantly alter soil properties. They observed that soils with charcoal showed an increase in soil organic carbon and nutrient content, which enhances soil fertility and structure. This improved structure can facilitate the movement of water and solutes, accelerating processes like podzolization. Furthermore, Czimczik et al. (2005) noted that pyrogenic carbon plays a critical role in the carbon cycle by providing a stable carbon pool that can persist for long periods, influencing soil organic matter dynamics and nutrient availability.

Similarly, Dymov and Gabov (2015) discussed how fire-induced changes in soil, including the addition of pyrogenic carbon, impact soil physical and chemical properties. Their research showed that post-fire soils exhibited changes in texture, porosity, and water retention capacity, all of which are important for processes like podzolization. The presence of charcoal and pyrogenic carbon can increase soil acidity and influence the mobility of metals like iron and aluminum, critical components in podzolization.

Tree species affect soil formation process

According to Lundstrom et al. (2000), the influence of coniferous forest soils on the podzolization process is significant when compared to other forest types. Coniferous forests typically produce a substantial amount of organic matter from fallen needles and other plant materials, creating an environment rich in organic acids. These low molecular weight organic acids, such as citric and oxalic acids, play a crucial role in dissolving and mobilizing essential minerals like aluminum and iron within the soil. The acidic nature of coniferous forest soils, often characterized by lower pH levels compared to other forest types, also facilitates the dissolution of minerals and enhances the mobility of aluminum and iron. This increased acidity can lead to a more pronounced formation of the illuvial B horizon, where aluminum and iron accumulate, a phenomenon that may not be as pronounced in other forest ecosystems. Additionally, mycorrhizal fungi associated with coniferous trees contribute to this process by creating numerous small pores in weatherable mineral grains, enhancing weathering. These fungi exude organic acids that further increase the solubility of minerals, thereby promoting podzolization.

The current research demonstrates that the species of tree significantly impact the development and characteristics of soil horizons. For instance, soils under pine (*Pinus sylvestris* L.) exhibit a distinct pattern with a relatively thick A horizon (0–12 cm) and pronounced Bhs and BC horizons, suggesting robust organic matter accumulation and podzolization processes. In contrast, soils under larch (*Larix decidua* Mill.) have deeper E and Bhs horizons, implying more intensive leaching and eluviation processes. Birch (*Betula pendula* Roth) soils exhibit a well-developed A horizon but also show significant Bhs horizon formation, indicating strong podzolization processes. Oak (*Quercus robur* L.) soils are characterized by a thicker A horizon and multiple E horizons, indicating pronounced eluviation of clay, organic matter, and iron oxides. Research by Chodak and Niklińska (2010) shows that different tree species can significantly affect the physicochemical properties of soil. Specifically, soils under Scots pine (*Pinus sylvestris*) have the lowest content of organic carbon (C_{org}) and total nitrogen (N_t), and the highest C_{org}/N_t ratio. This can lead to slower organic matter decomposition and affect soil microbial activity.

Conversely, soils under silver birch (*Betula pendula*) have higher pH, C_{org}, and N_t, as well as higher basal respiration rates and microbial activity, indicating a positive impact of birch on soil microbes. Devi (2021) highlights how different tree species influence soil carbon storage, with coniferous trees typically leading to greater soil carbon sequestration compared to deciduous trees. Woś et al. (2023) also reported that soils under pine had less stable soil organic matter than those under birch and alder, which may accelerate podzolization processes. These findings support the observed higher organic carbon content in birch and oak soils within this study.

The chemical properties of the soil also differ significantly among tree species. The data from the study indicate variations in pH, carbon content, cation exchange capacity (CEC), and iron forms (total Fe^{3+}, free Fe^{3+}, active Fe^{3+} and total Fe^{2+}) across different tree species. Pine soils, for example, typically have lower pH values and higher iron concentrations, indicating stronger podzolization effects and more acidic conditions. Conversely, larch soils exhibit lower carbon content and CEC, while birch and oak soils have higher organic carbon and CEC values, which can be linked to the higher quality and quantity of litterfall from these species. Howard et al. (1998) also noted that soils under oak (*Quercus* spp.) and birch (*Betula* spp.) forests show differences in the composition and characteristics of soil organic matter, reflecting the impact of plant litter from these tree species. Studies by Augusto et al. (2002) suggest that coniferous species like pine generally lead to more acidic soils with higher leaching rates, whereas Gurmesa et al. (2013) reported that total soil C stocks were significantly higher under conifers like larch than under oak. To reconcile this discrepancy, the study by Gan et al. (2020) emphasizes that in nutrient-poor regions, soil stoichiometry is affected by forest type and tree species, which leads to higher DOC leaching under coniferous forests. In other regions, tree species affect nutrient leaching through mechanisms not directly related to soil stoichiometry. As nutrient scarcity increases, microbes produce more CO_2 and DOC, driving nutrient leaching. Forest management primarily impacts nutrient cycling through the choice of tree species rather than soil nutrient balance. Research by Liu et al. (1998) cited in Chodak et al. (2010) also shows that larch species such as *Larix gmelinii* can reduce soil quality compared to mixed conifer-deciduous forests.

The existence of various iron forms indicates the extent to which soil formation processes are influenced by tree species. The higher concentrations of free Fe^{3+} and active Fe^{3+} in birch and oak soils suggest more active iron mobilization and complexation, which are essential for podzolization. These chemical variations emphasize the role of tree species in modifying soil chemistry through their unique litter and root exudates, which affect nutrient cycling and soil organic matter dynamics. Vesterdal et al. (2008) demonstrated that tree species diversity influences soil organic matter decomposition rates and nutrient mineralization, which corroborates the variations in organic matter content and iron mobilization observed in the present study, where different tree species foster unique soil environments conducive to specific biochemical processes.

Soil classification: USDA Soil Taxonomy vs. World Reference Base for Soil Resources

Both soil taxonomy systems, the USDA Soil Taxonomy (ST) and the World Reference Base for Soil Resources (WRB), offer frameworks for classifying soils, yet they differ in their approaches and criteria, leading to varied interpretations and classifications of soil properties observed in the field. The ST, primarily employed in the United States, emphasizes horizon differentiation and specific diagnostic features such as texture, structure, and organic matter content. In contrast, the WRB focuses on broader soil properties, including climatic and geographical influences, and is internationally recognized.

The correlation between the Soil Taxonomy and the WRB is only partial, as the two systems start from different classification strategies. The USDA soil taxonomy's detailed horizon-based approach allows for a precise classification of soils with distinct horizon boundaries, such as those observed in the pine and oak profiles. For instance, the presence of a thick A horizon and well-defined spodic horizons in pine soils is accurately captured by the ST, reflecting its emphasis on horizon morphology and specific diagnostic criteria. Conversely, the WRB system's broader categories may group these soils into less specific classes, potentially overlooking finer distinctions critical for understanding local soil dynamics.

Conclusion

This research discloses that in certain climate conditions and regenerating forests, the removal of charcoal and the choice of tree species markedly impact soil formation processes. The significance of charcoal removal in forest recovery after fire is emphasized by our results. Areas without charcoal removal exhibit more pronounced podzolization characteristics when contrasted with those that undergo charcoal removal, particularly under pine and birch stands. This underscores the role of charcoal in accelerating the development of soil horizons and the mobilization of crucial elements, such as organic carbon and iron. Furthermore, different tree species, like pine, birch, oak, and larch, also play a significant role in soil formation, each species contributing differently to soil acidity and organic matter content. According to the research, pine trees contribute to podzolization by promoting the accumulation of pronounced organic matter and acidic conditions. On the other hand, larch trees are known to intensify leaching processes, thereby reducing organic matter retention. Birch trees, due to their high-quality litter input, contribute significantly to strong podzolization. Oak trees foster eluviation and podzolization, thereby enhancing soil organic matter dynamics. It is important to note that each tree species has a unique impact on soil development post-fire, shaping podzolization processes accordingly.

In terms of soil classification, both the USDA Soil Taxonomy and the World Reference Base for Soil Resources (WRB) systems effectively categorize the soil profiles in Poland. However, when considering the broader European context, the WRB classification system is more widespread and might be more suitable for regional and international studies. Its comprehensive categorization and adaptability make it a valuable tool for comparing and understanding soil types across various geographic regions. Consequently, while both systems are applicable, the WRB's prevalence in Europe suggests it can be successfully implemented for broader comparative studies.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Thi Hong Van Tran, Bartłomiej Woś, Tomasz Wanic, and Agnieszka Józefowska. The first draft of the manuscript was written by Thi Hong Van Tran and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Acknowledgments

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Figures

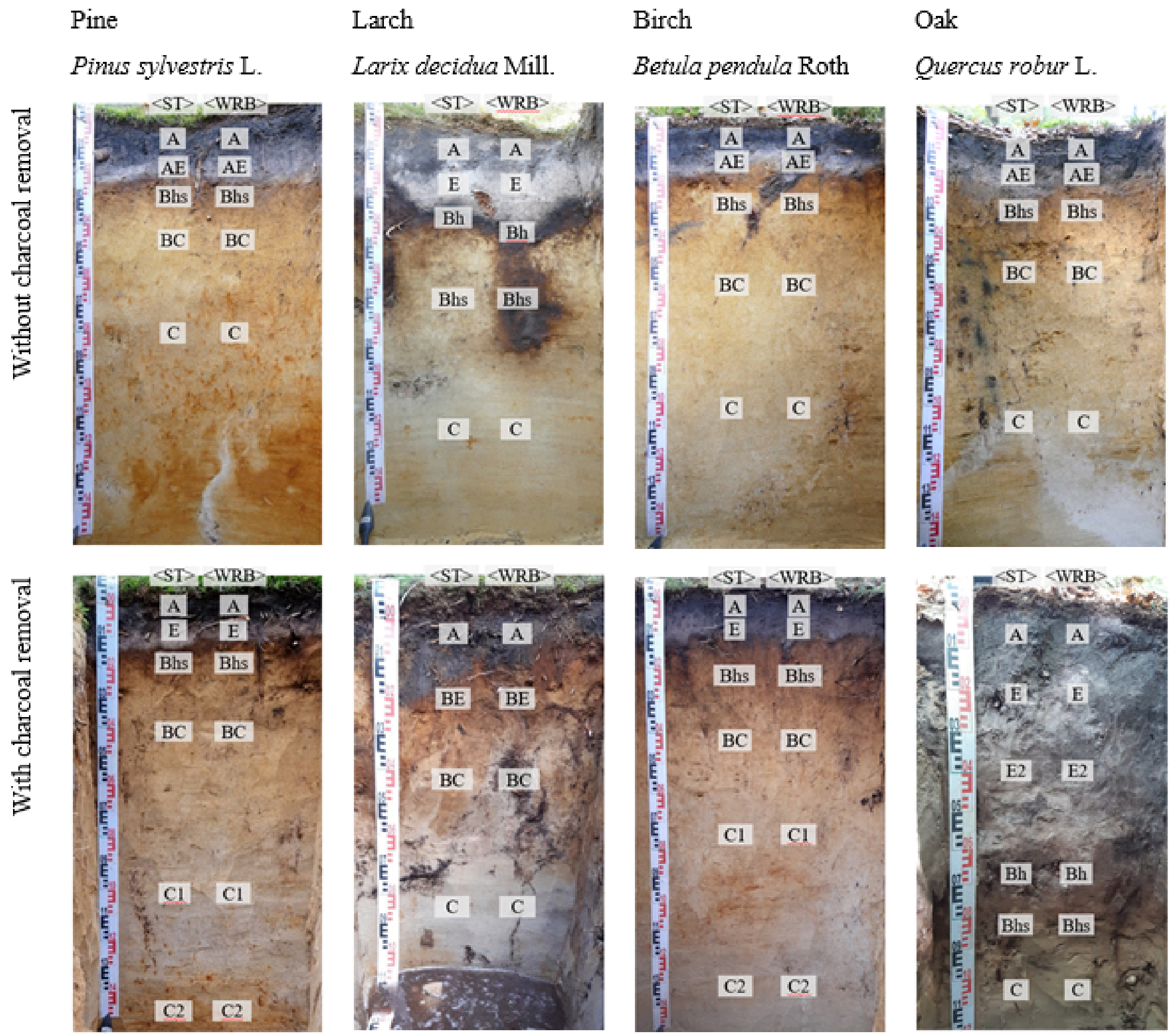

Figure 1

Soilpits from post-fire sites: with and without charcoal removal across four tree species

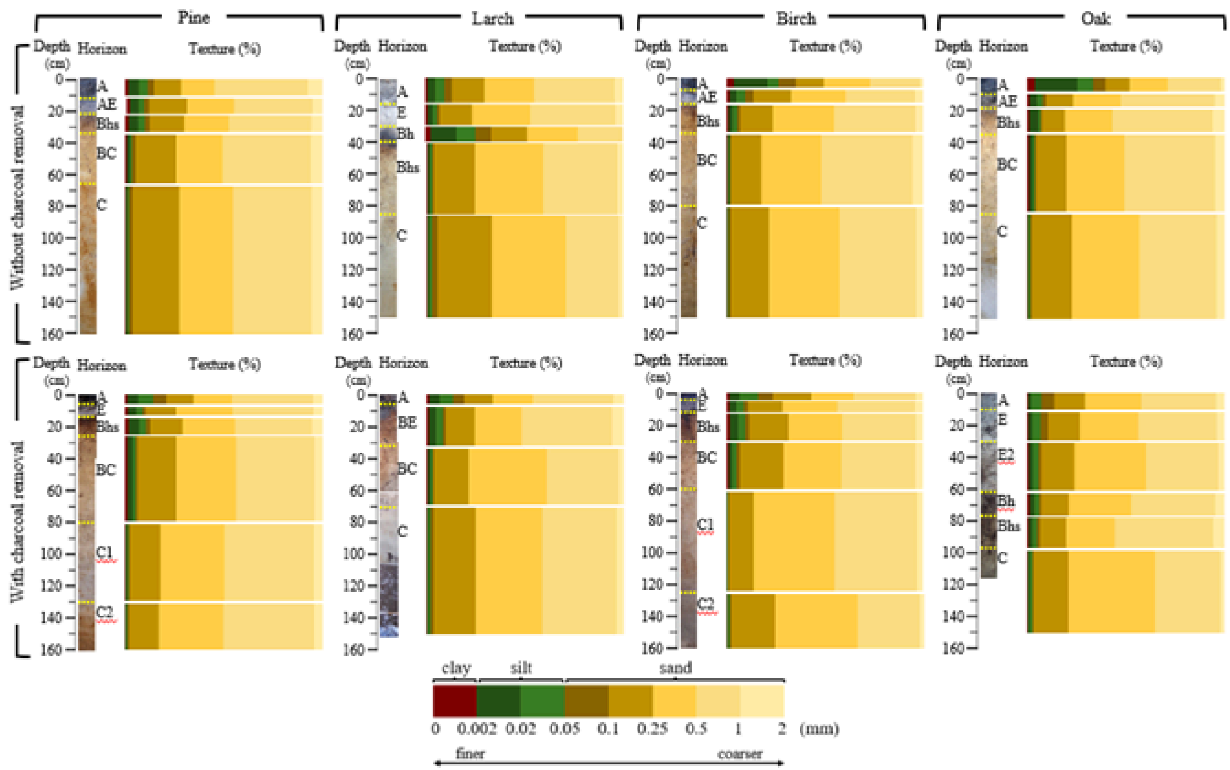

Figure 2

Depth plots of particle size distribution in soil profiles with and without charcoal removal post-fire across four tree species

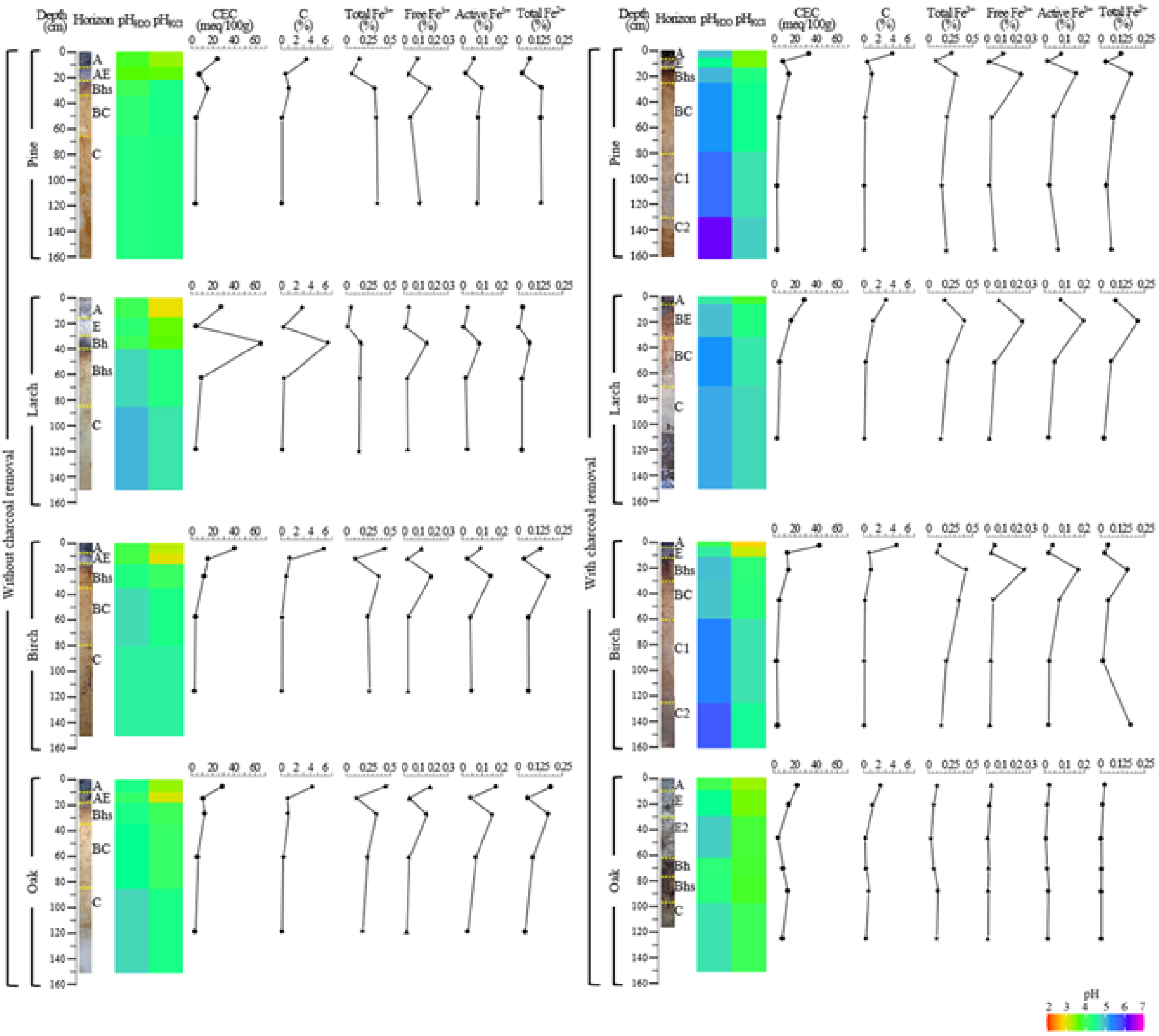

Figure 3

Chemical characteristics in soil profiles with and without charcoal removal across four tree species. pH_{H2O} - current pH; pH_{KCl} - potential pH; CEC - cation exchange capacity; C - organic carbon.

Figure 4

Correlation of Fe forms ($p < 0.05$)

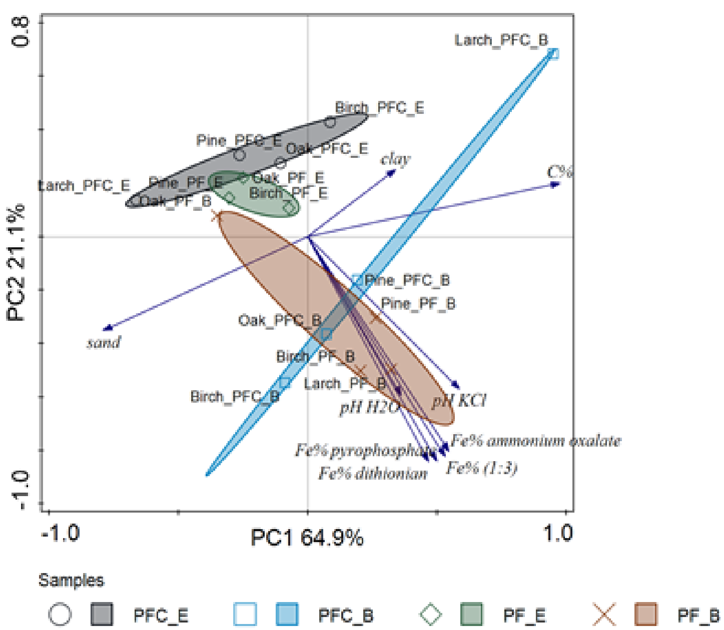

Figure 5

Principal Component Analysis (PCA) showing the main trends in the data set and indicating the approximate direction of soil variable effects ($p < 0.05$, Monte Carlo permutation, simple term effect) in the albic horizon (_E) and spodic horizon (_B) for areas without charcoal removal (PFC) and with charcoal removal (PF) under four tree species: pine, larch, birch, and oak. Soil variables include organic carbon (C%), sand, clay, current pH (pH_{H2O}), potential pH (pH_{KCl}), total Fe^{3+} (Fe% (1:3)), free Fe^{3+} (Fe% ammonium oxalate), active Fe^{3+} (Fe% pyrophosphate), and total Fe^{2+} (Fe% dithionian).

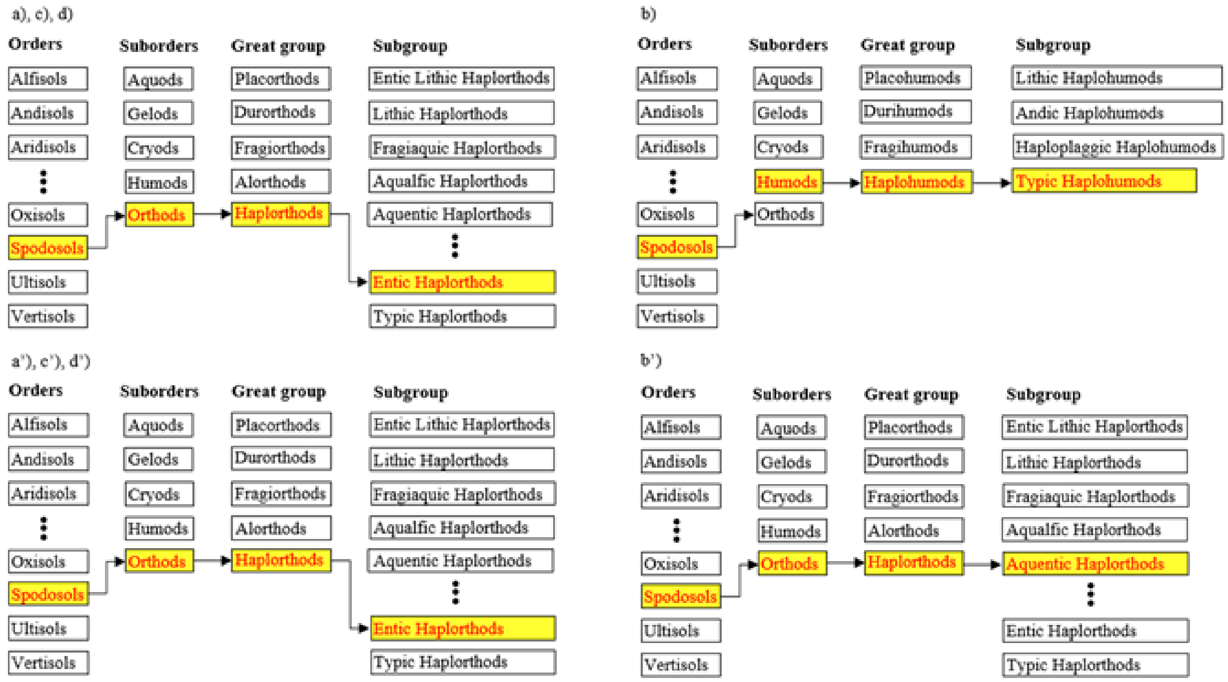

Figure 6

Soil classification of eight profiles comparing tree species and charcoal removal with USDA Soil Taxonomy - a) pine without charcoal removal, b) larch without charcoal removal, c) birch without charcoal removal, d) oak without charcoal removal, a') pine with charcoal removal, b') larch with charcoal removal, c') birch with charcoal removal, d') oak with charcoal removal

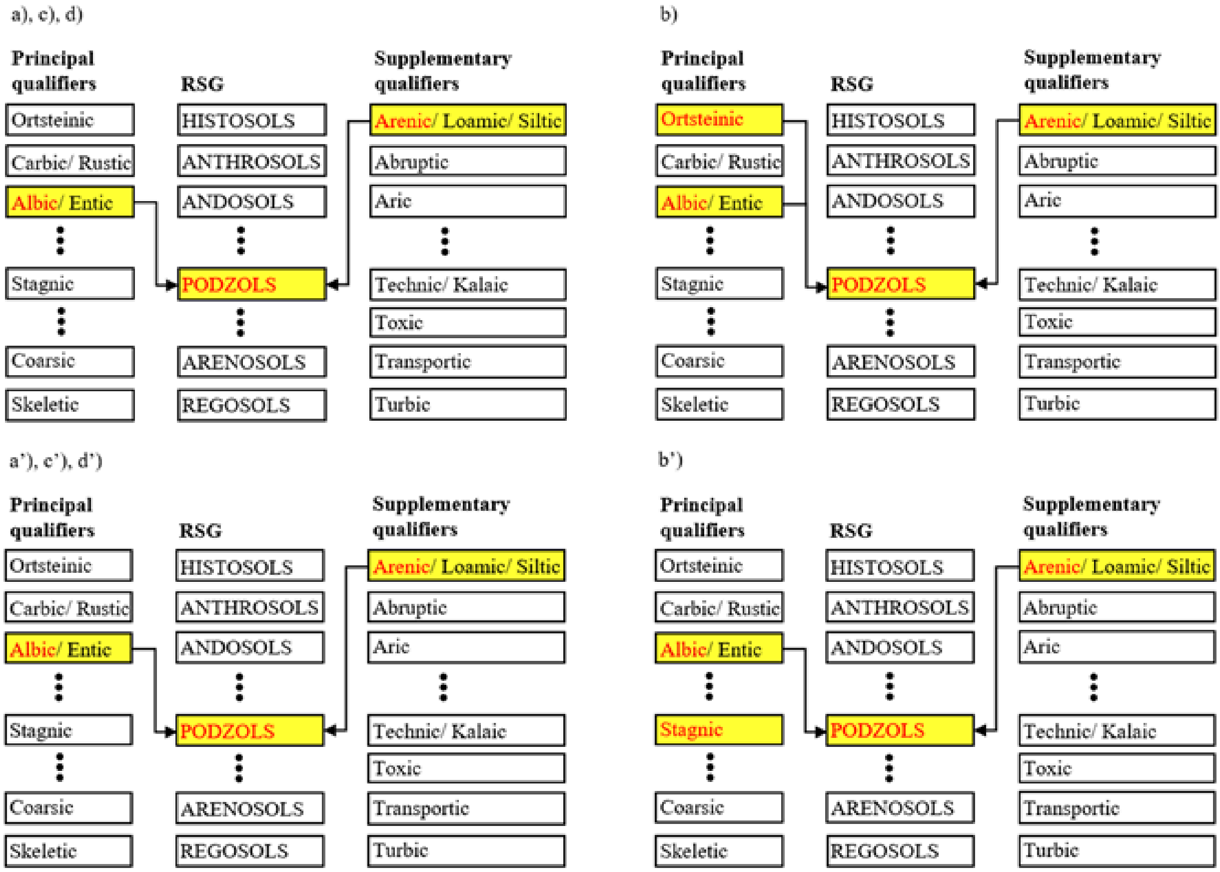

Figure 7

Soil classification of eight profiles comparing tree species and charcoal removal with World Reference Base for Soil Resources - a) pine without charcoal removal, b) larch without charcoal removal, c) birch without charcoal removal, d) oak without charcoal removal, a') pine with charcoal removal, b') larch with charcoal removal, c') birch with charcoal removal, d') oak with charcoal removal