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Effects of slope and tree position on soil properties in a temperate deciduous forest

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Abstract: This paper examines changes in soil physical and chemical properties in relation to tree proximity on different slopes. Topsoil and subsoil were sampled at 12 research plots on four slope types, the soil pits being placed at the base of a tree (near tree, NT) and between the test tree and an adjacent tree (between trees, BT). We observed a significant decrease in vertical topsoil response to slope on lower, middle and upper slopes, and a decrease in fine roots ($R < 2$ mm) on flat ground. Overall, middle and lower slopes showed the highest similarity, and upper slopes and flat ground the least, with the greatest subsoil changes observed mainly on middle slopes and least on lower slopes. There was clear topographic dependence between subsoil water stable aggregates (*WSA*) and C dynamics, with BT total carbon (C*tot*) higher on flat ground and lower on middle slopes; unlike topsoil, where the strongest *WSA* correlation was with distance from the tree. The highest N : *OM* (organic matter) ratios occurred on middle slopes facing north-west, and lowest on lower slopes facing north and flat ground. Our findings confirm the influence of slope type on soil characteristics, with NT soil supporting soil formation by transporting water to deeper layers, especially on slopes > 5°. These observations contribute to a better understanding of the dependence of soil properties on slope type and tree position when planning sustainable forest management.

Keywords: forest watershed; hydrological regime; soil chemical properties; soil physical properties; temperate forest; tree distance

Soil properties are often considered 'fingerprints' defining the processes to which the soil has been subjected, such as large-scale deforestation. For example, increased percolation rates increase chemical weathering, soil acidification and transport of particles and solute, thereby promoting soil development processes such as podsolisation, clay translocation and soil aggregation (Blume

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et al. 2010; Kaiser et al. 2015). Across ecosystems, these soil processes are linked to slope topography (i.e. degree of slope), with relative elevation and slope position corresponding to a wide range of soil properties, including soil carbon (C) content and clay content, and basic topographic attributes, such as slope, aspect and curvature (Krumbach 1959; Henninger et al. 1976; Robinson, Dean 1993; Nimmo, Perkins 2002). Famiglietti et al. (1999), for example, showed that flat sites tend to be wetter than upper slopes due to less intense subsurface drainage caused by fewer preferential pathways.

Generally speaking, forest soil processes and properties tend to be more complex at different spatial scales than those in fields or grassland. As a result, forest soils, and especially those close to trees, are poorly described in the literature and/or their influence remains controversial, especially in combination with other habitat factors, such as woody plant species composition or their ability to alter the chemical composition of rainwater, e.g. through stemflow (Levia, Frost 2003). While nutrient-rich soil islands near trees have been described in semi-arid scrubland (Wood et al. 1988; Koch, Matzner 1993; Whitford et al. 1997), for example, other studies, particularly those in temperate forests, have described soils near trees as nutrient-depleted (Wilke et al. 1993; Knoerzer, Gärtner 2003) or as areas with concentrated pollution or acidification (Neite, Runge 1986; Falkengren-Grerup 1989; Rampazzo, Blum 1992).

In almost all such studies, tree spacing (i.e. the dependence of soil properties on the distance to tree) is identified as a potential correlating factor for forest soil NT properties, particularly in relation to (*i*) the differences in soil chemistry with tree position (e.g. soil organic carbon and exchangeable cations; Gersper, Holowaychuk 1971; Wood et al. 1988; Rampazzo, Blum 1992; Nacke et al. 2016), and (*ii*) reduced soil water content (*SWC*) in the near-stem area due to reduced rain throughfall and higher water uptake by tree roots compared to open areas (Rashid et al. 2015; Metzger et al. 2017). The impact of stemflow as a point input of rainwater directly affects the chemistry and hydrological regime of NT soil; however, the area affected by stemflow varies widely in individual ecosystems, with levels ranging from 0.03 m^2 (Návar 2011) to 3 m^2 (Rashid et al. 2015), an area well outside the horizontal critical distance from a tree of 0.3–0.7 m has been modelled by Metzger et al. (2021). In such cases, reduced soil water retention near trees contributes to more intense drying and rewetting, leading to improved infiltration and seepage into the subsoil through preferential flow pathways (Beven, Germann 1982; Li et al. 2009). In addition, macropores in soil layers may be associated with living or decayed tree roots, which provide relatively efficient pathways for conducting water through the layers (Beven, Germann 1982). Many studies have confirmed the important function played by the roots of plants and trees, especially their role in improving the stability of aggregates (Rillig et al. 2014; Vergani, Graf 2016; Garcia et al. 2019; Li et al. 2023), and thus to the elimination of soil erosion (Sun et al. 2022). For example, Abdi (2014) found that Oriental beech *(Fagus orientalis* L.*)* is a beneficial 'ecological engineering species', reducing soil loss, stabilising soil mass on upper slopes and reducing soil degradation processes (e.g. water erosion; Sagheb-Talebi, Schütz 2002), thereby reducing the chances of landslides (Sedaghatkish et al. 2023). Thus, the impacts of individual species and their root systems may be key for soil protection and hydric functioning. Factors such as increased soil stability (Greenway 1987) and matric suction in the root zone (Fatahi et al. 2010) may also be of ecological significance.

Here, we undertake a complex assessment of forest soils by first assessing the effect of slope type on soil properties and, secondly, the effect of distance to tree stem in relation to slope position and soil depth. In doing so, we aim to provide insights into the effective power of trees to affect soil and soil water redistribution in a temperate forest and, thus, their influence on processes associated with water storage in the deeper soil layers of the forested watershed. Our findings will contribute to the planning of forest cultivation practices on a local scale and provide support for micro-catchment managers attempting to prioritise activities to improve soil stability and protection.

MATERIAL AND METHODS

Study area. The study area was situated in the upland watershed area of the Žiluvecký stream, close to the town of Babice nad Svitavou in the Czech Republic (49°17'24.4''N, 16°40'29.1''E; Figure 1). The 7.59 ha area lies at an altitude of 250–450 m a.s.l., has a prevailing N–NW slope of 5–10° (max. slope 39°), and features a humid continental climate typical of temperate forests, with a long-term aver-

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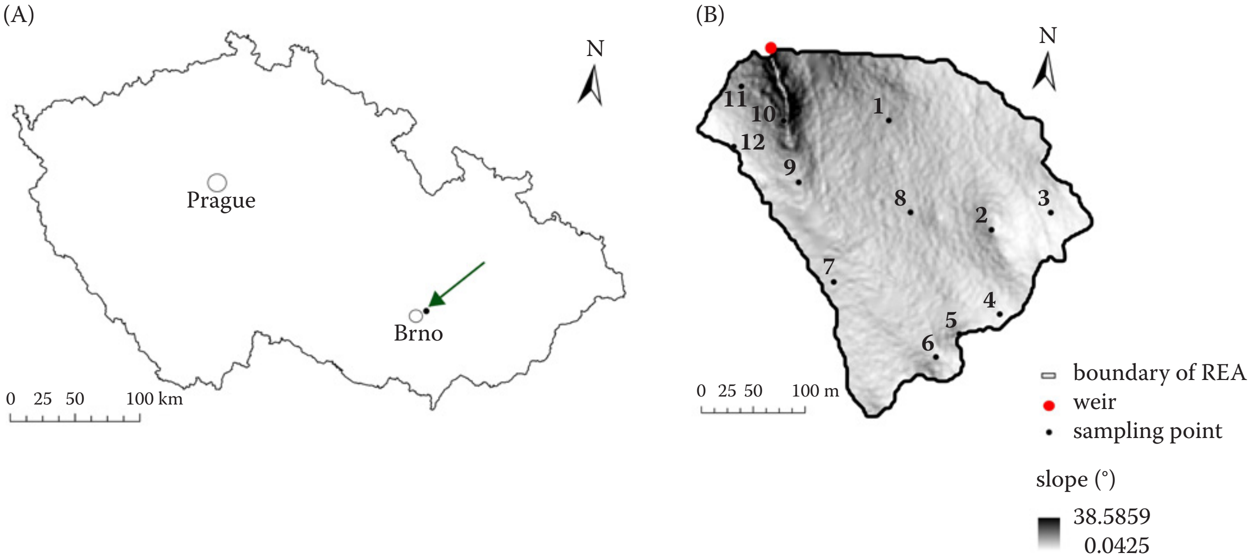

Figure 1. (A) Approximate location of the study area within the Czech Republic; (B) an inset showing the basic headwater area attributes

REA – representative elementary area

age annual temperature and rainfall of 10 °C and 606 mm, respectively (16.8 °C and 427 mm, respectively, during the growing season; temperature data from the Tuřany weather station and precipitation (1991–2020) from the Czech Hydrometeorological Station in Babice nad Svitavou (CHMI 2023).

Forests in the area are primarily Sessile oak (*Quercus petraea* L.), European beech (*Fagus sylvatica* L.), Scots pine (*Pinus sylvestris* L.), and European hornbeam (*Carpinus betulus* L.), with average proportions of 27.4%, 28.5%, 13.8%, and 12.5%, respectively, along with an admixture of European larch (*Larix decidua* Mill.), Norway spruce (*Picea abies* (L.) Karst.), Small-leaved lime (*Tilia cordat*a Mill.), European ash (*Fraxinus excelsior* L.) and silver fir (*Abies alba* Mill.). The substrate is primarily granodiorite with an irregular admixture of Quaternary sediments (loess and loess-like deposits). The predominant soil types are Leptosols, Cambisols, Stagnosols, and luvic Cambisols. Hyperskeletic Leptosol soils alternate with skeletic Cambisols on upper slopes, while eutric (haplic) Cambisols alternate with gleyic Stagnosols on middle and lower slopes, depending on proximity to the stream source, and skeletic Cambisols alternating with luvic Cambisols at flat sites (IUSS 2014). There are no obvious signs of soil erosion at any of the sites.

Experimental design. For the purposes of this study, 12 research plots were established on four slope types, i.e. upper, middle, lower, and flat. The plots were initially established using a semiautomatic geographic information system (GIS) analysis of a 2 m × 2 m resolution digital terrain model (DTM) of the area, with final verification undertaken in the field. This DTM can be considered a typical headwater source-area shape for Czech forested upland micro-watersheds. As a first step, the DTM was divided into the smallest possible hydrologically enclosed areas (i.e. representative elementary areas, REAs; Wood et al. 1988), using the hydrology toolset in ArcGIS v.10.6.1 (ESRI, USA). The ArcGIS 'topographic position index' tool [Iowa State University, Geospatial Laboratory for Soil Informatics, USA (Guisan et al. 1999; Weiss 2001)] was then used to classify the area into four slope position classes representing upper (UPPS), middle (MIDS), lower (LOWS) slopes, and flat (FLATS) sites (Figures 2, 3; Table 1). A representative forest stand was then chosen for each slope type, and a representative adult test tree was identified within each stand.

At the beginning of the 2021 vegetative season (September), two soil pits were established at each research plot (i.e. 24 in total), one located 0.5 m (critical distance of the tree-to-soil effect; Metzger 2005) perpendicularly below the base of the test tree's trunk (termed near tree, NT) and the other in the gap between the crowns of the test tree and an adjacent tree (termed between tree, BT; Figure 3).

Sampling strategy. Soil sampling, root analysis and *SWC* probe installation took place over

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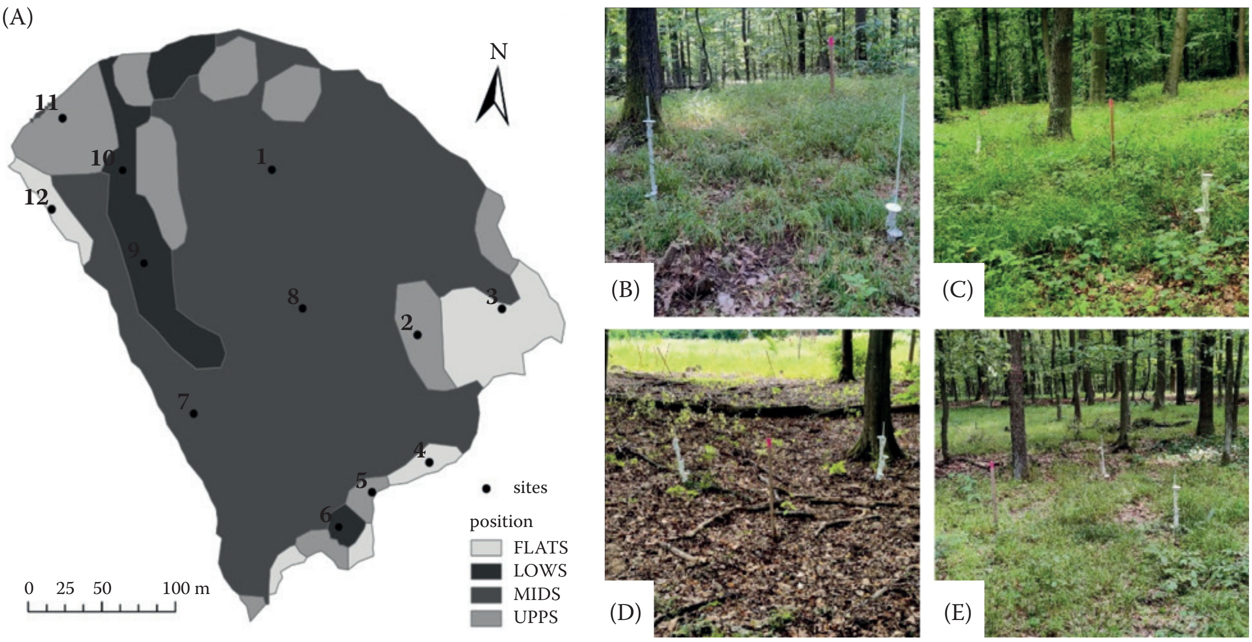

Figure 2. (A) Field study sites (1–12), with slope position classes indicated; representative photographs of the slope types: (B) upper slopes (UPPS, sites 2, 5, 11); (C) middle slopes (MIDS, sites 1, 7, 8); (D) lower slopes (LOWS, sites 6, 9, 10); (E) flat sites (FLATS, sites 3, 4, 12)

the 2021 vegetative season (September–October). After removing the upper organic horizon, two sample sets were then collected from each soil pit, one representing topsoil (0–30 cm) and the other subsoil (≥ 30 cm). Topsoil samples were taken at fixed depths of 0–5 cm, 5–10 cm, and 25–30 cm at each slope position, while subsoil samples were taken at fixed depths of 25–30 cm and 55–60 cm, and

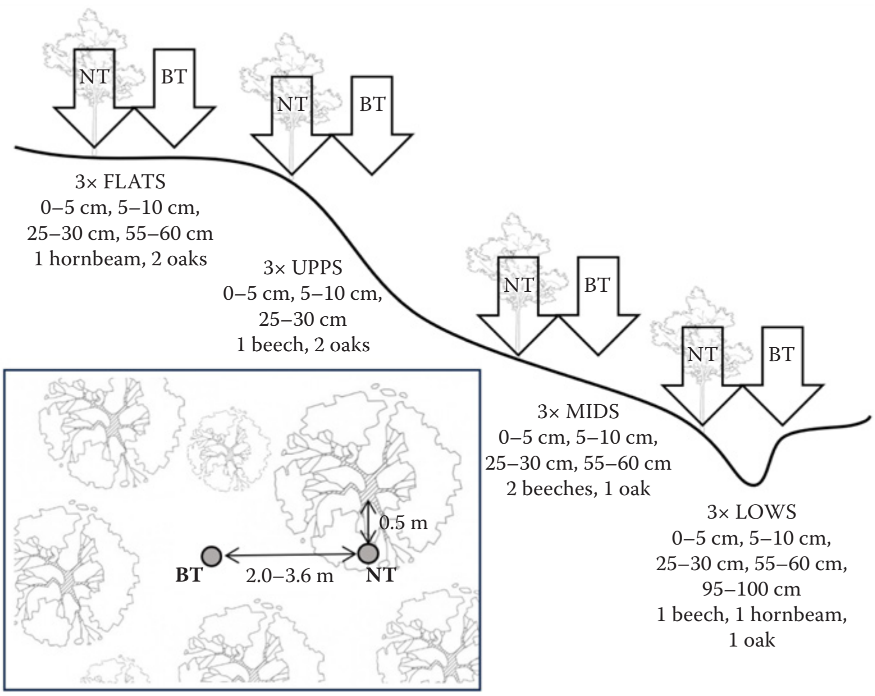

Figure 3. Sampling design, with sampling position and slope type illustrated

NT – near tree; BT – between trees; FLATS – flat sites; UPPS – upper slope; MIDS – middle slope; LOWS – lower slope

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Table 1. Characterisation of slopes and mean distances between sampling points and nearest tree

Slope type	Slope characterisation	Aspect	Mean distance		
			between NT and BT (m)	from NT to nearest five trees (m)	from BT to nearest five trees (m)
UPPS (n = 3)	upper slope > 10°, top of the hillslope	SW	2.0	2.0	3.1
MIDS (n = 3)	mean slope > 5°, middle of the hillslope	NW	3.6	3.2	4.0
LOWS (n = 3)	slight slope < 5°, lowest part of the hillslope	N	2.6	4.2	3.9
FLATS (n = 3)	flat slope < 5°, top of the hillslope	–	2.6	2.1	2.7

NT – near tree site; BT – between tree site; UPPS – upper slopes; MIDS – middle slopes; LOWS – lower slopes; FLATS – flat sites; n – number of repetitions; SW – southwest; NW – northwest; N – north

middle, lower, and flat slopes, with a further sample at 95–100 cm for LOWS slope sites. Subsoil samples were not taken at UPPS slope sites as the soil generally had a maximum depth of 30 cm. Two soil cores also were obtained from 5–10 cm, 25–30 cm, 55–60 cm, and 95–100 cm for measuring saturated hydraulic conductivity (*Ks*), and two disturbed soil samples [1× standard, 1× large (2–3 L)] were taken from 0–5 cm, 5–10 cm, 25–30 cm, 55–60 cm, and 95–100 cm for analytical analysis in the laboratory and quantification of soil coarse fragments, respectively. Before closing the soil pits, TMS-4 dataloggers (Tomst Ltd., Czech Republic; see Wild et al. 2019) were installed for continuous *SWC* measurement, the datalogger probes being set at the same depths as the soil cores, i.e. 5–10 cm, 25–30 cm, 55–60 cm, and 95–100 cm.

In addition, the walls of each pit were slightly roughened to expose the fine roots (R < 2 mm), after which a framed plastic sheet was placed against the wall and any clearly defined fine roots (R < 2 mm) dotted with a fine marker pen and thicker roots (R > 2 mm) with a thicker pen (Symonides, Bohm 1979). The proportion of each root type was then estimated for each sheet, and the number of roots for the total 10 cm soil layer was estimated (Symonides, Bohm 1979; Archer et al. 2016). The soil units at each pit were described according to the world reference base (IUSS 2014), including a description of H horizon (*Th_Ohor*) and A horizon thickness (*Th_Ahor*).

Finally, the average slope and slope exposure (aspect) were assessed at each site using a compass (Compass For Maps, Version 1.2.9 APK for Android; 2023) and inclinometer (Bubble Level, Version 3.31 APK for Android; 2021), and the tree diameter at breast height (*DBH*) was measured for 12 trees close to the NT probes.

Laboratory analysis. In the laboratory, the soil samples were analysed using two basic protocols. In the first, *Ks* was determined in the soil cores using a Permeameter S248 falling head permeability apparatus (MATEST S.p.A., Italy; determined using the BS EN ISO 2019 protocol), while for the second, the soil was divided into two portions, one for measuring water stable aggregates (*WSA*) and the other for further chemical and physical analysis. *WSA* was determined on the 2–5 mm soil fraction using a wet sieving apparatus (Eijkelkamp Co. Ltd., Netherlands), according to the procedure of Nimmo and Perkins (2002). Prior to chemical/physical analysis, the second soil portion was homogenised, then air-dried and passed through a 2 mm sieve. Next, total carbon (C*tot*) and total nitrogen (N*tot*) were assessed using a vario MACRO cube elemental analyser (Elementar, Germany), weight loss-on-ignition determined at 550 °C [sufficiently hot to burn off organic matter (*OM*) but not carbonate (CO_2^{-3}); Hoogsteen et al. 2015], and the active soil reaction (pH : H_2O) and soil redox potential (*Eh*) determined at a sample : water ratio of 1 : 0.3 $v \cdot v^{-1}$ (Husson et al. 2016). Next, the main soil texture classes (clay < 2 μm, silt 2–50 μm, sand > 50 μm) were determined using a Mastersizer 3 000 laser diffraction particle size analyser (Malvern Instruments Ltd, UK), with sample preparation performed according to Lisá (2016) while soil water repellence was determined for each sample using the water drop penetration test (*WDPT*), as determined in previous studies (i.e. Letey 1969; Dekker, Ritsema 1995; Bisdom et al. 1993; Doerr et al. 2000). Finally, the larger soil sample was used to quantify coarse soil fragment content (*SF*) using the wet sieving method (2–6 mm, 6–20 mm, 20–60 mm, 60–200 mm, > 200 mm fractions), according to the Cools and De Vos (2020).

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Data preparation and statistical analysis. Prior to statistical analysis, the raw TMS datalogger data were treated as follows: (*i*) the data were converted to 'volumetric water content' using TMS 'calibre tool' software (Robinson, Dean 1993); (*ii*) average, median, and delta (difference between maximum and minimum) *SWC* were calculated for the 2022 growing season; (*iii*) C : N ratios were calculated based on C*tot* and N*tot*; and (*iv*) horizontal textural differentiation in clay (*Texdif CLAY*) was calculated as the ratio of clay at 30 cm against clay at 10 cm.

For the purposes of this study, the values obtained were interpreted in two different ways, i.e. differences between NT and BT soil (Tables 1–4) and the

Table 2. Topsoil parameters in relation to slope type for near-tree (NT) sites, shown as +/– difference Δ with between tree (BT) sites

TOPSOIL	UPPS			MIDS			LOWS			FLATS		
Parameter	mean NT		Δ	mean NT		Δ	mean NT		Δ	mean NT		Δ
Th_Ohor [2] (mm)	40.00	+	3.33	56.67	–	10.00*	70.00	–	3.33	28.33	–	1.67
Th_Ahor [2] (mm)	86.67	+	3.33	80.00	–	10.00*	100.00	–	46.67*	58.33	–	5.00
C*tot* [2] (%)	4.98	–	0.04	2.03	+	0.01	3.04	–	0.72*	4.29	–	0.45
N*tot* [1] (%)	0.33	–	0.01	0.14	ND	0.00	0.20	–	0.04*	0.28	–	0.03
C : N [2]	13.72	+	1.27	13.93	+	1.03	14.14	+	0.03	14.49	–	0.97
OM [1] (%)	9.62	–	0.29	4.71	+	0.11	6.81	–	1.63*	8.46	–	0.47
C : *OM* [2]	3.51	–	0.64	3.29	+	1.20	3.03	+	0.07	2.79	–	0.05
N : *OM* [2]	92.82	–	26.89	78.51	+	123.97	46.06	+	12.25	41.95	–	8.47
pH : H_2O [1]	5.46	–	0.05	5.27	+	0.05	5.25	–	0.01	5.57	–	0.11
Eh [1] ($\mu S \cdot m^{-1}$)	359.89	+	1.44	381.11	–	2.56	369.33	+	4.11	362.67	–	1.00
CLAY [1] (%)	4.91	–	0.71	4.14	+	0.36	4.55	+	1.86	4.38	–	0.04
SILT [1] (%)	45.95	+	3.71	53.03	–	1.68	56.53	–	0.66	55.24	–	0.25
SAND [1] (%)	49.14	–	2.99	42.83	+	1.32	38.93	+	2.52	40.38	+	0.30
Texdif CLAY [1]	1.77	+	1.01	1.04	+	0.23	1.11	+	0.31	2.79	–	0.82
Ks [2] ($cm \cdot s^{-1}$)	5.08E-03	+	1.53E-04	1.07E-03	+	3.55E-04	6.09E-04	+	5.22E-06	3.63E-03	+	2.89E-04
WDPT [2]	1.59	–	0.17	1.11	–	0.11	1.30	–	0.17	1.54	–	0.13
WSA [1] (%)	86.58	–	7.85*	81.59	–	6.97	70.76	–	2.28	83.58	–	0.31
*SF*2–6 [2] (%)	12.48	+	0.04	16.97	–	0.87	8.64	–	1.10	15.10	+	0.81
*SF*6–20 [2] (%)	7.34	–	0.03	3.55	–	0.49	3.32	–	0.14	4.65	+	1.62
*SF*20–60 [2] (%)	15.54	–	6.50*	0.47	–	0.21	1.64	–	0.98	1.92	–	0.48
*SF*60–200 [2] (%)	18.27	+	3.78	0.00	ND	0.00	0.00	ND	0.00	0.00	ND	0.00
SFtot [1] (%)	53.63	–	2.71	20.99	–	1.57	13.60	–	2.22	21.67	+	2.91
SWC-med [2] ($cm^3 \cdot cm^{-3}$)	0.31	ND	0.00	0.28	+	0.03	0.35	–	0.02	0.27	+	0.01
SWC-avr [2] ($cm^3 \cdot cm^{-3}$)	0.30	+	0.02	0.27	+	0.04*	0.35	–	0.03	0.27	+	0.01
SWC-delta [1] ($cm^3 \cdot cm^{-3}$)	0.30	–	0.05*	0.24	–	0.02	0.22	–	0.02	0.29	–	0.03
R < 2 mm [2] ($pcs \cdot m^{-2}$)	95.00	+	15.93	78.89	–	20.56	96.85	–	23.70	139.44	–	26.67*
R > 2 mm [2] ($pcs \cdot m^{-2}$)	6.48	–	2.78	12.59	–	7.22*	17.22	–	12.41*	5.37	–	1.48

[1] Parametric paired *t*-test; [2] non-parametric Wilcoxon signed-rank test; * $P < 0.05$; ND – no difference; UPPS – upper slopes; MIDS – middle slopes; LOWS – lower slopes; FLATS – flat sites; NT – near-tree site; *Th_Ohor* – H horizon thickness; *Th_Ahor* – A horizon thickness; C*tot* – total carbon; N*tot* – total nitrogen; *OM* – organic matter; *Eh* – soil redox potential; *CLAY* – content of clay; *SILT* – content of silt; *SAND* – content of sand; *Texdif CLAY* – horizontal textural differentiation in clay; *Ks* – saturated hydraulic conductivity; *WDPT* – water drop penetration test; *WSA* – water stable aggregates; *SF*2–6 – soil fragment content 2–6 mm; *SF*6–20 – soil fragment content 6–20 mm; *SF*20–60 – soil fragment content 20–60 mm; *SF*60–200 – soil fragment content 60–200 mm; *SFtot* – total soil fragment content; *SWC-med* – median soil water content; *SWC-avr* – average soil water content; *SWC-delta* – delta soil water content; *R* – roots

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Table 3. Subsoil parameters in relation to slope type for near-tree (NT) sites, shown as +/– difference Δ with between tree (BT) sites

SUBSOIL	UPPS	MIDS			LOWS			FLATS		
Parameter		mean NT		Δ	mean NT		Δ	mean NT		Δ
C*tot*[2] (%)	NA	0.34	–	0.12*	0.34	–	0.02	0.40	+	0.05
N*tot*[1] (%)	NA	0.03	–	0.01	0.04	ND	0.00	0.04	+	0.01
C : N[2]	NA	11.48	+	0.30	9.29	+	0.59	12.01	–	2.38
OM[1] (%)	NA	2.07	+	0.35	2.06	+	0.07	2.30	+	0.12
C : *OM*[2]	NA	7.44	+	5.88*	6.92	+	1.18	6.95	–	0.12
N : *OM*[2]	NA	320.80	+	552.73*	215.00	+	133.01	325.78	–	119.12*
pH : H_2O[1]	NA	6.14	+	0.20	6.42	+	0.05	6.19	–	0.12
Eh[1] ($\mu S \cdot m^{-1}$)	NA	404.83	+	14.50	381.89	–	14.33	410.33	–	3.67
CLAY[1] (%)	NA	2.84	–	0.11	3.41	–	0.14	3.56	–	0.12
SILT[1] (%)	NA	35.79	–	0.63	42.55	–	3.83	37.00	+	4.47
SAND[1] (%)	NA	61.37	+	0.73	54.04	+	3.97	59.44	–	4.36
Texdif CLAY[1]	NA	0.67	–	0.14	0.76	–	0.28*	0.64	–	0.01
Ks[2] ($cm \cdot s^{-1}$)	NA	1.21E-03	–	4.46E-04	4.48E-04	–	3.02E-04	4.66E-03	–	7.13E-04
WDPT[2]	NA	1.00	ND	0.00	1.00	ND	0.00	1.00	ND	0.00
WSA[1] (%)	NA	66.77	–	5.87	49.03	+	1.98	76.48	–	0.38
*SF*2–6[2] (%)	NA	22.16	+	0.78	12.77	+	2.91	22.55	+	1.99
*SF*6–20[2] (%)	NA	3.79	–	0.54	4.18	+	0.66	7.20	–	0.14
*SF*20–60[2] (%)	NA	0.10	–	0.04	1.64	–	0.54	2.66	–	0.55
*SF*60–20[2] (%)	NA	0.00	ND	0.00	0.57	–	0.57	2.50	–	2.50
SFtot[1] (%)	NA	26.04	+	0.27	19.15	+	2.45	34.91	–	1.20
SWC-med[2] ($cm^3 \cdot cm^{-3}$)	NA	0.27	+	0.04*	0.36	–	0.02	0.28	+	0.02
SWC-avr[2] ($cm^3 \cdot cm^{-3}$)	NA	0.26	+	0.04*	0.36	–	0.03	0.28	+	0.02
SWC-delta[1] ($cm^3 \cdot cm^{-3}$)	NA	0.18	–	0.04	0.14	–	0.01	0.19	.	0.00
R < 2 mm[2] ($pcs \cdot m^{-2}$)	NA	30.56	–	13.89*	22.04	–	5.56	73.06	–	30.00*
R > 2 mm[2] ($pcs \cdot m^{-2}$)	NA	1.11	+	0.28	2.78	–	0.74	3.06	+	2.78

[1] Parametric paired *t*-test; [2] non-parametric Wilcoxon signed-rank test; * $P < 0.05$; ND – no difference; UPPS – upper slopes; MIDS – middle slopes; LOWS – lower slopes; FLATS – flat sites; NT – near-tree site; NA – data not available; C*tot* – total carbon; N*tot* – total nitrogen; *OM* – organic matter; *Eh* – soil redox potential; *CLAY* – content of clay; *SILT* – content of silt; *SAND* – content of sand; *Texdif CLAY* – horizontal textural differentiation in clay; *Ks* – saturated hydraulic conductivity; *WDPT* – water drop penetration test; *WSA* – water stable aggregates; *SF*2–6 – soil fragment content 2–6 mm; *SF*6–20 – soil fragment content 6–20 mm; *SF*20–60 – soil fragment content 20–60 mm; *SF*60–200 – soil fragment content 60–200 mm; *SFtot* – total soil fragment content; *SWC-med* – median soil water content; *SWC-avr* – average soil water content; *SWC-delta* – delta soil water content; *R* – roots

influence of tree position on soil response to slope type. For clarity, the topsoil and subsoil values are presented separately as correlation networks for NT topography, vegetation and soil parameters (Figures 3A, 4A) and differences (delta) between NT and BT (Figures 3B, 4B).

The data were statistically processed using the TIBCO Statistica™ software package (Version 14.0.1, 2022) and the R statistical software package (Version 4.2.1 GUI 1.79 High Sierra build, 2022) and RStudio [Version 2022.07.2 +576, 2022 (Michalzik et al. 2016; R Core Team 2017)]. The datasets for topsoil (0–30 cm; $n = 72$) and subsoil (30–100 cm; $n = 42$) were processed separately. All tests were preceded by the Shapiro-Wilk test to establish normality, following which the parametric paired sample *t*-test or non-parametric Wilcoxon paired *t*-test was used to compare paired values (NT × BT). Fol-

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Table 4. Effect of slope type on near-tree (NT) topsoil (TOP) and subsoil (SUB) properties (Δ)

NT	UPPS		MIDS		LOWS		FLATS	
Parameter	median TOP	median SUB	median TOP	median SUB	median TOP	median SUB	median TOP	median SUB
Th_Ohor (mm)	50.00[ab]	NA	60.00[b]	NA	60.00[b]	NA	30.00[a]	NA
Th_Ahor (mm)	70.00[ab]	NA	80.00[ab]	NA	110.00[a]	NA	50.00[b]	NA
C*tot* (%)	2.70	NA	1.36	0.26	2.18	0.28	1.79	0.36
N*tot* (%)	0.20	NA	0.09	–[a]	0.16	–[b]	0.12	–[b]
C : N	14.93	NA	13.89	10.75	14.46	7.20	14.92	12.20
OM (%)	–	NA	–	–	–	–	–	–
C : *OM*	2.03	NA	2.57	–	2.43	–	2.78	–
N : *OM*	10.55	NA	27.93	325.69	15.20	153.27	23.13	176.24
pH : H_2O	–	NA	–	–	–	–	–	–
Eh (μS·m^{-1})	–	NA	–	–[a]	–	–[b]	–	–[a]
CLAY (%)	–	NA	–	–	–	–	–	–
SILT (%)	–	NA	–	–	–	–	–	–
SAND (%)	–	NA	–	–	–	–	–	–
Texdif CLAY	1.13	NA	1.09	–	1.14	–	1.48	–
Ks (cm·s^{-1})	–	NA	–	8.44E-05	–	2.99E-04	–	4.55E-03
WDPT	1.00	NA	1.00	1.00	1.00	1.00	1.00	1.00
WSA (%)	94.19[a]	NA	87.10[ab]	–[ab]	71.01[b]	–[b]	86.78[ab]	–[a]
*SF*2–6 (%)	–	NA	–	19.72	–	10.32	–	27.74
*SF*6–20 (%)	8.25	NA	2.97	3.74	0.84	0.84	5.99	7.57
*SF*20–60 (%)	23.08	NA	0.00	0.00	0.00	0.00	1.48	1.76
*SF*60–200 (%)	20.79	NA	0.00	0.00	0.00	0.00	0.00	0.00
SFtot (%)	–[a]	NA	–[b]	–	–[b]	–	–[b]	–
SWC-med (cm^3·cm^{-3})	–[a]	NA	–[ab]	0.26	–[ab]	0.37	–[b]	0.27
SWC-avr (cm^3·cm^{-3})	–[abc]	NA	–[a]	0.26	–[c]	0.38	–[ab]	0.26
SWC-delta (cm^3·cm^{-3})	–	NA	–	–	–	–	–	–
R < 2 mm (pcs·m^{-2})	–	NA	–	–	–	–	–	–
R > 2 mm (pcs·m^{-2})	–	NA	–	0.00	–	0.00	–	0.00

Parametric ANOVA and non-parametric Kruskal-Wallis tests followed by multiple comparison tests; [a] significantly higher than [b], [ab], or [abc] ($P < 0.05$); [b] non-significant difference between [a] and [b], or [a], [b] and [c]; UPPS – upper slopes; MIDS – middle slopes; LOWS – lower slopes; FLATS – flat sites; TOP – topsoil ; SUB – subsoil; NA – data not available; '–' – mean topsoil and subsoil values (see Tables 1 and 2); *Th_Ohor* – H horizon thickness; *Th_Ahor* – A horizon thickness; C*tot* – total carbon; N*tot* – total nitrogen; *OM* – organic matter; *Eh* – soil redox potential; *CLAY* – content of clay; *SILT* – content of silt; *SAND* – content of sand; *Texdif CLAY* – horizontal textural differentiation in clay; *Ks* – saturated hydraulic conductivity; *WDPT* – water drop penetration test; *WSA* – water stable aggregates; *SF*2–6 – soil fragment content 2–6 mm; *SF*6–20 – soil fragment content 6–20 mm; *SF*20–60 – soil fragment content 20–60 mm; *SF*60–200 – soil fragment content 60–200 mm; *SFtot* – total soil fragment content; *SWC-med* – median soil water content; *SWC-avr* – average soil water content; *SWC-delta* – delta soil water content; *R* – roots

low-up ANOVA [followed by Tukey's Honestly Significant Difference (HSD) test] or Kruskal-Wallis tests were consistent with comparisons of unpaired NT soil properties and deltas (differences between paired NT and BT values) of soil properties affected by slope position. The 'cor' function in 'stats' package (Version 4.2.1; Michalzik et al. 2016) was used to express NT soil dependence and delta of soil properties. Spearman's rank correlation coefficient was used to establish correlations and the 'qgraph' package (Version 1.9; Epskam et al. 2012) was then used to visualise the resulting correlation networks. All analyses were performed at a significance level of $P < 0.05$.

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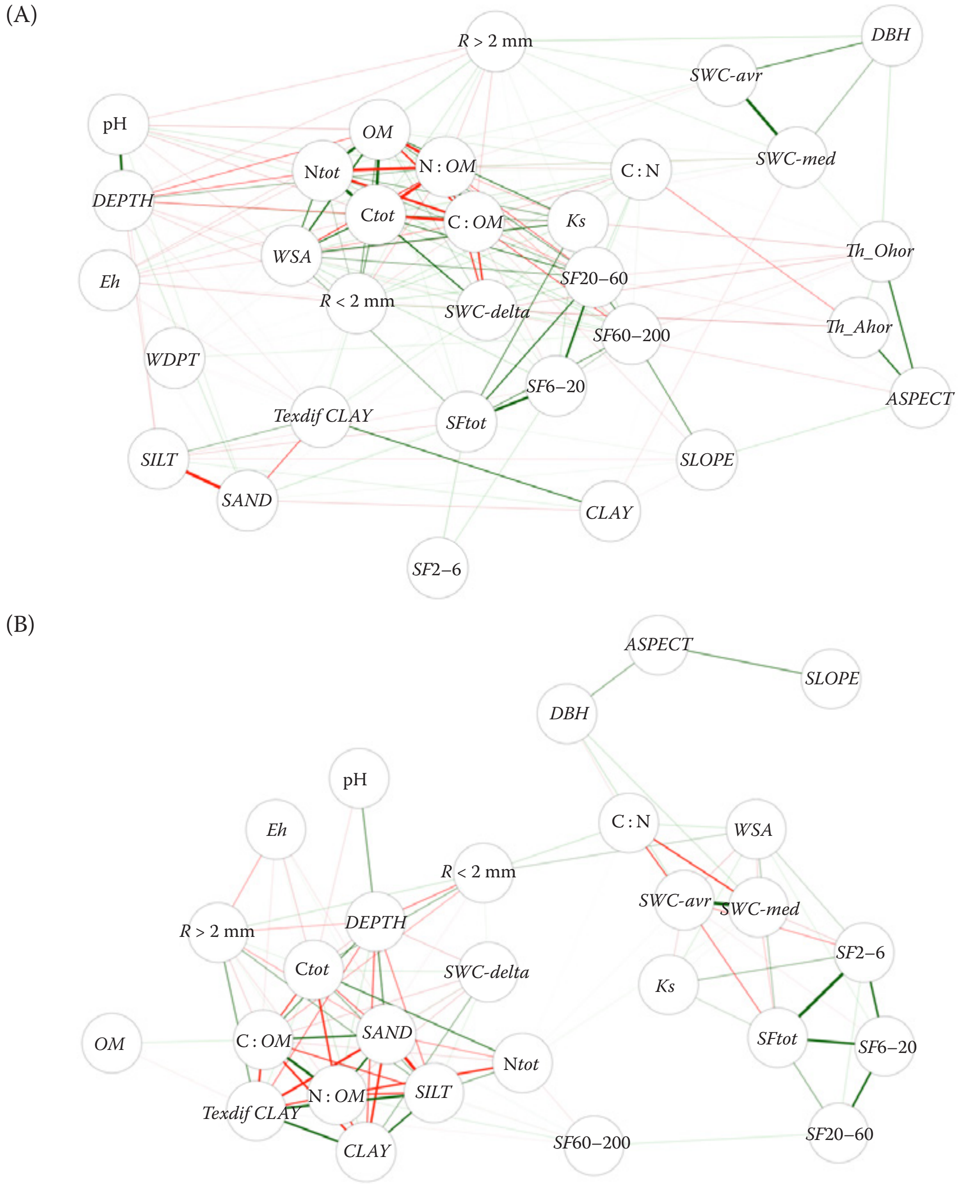

Figure 4. Correlation matrices for (A) near tree (NT) topography, vegetation and topsoil properties; and (B) the difference between NT and between tree (BT) topsoil properties (delta)

Red lines – negative correlations; green lines – positive correlations (correlation strength represented by line thickness and distance between properties; significant correlations at $P < 0.05$); *ASPECT* – slope orientation; *CLAY* – content of clay; C*tot* – total carbon; *DEPTH* – soil sampling depth; *DBH* – diameter at breast height; *Eh* – soil redox potential; *Ks* – saturated hydraulic conductivity; N*tot* – total nitrogen; *OM* – organic matter; *R* – roots; *SAND* – content of sand; *SF*20–60 – soil fragment content 20–60 mm; *SF*2–6 – soil fragment content 2–6 mm; *SF*60–200 – soil fragment content 60–200 mm; *SF*6–20 – soil fragment content 6–20 mm; *SF*tot – total soil fragment content; *SILT* – content of silt; *SLOPE* – slope inclination; *SWC-avr* – average soil water content; *SWC-delta* – delta soil water content; *SWC-med* – median soil water content; *Texdif CLAY* – horizontal textural differentiation in clay; *Th_Ahor* – A horizon thickness; *Th_Ohor* – H horizon thickness; *WDPT* – water drop penetration test; *WSA* – water stable aggregates

RESULTS

Near tree soil properties in relation to slope type. Our results confirmed significant delta differences ($P < 0.05$) between BT and NT soils with slope type. In NT topsoil (Table 2), there was a significant decrease in fine roots ($R < 2$ mm) at flat sites; a significant decrease in thicker roots ($R > 2$ mm), *Th_Ohor*, C*tot*, N*tot*, and *OM* on lower slopes; a significant decrease in *Th_Ohor*, *Th_Ahor*,

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SWC-avr, and thicker roots (*R* > 2 mm), and a significant increase in *SWC-avr*, on middle slopes; and a significant decrease in *WSA*, *SF*20–60, and *SWC-delta* on upper slopes.

In subsoil (Table 3), there was a significant decrease in NT N : *OM* and fine roots (*R* < 2 mm) at flat sites; a significant decrease in *Texdif CLAY* on lower slopes; and a significant decrease in C*tot* and fine roots (*R* < 2 mm), and a significant increase in C : *OM*, N : *OM*, *SWC-med*, and *SWC-avr*, on middle slopes (data unavailable for upper slopes). Pairwise comparisons of NT topsoil/subsoil parameters (Table 4) also confirmed significant changes ($P < 0.05$), with significantly higher *Th_Ahor* on lower topsoil and *WSA* on upper topsoil, and significantly lower N*tot* on middle topsoil and *Th_Ohor* on flat topsoil.

An examination of the differences between NT and BT soils as affected by slope type (Table 5) indicated

Table 5. Effect of slope type on between-tree (BT) topsoil (TOP) and subsoil (SUB) properties (Δ)

Δ	UPPS		MIDS		LOWS		FLATS	
Parameter	median TOP	median SUB	median TOP	median SUB	median TOP	median SUB	median TOP	median SUB
Th_Ohor (mm)	0.00	NA	–10.00	NA	0.00	NA	0.00	NA
Th_Ahor (mm)	0.00[a]	NA	–10.00[a]	NA	–40.00[b]	NA	–10.00[a]	NA
C*tot* (%)	–0.41	NA	–0.20	–[a]	–0.25	–[ab]	+0.08	–[b]
N*tot* (%)	–	NA	–	–0.01	–	0.00	–	+0.01
C : N	+0.03	NA	–0.34	–	–0.52	–	–0.06	–
OM (%)	–	NA	–	+0.37	–	+0.11	–	+0.12
C : *OM*	–[a]	NA	–[b]	+3.71	–[ab]	+0.44	–[ab]	–0.49
N : *OM*	–0.14	NA	+29.88	+278.84[a]	+6.00	+28.50[ab]	–4.88	–23.67[b]
pH : H_2O	–	NA	–	–	–	–	–	–
Eh (μS·m^{-1})	–	NA	–	–	–	–	–	–
CLAY (%)	–0.29	NA	–0.09	–	+1.10	–	–0.17	–
SILT (%)	–	NA	–	–	–	–	–	–
SAND (%)	–	NA	–	–	–	–	–	–
Texdif CLAY	–0.04	NA	+0.09	–0.04	+0.10	–0.17	–0.16	+0.01
Ks (cm·s^{-1})	–	NA	–	+8.12E-05	–	–2.14E-04	–	–2.39E-04
WDPT	0.00	NA	0.00	0.00	0.00	0.00	0.00	0.00
WSA (%)	–	NA	–	–	–	–	–	–
*SF*2–6 (%)	–	NA	–	–	–	–	–	–
*SF*6–20 (%)	–0.33	NA	–0.78	–0.37	–0.11	+0.86	+0.18	–0.53
*SF*20–60 (%)	–[a]	NA	–[b]	0.00	–[b]	0.00	–[b]	0.00
*SF*60–200 (%)	–	NA	–	–	–	–	–	–
SFtot (%)	–	NA	–	–	–	–	–	–
SWC-med (cm^3·cm^3)	–	NA	–	–	–	–	–	–
SWC-avr (cm^3·cm^{-3})	–	NA	–	–[a]	–	–[b]	–	–[ab]
SWC-delta (cm^3·cm^{-3})	–	NA	–	–	–	–	–	–
R < 2 mm (pcs·m^{-2})	–	NA	–	–6.67	–	0.00	–	–26.67
R > 2 mm (pcs·m^{-2})	–	NA	–	0.00	–	0.00	–	0.00

Parametric ANOVA and non-parametric Kruskal-Wallis tests followed by multiple comparison tests; [a] significantly higher than [b], [ab], or [abc] ($P < 0.05$); [b] non-significant difference between [a] and [b], or [a], [b] and [c]; UPPS – upper slopes; MIDS – middle slopes; LOWS – lower slopes; FLATS – flat sites; TOP – topsoil ; SUB – subsoil; NA – data not available; '–' – mean topsoil and subsoil values (see Tables 1 and 2); *Th_Ohor* – H horizon thickness; *Th_Ahor* – A horizon thickness; C*tot* – total carbon; N*tot* – total nitrogen; *OM* – organic matter; *Eh* – soil redox potential; *CLAY* – content of clay; *SILT* – content of silt; *SAND* – content of sand; *Texdif CLAY* – horizontal textural differentiation in clay; *Ks* – saturated hydraulic conductivity; *WDPT* – water drop penetration test; *WSA* – water stable aggregates; *SF*2–6 – soil fragment content 2–6 mm; *SF*6–20 – soil fragment content 6–20 mm; *SF*20–60 – soil fragment content 20–60 mm; *SF*60–200 – soil fragment content 60–200 mm; *SFtot* – total soil fragment content; *SWC-med* – median soil water content; *SWC-avr* – average soil water content; *SWC-delta* – delta soil water content; *R* – roots

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a significant increase in C : *OM* in BT middle slope subsoil, and a significant decrease in C*tot* in BT upper slope topsoil. The C : *OM* shift on upper slopes was most apparent at *SF*20–60 mm, with significantly higher levels in NT upper slope topsoil. Pairwise comparisons of BT soil parameters (Table 5) also revealed significant differences, with significantly lower *Th_Ahor* on lower slopes, and higher C*tot* in flat site subsoil and lower C*tot* on middle slopes.

Near tree/between trees soil properties – Correlation networks. Patterns in the NT soil network structure tended to be more robust in topsoil (Figure 4A) than in subsoil (Figure 5A). In topsoil, for example, soil properties linked to *OM* content were

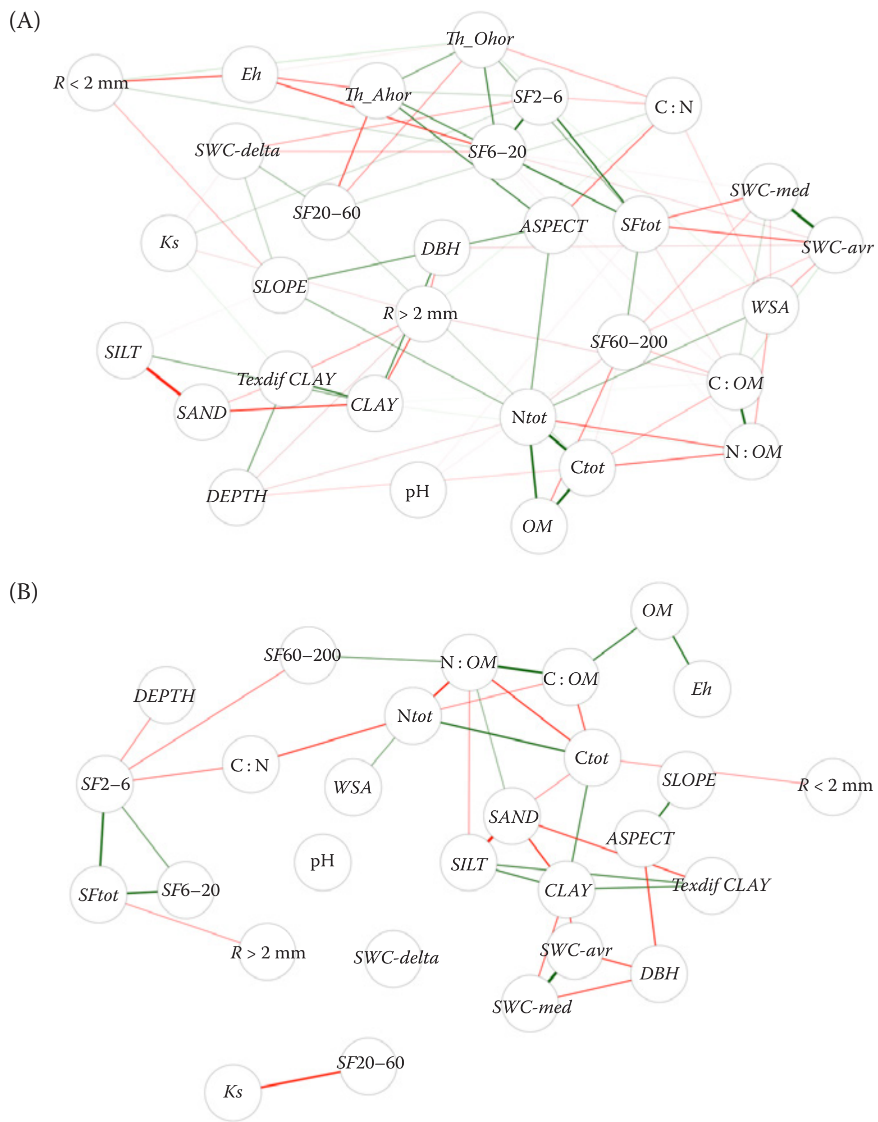

Figure 5. Correlation matrices for (A) near tree (NT) topography, vegetation and subsoil properties; and (B) the difference between NT and between tree (BT) subsoil properties (delta)

Red lines – negative correlations; green lines – positive correlations (correlation strength represented by line thickness and distance between properties; significant correlations at $P < 0.05$); *ASPECT* – slope orientation; *CLAY* – content of clay; C*tot* – total carbon; *DEPTH* – soil sampling depth; *DBH* – diameter at breast height; *Eh* – soil redox potential; *Ks* – saturated hydraulic conductivity; N*tot* – total nitrogen; *OM* – organic matter; *R* – roots; *SAND* – content of sand; *SF*20–60 – soil fragment content 20–60 mm; *SF*2–6 – soil fragment content 2–6 mm; *SF*60–200 – soil fragment content 60–200 mm; *SF*6–20 – soil fragment content 6–20 mm; *SF*tot – total soil fragment content; *SILT* – content of silt; *SLOPE* – slope inclination; *SWC-avr* – average soil water content; *SWC-delta* – delta soil water content; *SWC-med* – median soil water content; *Texdif CLAY* – horizontal textural differentiation in clay; *Th_Ahor* – A horizon thickness; *Th_Ohor* – H horizon thickness; *WDPT* – water drop penetration test; *WSA* – water stable aggregates

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noticeably more 'clumped' than in subsoil. Note, however, there were additional soil properties in subsoils defining soil texture, such as the negative correlations between retention water status, *WSA* and C : N. Topsoil soil properties also showed greater independence from soil depth than subsoil, along with a strong dependence between soil *OM*, conditional soil properties (*WSA*) and control of soil water dynamics (*Ks* and *SWC-delta*). The effect of *OM* tended to disappear with soil depth in favour of soil texture and gravel content. In contrast, the retention water status was strongly correlated with *DBH*.

Changes in NT/BT topsoil (Figure 4B) showed a more complex network with looser bonds than NT/BT subsoil (Figure 5B) and NT topsoil or subsoil (Figures 4A, 5A). Patterns related to matrix structure tended to dominate, especially that associated with the decrease in *OM*, followed by soil texture, both of these also being closely correlated to *DBH* and a decrease in coarse roots ($R > 2$ mm). Analysis of NT/BT subsoil delta indicated that some soil properties were independent of other soil properties (e.g. pH, *SWC-delta*), or supported single-bond changes only (e.g. *Eh* and *OM*, *Ks* and *SF*20–60). Deviations from these patterns were indicated by a tighter soil property network characterising individual forms of N (N*tot* and N : *OM*) and soil texture. Compared to NT/BT topsoil, however, connections between soil properties were an order of magnitude lower.

DISCUSSION

Changes in soil properties with depth. Textural differences in NT topsoil and subsoil revealed strong translocation of clay to the subsoil, with the decline in topsoil clay directly related to *DBH*. As such, changes in NT soil properties created 'microsites' that differed in composition from forest soils in the surrounding area. Clay translocation is likely to have occurred following decalcification during the soil formation process and will have been influenced by water flow and macroporosity (Blume et al. 2010), which was reflected in the topsoil through the delta of *Texdif CLAY*, *SWC*, and fine roots ($R < 2$ mm), further indicating that the microsite process increases with depth (Ludwig et al. 2005). Soil structure and texture are key factors affecting the hydraulic properties of soil, especially pore size and distribution, as confirmed in our study by an increase in *Ks* at NT soil microsites, indicative of higher macroporosity and the positive correlation between *Ks* and *WSA* stability in subsoil (Figure 5B). Similar changes in soil hydrophysical retention parameters have also been observed in previous studies, though Wei and Simko (2021) attributed this to increased NT macroporosity (as in the present study) while Metzger et al. (2017) attributed it to a reduction in *SWC*.

As in our own study, which determined *WSA* to a subsoil depth of > 30 cm, Salomé et al. (2010) noted important differences between topsoil and subsoil C dynamics. Further, Hishi (2014) showed that the distribution of differently sized soil aggregates contributed significantly to C dynamics in the subsoil, which also aligns with our own results. Such findings are relatively few and far between, however, as most previous studies have tended to focus on topsoil only (e.g. Mikha, Rice 2004), with *WSA* in the subsoil being largely ignored. Unlike topsoil microsites, where *WSA* was directly dependent on parameters associated with *OM*, such as N*tot*, C*tot*, and C : N, our *WSA* delta results (Figure 5B) indicated a stable subsoil *WSA* framework. Similar findings were reported by Levia and Frost (2003), Metzger (2017), and Metzger et al. (2021), who attributed compatible relationships between *WSA* and other soil organic properties with high organic loads in the stemflow (see also Garten et al. 1994; Chang, Matzner 2000) or increased accumulation of leaf fall around the tree trunk (Gersper, Holowaychuk 1971; Zuo et al. 2009).

Finally, the tree itself, through its growth, wind movement and root decomposition, promotes aggregation in clay soils (Ludwig et al. 2002). As such aggregates are formed, they will be strongly affected by processes such as freezing and thawing, which sorts the aggregates within profile horizons, with possible negative impacts on soil stability. Oztas and Fayetorbay (2003), for example, found that soils dominated by aggregates > 2 mm tended to be less stable after freezing and thawing compared to soils with aggregate sizes of 1–2 mm. Soil moisture, which is conditioned by soil type, organic matter and soil texture, will also have an important effect, particularly as regards the proportion of clay and silt, which bind soil particles more strongly than sand (Kochiieru et al. 2020), a feature confirmed in our own study. Overall, soils with a higher proportion of stable aggregates are more resistant to degradation processes and will have

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a more balanced hydric regime, thus contributing to the forest stand stability.

Influence of hill slope type on soil properties. Our results confirmed displacement of soil water in relation to *DBH* and root distribution in both topsoil and subsoil, with part of the flow required to infiltrate topsoil water being transported to deeper layers through preferential paths provided by thicker roots ($R > 2$ mm), as also noted by previous authors (e.g. Schwärzel et al. 2012; Metzger et al. 2017). Such changes to the NT drying and re-humidification regimen will affect soil aggregation, and thus *WSA* (Kaiser et al. 2015), possibly contributing to a shift in the soil microbial community (Rosier et al. 2016). However, our study showed that the degree of *WSA* impact differed in relation to slope type, with the lowest effect found at FLATS, thereby confirming the importance of slope position on the amount of water in soil, and particularly subsoil (Glover et al. 1962; Pressland 1976; Durocher 1990; Garten 1994; Chang, Matzner 2000; Návar 2011; Bialkowski, Buttle 2015). At the same time, the topographic dependence of *WSA* can also be affected by differences in the tilt of trees from vertical to 'S' shaped (Schweingruber 1996), the impact of this asymmetry being confirmed in our study by the *SWC-delta* parameter at UPPS sites.

In this study, the positive correlation between *WDPT* and C*tot*, N*tot* and C : N reflects adaptive root water intake or root redistribution in the soil matrix resulting in differences in water content at different depths (Beven, Germann 1982). Furthermore, the observed increase in *WSA* was positively correlated with increased *OM* (see also Boettcher, Kalisz 1990; Aponte et al. 2013), and thus biological activity, along with NT C : *OM* and N : *OM* (see also Nacke et al. 2016; Rosier et al. 2016). This increase in *OM* was mainly observed in the subsoil, with no significant effect of distance from the tree, a feature also reported by Boettcher and Kalisz (1990). These authors found that while C*tot* and N*tot* was similar under all tree species at 0–5 cm, the C : N ratio was highest on upper NT slopes. In our case, the C : N ratio was higher in NT samples at FLATS, most likely due to a higher proportion of macropores in the subsoil resulting in increased water flow to deeper layers through preferential flow pathways. The proportion of C*tot* also tended to decrease at MIDS and increase at FLATS, as also recorded for subsoil by Hishi et al. (2014), who recorded reduced *WSA* on more upper slopes. At the same time, the highest subsoil *Eh* values were recorded on LOWS slopes, despite *WSA* at such sites being comparable with that at MIDS.

Topographical factors, such as slope aspect and position, are important determinants of N transformation on a local scale, with N generally being more abundant at the bottom of upper slopes (Zak et al. 1986; Garten 1994; Hirobe et al. 1998). Numerous studies have examined the influence of slope orientation on the productive capacity of forests, especially when comparing north and south facing slopes (e.g. Hirobe et al. 1998; Venterea et al. 2003; Hishi et al. 2014). However, while noting that our study sites were situated predominantly on north-westerly to north-easterly facing slopes, it was not the intention of this study to examine the impact of slope on forest productivity *per se*. Nevertheless, Pastor et al. (1984) and Tateno et al. (2004) noted an indirect influence of slope position and aspect on soil N transformation and a direct correlation between slope position and vegetation with microclimatic factors. Furthermore, Hishi et al. (2014) recorded an increased C : N ratio on lower slopes when examining mineral horizons in a spruce stand. In comparison, the subsoil N : *OM* ratio in our study was highest on MIDS slopes, which mainly faced north-west, while N : *OM* decreased significantly at LOWS sites, which tended to face north (and therefore received slightly less sunshine), tending to confirm the influence of slope orientation on soil conditions. This would be especially true on southerly slopes as these are characterised by higher temperatures and lower humidity (Hishi et al. 2014). While there was a non-significant negative correlation between NT and BT C : *OM* and N : *OM* ratios with 'slope type' in topsoil, with C : *OM* decreasing at UPPS, NT, and BT subsoil *SF*20–60 mm readings were significantly higher at UPPS. These observations help explain the dependence of N transport in the soil, and especially subsoil, primarily through differences in litter quality (e.g. N content, C : N ratio) between tree species (Pastor et al. 1984) or differences between allocation gradients between leaf and root litter (Tateno et al. 2004). Consequently, the distribution of water (preferential flow) in the soil environment is influenced by both topography (i.e. slope type) and distance from the tree, which in turn affects the level of biochemical elements in the soil.

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CONCLUSION

Understanding the effective power of trees, conditioned by different slope types, to redistribute soil water and influence the soil environment is crucial for forestry management, whether from a hydrological or a pedological point of view. In this work, we focused on the impact of tree distance on soil and soil water properties, and to what extent these properties differed with soil depth and slope type. Our results demonstrated that tree proximity plays a significant role in soil formation processes, primarily through the transport of water into deeper soil layers and through a direct correlation between *DBH* and the distribution of topsoil and subsoil roots, with the degree of effect dependent on slope type (lowest effect at flat sites). Hydrological changes were also confirmed in different topsoil layers, with a significant decrease in multiple soil responses on lower, middle and upper slopes, compared to a decrease in fine roots (R < 2 mm) only at flat sites. Soil moisture was also positively correlated with *DBH* and rooting density nearer the tree, confirming the important role of tree age and size on forest hydric functioning.

The importance of topographic factors was also confirmed by the relationship between *WSA* and C dynamics, especially in the subsoil. In BT soils, these changes were manifested by a decrease in C*tot* at MIDS sites and an increase at FLATS sites. In topsoil, we observed a strong correlation between *WSA* and tree distance, but an even stronger negative correlation between C : *OM* and N : *OM* and slope, indicating that tree distance was less significant than slope type. Soil environment topographic factors also affected N transport in the subsoil, with the N : *OM* ratio being higher at MIDS oriented northwest, and lower on LOWS sites oriented north.

All these factors confirm the importance of topography and soil aggregate stability as indicators influencing the distribution of water in the soil profile, the mobility of biochemical elements in the soil and the overall stability of the forest stand. Our findings will help in planning forest cultivation practices on a local scale, and provide support for micro-catchment managers attempting to prioritise sustainable forest management that improves and protects soil stability.

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