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Research papers

Comparison of the effect of winch-assisted timber harvesting systems and cable yarding on soil water retention and surface runoff in a temperate deciduous forest

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ABSTRACT

Timber harvesting, especially when involving heavy machinery, significantly affects forest soil properties, including soil water retention and surface runoff. This study investigates the impacts of different timber harvesting systems (tracked harvester and forwarder (H+), non-tracked harvester and forwarder with tracks on uphill axles (H-), and cable yarding (MC)) on surface runoff and soil hydraulic properties in a temperate hardwood forest. We conducted rainfall simulation experiments (50 m^2 irrigation plots) before and after timber harvesting at a beech-dominated (*Fagus sylvatica* L.) site in the Vienna Woods, Austria, to measure changes in surface runoff. Additionally, soil samples were collected after irrigation experiments to assess bulk density, saturated hydraulic conductivity (Ksat), and water retention characteristics.

Surface runoff increased substantially after timber harvesting on skid trails, with the highest runoff on H+ (final runoff coefficient 0.67). In contrast, no runoff was observed on MC and the untrafficked control. Logging-induced soil compaction reduced Ksat (> 2 magnitudes; H+ and H-) and increased bulk density (up to 49 %; H-), particularly for ground-based timber harvesting methods. Water retention curves revealed a loss of macroporosity, and a shift towards a unimodal pore size distribution at 5 cm depth in all harvesting treatments. For cable yarding this shift was absent at 15 cm depth.

Our findings underscore the importance of selecting appropriate machinery and timber harvesting practices to minimize soil disturbance and its hydrological impacts, particularly as wetter winter conditions, affecting the typical hardwood logging period, become more common due to climate change.

1. Introduction

Undisturbed soils are of critical importance for water retention, contributing to reduce peak flows after heavy rainfall events. Forest soils generally have high infiltration rates (Alaoui et al., 2011; Chandler et al., 2018; Price et al., 2010) due to well-structured topsoil (Klöffel et al., 2022) that is rich in macropores (Jost et al., 2012). However, in managed forests, these soil functions could be increasingly endangered by climate change (Marchi et al., 2018), especially in combination with heavy timber harvesting machines (Cambi et al., 2015; Grünberg et al., 2023; Mohieddinne et al., 2019). Soil disturbance from ground-based extraction methods, especially when heavy machinery is used under wet soil conditions, often results in compaction and rutting, particularly in fine grained soils (Cambi et al., 2015; Labelle et al., 2022; Picchio et al., 2020). Given the critical influence of soil moisture on soil damage, the timing of timber harvesting operations is essential (Hoffmann et al., 2022; Labelle et al., 2022; Latterini et al., 2024a). While conifers are harvested year-round, hardwood harvesting in Central Europe is

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traditionally concentrated in the leafless winter months, when the risk to forest workers and damage to the remaining forest stand is lower. Timber harvesting should therefore take place mainly when the forest floor is frozen (e.g., Toivio et al., 2017), and therefore more resistant to compaction. However, winters in the mid- or lowlands of Central Europe are becoming increasingly wetter (Bender et al., 2017), there is less snow and fewer frost days due to climate change (IPCC, 2022; Olefs et al., 2021). As a result, the number of days with frozen soil is decreasing, especially in the altitudinal range of hardwood dominated forests. At the same time, the use of heavy timber harvesting machines has increased exponentially in recent decades (Cambi et al., 2015), with maximum loads of up to 70 t (Riggert et al., 2019).

As a result, forest soils are likely to be disturbed more severely, altering water retention capacity and increasing surface runoff, especially during heavy rainfall events. With compaction, coarser pores are preferentially lost (Katou et al., 1987), causing a reduction in macroporosity (Hansson et al., 2018; Hill and Sumner, 1967; Startsev and McNabb, 2001). This results in lower soil permeability (Koestel et al., 2018), which limits hydraulic conductivity (Nazari et al., 2021) and increases runoff (Cambi et al., 2015; Picchio et al., 2021). Most of the knowledge on the effects of runoff after timber harvesting comes from paired catchment studies. The specific effects of skid trails or yarding corridors on surface runoff during heavy rainfall events are less investigated (Picchio et al., 2021). Studies on undisturbed forest plots showed either little (Abari et al., 2017; Alaoui et al., 2011; Hartanto et al., 2003; Jourgholami et al., 2019, 2018; Karami et al., 2023; Zemke et al., 2019) or no surface runoff (Alaoui et al., 2011; Jost et al., 2012; Solgi et al., 2014). However, surface runoff was found to be elevated on skid trails (Abari et al., 2017; Croke et al., 1999; Hartanto et al., 2003; Jourgholami et al., 2019, 2018; Karami et al., 2023; Solgi et al., 2014; Zemke et al., 2019) and increased with traffic intensity (Jourgholami et al., 2018, 2017; Solgi et al., 2014). Haas et al. (2020) compared the impact of cable winching (tractor-based winch) and harvester/forwarder treatments on runoff. While their study presented insights, limitations in data quality prevented them from drawing definitive conclusions. While most of these studies rely on natural rainfall events (Abari et al., 2017; Haas et al., 2020; Jourgholami et al., 2019, 2018, 2017; Karami et al., 2023; Solgi et al., 2014), irrigation experiments are rare (Croke et al., 1999; Zemke et al., 2019). The aforementioned studies predominantly used rubber-tired skidders for timber extraction. To our knowledge, there is a lack of conclusive research assessing the impact on runoff of other common timber harvesting technologies, including harvester/forwarder technologies that might be less impactful (Picchio et al., 2020).

Timber harvesting and the associated soil compaction are expected to affect the hydraulic properties of the soil (Greacen and Sands, 1980; Hansson et al., 2018; Nazari et al., 2021; Simmons and Anderson, 2016; Startsev and McNabb, 2000). A recent review conducted by Nazari et al. (2021) shows a strong impact of timber harvesting on saturated hydraulic conductivity, suggesting further research on the impact of different machines. The effects on water retention and pore size distribution are consistent with the reduction in (saturated) hydraulic conductivity and the increase in runoff. Mostly, macropores, especially air-filled pores, are lost due to logging-related compaction (Dickerson, 1976; Hansson et al., 2018; Startsev and McNabb, 2001). The effects on available water capacity (AWC) differ. While some authors showed no effect (Startsev and McNabb, 2001), others demonstrated a site dependence, with increases or reductions in AWC (Smith et al., 2001). However, even without a major change in AWC, the pore size distribution may change within the range of AWC (Hansson et al., 2018). In general, a flattening of the water retention curve is typical of compacted forest soils, whether artificially compacted (Hayashi et al., 2006; Smith et al., 2001), by a forwarder (Hansson et al., 2018), or by a skidder (Simmons and Anderson, 2016). However, without a direct comparison, it is difficult to factor in the context of each timber harvesting operation.

Various technologies aim to reduce the impact of timber harvesting on the soil. The use of traction winch-assisted systems in steep terrain harvesting, which we had in this study, is considered to reduce the negative impacts of ground based timber harvesting (Allman et al., 2024; Haas et al., 2018; Holzfeind et al., 2020). At the same time, it enables harvester/forwarder technology in terrain with up to 60–80 % slope (Visser and Stampfer, 2015).

The use of bogie tracks, as also used in our experiment, is a widely accepted technique to reduce soil rutting (Haas et al., 2016) and thus soil disturbance. Cable yarding further reduces the impact, causing less soil disturbance (Krag et al., 1986; Latterini et al., 2024b; Spinelli et al., 2010), lower increases in bulk density (Laffan et al., 2001), and yarding corridors cover a smaller percentage of land than skid trails of ground-based systems (Miller and Sirois, 1986). Nevertheless, cable yarding increases bulk density (Laffan et al., 2001; Picchio et al., 2018), and Ursic (1991) showed increased runoff after a catchment was clearcut with cable yarders, but to a lesser extent compared to a clearcut with skidders. However, detailed studies of the impact of cable yarding systems on soil hydraulic properties and runoff seem to be lacking.

In our experiment we hypothesise that different timber harvesting technologies alter soil physical and hydraulic properties and consequently infiltration rate and surface runoff compared to pre-harvest conditions/ control with decreasing intensity: harvester/forwarder (tethered) with minimum bogie track application > harvester/forwarder (tethered) with bogie tracks > cable yarder. In detail we expect (i) increased surface runoff, (ii) altered water retention curves, (iii) a decrease in saturated hydraulic conductivity, and (iv) an increase in bulk density. To our knowledge, to date, no in-situ experiments have been conducted that examine changes in surface runoff in combination with laboratory measurements of soil hydraulic properties, resulting from soil disturbance and compaction caused by different timber harvesting systems (cable yarder, tethered fully mechanized tracked, and tethered minimally tracked harvesting system).

To test our assumptions, we compare the three timber harvesting treatments and a control on the same site with in-situ heavy rainfall simulation experiments before and after timber harvesting. The rainfall simulation experiments are paired with undisturbed core sampling, from which we derived water retention curves, saturated hydraulic conductivity, and bulk density.

2. Material and methods

2.1. Study site

The study site is located on the south-facing slope of *Steinplattl* (48°07′24.93“N 16°02’51.68“E, 530 m a.s.l.) in the Flysch zone of the Vienna Woods (Austria). It covers the upper parts of the headwater catchment of the *Münichbach.* The whole catchment is dominated by European beech (*Fagus sylvatica* L., 68 %) with an admixture of sessile oak (*Quercus petraea* [Matt.] Liebl., 13 %), European larch (*Larix decidua* Mill., 9 %), Norway spruce (*Picea abies* L., 8 %), sycamore maple (*Acer pseudoplatanus* L.), and wild cherry (*Prunus avium* L.) at the experimental site (stand age 2023: ca. 110 years). Average tree height and diameter are 26 m and 38 cm, respectively. The soil type is a Stagnic Cambisol with mull humus dynamics. Two representative profiles are described in the appendix (A 1, A 2). Understory vegetation was sparse due to the intensive shading by the beech trees, except for beech saplings from natural regeneration, which strongly dominated the understory. The most common vascular plants were *Cardamine bulbifera* (L.) Crantz and *Carex sylvatica* Huds.. In wetter areas, *Carex pendula* Huds. was also prevalent.

At 5 cm depth, the pH is 4.1 ± 0.2 (in 0.01 mol $CaCl_2$) and the SOC content is 4.0 ± 0.8 %. The catchment is also part of the LTER-CWN infrastructure project (https://www.lter-austria.at/cwn/) and has served as a long-term monitoring site for ICP Forests (https://icp-forests.net/) since 1995. Observations report an annual mean temperature of 8 °C and an annual precipitation of 801 mm (2010–2022) (Dirnböck et al., 2024, preprint).

2.2. Experimental design

The experimental design is based on a selective timber harvest operation of the Austrian Federal Forests (ÖBf) at Steinplattl, which was carried out in the winter of 2022/23 under wet and unfrozen conditions (Fig. 1). The harvesting operation reduced stand density from.

346n/ha to 224n/ha. Timber was harvested using a fully mechanized cut-to-length system (harvester and forwarder) and a tree-length system (with motor manual felling and cable extraction using a tower yarder (Table 1)). Further processing, after cable yarding, was done at the roadside.

We established four plots marked with circles in Fig. 2. The plots MC, H+, and H- represent different harvesting treatments, while plot C was used as undisturbed control plot that was not affected by skid trails or yarding corridors.

Soil disturbance in the MC irrigation plot was caused by cable yarding after motor manual felling (Table 1). Here the logs were yarded mostly partially and, in some areas, fully suspended, depending on the log length and the terrain. A total of 2189 m^3 of timber was harvested on 2460 m of yarding corridor (six corridors), resulting in a harvesting intensity of 0.89 $m^3 m^{-1}$. Soil compaction on skid trail irrigation plots marked with H was caused by 8 – 10 machine cycles of a tethered harvesting system – a combination of harvester and forwarder with a tire width of 710 mm (Table 1). Both machines were assisted by a T-Winch 10.1 (ecofrost GmbH, Großlobming, Austria) to improve traction. Irrigation plot H+ refers to the use of bogie tracks (width 860 mm) on all axles of both, the harvester and the forwarder, while irrigation plot H- refers to the approach of a minimum application of bogie tracks finally realized on one axle of the forwarder – showing the limits under wet conditions. In the following, we will refer to the treatments as "tracked" and "minimum tracked". On the block of six harvester/forwarder trails (2080 m in total length) 741 m^3 of timber were harvested with a harvesting intensity of 0.36 $m^3 m^{-1}$. The same harvesting intensity was applied for treatments H+ and H-, which are included in the six harvester/forwarder trails. Yarding and forwarding were performed uphill, and all four irrigation plots were in the mid slope, with an inclination of 25–34 % (C 24 %, MC 34 %, H+ 26 %, H- 25 %).

2.3. Rainfall simulation experiments and soil sampling

To investigate the effects of the different harvesting treatments on surface runoff, eight rainfall simulation experiments were conducted across the four established plots (Fig. 2). Each plot was irrigated once before timber harvesting in 2022 and once after timber harvesting in 2023. Details on the rainfall simulation setup can be found in Markart and Kohl (1995), Mayerhofer et al. (2017), and Ruggenthaler et al. (2015). In short, the rainfall simulation experiments were based on a transportable spraying installation surrounding the target irrigation

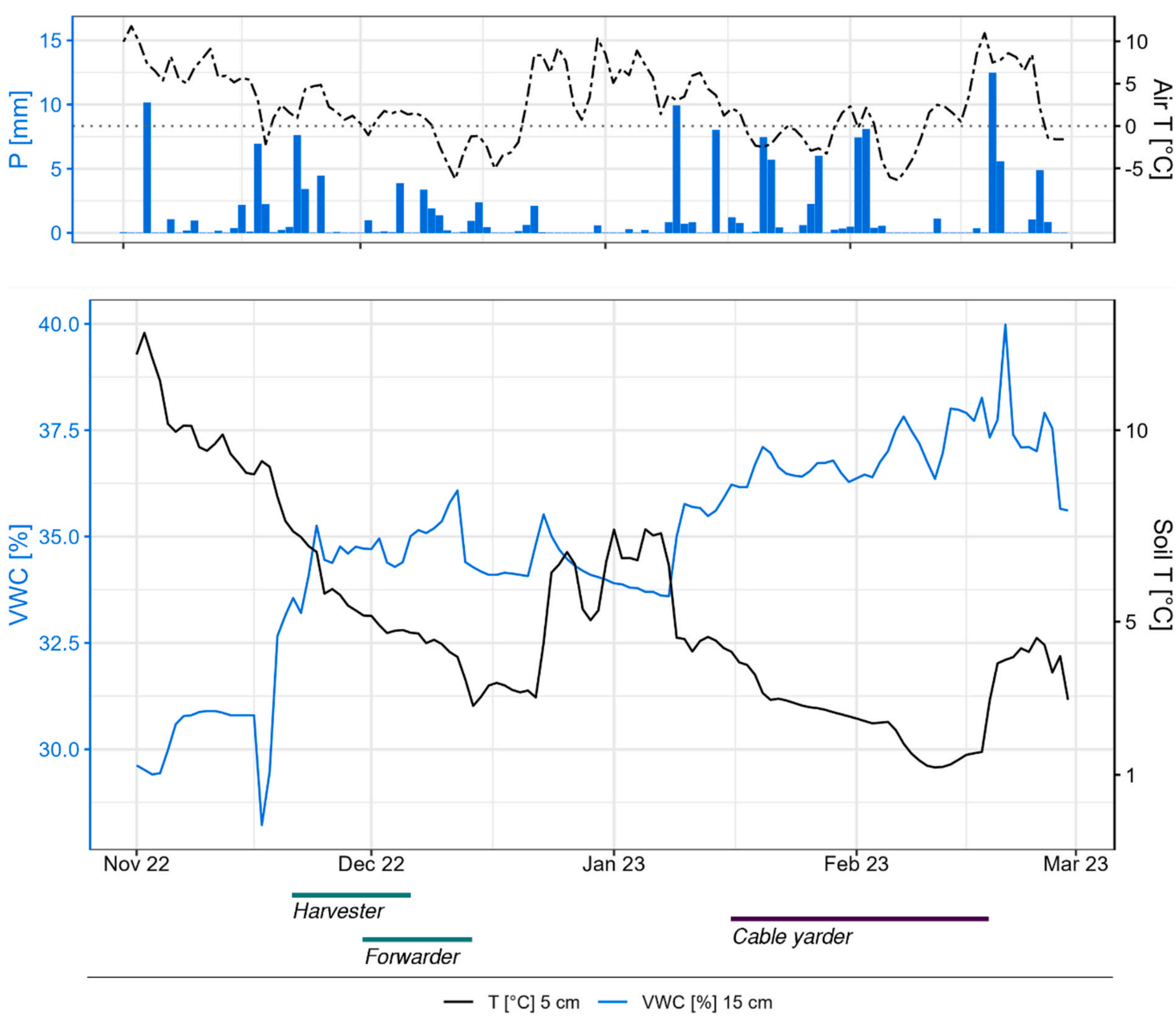

Fig. 1. Stand throughfall precipitation (mm/day). Daily means of stand air temperature (°C), volumetric water content in 15 cm depth (VWC%), and soil temperature at 5 cm depth at site Steinplattl. Horizontal lines indicate harvester, forwarder, and cable yarder operation periods.

Table 1
Overview treatments; all treatment plots were assessed before and after timber harvesting.

Label	Felling & processing	Machine type	Extraction	Machine type
H+	Harvester (8-wheeled, tethered)	John Deere 1270G (John Deere, Moline, IL, USA), tracked (*blue-track* series *duo flow* and *duo flow-perfect*, Pewag, Graz, Austria), operating weight 29.5 t	Forwarder (8-wheeled, tethered)	John Deere 1210G, tracked, operating weight 24.5 t + 13 t load
H-	Harvester (8-wheeled, tethered)	John Deere 1270G, non-tracked, operating weight 23.5 t	Forwarder (8-wheeled, tethered)	John Deere 1210G, tracks on uphill axles, operating weight 21.5 t + 13 t load
MC	Felling and delimbing (chainsaw); cross cutting (roadside processor)	Doosan DX210 (Doosan, Seoul, South Korea) with Woody 60 processor (Konrad Forsttechnik GmbH, Preitenegg, Austria)	Cable yarder	VALENTINI V600/M/3/1000/H (Valentini SRL, Cles, Italy) with Bergwald carriage (Franz Hochleitner, Bodman, Germany)
C	Thinned area not affected by yarding corridors or skid trails			

area of 50 m^2 in an inverted U-profile, framed by 5 m wide and 10 m long Pipelife® plastic tube segments (Fig. 3, left). To prevent lateral loss of surface runoff and also to avoid a tendency to delay runoff due to depressions, the microtopographic conditions are taken into account before each installation. This ensures that the irrigation plot is not located on a convex surface and that lateral runoff is not impaired by deadwood or stem bases. Water was evenly distributed over the irrigation area by using Rainbird®-MPR nozzles with a targeted inflow rainfall intensity of $i_T = 100\ mmh^{-1}$ to simulate a heavy rainfall event. This is considered plausible, as the 100-year precipitation event in this region with a duration of 60 min, estimated by the Austrian Hydrographic Service (eHyd, 2024), ranges between 120 mm (maximized modeled precipitation) and 60 mm (interpolated extreme value statistical precipitation). Due to the remoteness and low drainage of the *Münichbach* stream, the water supply was provided by the local fire brigade, which stored the water in 10 m^3 and 5 m^3 plastic tanks near the forest road. For each simulation run, the water was pumped to the individual irrigation plots and a total of 5 m^3 of water was sprinkled on the 50 m^2 plot area with a constant flow rate for one hour. From the beginning, the related outflow surface runoff (*Q*), if present, is collected in gutters at the downhill side of the irrigation plot, from where the water is diverted through a hose line into calibrated collection tanks where its volume per time is measured.

We opened, described, and sampled soil profiles on the downhill side of the plots after each rainfall simulation experiment in July 2022 and July 2023. We collected undisturbed soil cores (Fig. 3, right) for laboratory analysis using cylinders (h = 5 cm, 250 cm^3) at depths of 5 cm (2.5 – 7.5 cm; n = 3), 15 cm (12.5 – 17.5 cm; n = 3), and 25 cm (22.5 – 27.5 cm; n = 2). However, due to the high stone content, we could only sample the upper two depth levels for plots C and H-. We also performed pF curve measurements for all treatments at these two upper depth levels, which were the primary focus of further evaluations.

2.4. Measurements of soil properties

For determining soil water retention we followed the methods described in Hohenbrink et al. (2023) and Schelle et al. (2013). We used the HYPROP device (METER Group, GmbH, Munich, Germany) for measuring water retention in the wet (pF < 1.8; pF = log10(−h[cm]) and medium (pF = [1.8;4.2]) moisture range. Available air entry points were used according to Schindler et al. (2010). Water retention in the dry range (pF > 4.2) was measured using the dew point method (WP4C device, METER Group, Inc., Pullman, WA, USA) (Kirste et al., 2019; Schelle et al., 2013). We determined the saturated hydraulic conductivity (Ksat) using the falling head method (Ksat device, METER Group, GmbH, Munich, Germany). Our measurements were several times below or above the measurement limits of the device (<0.01 cm/d and > 5000 cm/d). Ksat was measured on all sampled cylinders. Other analyses (unless otherwise stated) were performed on only two cylinders per depth level, with the third sample as a backup. After the trafficking bulk density was also measured on all cores.

To obtain accurate estimates of the stone and coarse organic fragment content of the samples we sieved the slightly moist soil at 2 mm. Sieving after oven drying would have resulted in an overestimation of the stone fraction due to aggregation caused by the high clay content of the soil samples. A fine soil subsample was dried at 105 °C to calculate the factor for oven-dryness. Coarse fragments were dried to constant weight at 60 °C. Their volumetric content was calculated using a measured (AccuPyc 1330, Micromeritics, Norcross, GA, USA; measurement according to Austrian Standard EN 1097–7 (ÖNORM EN 1097-7, 2023)) rock density of 2.68 g/cm^3 and an estimated coarse organic matter (mainly roots and (decaying) wood) density of 0.5 g/cm^3. Fine soil bulk density was calculated as the quotient of fine soil mass and fine soil volume (Pacini et al., 2023). Total porosity for fine soil was calculated based on a particle density derived from a pedotransfer function (Equation (1), where P_{ds} is the soil particle density [g/cm^3]. The pedotransfer function was generated using data (n = 31) collected at the experimental site (adj. R2 = 0.93).

$$P_{ds} = 2.724 - 0.0482 * SOC[\%] \tag{1}$$

A subsample of the fine soil was rewetted to pF ~ 3.8 and allowed to equilibrate for at least 24 h before starting the dewpoint measurements. Total carbon and nitrogen content were analyzed using the LECO TruSpec elemental analyzer (LECO, St. Joseph, MI, USA). Texture (wet sieving and laser diffraction – Matersizer 3000, Malvern Panalytical, Malvern, United Kingdom; measurement according to DIN ISO 11277 (2023)) was determined for one composite sample per depth level for each plot.

3. Data processing

3.1. Surface runoff

Large-scale rainfall simulations enable the determination of characteristic surface runoff coefficients (Ψ), which result from the inverse relationship between an inflowing precipitation (*P*) and the corresponding outflowing surface runoff (*Q*) (Equation (Equation (2):

$$\Psi = \frac{Q}{P} \tag{2}$$

For this study, we provide information on two different surface runoff coefficients, derived from the rainfall simulation experiments.

The total surface runoff coefficient Ψ_t refers to the quotient of the total measured surface runoff and the total volume of inflow rainfall at the end of each experiment.

The final surface runoff coefficient Ψ_f accounts for the surface runoff coefficient, derived by fitting a constrained B-spline on the temporal progression of surface runoff during the experiment (surface runoff hydrograph), using the R package ‘cobs’ (Ng and Maechler, 2007). Similar to Meißl et al. (2023), the parameters for fitting the spline were adapted to the specific properties of the individual surface runoff

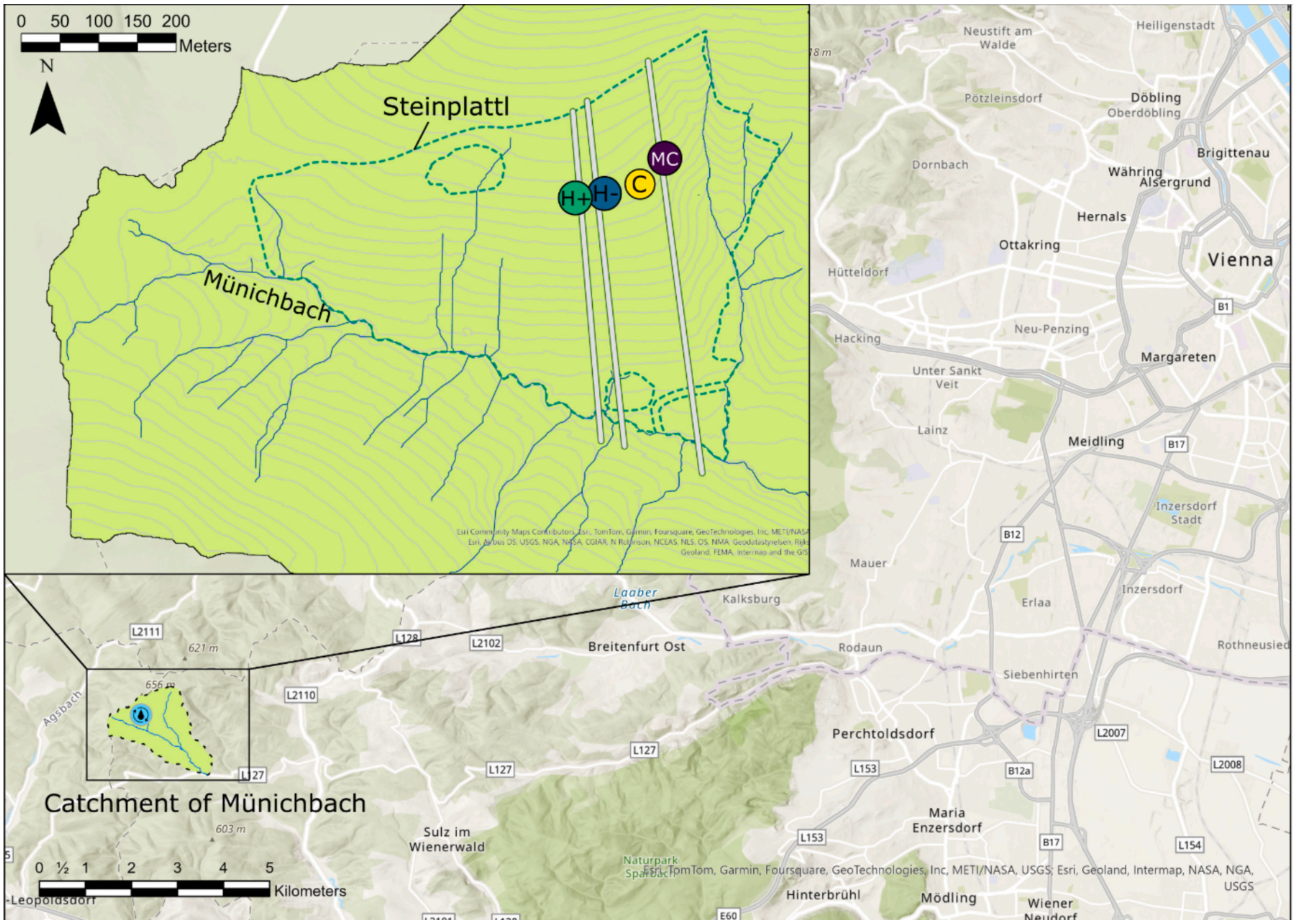

Fig. 2. Map of the catchment Münichbach showing the catchment boundary (external black line), stream network (blue lines), contours (5 m), stand edge (dashed blue line), and extraction corridors (light-grey lines). Colored circles indicate the irrigation plots for control (C), motor-manual felling and cable yarding (MC), tracked harvester/forwarder (H+) and minimum tracked harvester/forwarder (H-). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

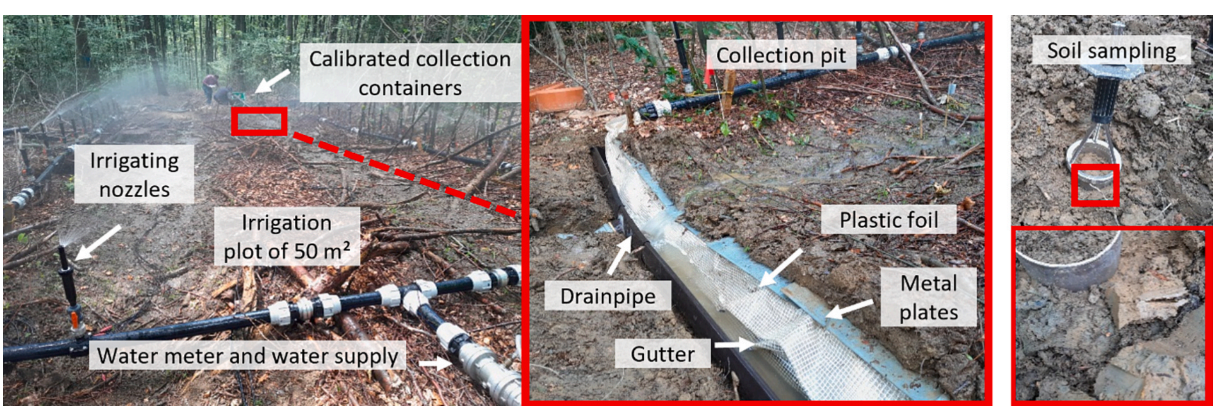

Fig. 3. Irrigation plot setup (left), undisturbed core sampling (right) showing hydromorphic soil properties in a skid trail.

hydrographs, with higher fitting weights (0.9) in the initial phase, which were linearly reduced to 0.5 towards the final phase. In contrast to the total runoff coefficient Ψ_t, which depends on the duration of the experiment, the final runoff coefficient Ψ_f refers to an estimate of the quasi-steady runoff achieved.

Other characteristic measures based on the individual surface runoff hydrographs are the time to runoff (t_r), which indicates the delay in the response to surface runoff, i.e., the time between the start of the experiment and the first measurement of surface runoff, and the linear temporal progression (m) of the surface runoff before it approaches its maximum. Here, m refers to the gradient, derived from a fitted linear model and depends on the roughness and slope of the irrigation plot under consideration.

To indicate retention capacity of the irrigation plot, we further estimated the maximum curvature (C), i.e. the maximum change of the gradient of the fitted constrained B-spline, as a characteristic further measure. A higher curvature value indicates delayed, continuous surface runoff, which indicates a higher retention capacity (c.f. Meißl et al., 2023). Fig. 4 shows the surface runoff hydrographs and characteristic measures for the two irrigation plots H+ and H- after timber harvesting.

3.2. Soil properties

Soil hydraulic property (SHP) data was checked according to Hohenbrink et al. (2023). However, the offsets were not corrected as the HYPROP devices were calibrated regularly. Deviations from the actual difference of 2.5 cm between tensiometers are explained by the low hydraulic conductivity of the samples which prevents the initial equilibration of the tensiometers. For the determination of the water retention curve (WRC), the impact of this effect is expected to be neglectable. Due to limited air conductivity, compacted samples frequently showed scattering at low suctions. In severe cases scattering at water contents pF $\ll$ 1.8 was omitted for model fitting. For better comparability among samples, the volume and weight of the coarse fraction ($>$ 2 mm) was subtracted before curve fitting. All complete measurements per sampled depth level and treatment were combined into one file for curve fitting. Additionally, we combined the upper two depth levels of untrafficked soil into one file each. A WRC was fitted to each of these files to serve as a combined control. We fitted the PDI (Peters-Durner-Iden) variant (Peters et al., 2024) of the bimodal Kosugi model (Kosugi, 1996). This model was used as the PDI variant yields more realistic results in the dry range of the moisture curve (Peters, 2013; Peters et al., 2021). The bimodality reflects both structural and textural pore space (Klöffel et al., 2024). To fit the model, we used LABROS SoilView Analysis software (METER Group, GmbH, Germany). We excluded the measured Ksat values for SHP model fitting, as they tend to reflect the single largest pore in undisturbed soils (Koestel et al., 2018), resulting in large variability. Additionally, the repeated exceedance of the device's limits justifies the exclusion of the measured data for SHP model fitting. Water content at field capacity (FC, θ at pF $=$ 1.8), permanent wilting point (PWP, θ at pF $=$ 4.2) and available water capacity (AWC, θ (pF1.8) – θ (pF4.2)) were derived from the fitted WRCs. Further processing, visualization and evaluation of the data were performed in RStudio (Posit team, 2023). We restricted the statistical analysis of soil properties (including Ksat, bulk density, porosity, SOC and coarse fraction) to samples from 5 cm and 15 cm depth following timber harvesting. We compared MC, H+, and H- to the control (C) using linear models, focusing on differences in intercepts relative to the control. Due to the small sample size, we refrained from pairwise comparisons. Model assumptions were checked visually using diagnostic plots.

4. Results

4.1. Surface runoff

Pre-harvest rainfall simulation experiments in 2022 produced no surface runoff on all four irrigation plots. After timber harvesting, rainfall simulations in 2023 again showed no surface runoff for C as well as for MC. In contrast, strong surface runoff responses were observed in rainfall simulation experiments carried out on the H+ and H- irrigation plots (Table 2). Surface runoff hydrographs for both H+ and H- irrigation plots are given in Fig. 4.

Following timber harvesting, higher total and final runoff coefficients were observed on H+ skid trails in comparison to H- skid trails. Although the time to runoff was approximately the same for both plots H+ and H-, a faster increase in surface runoff (higher gradient m) with a simultaneous higher retention capacity (higher maximum curvature C) was observed on H-.

4.2. Soil properties

The topsoil layer of all soil profiles was characterized by a biomacro structured mineral Ah horizon with high activity of endogeic and anecic earthworms. This changed with timber harvesting. A platy structure with hydromorphic features (mostly greyish mottles) appeared in the upper 10 cm of H+ and H- (Fig. 3, right). Gray mottles and altered soil structure (blokey structure) were also found at MC, however, less homogeneous and patchier. A strong anaerobic odor was noticeable when opening soil profiles and trenches (for irrigation experiments) at all harvesting treatments, indicative of anoxic decomposition of incorporated organic material under compacted conditions. Prior to harvesting, all soil profiles showed signs of stagnic conditions, but to a lesser extent

Table 2
Results derived from the rainfall simulations with total runoff coefficient Ψ_t, final runoff coefficient Ψ_f, time to runoff t_r, gradient m and curvature C. * 2022 was before timber harvesting, 2023 was after timber harvesting; The plot codes refer to: C to control, MC motor-manual felling and cable yarding, H+ tracked harvester/forwarder and H- minimum tracked harvester/forwarder.

Plot	Year*	Ψ_t[-]	Ψ_f[-]	t_r[min]	m[% min^{-1}]	C[% min^{-2}]
C	2022	0	0	–	–	–
MC	2022	0	0	–	–	–
H+	2022	0	0	–	–	–
H-	2022	0	0	–	–	–
C	2023	0	0	–	–	–
MC	2023	0	0	–	–	–
H+	2023	0.56	0.67	3.6	2.76	0.20
H-	2023	0.46	0.61	3.2	3.75	0.37

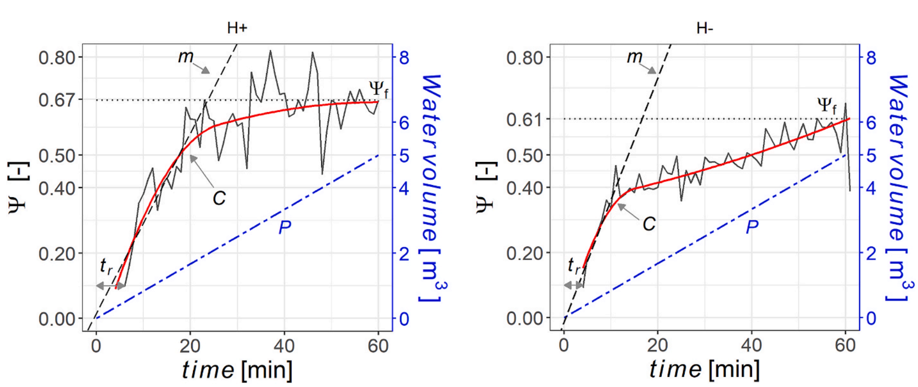

Fig. 4. Surface runoff hydrographs for the irrigation plots H+ (tracked harvester/forwarder) and H- (minimum tracked harvester/forwarder). The red solid line refers to a fitted B-spline, showing information on the final surface coefficient Ψ_f as well as the curvature C. Also indicated is time to runoff t_r and the progress of runoff generation at the initial phase of the experiment – given by the gradient m. The blue dashed-dotted line shows the amount of inflow water (rainfall P). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Measured soil properties prior to timber harvesting; Cf refers to coarse fraction (> 2 mm), SOC to soil organic carbon, BD to bulk density, ϕ to total porosity, n to the number of samples, Ksat to saturated hydraulic conductivity; + for Ksat geometric mean and sd (standard deviation) were used and n for 5 and 15 cm is 3, below that 2. #Clay and silt values based on composite sample; The plot codes refer to: MC motor-manual felling and cable yarding measured before the treatment, H+ tracked harvester/forwarder measured before the treatment and H- minimum tracked harvester/forwarder measured before the treatment.

Treatment	Depth [cm]	Cf [%]	SOC [%]	BD [g/cm^3]	ϕ [%]	n	Ksat [cm/d]$^+$	Silt [%] [<63 μm]$^\#$	Clay [%] [<2 μm]$^\#$
		mean	mean	mean	mean		mean		
MC	5	5.0 ± 0.8	3.59 ± 0.55	0.78 ± 0.15	69.4 ± 5.95	3	2513.32 ± 3.29	33.5	55.5
	15	3.5 ± 1.5	2.83 ± 0.19	1.00 ± 0.05	61.5 ± 2.02	3	1583.05 ± 1.85	22.4	68.3
	25	4.2 ± 0.7	2.06 ± 0.30	0.97 ± 0.01	63.0 ± 0.17	2	1632.32 ± 3.88	33.1	57.2
H+	5	4.3 ± 0.2	4.75 ± 0.38	0.69 ± 0.04	72.2 ± 1.64	2	3594.44 ± 1.77	32.9	53.1
	15	11.4 ± 6.6	2.88 ± 0.71	0.86 ± 0.02	66.9 ± 1.32	2	1597.00 ± 2.09	27.1	52.9
	25	19.0 ± 4.2	1.48 ± 0.10	1.06 ± 0.04	59.9 ± 1.45	2	1485.35 ± 1.77	32.9	43.6
H-	5	7.9 ± 2.5	3.10 ± 0.41	0.80 ± 0.15	69.1 ± 5.62	2	3853.89 ± 1.57	26.9	58.9
	15	4.8 ± 0.4	2.47 ± 0.16	0.97 ± 0.02	62.9 ± 0.53	2	2076.69 ± 1.19	38.2	53.3

and/or at greater depth (appendix A 1, A 2). The plots had consistently high clay content in the fine soil (> 40 %) throughout the profile, and the coarse fraction ranged from 3.5-13.1 % in the upper two depth levels (conditions prior to timber harvesting: Table 3; conditions after timber harvesting: Table 4). In deeper horizons, the volume of stones comprised higher shares of the total volume (appendix A 1, A 2). Before trafficking, the mean SOC concentrations in 5 and 15 cm were 3.98 ± 0.78 % and 3.12 ± 0.72 %, respectively. After trafficking an increase can be observed for all treatments. For MC and H- the increasing tendency of the SOC content is very small (Table 4).

The reduction of aeration in all treatments was visible in the saturated hydraulic conductivity (Ksat), which decreased drastically (Fig. 5a; Table 4). At 5 cm depth, a clear reduction in Ksat is evident for all treatments. However, at MC the impact is minimal at 15 cm and diminishes at 25 cm. H+ and H-, still have pronounced lower values at 15 cm, which persists for the available data at 25 cm. The impact of H+ and H- on Ksat could not be clearly distinguished. The geometric means show a trend in the upper two depth levels of the lowest impact of MC, followed by H+ and H-. The geometric mean was chosen as it provides a more conservative estimate for the logarithmically distributed Ksat, minimizing the influence of extreme values in the calculation.

Bulk density (BD) also reflects the patterns seen in Ksat (Fig. 5b, Table 4). All treatments show a higher BD after timber harvesting at 5 cm depth. This trend is consistent at 15 cm and 25 cm, but less pronounced for MC. The difference between the two ground-based timber harvesting systems is not significant, but there is a slight trend towards lower BD values with the use of bogie tracks (H+). Total porosity, as expected, shows the reversed trend of BD (Table 4). At 5 cm depth, fine soil porosity was 10 %, 15 % and 18 % lower for MC, H+ and H- compared to measurements prior to timber harvesting, respectively. This effect decreased at 15 cm resulting in 4 %, 15 % and 15 % lower porosity for the respective treatment (Table 3 Table 4).

The measured and fitted untrafficked water retention curves are very similar for the first two depth levels throughout the treatments (Fig. 6). After trafficking the following five effects of timber harvesting related compaction are evident: (i) At 5 cm depth, there is a notable flattening of all retention curves (between pF ∈ [0,4.2]), which corresponds to a loss of macroporosity and hence bimodality. While MC seems to have the porosity distributed more evenly throughout the AWC, treatments H+ and H- appear to have most pores in the drier range of the AWC (Fig. 6a). (ii) At 15 cm depth, the curve shape between H+ and H- is similar, while the impact of MC on water retention is neglectable (Fig. 6b). (iii) Small differences between the water retention curves, as observed in the untrafficked treatments as well (Fig. 6), can be explained by small scale

Table 4
Measured soil properties after to timber harvesting; Cf refers to coarse fraction (> 2 mm), SOC to soil organic carbon, BD to bulk density, ϕ to total porosity, n to the number of samples, Ksat to saturated hydraulic conductivity; + for Ksat geometric mean and sd (standard deviation) were used and n for 5 and 15 cm is 3, below that 2. #Clay and silt values based on composite sample; The plot codes refer to: C Control; MC motor-manual felling and cable yarding; H+ tracked harvester/forwarder and H- minimum tracked harvester/forwarder. n = 3 for 5 cm & 15 cm, n = 2 for 25 cm. Significance levels: $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), $p < 0.1$ (°), with non-significant values left unmarked.

Treatments: Parameter	Depth	C mean	MC mean	H+ mean	H- mean
Ksat$^+$ [cm/d]	5	2349.25 ± 2.01	54.88 ± 2.53	12.32 ± 9.47°	2.80 ± 137.60°
	15	488.81 ± 3.08	973.09 ± 1.57	2.37 ± 114.78°	0.11 ± 31.10**
	25		1111.78 ± 1.48	0.03 ± 3.72	
BD [g/cm^3]	5	0.83 ± 0.05	1.03 ± 0.11°	1.03 ± 0.08°	1.24 ± 0.18**
	15	1.01 ± 0.08	1.10 ± 0.06	1.24 ± 0.09**	1.36 ± 0.08***
	25		1.05 ± 0.04	1.18 ± 0.00	
ϕ [%]	5	66.8 ± 1.53	59.4 ± 4.10°	57.6 ± 3.81*	51.3 ± 6.24**
	15	60.2 ± 3.35	57.4 ± 2.08	51.9 ± 3.63*	47.5 ± 3.38**
	25		59.9 ± 1.45	54.5 ± 0.37	
SOC [%]	5	4.45 ± 0.58	4.14 ± 0.29	5.90 ± 0.56*	3.71 ± 0.97
	15	4.00 ± 0.53	2.90 ± 0.27°	2.78 ± 0.22°	2.72 ± 0.86°
	25		2.22 ± 0.16	2.70 ± 0.42	
Cf [> 2 mm; %]	5	11.4 ± 1.3	5.0 ± 1.4**	7.0 ± 1.1*	12.5 ± 2.6
	15	13.1 ± 3.2	3.8 ± 0.7	7.8 ± 4.5	10.3 ± 6.7
	25		3.0 ± 0.2	8.0 ± 1.2	
Clay [%]	5	58.8	52.1	49.7	58.5
[<2 μm]$^\#$	15	53.5	57.5	57.1	66.5
	25		58.4	60.8	
Silt [%]	5	31.7	43.1	40.7	35.4
[<63 μm]$^\#$	15	37.2	35.2	32.8	30.1
	25		33.3	26.5	

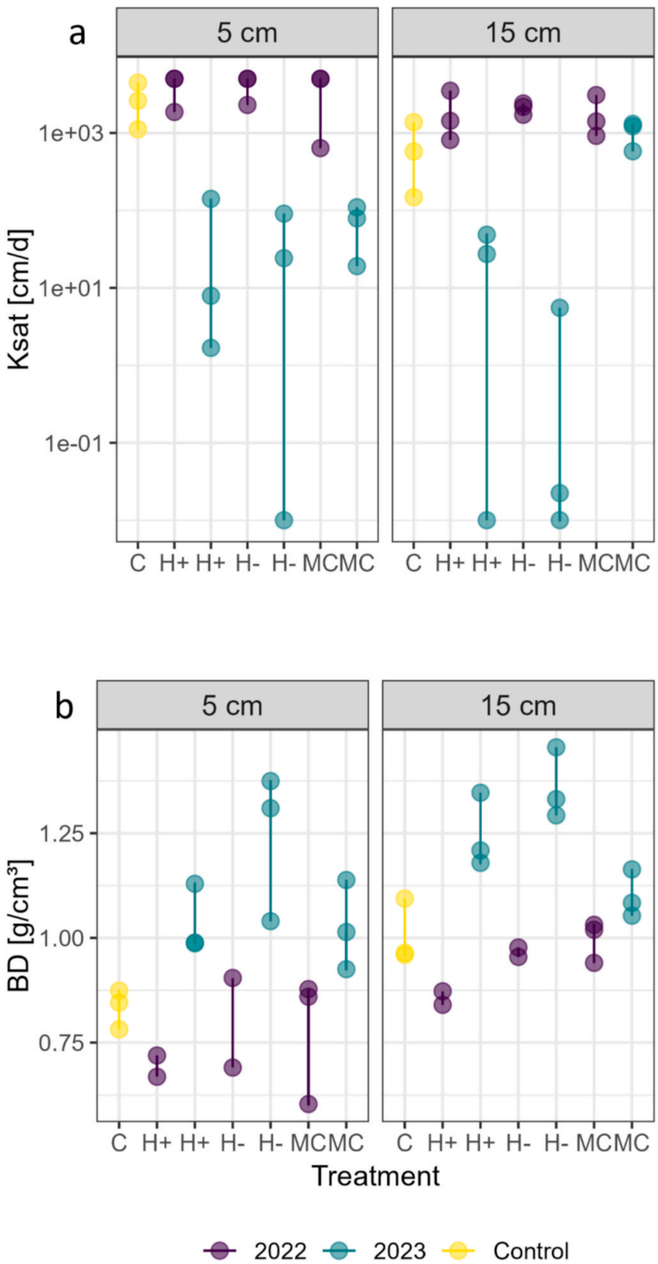

Fig. 5. a) saturated hydraulic conductivity (ksat) and b) bulk density (BD); samples from 2022 were taken before timber harvesting, 2023 samples and the samples from the untrafficked control plot (C) were taken after timber harvesting. H+ refers to the tracked harvester/forwarder plot, H- to minimum bogie track application and MC is the motor-manual felling and cable yarding treatment.

heterogeneity in site conditions (e.g. impacts of rock content, texture, SOC content, etc.). (iv) Coinciding with the changes in the water retention curves, typical estimates for soil water characteristics: FC (θ at pF = 1.8), PWP (θ at pF = 4.2) and AWC (θ (pF 1.8) – (pF 4.2)), are altered as well. Table 5 illustrates that the shifted pore size distribution after compaction results in a pronounced increase in FC and a less pronounced increase in PWP, resulting in an increased AWC at both 5 cm and 15 cm depths (at 15 cm depth neglectable for MC). This indicates an altered pore size distribution extending well into the range of mesopores and beyond θ at pF = 4.2. (v) While the initial water content at pF = 0 may appear to remain relatively constant, it is important to consider changes in total porosity. Large pores that drain immediately are lost during compaction. This is reflected in the changes in total porosity (Table 4).

5. Discussion

As expected, ground-based harvesting led to compaction and changes in soil physical properties and related soil functions. High soil moisture throughout the timber harvesting operations, combined with low initial bulk densities and high SOC concentrations, made our site highly susceptible to harvesting-related compaction (Nazari et al., 2023). With constantly wet and unfrozen soil conditions, we excluded an important confounding factor when comparing the impact of different machineries (Allman et al., 2015). While the soil was slightly drier at the beginning of the harvester operation, we expect this to be neglectable, as during the forwarder operation, which is the machine with the higher load, soil conditions were constant and wet (Fig. 1). The results of our study are largely consistent with our initial assumption: The ground-based systems exhibited stronger impacts, although the differences between the two ground-based systems (harvester/forwarder “tracked” and “minimum tracked”) were minimal or non-existent. The impact of the cable yarder was lower, as less weight was exerted on the soil, even though the harvesting intensity was higher on yarding corridors.

5.1. The impacts of timber harvesting on runoff

Our rainfall simulation experiments showed no surface runoff on any of the four irrigated plots prior to timber harvesting. The entire amount of water applied could be absorbed by the forest soil. Thus, the study site provides a well-developed macropore network under nearly undisturbed soil conditions. This ensures high infiltration capacities, despite the clay-rich flysch substrate and the associated low permeability of the substrate. Our findings are in agreement with Jost et al. (2012), who irrigated a comparable beech forest stand with the same rainfall intensity. In such biologically active sites, high macroporosity, as reflected by high saturated hydraulic conductivity values and low bulk densities, makes saturation excess overland flow unlikely (Jost et al., 2012).

After timber harvesting, no surface runoff was observed in the thinned control plot C and, contrary to our prior assumption, in the yarding corridor MC. This shows that the impact of cable yarding on surface runoff was even lower than expected, supporting the conclusions of other studies reporting that cable yarding is more environmentally friendly and hence has less negative impacts on soil functions than using winching and skidding approaches (Marchi et al., 2014; Schweier and Ludowicy, 2020).

However, for plots H+ and H-, considerable surface runoff was observed on skid trails created by ground-based timber harvesting. This agrees with our hypothesis, although the difference between H+ and H- was not pronounced and was opposite to our expectation. The saturated hydraulic conductivity values, measured in H+ and H- after timber harvesting, as well as the small maximum curvature values (c.f. Meißl et al., 2023), determined from the fitted B-spline model of the surface runoff hydrographs (Table 2), indicate a low retention capacity. This suggests rapid runoff processes, e.g. surface runoff due to infiltration excess in both plots. In the context of soil and ecosystem functions this leads to less water retention on the site. This is particularly problematic in the context of climate change, as droughts (Trnka et al., 2016) and heavy rainfall events (IPCC, 2022) are becoming more frequent. To improve water retention within the forest stand, strategies such as the creation of rills or small logs for cross-drainage in skid trails could be tested to redirect water back into the forest floor. In addition to water loss through surface runoff, erosion is also triggered which leads to a decline in SOC and nitrogen (Gall et al., 2024).

On average, total and final surface runoff coefficients of $\Psi_t = 0.51$ and $\Psi_f = 0.64$ were measured for H+ and H- together, with runoff predominantly recognisable in the ruts. For comparison, Jourgholami et al. (2020) report a total runoff coefficient from natural rainfall events of approximately 0.35 on heavily trafficked skid trails on loam with similar slope angles. Based on large-scale rainfall simulation

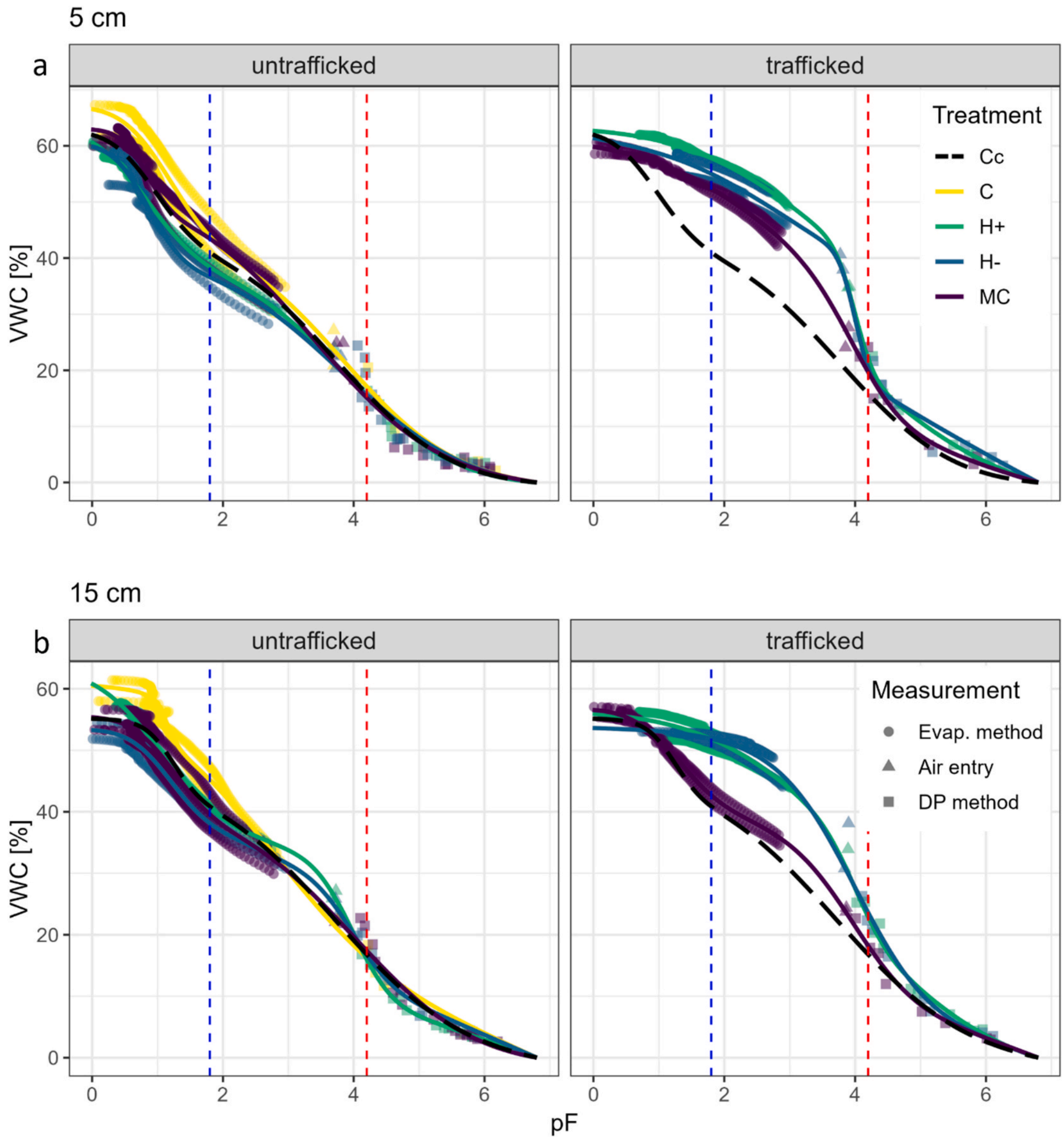

Fig. 6. Soil water retention of trafficked (right) and untrafficked (left) soil samples at 5 cm (a) and 15 cm (b) soil depth. Cc is a retention curve fitted to all untrafficked samples of the respective depth level, C is the control plot, H+ is the tracked harvester/forwarder plot, H- is the plot with minimum bogie track application, and MC is the plot from the yarding corridor of motor-manual felling and cable yarding. The blue and red dashed lines mark the field capacity at pF = 1.8 and the permanent wilting point at pF = 4.2, respectively. Measurement methods are the evaporation method (evap. method), the tensiometer air entry point, and the dewpoint (DP) method. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Typical estimates for soil water characteristics, field capacity (FC), permanent wilting point (PWP) and available water capacity (AWC) at 5 and 15 cm depth. * 2022 is before, 2023 after timber harvesting; The plot codes refer to: C control, MC motor-manual felling and cable yarding, H+ tracked harvester/forwarder and H- minimum tracked harvester/forwarder.

Treatment	Depth [cm]	FC [%]		PWP [%]		AWC [%]	
		*2022**	*2023*	*2022*	*2023*	*2022*	*2023*
MC	5	43.5	52.4	15.1	19.7	28.3	32.7
	15	39.6	42.7	17.4	18.2	22.2	24.5
H+	5	38.4	57.8	15.4	22.1	23.0	35.7
	15	40.6	51.8	16.0	22.9	24.6	29.0
H-	5	36.6	55.0	15.6	20.4	21.0	34.6
	15	38.2	51.9	16.8	23.6	21.4	28.3
C	5	–	43.9	–	17.1	–	26.8
	15	–	45.2	–	16.3	–	28.9

experiments (plot size = 300 m^2) applied five years after logging, Croke et al. (1999) found clear evidence that the runoff response to harvesting operations due to infiltration-excess processes and that the degree of land disturbance, given by the highly compacted skid trails, is the determining factor. They report typical runoff coefficients between 0.50 and 0.60 on skid trails during a 100-year rainfall event (110 mmh^{-1}). Similar results are reported by Zemke et al. (2019), who measured a runoff coefficient of 0.60 on compacted skid trails using a small-scale rainfall simulator (plot size = 0.64 m^2). Considering the effect plot length and soil texture on surface runoff reveals additional insights. While the short plot length of Zemke et al. (2019) should result in higher runoff, the sandy and loamy texture reduces the runoff compared to the clayey soil at our site (Jourgholami and Labelle, 2020). Croke et al. (1999) investigated plots with a length of 15 m on sandy soil, yielding comparable results to ours, while lower values would be expected. However, this is likely due to the more invasive construction of skid tracks in their study, where bulldozers were used to blade the tracks prior to skidding.

In our study, it should be noted that the measured and reported runoff coefficients refer to the entire irrigation area. As already mentioned, most of the surface runoff was observed in the effectively compacted ruts, which covered about 40 % – 50 % of the total irrigation plot. Therefore, if only the runoff coefficients on the effectively compacted areas in and next to the ruts are considered, significantly higher values must be expected.

While some studies reported higher runoff on skid trails from ground-based timber harvesting with steeper slope gradients (Jourgholami et al., 2017; Khan et al., 2016; Solgi et al., 2014), our findings suggest that cable yarding, which is often the only harvesting option in steep terrain, does not have a significant impact on runoff generation. We observed no surface runoff in the yarding corridor, despite being 10 % steeper (34 % slope) than all other plots.

Considering the runoff behaviour of the individual plots on skid trails created by ground-based timber harvesting, higher total and final surface runoff coefficients were measured on H+ . We associate these higher surface runoff coefficients with the greater width of the ruts which are extended from 0.924 m to 1.154 m using bogie tracks. This results in a higher proportion of the soil surface affected by machine traffic in relation to the total irrigated area.

The influence of bogie tracks is probably also reflected in the temporal progression (*m*) of the surface runoff before it approaches its maximum. Contrary to plot H-, where we tested the approximation to a minimum use of bogie tracks, the slope *m* determined from the hydrograph of plot H+ is smaller, indicating a slightly delayed initial runoff formation due to higher surface roughness. We attribute this to (i) the incorporation of organic material into the ruts by the bogie tracks, likely also reflected in the higher SOC content after harvesting here, and (ii) the shallower rut depth, which allows a greater lateral distribution of surface runoff. Rut depth, was found to be highest with minimum use of bogie tracks (0.109 m), compared to 0.085 m with boogie tracks. This is consistent with Haas et al. (2016), who reported higher rut depths without bogie tracks.

In principle, runoff generation after the start of the irrigation is fast, for both plots. With observed times to runoff below 4 min, they are close to the minimum published times for runoff onset (3 min – 19 min) observed by Zemke et al. (2019). However, even shorter runoff times of about 1 min were reported by Croke et al. (1999) for rainfall simulation experiments on skid trails with an applied amount of rainfall corresponding to a 100-year event.

The maximum curvature values *C* (Table 2) determined for plots H+ and H- show the small difference in the retention capacity of skid trails of both ground-based treatments in this study. However, the difference is marginal compared to the maximum curvatures of equally fitted surface hydrographs based on similar precipitation simulators by Meißl et al. (2023). The slightly higher retention capacity on plot H-, deduced from the marginally higher maximum curvature, might also result from a higher share of undisturbed, i.e. uncompacted surface in this treatment.

5.2. The effects of timber harvesting on soil hydraulic properties

The impacts of timber harvesting were clearly visible in the soil profiles. We observed altered soil structure and hydromorphic features (e.g., mottling), indicating a lack of oxygen, in the skid trails and, to a lesser extent, in the yarding corridor. Morphological changes in the skid trail surface soil were also reported by Klein-Raufhake et al. (2024) and Startsev and McNabb (2009). We assume that the slight increase in SOC in the top layer shortly after trafficking is mainly related to physical processes (e.g. crushing and soil mixing). Increases for H+ are higher, likely due to finer crushing and incorporation of organic matter by the bogie tracks.

Strong reductions in saturated hydraulic conductivity (Ksat) underscore these structural changes. We can confirm our hypothesis that the impact of the cable yarder (MC) was smaller than that of ground-based harvesting. Differences between the ground-based timber harvesting systems, H+ and H- respectively, are not very clear, partly due to the considerable variability of Ksat in both treatments. However, in agreement with our hypothesis there is a small tendency of a stronger reduction in Ksat for H-. All undisturbed soil sampling methods induce disturbances around the edges of the sampling ring (Carr et al., 2020). We expect this effect to be greater in rocky soils, with the location of rocks determining the degree of disturbance. This could lead to greater variability in Ksat, especially if the soil is otherwise compact, and the small disturbances around the edges could be the critical pore diameter, governing Ksat (Koestel et al., 2018). In their *meta*-analysis, Nazari et al. (2021) showed a 40.2 % reduction in Ksat after compaction across all studies. Except for the cable yarder, the decrease in Ksat in our study is much stronger and likely still underestimated, because samples exceeded the measurement limits of the Ksat device before trafficking (>5000 cm/d; at least once for MC, H+, and H- at 5 cm) and after trafficking (<0.01 cm/d; at least once for H+ and H- at 15 cm). Simmons and Anderson (2016) also showed stronger reductions in Ksat than Nazari et al. (2021) in their study of logging operations on wet (slightly below field capacity) fine-textured loamy soils. The strong reductions in Ksat coincide with a loss of macroporosity and, if homogeneous over larger sections (e.g. in ruts), the formation of surface runoff.

Bulk density is increased in a similar pattern as Ksat decreased. We can confirm our hypothesis that yarding corridors (MC) caused smaller increases in bulk density. While some sources showed no impact (Marchi et al., 2014) or even higher impacts of cable yarding on bulk density compared to ground-based logging (Miller and Sirois, 1986), most studies agree with our finding of a lower impact of cable yarding (Krag et al., 1986; Laffan et al., 2001; Picchio et al., 2018). This underlines the importance of the specific setup of the cable yarder on soil disturbance (Varch et al., 2021). The strong increases in bulk density for H+ and H- are consistent with the results of Startsev and McNabb (2000), who showed that bulk density increases especially when logging is conducted under wet conditions. Grünberg et al. (2024, submitted) showed that, under site conditions similar to ours – fine-textured soil, high SOC, and low bulk density – but with dry conditions, only small increases in bulk density occurred. Machines that induce less ground pressure have less impact on bulk density and porosity (Solgi et al., 2023). This is, consistent with our hypothesis, reflected in the tendency for smaller increases in BD for H+ at 5 and 15 cm. While Cambi et al. (2015b) also observed a non-significant trend of lower impacts from tracked vehicles in wet conditions, Haas et al. (2016) found no difference in bulk density between forwarders with and without bogie tracks. The total porosity results mirror the effects on bulk density. Our data clear clearly agree with Klein-Raufhake et al. (2024), who show that increases in bulk density below “critical values”, e.g. 1.4 g/cm^3 for clay soils (Picchio et al., 2020), can alter soil functions considerably.

Water retention curves (WRC) are affected by timber harvesting in a similar pattern to the other soil parameters we measured. Corresponding to the smaller increase in bulk density, the WRC of MC drops slightly steeper, indicating a higher proportion of larger pores compared to ground-based timber harvesting treatments. This agrees with our hypothesis of the lower impact of MC. At 5 cm depth, all treatments exhibit a shift from a bimodal WRC, with two distinct peaks, to a unimodal distribution (Fig. 6). The bimodality, which is driven by soil structure (Durner, 1994; Klöffel et al., 2024; Zhang et al., 2022), is lost due to compaction (Matthews et al., 2010). However, the small differences between H+ and H- treatment at 5 cm, is likely due to the slightly larger variability between HYPROP measurements for H-. Hence, we cannot confirm the hypothesis that H+ has a lower impact on water retention than H-. At 15 cm, both H+ and H- show similar compaction effects, while MC shows no clear effect and retains bimodality.

Together with the loss of bimodality a flattening of the retention curves in the pF range [0, 4.2] is visible, a pattern also observed by other authors (e.g., Katou et al., 1987; Smith et al., 2001; Zhang et al., 2022). Thus, we can demonstrate the well-known loss of macropores after timber harvesting (e.g., Bottinelli et al., 2014; Greacen and Sands, 1980; McNabb et al., 2001). Notably, despite similar initial water contents at pF = 0 before and after timber harvesting, all treatments show a reduction in total porosity of at least 10 % at 5 cm (Table 3 and Table 4). This reflects the loss of large macropores that drain immediately before HYPROP measurements are started.

At 5 cm depth for all treatments, and at 15 cm for H+ and H-, the air-filled porosity at field capacity (pF $\in$ [0, 1.8]) falls below the critical value of 10 % (Startsev and McNabb, 2009; Xu et al., 1992), limiting aeration at field capacity. Additionally, the WRC flattens in the range of available water capacity (AWC), especially for H+ and H-. This indicates that coarser pores in the range of AWC, which typically drain quickly, are lost, prolonging periods of limited aeration. This limitation, which is often observed after logging-related soil compaction (Hansson et al., 2019; Startsev and McNabb, 2001), restricts root growth (Wall and Heiskanen, 2009, 2003), alters microbial communities (Frey et al., 2011; Hartmann et al., 2014), and affects the soil greenhouse gas balance of carbon dioxide, methane, and nitrous oxide (Hernandez-Ramirez et al., 2021; Vantellingen and Thomas, 2021).

An increase in water retention was observed in the range of AWC. This response appears to be site-dependent (Smith et al., 2001), as studies report varying effects, including no change (Startsev and McNabb, 2001), increases (Ares et al., 2005; Smith et al., 2001), and decreases (Smith et al., 2001) following forest soil compaction. The increase in AWC can be attributed to the loss of well-developed macroporosity and a simultaneous rise in field capacity due to an equivalent rise in the proportion of mesopores. However, the increase in field capacity is more pronounced than the increase of water content at the wilting point (Smith et al., 2001). Nevertheless, due to limited aeration, the benefits of increased AWC are likely to be negligible, especially considering reduced infiltration and increased water loss through surface runoff.

5.3. Limitations and management implications

This study was conducted at a single experimental site, which may limit the generalizability of the findings. However, our results strongly agree with those reported in multiple previous studies, as discussed above. Clayey soils are known to produce higher runoff than other soil types (Jourgholami and Labelle, 2020) and are more susceptible to compaction and rutting (e. g., Cambi et al., 2015). Additionally, undisturbed soils within the same geological formation, as studied by Jost et al. (2012), did not produce surface runoff either. This consistency across studies provides confidence in the broader relevance of our findings. Some degree of natural variability is present in the data, reflecting the inherent complexity of environmental systems. Consequently, while clear treatment effects are evident (Fig. 5), p-values and other measures of statistical significance should be interpreted with caution, as they may not fully capture this variability. Despite these considerations, the study provides valuable insights into the effects of different timber harvesting systems on soil water retention and surface runoff. It also underscores the need for further investigations across diverse sites to validate and expand these findings. Furthermore, we plan to conduct additional experiments at the same site to monitor the recovery of the plots over time.

Our study unequivocally demonstrates that cable yarding is the least impactful timber harvesting system, particularly in sloped terrain with fine textured soils. Compared to ground-based systems, cable yarding resulted in less disturbance of soil physical characteristics and no surface runoff. This highlights its potential as the most sustainable option for timber harvesting in such challenging environments.

Both ground-based systems in our study site were operated using a winch to improve traction. Winch application likely helped reducing track wander and ruts depths (Green et al., 2020). Observations from a nearby forest stand support this assumption, where logging was conducted without winch assistance.

Our findings indicate that bogie tracks exhibit a slightly lower impact on soil due to an improved weight distribution of the machines. To further mitigate mechanical stress on the soil, the use of thicker brush mats as a protective layer (Labelle et al., 2022) is recommended. In beech forests, widening the spacing of skid trails with motor manual lateral felling prior to harvester operation could facilitate the creation of thicker brush mats, as beech crowns yield less brush compared to, e.g., spruce. Increasing the spacing from the current 20 m to 40 m would effectively reduce the trafficked area from 20 % to 10 %, thereby limiting surface compaction and runoff creation.

Moreover, the implementation of specific structures, e.g., diagonal logs in skid trails or pit-mound structures, to laterally divert water into the forest stand, could help to reduce runoff. This would prevent linear flow in skid trails through slope sections. Further, the positioning of culverts from forest access roads can affect the runoff behavior of catchments (Buttle et al., 2018). Hence, skid trails should not be located directly below culverts in order to avoid channeling forest road drainage via skid trails to downhill streams. Other culvert placements could increase the water retention in the forest stand.

These measures could limit runoff creation, increase water retention and therefore potentially limit peak flows in stream channels, particularly crucial in anticipation of increased heavy rainfall events.

The most effective method preventing soil damage would still be proper timing of harvesting operations, restricting use of heavy machinery to periods with frozen or dry soil conditions.

6. Conclusion

Our study demonstrates that timber harvesting, particularly with ground-based timber harvesting systems, alters soil hydraulic properties and increases surface runoff. The use of heavy machinery, especially under wet conditions, resulted in a marked decrease in saturated hydraulic conductivity (Ksat), and a substantial increase in bulk density in the upper soil layers. These changes were more pronounced on skid trails than on yarding corridors. While bogie tracks slightly reduced the impacts on bulk density and soil hydraulic properties, the differences were marginal. Bogie tracks helped reduce rut depths, but increased surface runoff, likely due to their larger surface area. In contrast, cable yarding had a lesser impact on bulk density and hydraulic properties and did not produce any surface runoff. This suggests that this technology is a more sustainable option for timber harvesting in sensitive forest ecosystems, especially in steeper terrain. We also highlight the role of macroporosity loss in reducing water infiltration and increasing runoff, particularly on skid trails of ground-based systems.

These findings underscore the importance of selecting appropriate timber harvesting technologies to mitigate soil disturbance, especially as climate change leads to wetter and warmer winters. This means that soils become particularly susceptible to compaction during the traditional harvesting period. To reduce negative impacts on soil water retention, Ksat, and related soil and ecosystem functions, forest managers should consider using less impactful harvesting techniques on sensitive sites, such as cable yarding, or limiting ground-based systems to dry conditions.

7. Declaration of generative AI and AI-assisted technologies

During the preparation of this work the authors used DeepL Write and ChatGPT to improve language and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Maximilian Behringer: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Julian Grünberg:** Writing – review & editing. **Klaus Katzensteiner:** Writing –

review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Barbara Kitzler:** Writing – review & editing. **Bernhard Kohl:** Writing – review & editing, Methodology, Formal analysis. **Veronika Lechner:** Writing – review & editing, Investigation, Data curation. **Armin Malli:** Writing – review & editing, Data curation. **Gerhard Markart:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Gertraud Meißl:** Writing – review & editing. **Christian Scheidl:** Writing – original draft, Visualization, Supervision, Methodology, Investigation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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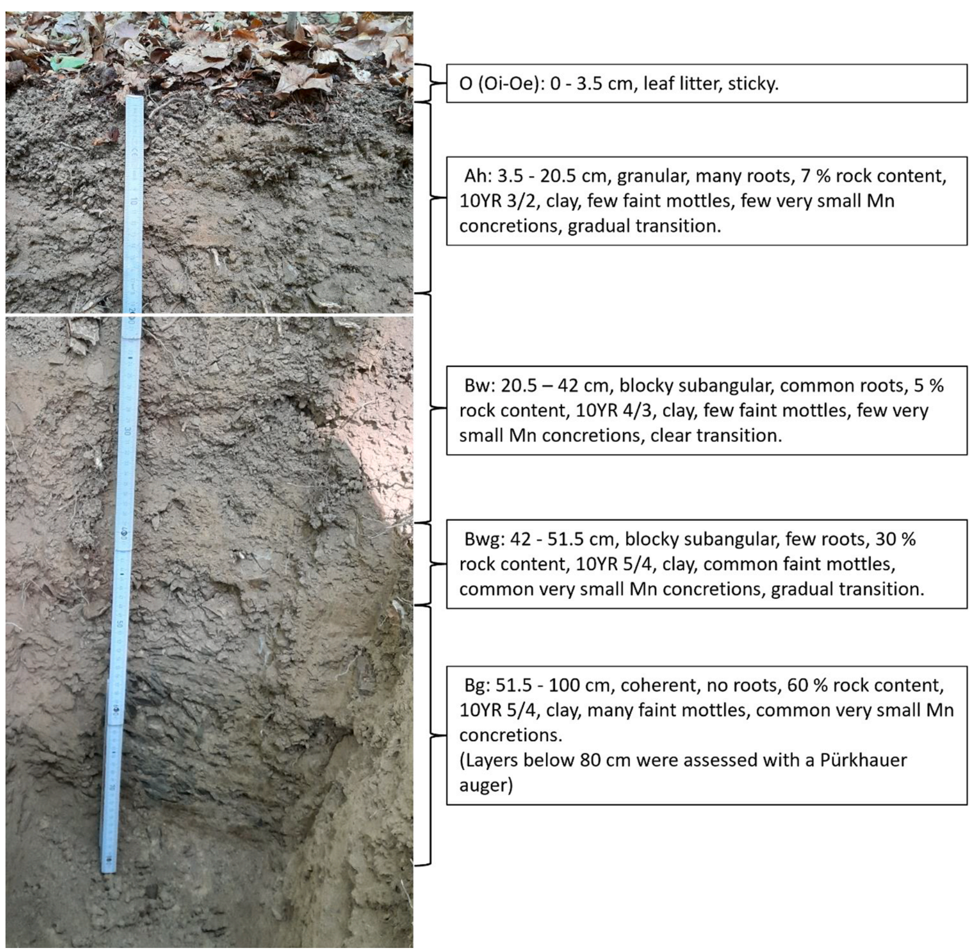
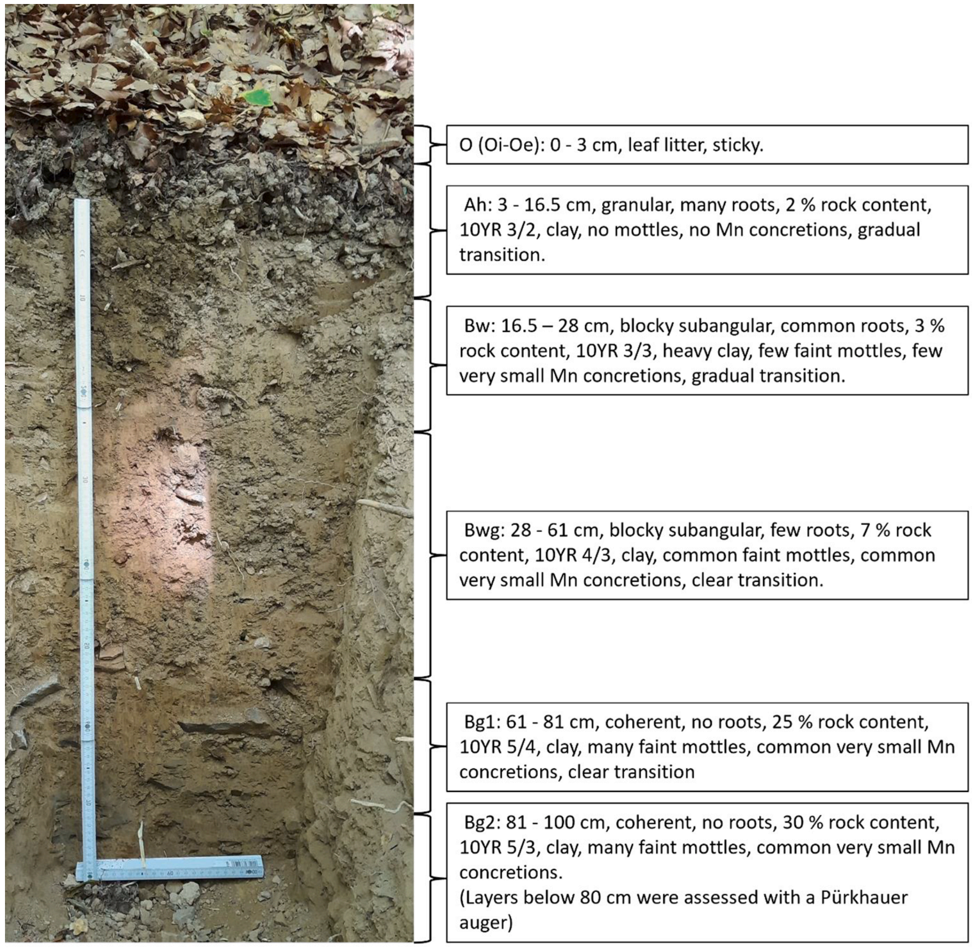
Appendix



A 1: Example soil profile 1.



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A 2: Example soil profile 2.

Data availability

Data will be made available on request.

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