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Soil Compaction Effects on Root-Zone Hydrology and Vegetation in Boreal Forest Clearcuts

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Soil compaction is a common consequence of forestry traffic traversing unprotected, moist soils; it decreases porosity and affects hydraulic conductivity even in coarse-textured soils. The aim here was to study root-zone hydrology and vegetation in three microsites (in, between, and beside wheel tracks) 4 to 5 yr after forwarder traffic, on stony and sandy till soils in two clearcuts in northern Sweden. Measurements of soil volumetric water content (VWC), vegetation indicators and one-dimensional hydrological modeling (Hydrus-1D) of wheel tracks and undisturbed soil were conducted. Soil VWC was monitored hourly during 2017 and 2018 in three or four plots along a slope on each site. Soil VWC was also measured once with a portable sensor in 117 plots along two slopes at each site, where the vegetation was recorded and analyzed using Ellenberg indicator indexes. Soil VWC was highest in wheel tracks and lowest between tracks; this was corroborated by the species composition in the wheel tracks (Ellenberg indicator for soil moisture). Bare soil was more frequent in wheel tracks and between tracks than in undisturbed soil. The model simulations indicated that the changed soil hydraulic properties influenced the VWC results in the wheel tracks. However, the differences in average pressure heads in the root zone were small between the microsites and only apparent during dry periods. In the wheel tracks, air-filled porosity was <0.10 m^3 m^{-3}, indicating insufficient soil aeration during 82% (Site T) and 23% (Site R) of the 2017 growing season. Insufficient aeration could be one explanation for the presence of some still unvegetated areas.

Abbreviations: VWC, volumetric water content.

Core Ideas

- **Impact of forwarding on soil water and vegetation was investigated after 4 to 5 years.**
- **Soil water content was highest in wheel tracks and lowest between tracks.**
- **Bare soil was more frequent in tracks and between tracks than in undisturbed soil.**
- **In wheel tracks, soil aeration may be restricted in periods with high precipitation.**
- **Simulated root-zone pressure heads showed little variation between microsites.**

Soil compaction and rutting (wheel tracks) are common disturbances associated with forestry operations on unprotected, moist soils and may result in decreased porosity and hydraulic conductivity, even on coarse-textured soils (Cambi et al., 2015; Hansson et al., 2018a; Toivio et al., 2017) and decreased aeration and infiltration capacity (Meek et al., 1992; Startsev and McNabb, 2009). Hansson et al. (2018a) found that soil compaction increased the risk of poor aeration by means of reduced total porosity, pore connectivity, hydraulic conductivity as well as longer periods of high water content, due to a higher water holding capacity.

Soil recovery after off-road traffic is usually slow and disturbances have been found to persist for many decades (Cambi et al., 2015; Ebeling et al., 2016; Klaes et al., 2016; Wei et al., 2016), even when freeze–thaw cycles occur (Corns, 1988). The growth and decay of roots and mycorrhiza promote the recovery process (Bottinelli et al., 2014; Meyer et al., 2014) and are important when no or few earthworms or other soil-mixing fauna are present in the soil or when early and thick snow cover reduces soil frost.

Soil compaction may reduce tree seedling survival and growth (Kabzems, 2012; Murphy et al., 2004), but growth can also be unaffected (Ares et al., 2005; Kamaluddin et al., 2005; Page-Dumroese et al., 2006), or increased (Brais, 2001; Ponder et al., 2012), depending on a number of factors, including soil moisture

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availability and aeration: a decreased soil gas permeability in the upper 5 cm of the mineral soil has been found to decrease root density of oak (Gaertig et al., 2002). Soil moisture availability is also important for predicting species composition of the ground vegetation (Härdtle et al., 2003). Wei et al. (2015) found that soil moisture in skid trails was positively correlated with the number of species that prefer moist or wet conditions.

Ground vegetation responds rapidly and at fine scales to management practices and disturbances, and thus, it is suitable for detecting changed soil conditions caused by off-road traffic (Duguid and Ashton, 2013). For example, the Ellenberg indicator values (Ellenberg et al., 1991) can be used to reveal changed soil moisture conditions or disturbances. These site-specific values (usually between 1 and 9) are commonly used to indicate environmental conditions based on the species present (Bartelheimer and Poschlod, 2016). Species diversity (the number of species and their distribution) can also be used for detecting changes in vegetation between different microsites.

Air-filled porosity (i.e., total porosity minus volumetric water content [VWC]) is considered to be the main limiting factor for soil aeration and VWC is commonly used for quantifying soil aeration (Ben-Noah and Friedman, 2018). After water and nutrient availability, aeration is the most important soil factor affecting plant growth (Ben-Noah and Friedman, 2018). Oxygen is consumed by plant roots and microorganisms, CO_2 is produced by respiration, and, if soil conditions become anaerobic, toxic gases are formed by chemical reduction processes (Ben-Noah and Friedman, 2018). Gas diffusion essentially stops when the air-filled porosity decreases below 0.10 $m^3\ m^{-3}$ (Xu et al., 1992). This value has also been found to be a threshold for reduced seedling growth (Wall and Heiskanen, 2003).

Hydrological models can be used to analyze how changes in soil physical properties caused by off-road traffic may affect the root-zone soil water dynamics. Hydrus-1D (Šimůnek et al., 2008, 2016) is a public domain, one-dimensional modeling environment that can be used for the analysis of water, heat and solute movement in soils. The program solves numerically the Richards equation for both saturated and unsaturated water flow and the Fickian-based advection-dispersion equations for solute and heat transport. In this study, Hydrus-1D was used to assess the impact of changes in hydrological properties such as total porosity, water retention, and saturated hydraulic conductivity, on root-zone water dynamics.

Our overall aim was to study how soil compaction affected the soil water conditions in the root zone, as well as the vegetation cover, at three microsites (in, between, and beside wheel tracks), 4 to 5 yr after forwarder traffic on coarse-textured till soils in two forest clearcuts in northern Sweden. We wanted to test whether differences in soil physical properties between wheel tracks and the undisturbed soil, measured at the same sites in the upper parts of the slopes (0–5 cm in the mineral soil) by Hansson et al. (2018a), influenced the soil water dynamics in the wheel tracks and thus, prolonged the time when air-filled porosity was below the threshold for sufficient soil aeration for roots and microorganisms. We also wanted to study the vegetation species composition and cover to determine whether there were signs of non-optimal growth conditions, such as restricted aeration. We formulated the following research questions:

1. Does the VWC differ between the microsites (wheel tracks, between tracks, and undisturbed soil) and, if so, are there any differences along the slopes or between sites?

2. Are there differences in the species present and/or their cover between microsites and do these indicate differences in the soil moisture or disturbance level (as expressed by Ellenberg indicator values)?

3. Are there any areas where soil aeration could be restricted due to high VWC?

4. Do the previously measured differences in soil physical properties in the upper mineral soil between wheel tracks and the undisturbed soil (Hansson et al., 2018a) change the simulated root-zone hydrology, and if so, are the results sensitive to different weather conditions?

MATERIALS AND METHODS

Study Sites and Experimental Design

This study was performed at the field sites 294 Rotflakamyran (hereafter Site R) and 296 Trågalidsberget (Site T) (Hansson et al., 2018a; Ågren et al., 2015). Site R (64°32.5′ N, 20°4.5′ E; 305 m AMSL) and Site T (64°19.3′ N, 20°35.7′ E; 145 m AMSL), are situated in northern Sweden on podzolized glacial till soils (Cryods) with a high stone and boulder content; approx. 50% of the soil consists of rock fragments with diameters >20 mm (Stendahl et al., 2009). Soil textures are mainly sandy loams. When only particles smaller than 20 mm are considered, the average mixture in the upper 0 to 5 cm of the mineral soil consists of 14% pebbles, 51% sand, 31% silt, and 3% clay. The silt and clay fractions increase in downhill positions at Site T (Hansson et al., 2018a). The depth of the humus layer is ~3 to 7 cm at Site T and ~7 to 12 cm at Site R, with higher values in downhill positions. Each site contains two slopes (A and B) with inclinations <10%. At Site R, Slope A is facing south and Slope B west, while at Site T, Slope A is facing south-west and Slope B north-east. The mean annual temperature is ~1 to 2°C and the precipitation is ~600 to 700 mm yr^{-1} (ref. period 1961–1990; SMHI, 2019a, 2019b).

The mixed Scots pine [*Pinus sylvestris* L.] and Norway spruce [*Picea abies* (L.) H. Karst] stand at Site R was harvested in December 2011 and the Norway spruce stand at Site T was harvested in February 2012 (winter conditions at both sites). The harvester and forwarder drove over slash mats in 4-m wide strip roads located between the study plots. As a result, the study plots were unaffected by traffic during clearcutting. Each slope contained three or four study plots subjected to different driving treatments. The plots were about 15 m wide and ~100 to 150 m long, depending on the length of the slopes. In this study, however, all measurements were undertaken within the study plots where the laden forwarder (John Deere 1410D, total weight approximately 34 Mg, including timber load of ~10 Mg) drove down and up the slope three times, in total six passes, without applying any soil protection (logging residues removed). Due to severe rutting and risk of getting stuck on the lower part of Slope B at Site R and Slope A at Site T, the part of the slope subjected to driving had to be shortened after the first two passes (and for Site T even more during passes 5 to 6). The driving was performed in June during the summer following clearcutting (2012) at Site R and the following summer (2013) at Site T (Hansson et al., 2018a; Ågren et al., 2015). Three types of soil microsites were identified: wheel tracks (WT; each ~0.7–1 m wide), between the wheel tracks (BT; ~1.3–1.5 m wide) and undisturbed soil at least 2 m beside the wheel tracks (U; Fig. 1).

Vegetation Survey and Soil Water Measurements (Portable Sensor)

A vegetation survey was performed at the end of May 2017 to assess whether there were any differences in the vegetation cover and species composition at different microsites and if the soil water conditions were reflected in the species present. Plots for vegetation survey (0.4 m by 1 m) were laid out at 10-m intervals at 10 (9 at Site T, Slope A, due to a shorter slope length) sampling locations (numbered 1–10) along each of the four slopes. Each location contained three plots, in total 30 or 27 plots per slope, and they represented undisturbed soil (microsite U), wheel track (microsite WT, located in the left wheel track) and the area between the left and right wheel tracks (microsite BT). The first plot (U, within Location 1) was laid out at a distance of 1 to 6 m from the lowest end of the traversed plots on the undisturbed soil, ~4 m to the left of the wheel tracks (Fig. 1). The following data were recorded for each of the 117 vegetation plots: a track depth (microsite WT), the area of ponded water (%), the area with bare soil (%), heights of planted pine seedlings (if present) and self-seeded seedlings of pine or other tree species. Finally, the occurrence of species and their cover (at estimated full seasonal development) were recorded according to the Braun-Blanquet abundance-dominance classification (as it is described by Wei et al., 2015): *i,* one individual, the cover <5%; +, very few individuals, the total cover <5%; 1, few to many individuals, the total cover <5%; 2, many individuals, the total cover 5 to 25%; 3, the total cover 25 to 50%; 4, the total cover 50 to 75%; and 5, the total cover >75%. The seven coefficients were later transformed into the following percentile cover values: *i*, 0.1%; +, 0.5%; 1, 5%; 2, 17.5%; 3, 37.5%; 4, 62.5%; and 5, 87.5% (Wei et al., 2015). The species were divided into the following groups: self-seeded tree seedlings, *Ericaceae*, graminoides (species with grass-like morphology), mosses, and other species (Appendix A). In the middle of July, the plots at both sites were briefly resurveyed to see whether there were any new species that emerged late in the season. Only a few new individuals were found and they were added to the data.

Each species' Ellenberg values were obtained from the literature for the following indicators (Appendix A): soil moisture (F, where 1 indicates that the plant prefers xeric conditions, 5 mesic, 9 wet and 12 underwater conditions), disturbance (D, where 1 indicates that the species can colonize and compete in already closed forests and 9 that the species quickly colonizes bare soil and disappears quickly), light (L, where 1 indicates that the species prefers deep shade and 9 full light), reaction of soil (R/pH, where 1 represents extremely acidic conditions and 9 alkaline), nitrogen/fertility (N, where 9 indicates the most fertile conditions) (Ellenberg et al., 1991; Hill et al., 2004, 2007; Sundberg, 2018; Tyler and Olsson, 2013). For each vegetation plot (p), a weighted mean indicator value (y_{EIp}) was calculated for each Ellenberg indicator (EI) by averaging the indicator value (e) of each species (i) and weighting these with the respective cover value (x_i), using the following equation:

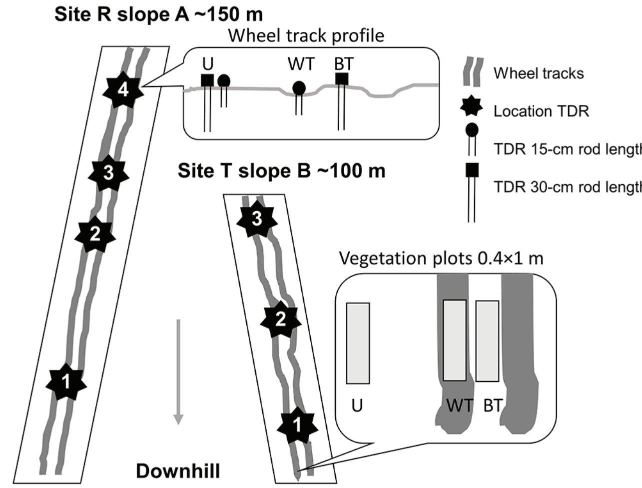

Fig. 1. Schematic representation of the experimental design with (i) locations of TDR sensors at Site R (Slope A) and Site T (Slope B); (ii) close-up of TDR installation in microsites undisturbed (U), wheel tracks (WT), and between wheel tracks (BT); and (iii) close-up of the layout of the vegetation plots in microsites U, WT and BT from above. At Location 2, Site T, there was an extra 15-cm-long TDR in the wheel track and an extra 30-cm-long TDR in the undisturbed soil. Plots for vegetation survey were established at ten locations along each of the two slopes at both sites, except Site T, Slope A, with nine locations (in total 117 plots).

$$y_{\mathrm{EIp}}=\sum_{i=1}^{n}\frac{x_i}{x_{\mathrm{tot}}}*e_i$$

The weighted mean indicator values for each plot and Ellenberg indicator were used to determine whether there were any differences between microsites, sites and slope positions. As a measure of species diversity in the plots, the Shannon diversity index (Shannon, 1948) was calculated. This is the most commonly used measure of diversity (Spellerberg and Fedor, 2003) and a relatively low number indicates that few species dominate most of the area and other species are not abundant (even if there are many different species), whereas a relatively high number indicates that there are many species and they are equally abundant.

In each of the vegetation plots, the soil VWC was measured at three points (evenly distributed within the plot) with a portable time domain reflectometry (TDR) sensor (TRIME-PICO64, HD2, IMKO Micromodultechnik GMBH, rod length 16 cm) using the standard calibration for universal soil, provided by the manufacturer. At Site T, VWC measurements were performed on the same day as the vegetation survey (27 May 2017). At Site R, due to a rod breakage, VWC measurements were made 6 wk later (12 July 2017). In 45 of the 117 plots (mainly in the upper parts of the slopes), no measurements could be recorded, due to the stoniness of the soil preventing a complete insertion of the rods.

Soil Water Content at the Permanent Plots

The VWC was measured hourly between 30 May and 6 Oct. 2017, and during June 2018 at four locations along Slope A (16 sensors) at Site R and at three places at Site T, Slope B (14 sensors; Fig. 1). The measuring period in 2017 covered most of the growing season (17 May to 6 October), which was defined as the period starting with the first 6 d in a row in the spring when the diurnal mean air temperature was >5.0°C and ending at the first 6-d period with temperatures <5.0°C (Frich et al., 2002). The instruments used were CS616 TDRs (Campbell Scientific Ltd); in the wheel tracks, they were shortened to 15 cm as we anticipated that insertion of 30-cm rods would be very difficult in the compacted and stone-rich soils. In undisturbed soil, both 15- and 30-cm long TDRs were installed (Fig. 1). Only 30-cm TDRs were inserted in the between-track microsites. The sensors were connected to a CR1000 datalogger with an AM16/32B multiplexer and a CR10X datalogger with an AM416 multiplexer (Campbell Scientific Ltd.) at Sites R and T, respectively. In the laboratory, site-specific calibrations, as described in Campbell Scientific (2016) for the 30 and 15 cm TDR-sensors, were performed at 12 different water contents, using soil collected in two pits from each site and then all mixed. At each water content, measurements with the TDRs were compared with water contents derived from oven-drying for 24 h at 105°C (three cylinder samples [diameter 7 cm, height 5 cm] collected for each water content). The VWC measurements were corrected for variations in soil temperature by the temperature correction function of the output time signal (Campbell Scientific, 2016). Soil temperature was measured next to each TDR with thermocouples (T107, Campbell Scientific Ltd., length 10 cm) inserted vertically into the soil from the soil surface (from the top of the humus layer).

Estimated insufficient soil aeration at the different microsites along the slopes was assessed by counting the number of days when the daily mean VWC reduced the air-filled porosity to <0.10 $m^3 m^{-3}$ (Hansson et al., 2018b; Wall and Heiskanen, 2003; Xu et al., 1992). At Site T, 0.10 $m^3 m^{-3}$ air filled porosity corresponded to a VWC of 0.45 $m^3 m^{-3}$ in the undisturbed soil and 0.38 $m^3 m^{-3}$ in the wheel track. At Site R, the corresponding values were 0.49 and 0.35 $m^3 m^{-3}$ in the undisturbed soil and the wheel tracks, respectively (Hansson et al., 2018a).

Hydrological Modeling with Hydrus-1D

Hydrus-1D version 4.16.0110 (Šimůnek et al., 2013) was used for modeling hourly water flow and root uptake in the wheel tracks and the undisturbed soil microsites, separately, in the upper part of the slopes (Locations 2 and 3, Site T, Fig. 1), the same part that was studied by Hansson et al. (2018a), including sampling and analysis of 36 soil samples from each site. We selected Site T for the modeling, as the wheel tracks in the upper 50 m of the slopes there were shallow (0–5 cm), and the traffic impact was mostly in the form of soil compaction, that is, the rutting profile was negligible for the hydrology and thus, the groundwater level (the lower boundary condition, measured at the site) could be assumed to be the same in both microsites. The upper boundary conditions, that is, the atmospheric conditions based on measurements from the sites, were also the same and thus the only differences between the two modeling setups for the two microsites, WT and U, were the soil hydraulic properties in the upper 0 to 5 cm of the mineral soil (Table 1; Hansson et al., 2018a).

In Hydrus-1D, measurements can be compared with simulated values when the model is run in the inverse mode and the model parameters can be optimized by improving the correspondence between simulated data and measurements. To evaluate whether the modeled water contents were comparable to the measured ones, mean values for the 15-cm-deep TDRs (n = 3 in WT, n = 2 in U) in Locations 2 and 3 were linked to the observation node 3 (8 cm depth) in the undisturbed soil and wheel tracks, respectively, and the 30-cm TDRs (n = 3) were linked to subregion 1 (0–30 cm) of the undisturbed profile. See Appendix B for more details about the model set-up.

Weather conditions, groundwater, and VWC measurements from June 2018 were also used with the same model setup, to validate it, and test the impact of different weather conditions on the differences in water flows and pressure heads between the two microsites.

Statistical Analyses

To analyze the results of the vegetation survey, linear mixed-effect models were constructed in R (version 3.4.2, package "nlme"), using the function "lme" to examine the effect of the

Table 1. Soil hydraulic parameters used in Hydrus-1D for the undisturbed (U) and wheel track (WT) microsites. When the values for the two microsites differ, the wheel track value is given in *italics*. The van Genuchten parameters (Q_r, Q_s, α, and n) and the saturated hydraulic conductivity (K_s) in the mineral soil are based on measurements of soil samples from the sites published in Hansson et al. (2018a), except for Layer 3, which is unpublished but sampled on the same occasion as the other samples. The pore connectivity factor, l, was obtained using the inverse solution parameter optimization.

		Soil hydraulic property						
Layer†	Depth	Q_r	Q_s	α	n	K_s	l	Reference
	cm	$cm^3 cm^{-3}$		cm^{-1}		$cm\ h^{-1}$		
1 (F/H)†	0–5	0.07	0.76	0.56	1.27	1208	3	Lundmark and Jansson (2009), Laurén and Heiskanen (1997)
2 (E)	6–11	1.00×10^{-8}	0.55/*0.48*	0.12/*0.03*	1.28/*1.29*	25.2/*7.1*	6/*2.1*	Hansson et al. (2018a)
3 (B and C)	12–100	1.00×10^{-8}	0.53	0.04	1.26	3	0.5	Hansson, unpublished data

† F/H, partly decomposed litter and organic layer; E, eluvial horizon; B, illuvial horizon; C, unaltered horizon with parent material.

microsite (U, WT and BT), site (R or T) and sampling location (numbered 1–10) on different response variables such as VWC, fraction of bare soil, diversity index, cover of different groups of species and weighted Ellenberg indexes. The fixed effects in the model were: site, location along the slope and microsite. The random effect was microsite within each slope (=subject). An autoregressive covariance structure was introduced for the relationships between different locations (=Distance.from.lower.end) of the microsites along each slope [random=~1|subject, correlation=corCAR1(form=~Distance.from.lower.end|subject)]. All models were tested with the interaction effect of location and microsite, but it was never significant, and was thus excluded from the model. The response variables bare soil, graminoides (plants with grass-like morphology) and *Ericaceae* were square root-transformed and VWC was log-transformed to obtain more normally distributed residuals. The Wald test was used as a post hoc test (function "emmeans") for differences between microsites, locations and sites, including the Tukey method for adjustment of p-values. Effects with p-values below 0.05 were considered significant in all analyses.

The seasonal means and medians of the VWC measurements were tested with the same model as described above. However, in this case, the interaction effect of location and microsite was significant and retained in the model. Sampling locations were 1 to 3 at Site T and 1 to 4 at Site R (Fig. 1). Fisher's exact test was used to evaluate the significance of differences between microsites in numbers of days when the daily mean air-filled porosity was below 0.10 $m^3\ m^{-3}$.

The Hydrus simulations were evaluated by comparing the root mean square error (RMSE) and the coefficients of determination (R^2) for the predicted versus observed values from 2017. The results of 2017 represent a calibration and the results of 2018 a validation of the model setup.

RESULTS

Soil Water and Vegetation along the Slopes

The measurements with the portable soil water sensor in the vegetation survey plots indicated that 4 to 5 yr after forwarder traffic, the VWC was highest in wheel tracks and lowest between the tracks (Table 2); this was also corroborated by the species composition in the wheel tracks (the Ellenberg indicator value, F; Table 2). The wheel track depth in the vegetation plots varied between 0 and 70 cm, with average values of 31 cm at Site R (n = 20) and 19 cm at Site T (n = 19). Bare soil was more frequent in the wheel tracks and between the tracks than in the undisturbed soil when all locations were included (Table 2). Two plots (Site R, Slope A, WT, Location 1, and Site T, Slope A, Location 3) were covered by ponded water (and were excluded from the statistical analysis of VWC). Another four plots on the lower parts of the slopes were partially ponded (2–10% of the plot area).

The wheel tracks and between-track microsites had less moss cover than the undisturbed soil and the wheel tracks had less cover of *Ericaceae* than the other two microsites. However, the species composition and cover indicated no difference in di-

Table 2. Microsite and site mean values (across all slopes, sites, and locations) of the response variables in the linear mixed effect models. Vegetation plot locations are numbered from 1 to 10 (situated 10 m apart), starting at the lower end.

	Bare soil†	Total cover	Graminoides†	*Ericaceae*†	Mosses	VWC‡	Shannon index	Weighted Ellenberg index¶ L	F	R/pH	N	D
	%		% cover			$m^3\ m^{-3}$						
Microsite												
Undisturbed	0.03 a§	153 a	35 a	43 a	75 a	0.33 ab	1.57 a	5.9 a	5.4 a	2.5 a	2.3 a	1.8 a
Wheel tracks	13 b	106 b	42 a	13 b	47 b	0.45 b	1.41 a	6.0 a	5.7 b	2.5 a	2.5 a	1.9 a
Between tracks	6 b	134 a	41 a	42 a	49 b	0.28 a	1.47 a	5.9 a	5.4 a	2.3 a	2.5 a	1.9 a
Site												
R	10 a	132 a	23 a	47 a	61 a	0.27 a	1.58 a	6.0 a	5.6 a	2.4 a	2.3 a	1.8 a
T	3 a	128 a	56 b	17 b	52 a	0.39 b	1.39 b	5.8 b	5.4 b	2.5 a	2.6 b	1.9 a
Location diff.#	3 > 7					1 > 4–9 2 > 8–9	1, 8 > 3	1 > 7,9,10	1 > 7–10			

† The response variable was square root-transformed in the model.
‡ VWC, volumetric water content; The response variable was log-transformed in the model.
§ Values with different letters (by columns) are significantly different ($p < 0.05$) in the post hoc Wald tests.
¶ Weighted Ellenberg index values were light (L), soil moisture (F), reaction of soil (R/pH), nitrogen/fertility (N), and disturbance (D).
# Numerals of the locations that differ significantly (e.g., Location 3 had a higher proportion of bare soil than Location 7).

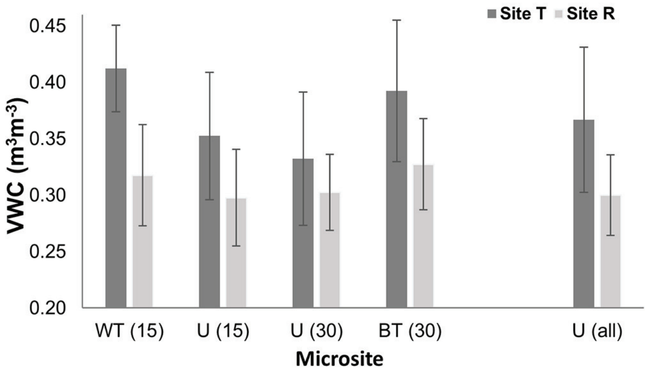

Fig. 2. Mean seasonal volumetric water content (VWC) values for each microsite of wheel tracks (WT), between wheel tracks (BT) and undisturbed soil (U) at Sites T (dark gray) and R (light gray). The error bars indicate standard deviations. The rod length of the sensors (measurement depth from the surface of the humus layer in centimeters), is given in parentheses. The post hoc test of the statistical model (including both sites) did not indicate significant differences between microsites.

versity (Shannon diversity index), light tolerance (L), fertility (N), pH (R) or disturbance (D) between microsites (Table 2). Neither were there any statistically significant differences in the total number of species or the number or cover of self-seeded tree species for microsite, site, or location. There were no planted seedlings within any of the vegetation plots in the undisturbed soil. The average height of planted seedlings was 29 cm in the wheel tracks (standard deviation [SD] = 9.5 cm) and 31 cm between tracks (SD = 9.2 cm, n = 21 for both microsites). The average height of self-seeded seedlings (*Betula* spp., *Sorbus aucuparia* L., *P. abies*, *P. sylvestris* and *Salix* spp.) was 33 cm (SD = 35 cm, n = 8) in the undisturbed soil, 17 cm (SD = 17 cm, n = 22) in the wheel tracks, and 27 cm (SD = 20 cm, n = 14) between wheel tracks. The difference in the cover of other species (e.g., herbs) could not be tested using the statistical analysis, as no transformation was found to make the residuals normally distributed: the standard deviations for the cover of other species at the different microsites were larger than the mean values.

Ericaceae were more common at Site R than at Site T, where graminoides were more common. Furthermore, Site R had a higher Shannon diversity index than Site T (Table 2). The weighted mean Ellenberg index for light tolerance (L) and soil moisture (F) was also higher for Site R than Site T, whereas the fertility was higher for the latter site (Table 2).

The slope position (Location in the statistical models) was significant for both measured VWC and the Ellenberg indicator of soil moisture. The location at the bottom of the slope, Location 1, was wetter than the upper locations (VWC, Locations 4–9; F, Locations 7–10). Location 1 also had more light tolerant species than Locations 7, 9, and 10 (Table 2).

Seasonal Soil Water Measurements

There were statistically significant differences in seasonal means and medians of VWC values between sites (p < 0.01) and locations along the slope (p < 0.01), but not for microsites (p = 0.29; Fig. 2), and not for the interaction effect between locations and microsites (p = 0.06). However, the differences between sites and locations were not significant in the post hoc test.

The number of days during the 2017 growing season when aeration could have been restricted was highest at both sites in the wheel tracks (except at Location 2, Site R, where no days were over the threshold value) and the lowest at the between-track microsite, BT, at Site T (Table 3). At Site R, there were no days with potentially restricted aeration in either the undisturbed soil or in the between-track microsites. In total, the air-filled porosity may have been too low for sufficient aeration of roots in microsite WT during 82% and 23% of the 2017 growing season, at Sites T and R, respectively (Table 3).

Hydrological Modeling with Hydrus-1D

The coefficient of determination, R^2, for predicted versus observed water contents was 0.86 for the undisturbed microsite and 0.69 for the wheel track in 2017. Root mean square errors, RMSE, were 0.010 and 0.015 for undisturbed soil and wheel tracks, respectively. When validating the modeling setup with the weather, groundwater level, and VWC data for June 2018, the R^2 values were 0.97 and 0.54, and RMSEs were 0.026 and 0.040 for the undisturbed soil and wheel tracks, respectively. These values indicated that the models could describe sufficiently well the water fluxes and pressure heads in the soil profiles. The simulated pressure heads at the two microsites U and WT were similar, except for the surface of the humus layer where it was drier on some occasions in the undisturbed soil (Fig. 3). The average pressure head of the root zone was also influenced during the driest periods with somewhat lower pressure heads in the undisturbed soil (Fig. 3). The groundwater level was lower in June 2018 (0.9 m from the soil surface on 1 June), than in June 2017 (0.5 m), and thus the surface layer became even drier in the undisturbed soil, compared to the wheel tracks (Fig. 3). At the 8-cm depth, in the middle of the upper mineral layer, the simulated VWC was higher in the wheel track compared to the undisturbed soil (Fig. 4). There were no dif-

Table 3. Numbers of days (30 May to 6 Oct. 2017) with daily mean volumetric soil water contents above the threshold value of an air-filled porosity of 0.10 m^3 m^{-3}. Time domain reflectometry (TDR) sensors were positioned at three locations at Site T and at four locations at Site R in undisturbed soil (U), in wheel tracks (WT), and between tracks (BT).

	Site T			Site R		
TDR location	U	WT	BT	U	WT	BT
1	45.5 a†	129 b	2 c	0 a	95 b	0 a
2	2 a	83.5 b	33 c	0 a	0 a	0 a
3	7 a	106 b	0 c	0 a	19 b	0 a
4				0 a	7 b	0 a

† Different letters indicate significant differences between microsites, row-wise comparisons within sites (p < 0.05; Fisher's exact test).

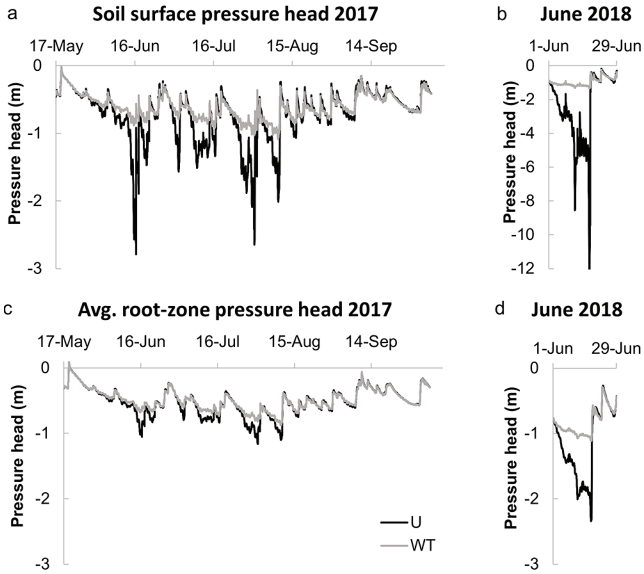

Fig. 3. Simulated pressure heads (meter) at the surface of the humus layer (a, b) and the average value of the root-zone (depth of 25 cm; c, d) in the undisturbed soil (U, black lines) and the wheel tracks (WT, gray lines) in the upper 50 m of Site T during the 2017 growing season (a, c) and June 2018 (b, d). Note the different scale on the *y* axis in panel (b).

ferences between the two microsites in evaporation, transpiration or bottom cumulative fluxes.

DISCUSSION

At these boreal low-productivity sites, the reestablishment of vegetation and regeneration of trees are slow processes. Four to five years after clearcutting and off-road traffic, there were still areas of bare soil, especially in the wheel tracks, not only in the discharge areas on the lowest part of the slopes but also in the recharge areas up-slope. The reestablishment of vegetation varied between microsites with more graminoides and less *Ericaceae* and mosses in the wheel tracks, a similar pattern as noted in other soil disturbance studies (i.e., stump harvest) in Fennoscandia (Andersson et al., 2017; Hyvönen et al., 2016). However, no difference was found between the number or cover of self-seeded tree seedlings in the present study. The slow natural regeneration of trees is the main reason why clearcuts like these need to be planted to assure a sufficient regeneration of trees as specified in the Swedish Forestry Act (Swedish Forestry Agency, 2017).

Our results indicate that restricted soil aeration may be a problem in the wheel tracks, especially in normal to wetter years. During the 2017 growing season, the estimated air-filled porosity in the wheel tracks was below 0.10 m^3 m^{-3} on the majority of days at Site T (82%) and one fourth of the days at Site R (23%; Table 3). In the study by Fründ and Averdiek (2016) on skid trails in Germany, no recovery of soil aeration in the 12- to 24-cm depth was found during the first 3 yr after harvester and forwarder traffic. In Finland, the growth of Norway spruce seedlings was reduced when air-filled porosity was below 0.10 m^3 m^{-3} (Wall and Heiskanen, 2003); also, when studying mature stands of Scots pine, the growth-rate was reduced when this threshold was exceeded (Wall and Heiskanen, 2009).

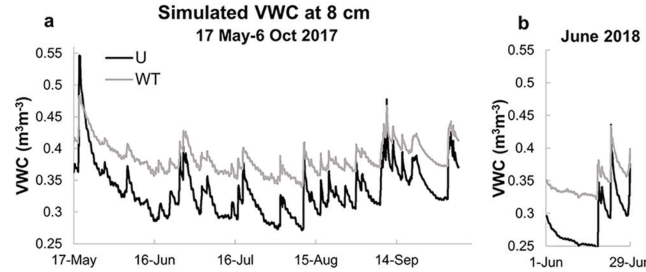

Fig. 4. Simulated volumetric water content (VWC, m^3 m^{-3}) in the middle of the upper 5 cm of the mineral soil of the undisturbed soil (U, black lines) and the wheel tracks (WT, gray lines) at Site T during the growing season 2017 (a) and June 2018 (b).

Wetter conditions in the wheel tracks were indicated by both the measurements with the portable TDR along the slopes and the Ellenberg indicator value F (soil moisture). This is commonly found in soil compaction studies on forestland (Ares et al., 2005; Fründ and Averdiek, 2016; Wei et al., 2016). However, in dry years, the higher water-holding capacity in the wheel tracks may be beneficial for seedlings, as long as the soil is not too compacted for root penetration. Steber et al. (2007) found that high-porosity soils often show improved root–soil contact, water holding capacity, thermal regimes and/or nutrient uptake after compaction, if the forest floor cover is also removed. The mean porosity of the upper 0 to 5 cm of the mineral soil at Site R was 0.59 m^3 m^{-3} in the undisturbed areas (Hansson et al., 2018a), and moderate soil compaction at this site may have been beneficial. However, the soil compaction measured by Hansson et al. (2018a) was substantial in the upper parts at Site R (mean porosity in WT was 0.45 m^3 m^{-3}, i.e., it was reduced by 34%), and the mean dry bulk density (1.44 g cm^{-3}) fell within the range 1.3 to 1.5 g cm^{-3}, at which it could start to impede growth of various conifer species after the seventh year, according to Zhao et al. (2010). In some places at Site R, in the study by Hansson et al. (2018a), the dry bulk density was as high as 1.6 to 1.7 g cm^{-3}. These areas are probably too compacted for optimal root growth (Daddow and Warrington, 1983; Zhao et al., 2010) and this may be one of the explanations for there still being areas without vegetation on the upper parts of the slopes. At the low slope positions, where the VWC is high all year round, the slow reestablishment of vegetation in the wheel tracks is probably due to the restricted aeration and because the wheel tracks sometimes contain standing water during snowmelt and high precipitation events. In mid-slope positions, however, the visual impression was that both the establishment and growth of both planted and self-seeded seedlings were good, especially in the between-track microsite; this, however, could not be proven with the experimental design and statistical approach used in this study.

Root and mycorrhizal growth is important for soil structure recovery after soil compaction (Flores Fernández et al., 2018; Kabzems and Haeussler, 2005; Meyer et al., 2014), especially in naturally acid podzols as at Sites R and T, where worms and other soil mixing fauna do not thrive, and an early, thick snow cover often inhibits soil frost. Thus, it is especially important not to exceed the compaction levels where root penetration is reduced or inhibited, and also to avoid reducing porosities to levels where the air-filled porosity readily falls below 0.10 $m^3 m^{-3}$. However, more studies are needed to investigate how soil scarification can mitigate soil compaction effects in the topsoil on these types of sites that are naturally compact, beneath the topsoil, due to the pressure of the ice during the last glaciation.

Differences in the simulated root-zone pressure heads between the wheel tracks and the undisturbed microsite were small but the differences increased during dry periods (Fig. 3). A smaller range of pressure heads in the wheel tracks compared to the undisturbed soil is in line with the results presented by Fründ and Averdiek (2016). However, there were no differences found between the water balances of the two microsites, which was expected for the present modeling approach when the same weather data, plant descriptions and groundwater level data were used for both microsites, and the only difference was in the hydrological properties of the upper 0 to 5 cm of the mineral soil. Nevertheless, the simulations did corroborate the higher VWC in the wheel tracks than in the undisturbed soil in the upper parts of the slopes. An explanation for this is that the shape of the water retention curve caused a higher simulated VWC in the wheel tracks. The water holding capacity was higher in WT for pressure heads more negative than −0.2 m (statistically significant below −0.5 m; Hansson et al., 2018a).

Our study could not detect any statistically significant differences between microsites, locations, and sites with respect to the number of species present. Generally, there were very few (median 7; range 0–11) species in each plot of 0.4 m^2. There were no differences in species diversity between the microsites, but regeneration (clearcutting) itself probably increased species diversity compared to the diversity of the mature forest (Widenfalk and Weslien, 2009).

Forest till soils with a high content of rock fragments are difficult to sample, as pebbles, stones, and coarse roots aggravate the insertion of the sensors. Once a point is found where a TDR can be inserted to its full length, the sensor cannot be removed and installed again at the same place without causing gaps of air close to the rods, with underestimation of the VWC as a result. Thus, the humus layer could not be removed after a proper installation point was found. The relationship between the dielectric constant and VWC is different in humus compared to mineral soil (Pumpanen and Ilvesniemi, 2005; Schaap et al., 1997), and as a consequence, there is an uncertainty in the VWC results, as the calibration was performed on mineral soil but the VWC reflects both the humus layer and the mineral soil.

Combining TDR measurements, vegetation data, and hydrological modeling for estimating soil water conditions in this study has the advantage that even if measured differences by one method are not clear, the ensemble of results can add to our knowledge about the conditions in the soil after off-road traffic on clearcuts. The VWCs measured with the portable TDR on a single occasion give a snapshot of the VWC differences in the three microsites along the slopes, whereas the Ellenberg indicator for soil moisture reflects conditions over time. The number of permanently installed TDRs may be too few to get clear statistical results with the linear mixed-effect model, but instead they indicate the VWC dynamics over the growing season in different parts of the slopes. Finally, the hydrological model may give us some explanations for the recorded differences in VWC.

The results of our study support the conclusion of previous studies that severe soil compaction should be avoided or reduced in order not to impair regeneration (Daddow and Warrington, 1983; Zhao et al., 2010). At the same time, intermediate soil compaction may promote regeneration (Brais, 2001; Cambi et al., 2015; Ponder et al., 2012), and the rutting in some parts of the slopes may serve as a form of thorough soil scarification. By careful planning, both before and during the forest operation, the area of severe soil disturbance can be reduced and driving on slash can further reduce the impact (Han et al., 2006). It is important to follow the growth and development of planted and self-seeded seedlings as well as the ground and field vegetation at these sites to assess the overall long-term impacts of off-road traffic. Skid trails or wheel tracks normally cover about 12 to 30% of the clearcuts (Brais, 2001; Eliasson, 2005; Mohtashami et al., 2017; Solgi and Najafi, 2014), and reduced soil aeration in some parts may be of less importance for the future stand, especially if they are subjected to soil scarification. However, more investigations are needed on these matters.

CONCLUSIONS

To conclude, differences between the three microsites created by off-road traffic remained 4 to 5 yr after forwarder traffic, mainly apparent in the cover of different species groups, proportion of bare soil and soil water contents. The risk of restricted aeration was highest in the wheel tracks and was more pronounced during wetter periods on the lower parts of the slopes, where both the VWC and the weighted mean Ellenberg value for soil moisture were higher.

The changed soil physical properties after off-road traffic in the upper parts of the slope influenced VWCs, having higher water contents in the wheel tracks than in the undisturbed soil. However, according to the simulation results, the changed soil physical properties only influenced the average root zone pressure head during dry conditions. During dry years, with low groundwater levels, differences will be more pronounced in the top soil of the two microsites, and the increased VWC in the wheel tracks may then be beneficial for seedling establishment and growth.

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APPENDIX A

Table A1. Species present in vegetation plots at Sites R and T and their Ellenberg indicator values, arranged in the groups used in the statistical analyses. Light (L), soil moisture (F), pH or soil reaction (R) and nitrogen/fertility (N) values are based on Hill et al. (2004, 2007), and Ellenberg et al. (1991) and modified for Swedish conditions by Sundberg (pers. comm., 2018). The soil disturbance (D) values are from Tyler and Olsson (2013). Species without Ellenberg indicator values are denoted (–). The scientific names are from the Swedish Taxonomic Database (www.dyntaxa.se).

Scientific name and group in the analyses	Site	Ellenberg indicator values L	F	R	N	D
Self-seeded tree seedlings						
Pinus sylvestris L.	RT	7	6	2	3	1
Picea abies (L.) H. Karst.	RT	7	6	3	4	1
Betula spp. (*Betula pubescens* Ehrh.)	RT	7	7	3	3	5
Salix spp. (*Salix caprea* L.)	R	7	7	7	7	5
Sorbus aucuparia L.	RT	6	6	3	5	5
Ericaceae						
Rhododendron tomentosum Harmaja	R	6	9	2	2	5
Empetrum nigrum L.	R	7	6	2	1	2
Calluna vulgaris (L.) Hull	R	7	6	2	2	5
Andromeda polifolia L.	R	8	9	1	1	1
Vaccinium myrtillus L.	RT	6	6	2	3	2
Vaccinium vitis-idaea L.	RT	6	5	2	2	2
Vaccinium oxycoccos L.	R	8	9	2	1	1
Vaccinium uliginosum L.	R	7	6	2	2	2
Graminoides						
Avenella flexuosa (L.) Drejer	RT	6	5	2	3	2
Luzula pilosa (L.) Willd.	RT	5	5	5	4	4
Calamagrostis phragmitoides Hartm.	R	6	8	5	3	1
Eriophorum vaginatum L.	R	8	8	2	1	1
Mosses						
Hylocomium splendens (Hedw.) Schimp.	RT	6	5	4	2	2
Pleurozium schreberi (Brid.) Mitt.	RT	6	5	2	2	1
Ptilium crista-castrensis (Hedw.) De Not.	RT	5	6	3	2	1
Pohlia nutans (Hedw.) Lindb.	RT	5	5	2	2	–
Aulacomnium palustre (Hedw.) Schwägr.	R	7	8	3	2	2
Dicranum spp.	RT	4	6	3	2	2
Polytrichum commune Hedw.	RT	6	7	3	2	1
Polytrichum strictum Menzies ex Brid.	RT	8	7	2	1	2
Sphagnum spp.	RT	8	7	1	1	1
Tiny *Bryopsida/Polytrichopsida* spp.	RT	–	–	–	–	–
Marchantiophyta Stotler & Crand.-Stotl. spp.	RT	–	–	–	–	–
Others						
Juniperus communis L.	R	8	5	4	3	2
Lycopodium annotinum L.	T	6	6	3	3	1
Gymnocarpium dryopteris (L.)	T	4	5	4	4	1
Equisetum sylvaticum L.	RT	5	8	5	4	2
Rubus idaeus L.	T	6	5	5	7	6
Linnea boeralis L.	RT	5	5	2	2	1
Melanpyrum pratense L.	RT	5	5	2	3	1
Veronica officinalis L.	T	6	5	4	4	4
Chamaenerion angustifolium (L.) Holub.	RT	6	5	6	6	5
Epilobium palustre L.	T	7	8	5	3	4
Epilobium adenocaulon Hausskn.	T	7	6	6	6	6
Rumex acetosella L.	T	7	5	4	3	4
Oxalis acetosella L.	T	4	6	5	5	1
Solidago virgaurea L.	T	5	5	4	4	3
Lysimachia europaea (L.) U. Manns & Anderb.	T	5	6	3	3	1
Maianthemum bifolium (L.) F.W. Schmidt	RT	3	5	3	3	1
Cladonia Hill ex P. Browne spp.	T	–	–	–	–	–

APPENDIX B
Set-Up in Hydrus-1D

The 1 m-deep soil profiles were discretized into a 101-node finite element mesh and observation nodes were inserted at depths of 2, 5, 8, 15, and 30 cm. The van Genuchten-Mualem single-porosity model with an air entry value of −2 cm was used to describe the soil retention and hydraulic conductivity functions (van Genuchten, 1980). The soil hydraulic parameters (porosity, organic matter content and the van Genuchten model parameters) for the 5 cm deep humus (F/H) layer were taken from Lundmark and Jansson (2009) ("Swedish till" 0–10 cm) and the saturated hydraulic conductivity, K_s, from Laurén and Heiskanen (1997) (Table 1). In the upper 0 to 5 cm of the mineral soil (5–10 cm in the model) the properties are based on the results of the soil physical analyses at Site T presented in Hansson et al. (2018a) (Table 1). Soil sampling beneath this depth was not possible in the upper part of the slopes at Site T due to the high stone content, but a soil pit was dug out in the lower part and samples was collected at a depth of 25 to 30 cm and assumed to be representative of the mineral soil in both the undisturbed soil and the wheel track in the upper part.

The van Genuchten parameters were derived by fitting the van Genuchten function (van Genuchten, 1980) using nonlinear regression and least squares fitting to the mean of the water tension measurements (n = 36, at 0.5, 2, 5, 10, 60, and 1500 kPa) of the soil samples from Site T (diameter: 7 cm, height: 5 cm). The residual water content parameter, Q_r, was not allowed to be lower than 1×10^{-8} ($cm^3\ cm^{-3}$) in the fitting process. As a starting point, the pore connectivity factor, l, was set to 0.5 (Mualem, 1976) for all layers. The selected l-values are based on manual tuning and inverse solution calibration of both profiles separately: the values that improved the fitting of the simulated versus observed VWC the most for both profiles were selected for the first and the third layer (Table 1). For the second layer (the upper 0–5 cm of the mineral soil), we separately calibrated the l-value of the microsites as the x-ray image analysis by Hansson et al. (2018a) showed that the pore connectivity was reduced in the wheel tracks compared to the undisturbed soil.

Air temperature at the height of 2 m (T107 Campbell Scientific Ltd.) and precipitation at the ground level (tipping bucket ARG100) were measured bihourly at the site. In addition, global (solar) radiation (pyranometer 2000SZ, Li-Cor Inc., USA); relative humidity (Hygroclip probe, Rotronic AG, Switzerland), and wind speed (A100R Contact Closure Anemometer, Vector Instruments, UK, at 2 m 2017 and 1.75 m 2018) measured at Site R were used (the sites are situated 34 km apart). The wind sensor broke in July 2017 and data from the closest meteorological station measuring wind speed (Petisträsk) of the Swedish Metrological and Hydrological Institute

(SMHI) were used for the rest of 2017. A variable pressure head boundary condition, based on bihourly groundwater measurements (CS450 Campbell Scientific Ltd.) from the site, was used as the lower boundary condition for water flow. The groundwater level, measured about 12 m up from the down-slope end of the plots in a control area, was assumed to follow the topography along the slope and thus, mimic conditions higher up the slope. However, during 7 to 8 Sept. 2017, the drastic increase in groundwater level down-slope indicated that water was also coming from up the hill and, to adjust the dynamics to up-hill conditions, the groundwater level was lowered by 10 cm during the rest of the period. A surface water layer, i.e., ponded water, of 1 cm was allowed in the simulations.

The albedo, used in Hydrus to reduce the incoming shortwave radiation, was set to 0.17, which is representative of old *Vaccinium*-type clearcuts with *Avenella flexuosa* (L.) Drejer (Jansson and Jutman, 1975). Solar radiation was selected for Hydrus calculations of cloudiness for estimating the net longwave radiation. The leaf area index (LAI) was set to 2 $m^2 m^{-2}$ at both microsites. Roots were assumed to be distributed down to 25 cm in both soil profiles with a distribution based on Persson (1983). The S-shape water up-take reduction model with parameters P50 = −800 cm and P3 = 3 (−) was used. A default interception constant of 1.5 mm was selected. The spatial root distribution in both profiles was kept the same, even though the roots might have been affected by soil compaction, as we wanted to focus on the soil water differences caused by the different soil physical properties in the upper 0 to 5 cm of the mineral soil.

The initial conditions were selected so that the pressure heads at all depths were in equilibrium with the measured groundwater level of that day. If not otherwise noted in the description above, the default settings in Hydrus-1D were used.

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