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Roots under the load of heavy machinery in spruce trees

Abstract The effects of the passage of forwarders on soil and damage to spruce root systems along an experimental trail were studied. The site was characterized by medium-textured soil of the pseudogley type under favorable moisture conditions. Due to the passages, the soil was compacted down to a depth of 20 cm, soil porosity was decreased by 5% (volume) and soil aeration was decreased by more than 5%. Substantially higher values of mechanical soil resistance occurred (estimated by penetrometric measurements) in a soil pit situated in a rut after passages. Pressure measured by sensors placed at a depth of 10 cm below the soil surface reached values ranging from 0.09 to 0.11 MPa in plots uncovered with slash and 0.03–0.07 MPa in plots covered with slash after two to four passages, and 0.06–0.07 after six to ten passages. Soil surface deformations occurred in the upper soil layers through tire impression. This resulted in the origin of ruts, whose depth and width was dependent on the type of tires, their load, surface conditions, type and texture of soil, soil moisture and number of passages. Pressure in the soil layers imposed by the tire of a given type, inflation and load changed in relation to depth, ground cover, soil properties and reinforcing components on the soil surface. Sap flow in coarse roots actually treated by a moving heavy load clearly and immediately responded with a sharp increase followed by a similar decrease (peak flow) after several minutes. On average, the flow rate decreased by about 8% after the first treatment compared to the untreated state, and remained the same after passing the peak during the second pass when the maximum load was applied. However, this decrease amounted to about 40%, when compared to the "relative zero flow" after root severing. This indicates serious local damage to the conducting system. Even when loading directly damaged rather small fractions of the total root systems, it opened tree tissues to subsequent fungal infection, whose impact could be very serious in future years. Flow in stem sections oriented in the opposite direction to the trail and the flow in stem sections and root buttresses oriented toward the trail (but where roots were not actually growing below the trail or grew deeper in the soil), neither responded to the treatment or responded insignificantly. Sap flow responded only in surface roots below trails, occurring down to a depth of about 10 cm below the original soil (litter) surface. This occurred only when a significant part of the roots (with the total projected area of treated root branches more then 500 cm^2) were under the tires. This indicates the protective ability of soils and also, a possible method of artificial root protection.

Keywords Forwarder · Passage frequency · Peak responses · Penetrometry · Physical conditions · Radial pattern · Root damage · Sap flow · Soil compaction · Soil damage

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Introduction

During both the tending measures in all age stages of forest stands and their regeneration, the applications of progressive logging technologies using mobile means of mechanization (particularly harvesters and forwarders) increase in extent. Compared to previous chain-saw/manual technologies, this machinery makes it possible to markedly increase labor productivity and occupational safety, to decrease health risks and to facilitate felling records. However, its impact on soils and tree roots has remained questionable.

The majority of the machines used is of considerable weight and equipped with wheeled undercarriages. During the passage of such machines, unfavorable structural changes occur in forest soils. According to the

literature, changes can cause losses in forest production by 17% and even more (Becker 1999). Damage to the root systems of neighboring trees can be expected even under the directed movement of machines along determined tracks, i.e. extraction lanes (Wasterlund 1992). It is possible to suppose a direct relationship between the rate of damage to both soils and tree roots, and the frequency of passages of machines along tracks, weight, undercarriage specific pressure, soil character, weather and other effects (McMahon 1995).

Through the interactions of a wheeled working machine, the operational pressures induced in the soil are dependent particularly on the level of tire inflation, their stiffness and on the adhesion load of a traction system. This includes energy source, special adapter or aggregate and the stand soil surface during logging and transport. Deformations in the upper soil layers occur via the impression of tires into the soil surface resulting in the origin of ruts whose depth and width are related to the type of tires, their load, surface conditions, the type and texture of the soil, soil moisture and the number of passages. The level of pressure transferred into the soil by the tire of a given type, is given by inflation and load changes in relation to depth (decreases) where it is determined, also in relation to ground cover, the occurrence of coarse and reinforcing components in the soil, etc.

The aim of the presented research was to objectively estimate the impact of mechanical perturbations of the soil, namely, its compaction and changes in water capacity, along the skidding trails in forest stands caused by the movement of heavy logging and hauling machinery on tree roots, especially their health as reflected by water-absorbing functions. The present class of electronic measuring techniques available in the field of tree ecophysiology and structure allowed us to detect the impact immediately, to quantify its harmful effects on both the individual root and whole tree level, and to specify, which are the most important features of the injury.

Materials and methods

Experimental site and sample trees

Three experimental sites were located in the Training Forest Enterprise of Mendel University situated north of

Fig. 1 Scheme of the Jedovnice experimental plot with spruce trees treated by the movement of a heavy trailer with skidder. *Red lines* mark the ruts during two experiments, carried out in May and June 2002
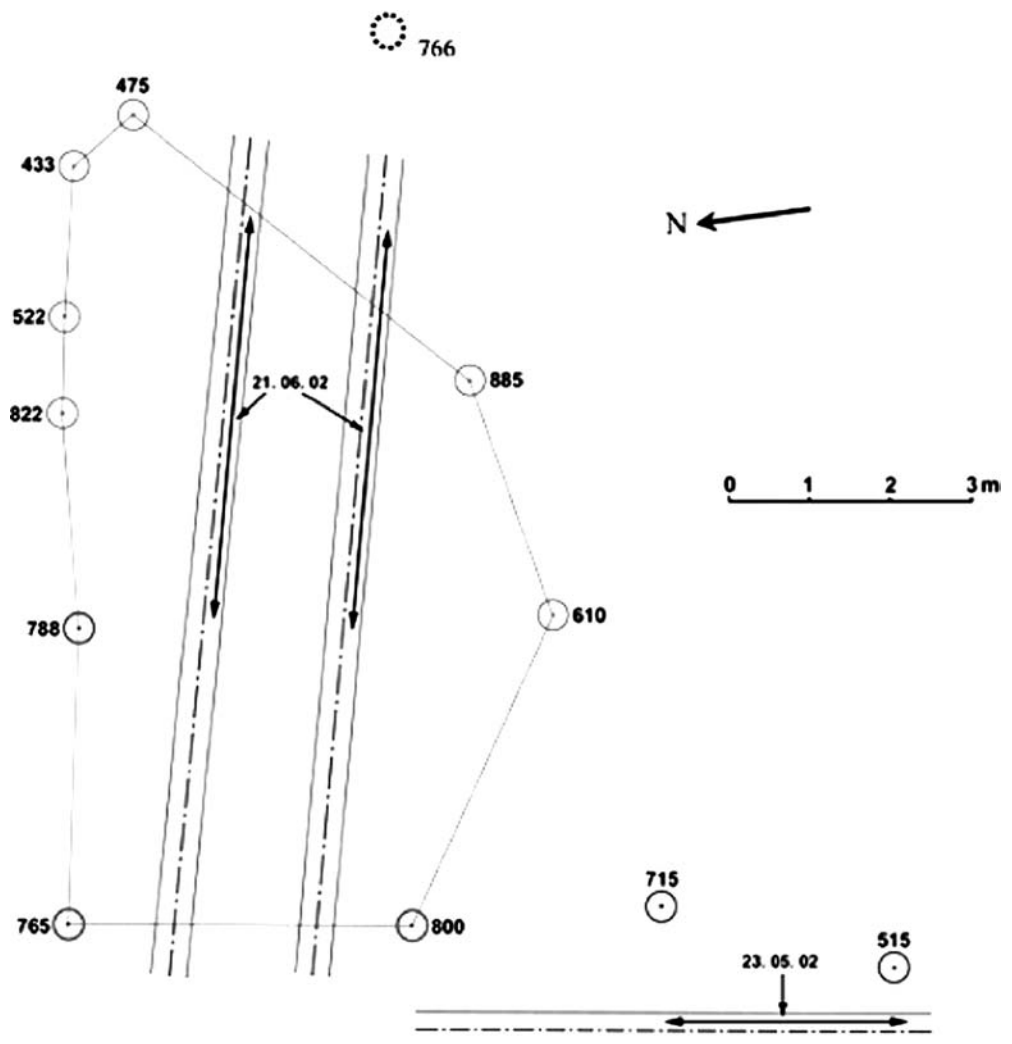
Brno, South Moravia, in the forest district of Jedovnice. The area is characterized by a long-term mean annual precipitation rate of 620 mm and a mean annual temperature of 7.5°C. Norway spruce (*Picea abies* (L.) Karst.) trees of different size and age were studied.

The first experimental plot was at the Krtiny Arboretum (25 km NE of Brno), latitude 49°19′12″N, longitude 16°44′37″E, (JTSK: $y = 587027.05$, $x = 1147990.31$), at an altitude ranging from 465 to 480 m, with a slightly sloped *E* aspect. The parent rock is sandsoil (culm droba), the soil-forming substrate is silt loam. The soil type is slightly acidic illimerized brown soil with the humus form mull moder. The site is classified as *Querceto-fagetum illimeresum trophicum* (Zlatnik 1976). The responses of sap flow to the loading and ultimate treatment—root severing—were studied there. Two 120-year-old sample trees were selected (the experimental and the control), with diameters at breast height (DBH) = 45.0 and 43.8 cm, respectively, with big coarse roots (width/depth of 12.5/14.5 and 13.0/18.7 cm, respectively, at the sap-flow measuring point) growing across the trail. Sap-flow sensors were installed 1.5 m from stems at the upper part of these roots, which were close to the soil surface, but the roots penetrated to a depth of about 20 cm below the soil surface 3.0 m from stems.

The second experimental plot was situated in the stand No. 289 C3Y about 5 km *E* of the town of Jedovnice latitude 49°20′48″N, longitude 16°45′38″E, (JTSK: $y = 5833184.70$, $x = 1147842.839$), with an altitude of 450 m. The parent rock consisted of sandsoil (culm droba), and the soil-forming substrate was the slopy silt loam. The soil type is slightly acidic gley-soil with the humus form moder. The site is classified as *Abietum piceosum paludosum mesotropicum* (Zlatnik 1976). The forest stand was 40-year old and represented a homogenous plantation of Norway spruce. The second experimental plot, where no machinery had been previously applied, was flat, 12-m long and 4-m wide, such that all sample trees were located along its edge (the numbers of trees corresponding with their breast height circumference in mm is shown in Fig. 1). Twelve trees, 11 experimental and one-control, with Diameter-at-Breast-Height (DBH) in the range of 14–28 cm, were selected for the study (Table 1). More complex treatment was performed there.

Soil monitoring

The effect of damage to the soil environment after encroachment was monitored by taking intact soil samples (Kopecký's rollers) from (1) a dug soil pit situated in a noticeable rut after the passage of a tractor and (2) in a nearby (3–5 m distant) intact place from the first pit in a neighboring spruce stand. At the same time, disturbed soil samples were taken from both the soil pits to characterize basic soil properties, i.e. soil texture, physical clay, soil aggregates, humus content and soil reaction in KCl (Tables 2, 3). Subsequently, a series of measurements was carried out using a hand penetrometer (STS Šumperk type) both in a rut made by a tractor and in an intact place in the forest stand. Soil samples were analyzed in the laboratory of the Department of Soil Science and Microbiology, Faculty of Agronomy, Mendel University of Agriculture and Forestry in Brno.

Pressure conditions in the soil at a depth of 10 cm were determined under two conditions: (a) in a soil with uncovered surface and (b) in a soil covered by the spruce slash layer about 40 cm thick in this experimental site. During practical logging operations carried out by harvesters, extraction lanes serving for the movement of heavy machinery and subsequently also forwarders, were intentionally covered by a layer of slash in order to protect both the soil and tree roots, a practice which we

Table 1 Biometric data of sample trees and the position of their stems to loaded trail (distances of stem axis to the nearest tire track axis) in the Jedovnice experimental plot

Experimental plot	Sample tree No.[a]	Note	DBH	Xylem radius (cm)	Basal area (cm^2)	Distance to tire track (cm)
May experiment						
	515	Exp.	16.4	7.4	211	80
	715	Exp.	22.8	10.6	408	150
	765	Control	24.4	11.4	468	580
	766	Control	24.4	11.5	468	1880
	788	Control	25.1	11.8	495	700
	800	Control	25.5	11.8	510	150
June experiment (control tree No. 766 remained the same as in May)						
	885	Exp.	28.2	13.2	625	130
	822	Exp.	26.2	12.2	539	225
	610	Exp.	19.7	9.1	305	260
	522	Exp.	16.6	7.6	216	225
	475	Exp.	15.1	6.9	179	170
	433	Exp.	13.8	6.0	150	250
	766	Control	24.4	11.5	468	700

[a]Number of tree corresponds to its circumference at breast height

Table 2 Humus content and soil acidity

Depth (cm)	Humus (%)	pH (KCl)
Soil pit 1–control		
7–15	2.08	4.54
15–25	0.89	5.17
25–35	0.49	5.32
40–50	0.25	5.39
Soil pit 2–rut		
7–15	1.92	3.20
15–25	1.08	3.85
25–35	0.78	5.04
40–50	0.38	5.16

Table 3 Description of soil pits

Soil pit 1—control	
0–5 cm O	Typical moder
5–15 cm AE	Dark brown, loamy, slightly humic, freshly moist, loose crumb soil. Abundant root penetration
15–28 cm En	Brown, loamy, slightly compacted, freshly moist soil, polyhedron structure. Low occurrence of Fe and Mn pellets
28–70 cm Bm	Light rusty-grey, mottled, loamy, moist, slightly compacted soil. Abundant occurrence of Fe and Mn pellets and stains
70–90 cm BC	Light-rusty, sandy-loam, moist, compacted soil

Soil pit 2—rut	
0–6 cm O	Typical moder
6–8 cm A	Black, loamy, freshly moist, humic, compacted soil
8–15 cm AE	Brown, loamy, compacted, freshly moist soil. Medium root penetration
15–30 cm En	Light brown, loamy, freshly moist soil. Occurrence of tiny Fe and Mn pellets
30–60 cm Bm	Yellow-brown, loamy, moist, slightly compacted soil with manifestations of slight mottling. Abundantly pellets of Fe and Mn. Sporadic root penetration
60–90 cm BC	The same as Soil pit 1

simulated in our experiments. The defined repeated passages (up to ten times) of heavy forest machinery in this study simulated those conditions known to occur in practice. The simulated load mounted on wheeled undercarriages moved in a trial plot in a spruce stand, over the same track (extraction trail), defined inflation and therefore specific tire pressures. The actual pressures exerted on the soil were measured at a depth of 10 cm under the ground surface during the tire passage. The width as well as the depth of ruts and changes in the penetration resistance of the soil were also measured. Further, the basic soil characteristics and changes in them caused by the passages were determined.

Experimental treatment

The first part of the study performed at the Krtiny arboretum focused on a general testing of the instrumentation and procedure (Ulrich et al. 2000), and on the short-term responses of sap flow to the mechanical load and to the ultimate treatment (cutting the roots) only for orientation. The tractor moved back and forth three times 3.0 m from the stems of the sample trees around noon under relatively fine weather conditions and caused a high pressure at the soil surface. The upper part of the experimental root was then cut to the depth of 25 mm about 10 min after the last mechanical loading.

Further study in the Jedovnice experimental plot was similarly done, but on a series of sample trees. The soil load was simulated using a heavily loaded two-wheeled trailer (total weight amounted to 3,300 kg). The trailer was pulled by a farm tractor Zetor 7245 and was equipped with 10.5/16 Chemlon Ply Ratting tires of inflation pressure 0.2 MPa. Based on the value and with the size of the contact area of each of the tires, 770 cm^2, we calculated a relatively highly rated footprint pressure of trailer tires on the soil, about 0.2 MPa, i.e. a specific pressure comparable or even higher than that commonly caused by heavy forest machinery. The tractor Zetor 7245 itself was equipped with low-pressure tires Trelleborg TWIN 600/60/30.5 (tread width 600 mm), inflated to a value of 0.1 MPa. This caused a rated footprint pressure of about 0.07 MPa, i.e. significantly lower than the pressure under the trailer tires.

The main physical soil parameters (water content, water potential and density) were estimated before treatment. The sap-flow sensors were installed on stems and roots and the soil properties were measured several hours before the experimental treatment; in other words, under conditions of no load. Then, a trailer moved along the trail, crossing roots. Two experiments were subsequently done:

Jedovnice—experiment 1: Six trees were under study during May 23—control tree No. 766 and five others located along the western edge of the experimental plot. Sap flow was measured at the stem base of two trees (Nos. 788 and 765) from the North side and in three other trees (Nos. 800, 715 and 515) from the West side—all facing the trail (see Fig. 1). Altogether, eight multi-point sensors were installed in the stems and three similar sensors in the coarse roots (Table 4: May experiment). The tractor moved in a North/South direction 2×15 times alongside trees Nos. 515 and 715 during 30 min shortly after midday (14.00–14.30) and then the load remained above the roots of tree No. 515 for the following 30 min. The treatment was later interrupted due to persisting low-evaporation demands.

Jedovnice—experiment 2: Seven trees were under study during June 26—the control tree remained the same as in the first experiment (No. 766) and six others were treated in the stand, where the tractor moved in the East/West direction. Sample trees Nos. 610 and 885 were

Table 4 Positioning of multi-point radial sap-flow sensors on the main stems and big coarse roots and single-point sensors on small coarse roots of spruce trees in the Jedovnice experimental plot

Type of sensor	Sensor positioning	Sampletree No.	Orientation (deg.)	Height or distance. from stem[a] (cm)	R_{xyl} or width (depth[b] (cm)	Depth[c] below cambium (mm)	Distance between thermo-couples (mm)	Time of root cutting	Distance of cut from sensor (mm)
May experiment									
Multi	Stem	515	NW	20	8.9	0	6	15:25 15:45	
		715	NW	20	13.1	0	6		
		765	SW	20	14.6	3	10		
		765	NE	35	14.3	3	10		
		766	W	60	11.5	2	16		
		788	SW	20	13.7	3	10		
		800	NE	60	12.7	1	10		
		800	SW	60	12.7	2	10		
	Large root	765	S	25	10.2	3	6		
		765	S	35	8.3	0	6		
		800	NE	30	8.8	0	6		
June experiment									
Multi	Stem	433	S	20	7.4	0	6		
		475	S	30	8.2	0	6		
		522	SE	30	8.3	3	10		
		610	N	30	10.3	2	10		
		766	N	55	11.5	10	16		
		822	S	43	14.4	1	10		
		885	S	53	15.1	3	6		
		885	N	33	15.1	1	10		
	Large root	822	SE	40	8.8	3	10		
		885	NE	50	7.6×9.9	1	6	14:36	15
		885	NW	40	11.2	1	6		
Single	Small root	475	S	57	5×6.9	5		14:26	12
		522	S	37	3.7×7.7	5		14:51	10
		522	SE	70	3.5×4.0	5		14:17	15
		822	SE	100	3.5×3.7	5		14:47	5
		822	SW	130	3×3.5	5		14:16	5

[a]Height from soil surface for stem sensors or distance from stem for root sensors
[b]Xylem radius for stem, width of buttress or width × depth for small lateral roots
[c]Depth below cambium for the first thermometers in multi-point sensorsRoot branch diameters were measured at the nearest edge of the tire track

facing the loaded trail from the North and sample trees Nos. 475, 433, 522 and 822 from the South (see Table 4: June experiment). The tractor moved during two subsequent periods of time, seven times back and forth in the first period, and similarly eight times in the second, one drive followed another by about 30 s during each treatment. The second loading period followed the first one by about 15 min.

Sap-flow measurement

Sap-flow rate in trees was measured using the heat field deformation (HFD) method (Nadezhdina et al. 1998; Nadezhdina and Čermák 1998; Čermák et al. 2004) using single-point sensors on small lateral roots and five-point radial sensors on large lateral roots (or root buttresses) and main stems (see Table 4). Sensors were placed close to the stem basis or at ground level in the case of roots. Each sensor was composed of a linear heater and two pairs of differential thermocouples, inserted in stainless steel hypodermic needles 1–1.2 mm in the outer diameter. Five thermocouples were arranged at 6–16 mm distances along the needle in the multi-point sensors, which allow for sap-flow measurements in different xylem depths below the cambium. Data were recorded at 1 min intervals by dataloggers Midi 12, EMS/ UNILOG (Brno, Czech Republic) and DL2e, Delta_T, (Cambridge, GB).

Deformation of the heat field around the heater occurring due to the movement of water was evaluated as a measure of sap flow, particularly through the ratio of two temperature differences, dT_{sym} and dT_{as}, recorded in the axial and tangential directions from the heater by two pairs of differential thermocouples. Sap flow at a certain tangential "i" root or stem section (q_i) was than calculated according to the equation:

$$q_i = 3.6D \times Z_{ax}/Z_{tg} \times (K + (dT_{sym} - dT_{as}))/dT_{as} \ (\mathrm{kg\,cm^{-1}\,h^{-1}}) \quad (1)$$

where D is thermal diffusivity of fresh wood ($\mathrm{cm^2\,s^{-1}}$). A nominal value for D was assumed to be equal to 2.25×10^{-3} ($\mathrm{cm^2\,s^{-1}}$); $K = (dT_{sym} - dT_{as})_0$ is the temperature difference between both measured temperature gradients under conditions of zero-flow (K); Z_{ax} is the

Fig. 2 a General view of the Jedovnice experimental plot with roots from spruce trees treated by movement of a heavy trailer (*upper photo*). Lines mark trails of both wheels. Rut width was 30 cm. Measured roots (with sensors installed), which occurred under wheels, are color-coded with paint. Majority of treated roots belong to the spruce tree No. 885, for which the position of the multi-point sensors on two coarse roots are shown. Additional multi-point sensors, located on the opposite sides of the stem (S and N), are not shown. **b** Detailed view of treated roots of spruce No. 885 (*lower photo*). Roots painted yellow, green and white (from the *left*) were connected to the root NE (sensor on root NE was installed on its branch, painted white color). Roots painted yellow (from the *right*) were connected with the coarse root NW
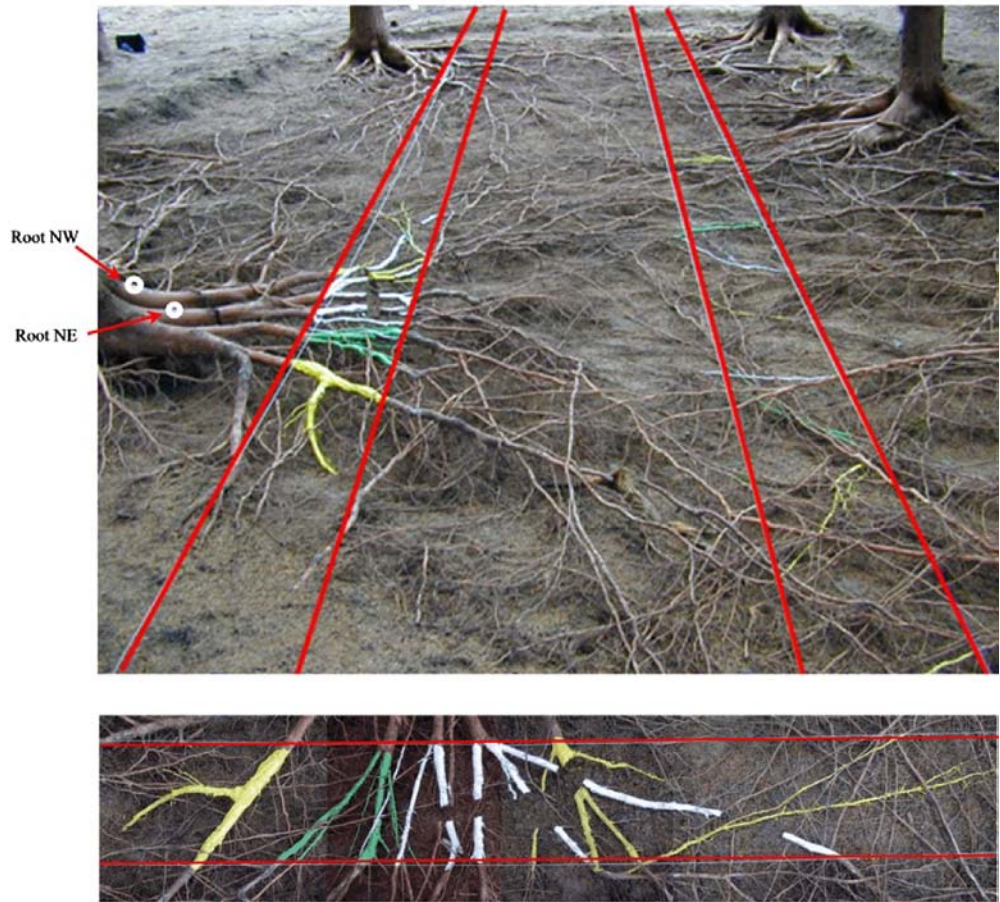

axial distance between the upper end of the symmetrical thermocouple and the heater (1.5 cm was used); Z_{tg} is the tangential distance between the upper end of the asymmetrical thermocouple and the heater (0.5 cm was used); dT_{sym} and dT_{as} are the temperature differences (K), recorded by the symmetrical and the asymmetrical pair of the thermocouples, respectively.

Evaluation of root systems

Only a small part of the roots close to the sap-flow sensors were opened in the sample trees growing in the arboretum experimental plot, in order to allow for manipulation with the saw during the cutting experiment. However, root systems of sample trees were

Fig. 3 Measured rut depth after the passage of a tractor with a loaded trailer
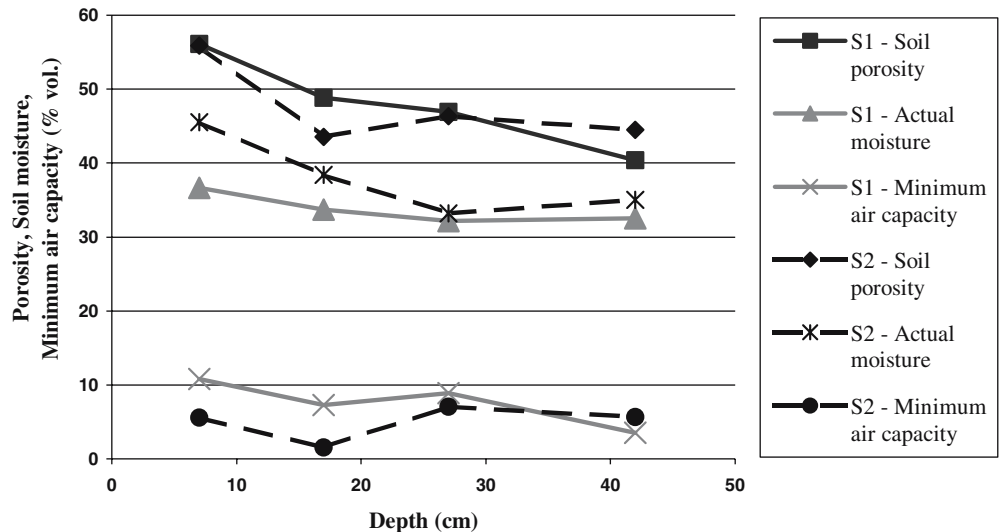
opened over an area of more than 60 m^2 to a depth of about 30–50 cm in the Jedovnice experimental plot. A supersonic air stream (the air-spade technique, Concept Engineering Group Inc., Verona, PA, USA) was used for this purpose. The entire opened area was photographed from a ladder fastened to the stems of the surrounding trees. The positions of individual roots associated with root buttresses and lower stems, where the sap-flow sensors were situated, were precisely located. Parts of the actually loaded roots (those which occurred under the wheels) were marked with different colors (Fig. 2). The depth of the treated roots was measured after they have been opened in all the sample trees. The actual integrated magnitude of the loaded root area (including all connected root branches) as measured by a particular sensor was estimated as the length of that part of the roots under the wheels multiplied by the root width in the second experiment.

Two kind of sap-flow responses were distinguished: (1) a reversible increase of flow, which occurred in the course of loading, and (2) an "irreversible" decrease of flow after the treatment (we counted irreversible at least during the study period). Only this "irreversible" change was considered to be the root damage. We defined the magnitude of such root damage as the integrated difference in flow rates between its levels in different sapwood depths before the treatment (Q_{w_orig}) and that at stabilization of flow after loading (Q_{w_load}), compared to flow rate after root severing (Q_{w_sev}). While not necessarily zero, because of water supplied by deep undamaged root branches, it was considered as "relative zero" for a particular treated root. The original level of sap flow per unit section (in kg cm^{-1} h^{-1}) when expressed as (Q_{w_orig} - Q_{w_sev}) was taken as 100% and the decreased level after root damage as (Q_{w_load} - Q_{w_sev}). The values at different sapwood depths or integrated values from all sapwood depths (i) were considered when calculating the remaining relative level of sap flow ($Q_{\%\_rem}$). The relative root damage ($Q_{\%\_dam}$) was calculated from sap-flow

measurements, i.e., the remaining flow in percent of the original flow level thus can be expressed as

$$Q_{\%\_rem} = \sum_{i=1}^{i=n} 100 \times \frac{Q_{w\_load} - Q_{w\_sev}}{Q_{w\_orig} - Q_{w\_sev}} \quad (2)$$

and the percentage of root damage, i.e., fraction of reduced flow Q_{w_dam} as

$$Q_{\%\_dam} = 100 - Q_{\%\_rem} \quad (3)$$

Results

Evaluation of the soil environment after tractor passages

Laboratory analyses indicated a loamy soil with a clay particle content from 39 to 44% and low humus content in the mineral soil profile at the Jedovnice experimental site. The forest floor was formed by a relatively thin O horizon of 5–6 cm in thickness. The soil reactions in both the control and experimental plots (Soil pits 1 and 2) was acidic; in the surface horizons heavily so.

The actual soil moisture in the control plot (at Soil pit 1) was about 6%$_{vol}$ lower at the upper part of the soil profile than the retention water capacity (RWC) in the course of treatment on May 2002. It almost reached the value of RWC in the lower horizons, i.e. roughly the optimum moisture content for the undisturbed transpiration of forest trees. Soil moisture was nearly the same throughout the soil profile in the treated plot (Soil pit 2), amounting to approximately the value of RWC in the course of the passage of a tractor. Surface soil layers were thus partially "moistened" during soil compression in the course of treatment. The determined soil moisture (expressed as storage) reached 103 and 111 mm for the soil layer 0–50 cm deep in the Soil pits 1 and 2, respectively. The wilting point was estimated at 80 mm for

Table 5 Physical parameters of the soil

	Specific density (g cm^{-3})	Bulk density (g cm^{-3})	Porosity (% vol)	Actual soil moisture content (% vol)	Actual air capacity (% vol)	Max. capillary capacity (% vol)	Min. air capacity (% vol)	Retention water capacity, RWC (% vol)	Air capacity, RWC (% vol)
Soil pit 1									
	2.59	1.14	56	37	20	45	11	42	14
7–11									
	2.62	1.34	49	34	15	42	7	39	10
15–19									
	2.64	1.40	47	32	15	38	9	35	12
25–29									
	2.67	1.60	40	33	8	37	4	34	7
40–44									
Soil pit 2									
7–11	2.59	1.14	56	46	10	50	6	48	8
15–19	2.63	1.48	44	38	5	42	2	39	4
25–29	2.67	1.43	46	33	13	39	7	35	11
40–44	2.65	1.47	44	35	10	39	6	35	9

Table 6 Particle-size distribution

Depth (cm)	Content of a fraction (%)				
	2.00–0.25 (mm)	0.25–0.05 (mm)	0.05–0.01 (mm)	0.01–0.001 (mm)	< 0.001 (mm)
Soil pit 1					
15–25	4.6	14.8	39.6	26.9	14.1
25–35	5.9	15.4	39.8	24.8	14.1
40–50	3.8	15.9	36.3	22.8	21.2
Soil pit 2					
15–25	3.3	13.1	41.4	25.4	16.8
25–35	3.8	16.2	40.4	25.3	14.3
35–50	3.0	12.9	43.5	24.4	16.2

both the pits. Therefore, we can conclude, that the above values represented sufficient soil water supply for transpiration of forest trees.

The physical soil conditions showed the typical values for a given soil type (Fig. 3). Under the forest floor of the moder type, soil porosity amounted to about 56% in both soil pits in the 7–11 cm layer. The relatively high soil porosity in the treated plot (Soil pit 2, with respect to the expected lower value due to soil compaction) was obviously caused by the higher content of organic matter admixtures in this layer. The highest compaction occurred in the treated plot (Soil pit 2) at the 15–19 cm depth where soil porosity decreased by as much as 5% when compared to the control (Soil pit 1). Soil porosity values amounted to around 40–46% at the 25–29 cm depth and lower in both the soil pits. Thus, it was possible that almost no compaction occurred in deeper layers.

The value of volume weight of dry soil is also an important indicator of soil compaction. It increased to a value of 1.49 g cm^{-3} at a depth of 15–19 cm in the

treated soil (Soil pit 2) when compared to the control (in Soil pit 1, it reached only 1.34 g cm^{-3}). These values were almost identical at a depth of 25–29 cm. A slightly higher value of the dry soil volume weight in the control plot at a depth of 40–44 cm when compared to the treated one occurred probably due to the local heterogeneity of soil layers.

Important evidence for the process of soil compaction in a rut after the tractor passage is also the value of soil aeration. This decreased by more than 5%$_{vol}$ within a 20-cm depth in the treated plot (Soil pit 2) when compared to the control pit under soil moisture corresponding to the soil 'hydrolimit' RWC (see Fig. 3). Complete results of the physical condition of undisturbed and disturbed soil after loading treatments are given in Tables 5 and 6.

A significant difference in soil compaction was also indicated by a series of measurements taken using a hand penetrometer (Fig. 4). The needle of the penetrometer entered rather easily into the soil profile in the

Fig. 4 The course of selected physical parameters of soil porosity; actual moisture and minimum air capacity
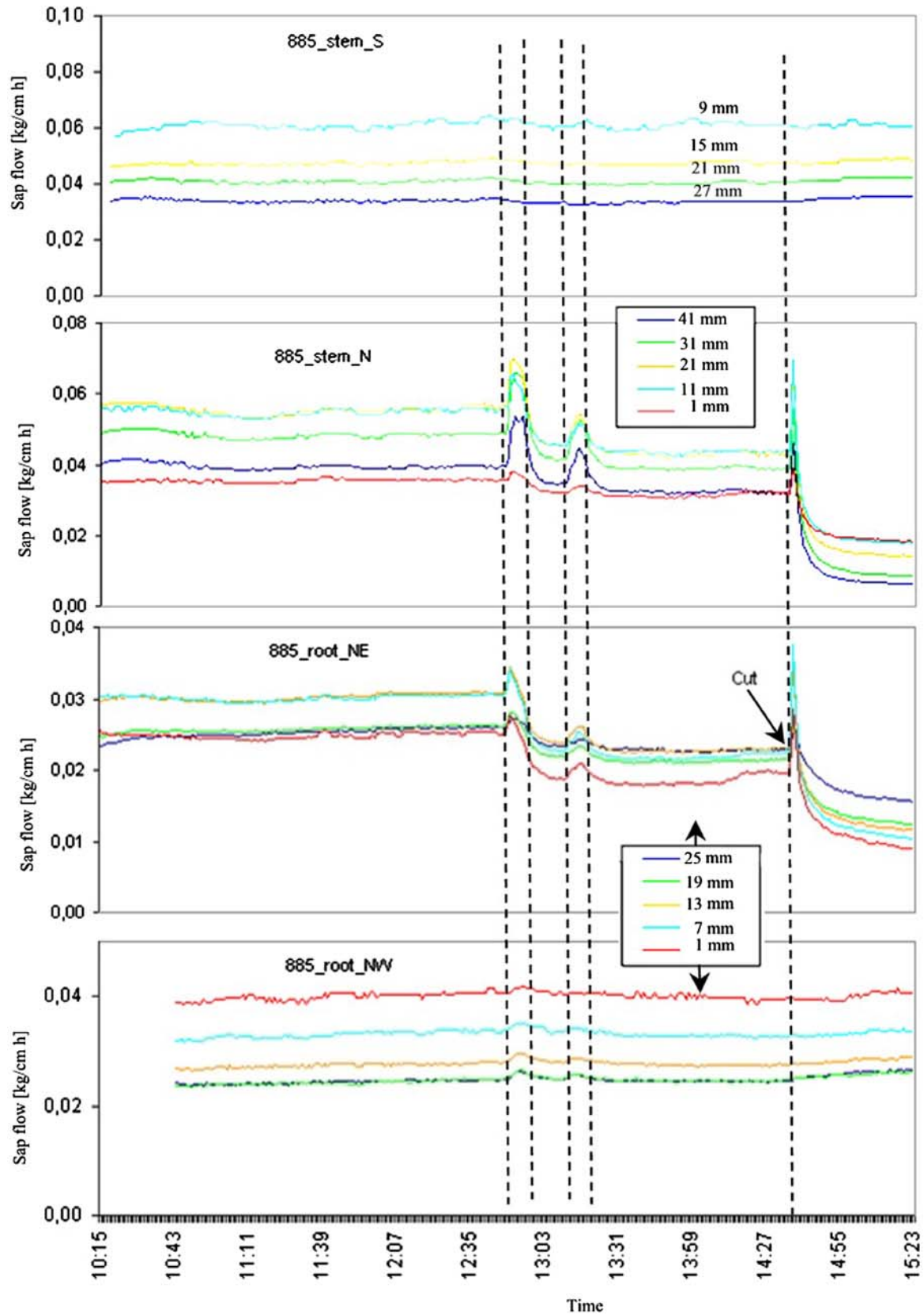
$y = 0,883Ln(x) + 2,139$

$y = 1,8444Ln(x) - 1,4586$
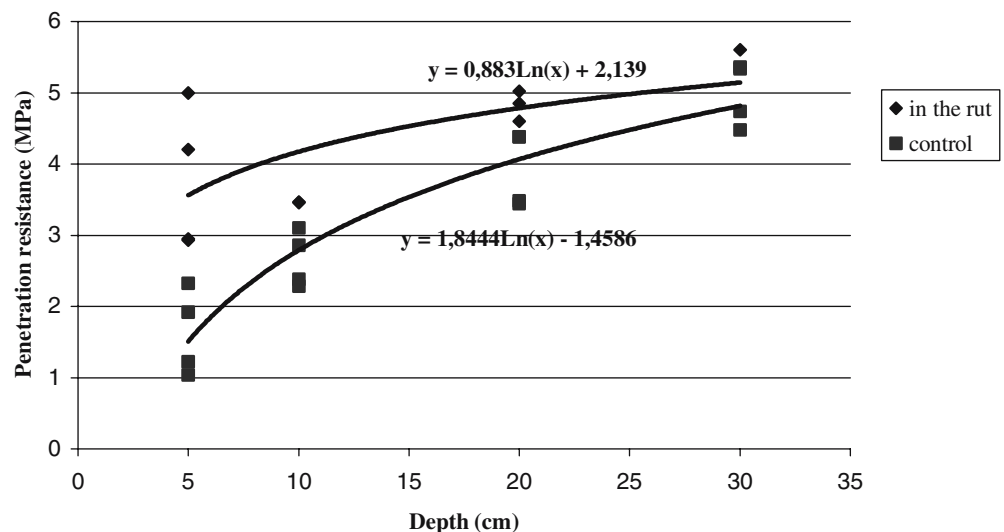
Fig. 5 Sap-flow rate in the stem of treated spruce tree No. 885 (two opposite sides) and in two coarse roots. *Vertical lines* indicate periods of trailer moving and root cutting

control (Soil pit 1), where penetration resistance ranged from 1 to 2 MPa at a depth of 5 cm to 5 MPa at a depth of 30 cm. In a compacted rut (Soil pit 2), resistance values at a depth of 5 cm ranged from 3 to 5 MPa and deeper up to a value greater than 6 MPa, i.e. virtually in an immeasurable range.

Evaluation of soil pressures caused by passages

Tire pressure is transferred to the soil surface of a forest stand over the contact area. According to the extent of pressure in a tire, adhesion load, components of the fraction force of a wheel originating through the inter-action of the transferred turning moment, the tire acts on the soil by a specific pressure of a certain value and, thus, it is pressed into soil in relation to its actual condition. The rut depth after the passage of a tractor increased with the increasing number of passages. For example, the depth of ruts was about 6 cm after six movements and increased up to 15 cm after ten movements when we worked with the Zetor 7245 tractor in the Jedovnice experimental plot. The soil below the tires was compressed, but it was also partially pushed out at the rut edges.

The values of the parameters of the relations can be recorded and used in the preparation of criteria for assessing the consequences of the passages of various forest machines, primarily forwarders, which show the highest total load derived both from the weight of the machine itself and its load. According to the type of machine, the weight amounts to about 10–20 t. For example, a ROTTNE Solid F 9 forwarder of medium class, weighs 10,600 kg and with a load capacity of 9,000 kg, it is equipped with four low-pressure tires of a dimension of 600/50. With the contact area of one wheel about 4,200 cm^2, the specific pressure of a tire amounts to about 0.12 MPa.

Effects derived from the weight of machines consider, among others, two problems:

1. Primary effects of heavy forest machinery through pressures brought about during their passages (tractors with semi-suspended load, harvesters and forwarders loaded with logs) cause direct damage to roots, viz. on the one hand, damage to large-diameter roots which can be macroscopically observable particularly in shallow-rooting species (Norway spruce) and, on the other hand, damage to the absorption zones in the thinnest parts of the roots which can only be detected by special instruments.
2. Secondary effects of machinery caused soil compaction either temporarily or permanently. It can result, e.g. in changes in the absorption capacity of soil for water, changes in the permeability of soil for air as well as roots, etc. Pressure measured by sensors placed at a depth of 10 cm below the soil surface reached a value ranging from 0.09 to 0.11 MPa in plots uncovered by slash and 0.03–0.04 MPa after two to four passages in plots covered by slash (when the

original thickness of the slash was 40 cm). However, the effect of the slash decreased with the number of passages: it reached 0.06–0.07 MPa after 6–10 passages. It is evident that from the results of the measurements that the actual pressure at a shallow depth (such as 10 cm below the soil surface) is lower than the value of the specific pressure of a tire calculated from the size of load and the size of the tire-contact area. The effects of the slash layer on the distribution of pressure in the soil caused by the passage of a tire are also favorable.

Sap-flow responses on loading

Arboretum experimental plot (data not shown)

No sap-flow response occurred in either the stems or roots of spruce sample trees growing in the arboretum experimental plot. This occurred, most probably, because a rather low load was applied far away from stems and was applied in those places, where the roots were too deep. However, that sap flow clearly responded to the cutting of surface xylem layers was observed when the experimental root was cut to a depth of 2.5 cm. No change in sap flow appeared in the deeper xylem layers. Thus, in principle, sap flow responded to root damage, but evidently roots were not damaged by loading treatment under the given experimental conditions. The first experience helped us to improve the following treatments.

Jedovnice experimental plot

Experiment 1–responses of sap flow to machinery under low-evaporation demands (data not shown)

Sap flow in tree No 515 (which was treated most) responded very little to the heavy load by slight continuous decrease during 30 min. No response to loading occurred in another sample tree (No. 715), in keeping with all control trees. This experiment confirmed that similar studies should be performed only under higher-evaporation demands, when transpiration and sap flow are higher. However, sap flow clearly responded to root cutting even under unfavorable conditions.

Experiment 2–responses of sap flow to machinery under high evaporation demands

Heavy-load root treatment was performed when root positions was unknown. Therefore, sap-flow sensors were installed on stems and root buttresses facing the trail when we were "blind", i.e., only supposing a higher probability that corresponding roots would occur under the wheels according to the positions of visible root parts close to the stems. No sap-flow re-
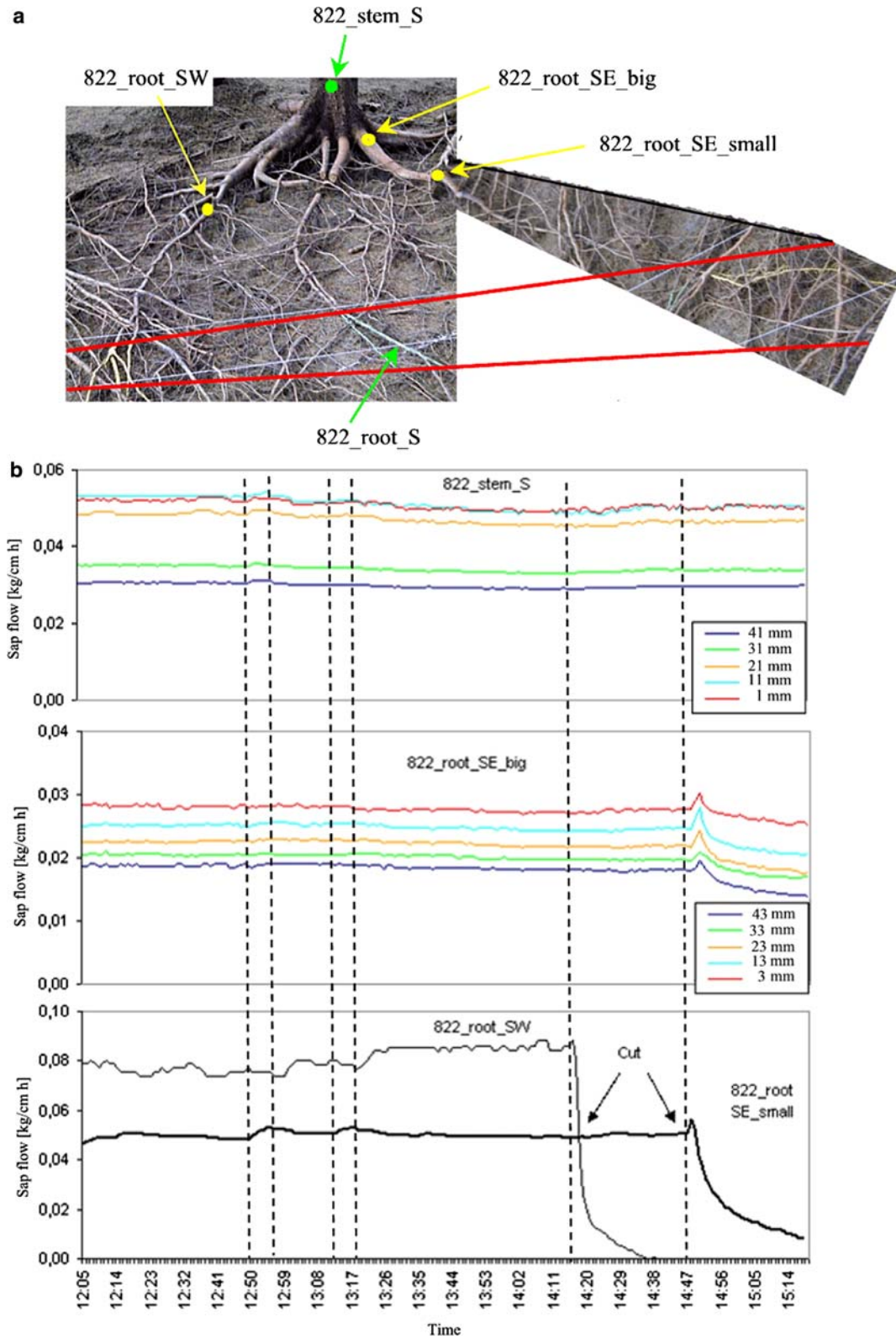
Fig. 6 a Detailed view of the root system of spruce tree No. 822 with the positioning of sap-flow sensors: one sensor was installed on the stem (*S*), two sensors on the same root, oriented SE, and one sensor on the root, oriented SW. *Red lines* mark wheel trails. **b** Sap-flow rate in stems and roots of treated spruce tree No. 822. The flow responded remarkably to mechanical treatment by the movement of heavy machinery in the small root SE, not quite clearly in root SW, but no responses were recorded in the big coarse root and the stem. Flow responded significantly to the subsequent cutting of small roots (SW and SE), performed below the single-point sensors. This was also reflected in the big coarse root (SE), but no response was recorded by the sensor, installed in the stem oriented to S
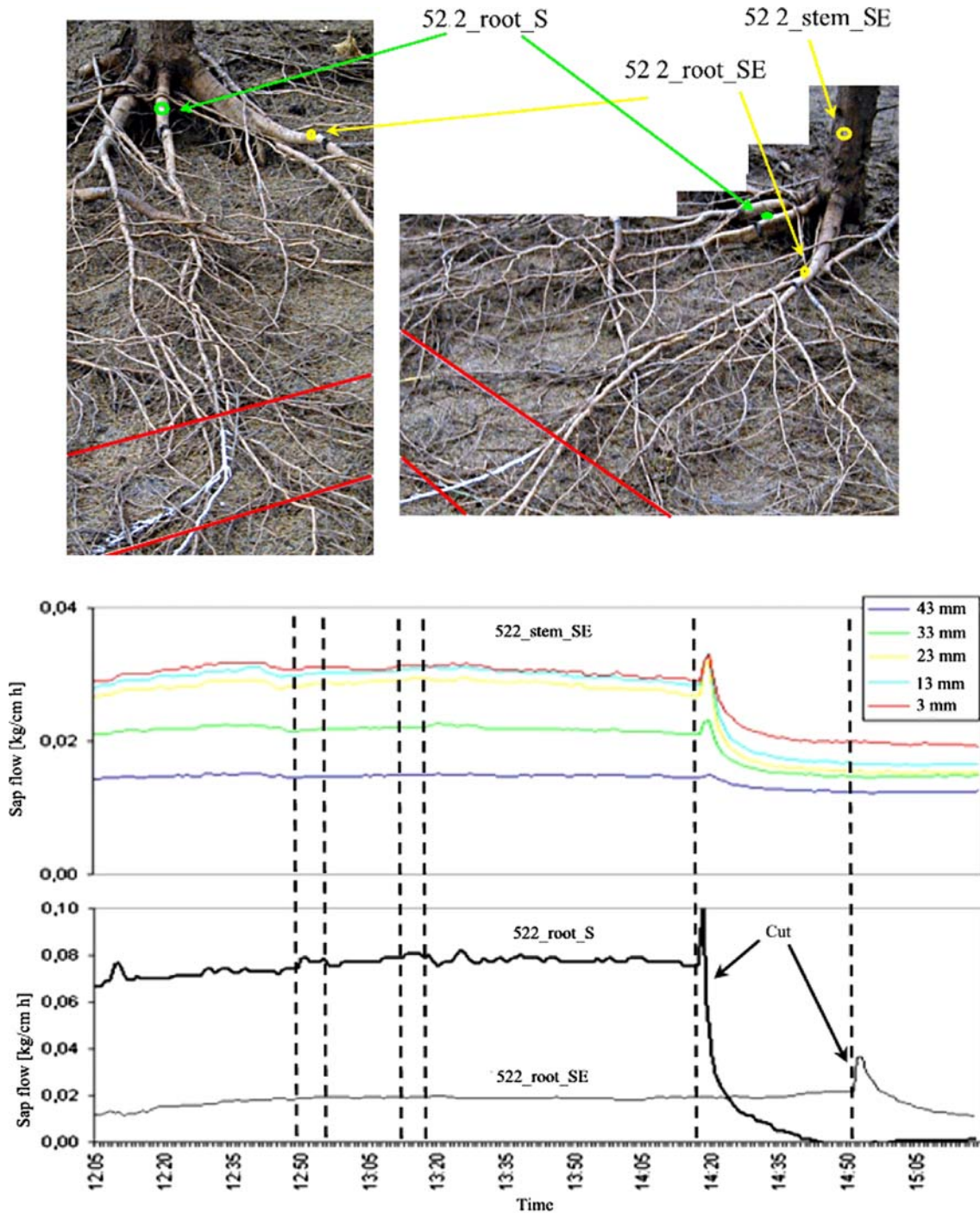
Fig. 7 a Detailed view of the root system of spruce tree No. 522 with positioning of sap-flow sensor on the stem (SE) and on two roots (S and SE). *Red lines* mark-wheel trails. b Sap-flow rate in the stem of treated spruce tree No. 522 in different sapwood depths and two small roots, S and SE. No response to mechanical treatment occurred in the stem or both roots. In contrast, clear responses to root cutting occurred in all sensors

sponse to treatment was observed in control tree No. 766, remote from the experimental plot, nor in the experimental tree No. 610, irrespective of the fact that the sensor on its stem was facing the trail directly. Sap flow did not respond in the sensor facing opposite sides of the stem then treated, e.g. the south side of stem No. 885 (Fig. 5). Surprisingly, sap flow did not respond at all or only responded slightly to treatment in most (of altogether 5) sensors on stems and (seven sensors) roots facing the trail. A very slight response was recorded in the SW and SE growing roots of tree No. 822 (Fig. 6) and, there was absolutely no response of sap flow, e.g. in the stems and roots of trees No. 522 (Fig. 7), 433 and 475.

However, sap flow in coarse roots, which were actually treated (i.e., in tree No. 885—see painted roots in Fig. 2), as well as the flow in the corresponding part of the stem of this tree responded substantially (see Fig. 5). Roots oriented to NE (see yellow, green and white marked roots) occurred at a depth of about only 5 cm. Flow increased immediately when the imposed load compressed these roots, reaching its peak after 1–2 min (i.e., after the first movement of the load), but decreased again about 4–5 min after this period of time, when the roots were still load-treated. Sap flow significantly decreased below its original level (that just before the treatment), when the peak flow passed after about 5 min. A very similar situation was observed during the second treatment, although the response was not so significant (the peak was lower). The flow stabilized shortly after the second treatment (second peak flow) and its level remained the same as before (see Fig. 5). The amplitude of response in stem N was about twice higher than in root NE. This happened because the sap flow also integrated the behavior of other roots (marked by yellow and green colors). No time shift in the sap-flow response in the stem behind the flow in roots was observed. The flow response was very slight in a neighboring root oriented NW, which was situated deeper in the soil (around 10 cm—notice that yellow roots grow under white roots–see Fig. 2).

Sap flow responded at varying magnitudes at different sapwood depths. The original magnitude of flow in stem N was the highest in the medium sapwood layers, followed by that of the deep and surface layers. Maximum flow change during the treatment occurred at the deep and medium sapwood layers, and the lowest change occurred at the surface sapwood layers (see Fig. 5). A contrasting flow pattern of the original level of flow and its responses were observed in root NE of this tree: maximum changes in flow during the treatment occurred at the surface and medium sapwood layers and minimum changes at the deep layers (see Fig. 5). We should keep in mind, that the given sap-flow data were expressed per sapwood section, where the measured thermometers were replaced. Outer xylem layers always represented larger sapwood area than the inner layers. Thus, the total flow per corresponding outer sapwood annuli was higher then per inner annuli.

Responses of sap flow to root severing from stems

Sap flow responded strongly in all stems and roots when the roots were cut (see Figs. 5, 6 and 7). This happened irrespective of root or stem diameter and actual evaporation demands (during cloudy weather in May as well as during better weather in June). However, magnitude and character of sap-flow response differed significantly.

Sap flow in tree No. 855 root NE responded with a very sharp peak to root severing (see Fig. 5). Root sap flow did not decrease to zero during 40 recorded minutes, but remained at a level of about 40–80% of that before the cut. There was no apparent time delay between peak flow in the root and in the stem (over a distance of about 2 m), they both changed at the very same time in parallel. Sap flow slightly increased in the neighboring root oriented NW immediately after severing the root NE, especially in the deeper sapwood layers. The response of sap flow to root cutting was naturally much sharper than to root treatment by heavy load. The onset of both types of responses occurred without delay, but the peak flow occurred 2–3 min later when the roots were compressed (especially during the second treatment) compared to the situation, which occurred when roots were cut-off.

Sap flow in the root SE (tree No. 822—see Fig. 6) did not respond when the neighboring root, SW was cut. Flow in the SW root fell down immediately after the cut, showing almost no peak increase as in most other cases and decreased exponentially to zero during 20 min. Cutting the small SE root belonging to the larger SE root was followed by a similar sap-flow response, but a small peak flow occurred before the flow fall approached zero after a longer period of time (after 40–50 min). Flow in the larger SE root responded to peak simultaneously, but with some delay (about 3 min, thus less abruptly). The flow decreased a little when the peak passed, but continued further, evidently due to the activity of other attached deeper roots, which remained uncut. There was absolutely no flow response to the severing of SW and SE roots in the stem section oriented toward S.

Sharp peak flow occurred in both roots (S and SE oriented), when they were cut one after another from the tree No. 522 (see Fig. 7). Rather, high flow clearly decreased to zero in root SE after about 30 min, while very little flow was still recorded after a similar period of time in low-flowing root, S. Sap flow in the SE-oriented stem section clearly responded by a peak flow to the severing of a neighboring SE root. The stem response was clearly postponed by 2–3 min. It was most pronounced in the surface and medium sapwood layers, but very little in the deep sapwood layers. This also fits the level of flow after passing the peak (which took about 15 min), when the resulting flow was lowered by about 30–40% in the surface and only by a few percent in the deep sapwood layers.

Discussion

Evaluation of soil pressure during tractor passages

It is known, that soil compaction due to the passage of logging machinery is always markedly dependent on the actual condition of soil moisture (Hadaš 1987; Neruda 2000, 2002). A similar decrease in soil porosity as occurred in our soils was also mentioned by Tijink et al. (1988), particularly by 4–6% after loading under similar conditions. Soil compaction was reported down to a depth of 27–35 cm in a medium-textured soil after the passage of a tractor (Smith 1985). This indicated the

possibility that part of the root system of trees could be damaged at the same time. Changes in root growth due to soil compaction after tractor passages were earlier described by Bredberg and Wästerlund (1983).

Spruce tree root systems and assessment of their damage

Typical species features characterized the root systems of analyzed trees. The density of coarse roots was higher toward tree stems, while that of fine and medium roots were more evenly distributed. Most roots were reaching far beyond the crown-projected area, while mean crown radius, $r_{crown} = 1.5$ m, mean social radius, $r_{soc} = 2.4$ m and prevailing root radius, $r_{root} = 3.3$ m. However, some roots were very long, reaching over 10 m, i.e., approaching the tree height. Such parameters are very important for tree survival and are rather typical for spruce and coniferous species in general (Stone and Kalisz 1991; Fayle and Scott 1995; Drexhage and Gruber 1998; Wang et al. 2002). The biomass of root systems can be reasonably derived from allometric equations in woody species (Drexhage and Gruber 1999; Drexhage et al.1999; Bond-Lamberty et al. 2002), especially when site drainage is taken into account (Konopka 2002). However, their morphology and spatial arrangement can hardly be generalized due to strong edaphic constraints such as very local substratum and soil structures (Curt et al. 2001).

The movement of heavy skidders did not directly jeopardize vertical roots, but does so, especially for large surface roots and root buttresses. When bark was damaged or even completely removed on the upper root surfaces, cambium was destroyed and xylem tissues become fully opened to deep desiccation (which gradually destroys the conducting system) and subsequent fungal infection (Ronnberg 2000). Similar observations were easy to perform; however, it was impossible to evaluate latent root damage this way. That is why sap-flow measurement was important.

Methodical questions of sap-flow measurement

The applied sap-flow sensors based on the HFD method fulfill the general needs for root measurements, i.e., measuring slow and reverse rates of flow and that which do not require assumptions of zero flow during the night are applicable to root studies (Burgess et al. 2000). Extremely fast-recorded flow responses were especially pronounced after root severing and characterize the high dynamic sensitivity of the HFD method. Maximum deceleration rate as a response to stem severing just above the measuring point, which was recorded by the tree-trunk heat balance (THB) method was -30% min^{-1} when using a constant power supply and -60% min^{-1} when using a more sensitive system (Kučera et al. 1977) with a constant temperature difference (Čermák and Kučera 1991). Maximum deceleration caused by heavy rain showers reached only -20% min^{-1} under the same

conditions. Similar results were also obtained in other studies based on branch severing (Rychnovska et al. 1980; Čermák et al. 1984).

At the beginning of the study, it was not clear why some roots, which were seemingly directed into the trail responded to loading treatment and some did not.. However, this seemingly strange behavior became clear after opening the root systems of all the sample trees at the end of the experiment, when the roots were visualized and the treated roots were reliably identified (see Fig. 2). The coarse roots of non-responding trees, whose buttresses were grown in the direction of the trail, shortly moved away from this direction. As a result of this, no root branches (or only an insignificant fraction of them) were actually treated, while the roots of the responding trees occurred directly under the tractor wheels. Sap flow clearly decreased to zero within a short period after small root cutting, which was confirmed in some trees (e.g. Nos. 822 SW and 522 S—see Figs. 6 and 7, respectively, where high flow was observed before root severing). However, some flow persisted in the roots of other trees under the same conditions (e.g. Nos. 822 SE, 522 SE—see Figs. 6 and 7). This may have been partially caused by the following reasons:

1. Some roots (particularly those with an originally lower flow, e.g. in trees Nos. 822 SE, 522 SE—see Figs. 6, 7) needed more time to approach zero flow, because more time was also needed to remove water from the relatively larger, remaining storage in the cut part of the root below the sensor.
2. Flow response at the sensor depends on the level of flow integration by the particular root branch at the particular position of the sensor. Sap flow need not necessarily have reached zero when it was measured in the main branch, if one of the secondary branches was severed. This happened in roots where some branches out of the measuring points were growing vertically into deep soil layers due to the connection of other additional roots (mostly deeper ones) between the places of measuring and those of cutting (see Fig. 6—root 822 SE big).
3. Root sapwood is usually extremely heterogeneous when compared to that in stems. Their cross section is highly asymmetric (prolonged ellipsoid or better of an egg-like form, with the pith in the center of its narrower, deeper end). That is why it is not easy to integrate the sap flow across roots in order to exactly quantify the whole root flow.
4. Flow variation could also indicate certain measurement errors, possibly caused by the non-parallel drilling of holes in sapwood, where the needles were placed.

Analysis of root damage

In general, the hydraulic conductance of spruce roots is larger than stems and branches (Sellin 1988; Hallgren

et al. 1994). Roots can be damaged in several ways by mechanical loading: (1) at the soil-root interface (including mycorrhiza), (2) absorbing fine roots, (3) coarse skeleton roots growing in the soil and (4) roots and root buttresses partially growing above the soil surface. Sap-flow patterns are suitable for direct estimation of the magnitude of the damage in terms of changed transporting properties, but morphological characteristics of the damage can only be assessed indirectly. Increased pressure on root surfaces evidently initiates hydraulic forces in conducting tissues. Such forces cause a dominating apoplastic flow around protoplasts, even in the endodermis and exodermis (Steudle 2000). A certain tendency to restore the flow in the outer sapwood layers was observed approximately 1 h after treatment in some trees (see Fig. 5: stem S and root NW). However long-term observation is needed to clarify these phenomena.

Possible consequences of root damage

When the mechanical loading damaged only the surface roots, it indicates that possible consequences can affect leaf conductance or water potential more significantly than if deep-oriented roots were to be damaged (Carlson et al. 1998). Roots can mechanically reinforce shallow soils in forested landscapes. Median lateral-root cohesion ranges from 7 to 23 kPa in industrial forests to 26–94 kPa in natural forests dominated by coniferous vegetation. Cohesive soil reinforcement due to roots is determined by the tensile strength, species, depth, orientation, relative health and the density of the roots greater than or equal to 1 mm in diameter (Schmidt et al. 2001). There is a functional difference between horizontal and vertical roots in spruce, that points out the importance of extensive, long vertical roots, which insure sufficient water and nutrient uptake (Drexhage and Gruber 1998).

Differences in the responses of sap flow to root compression and root severing

It is known, that soil drying and compaction have large species-specific effects on the distribution, growth and physiology of roots (Liang et al. 1999). This considers long-term impact of the involved factors. Changes in sap-flow parameters naturally represent only the short-term characteristic of root damage. Such damage could regenerate or could be more pronounced later after different periods of time. To answer such questions will be the aim of following studies.

The repeated mechanical loading of soil surface during short periods of time (about 30 s) represents a rather fast "pulsing" treatment (see tree No. 885, Fig. 5). Water is probably forced to move in acropetal, but to some extent also in a basipetal, direction from the treated point, when roots are compressed anywhere along their length. This considers presumably the pres-

sure waves of course. It is known that rigidity can vary between and along individual roots in spruce (Coutts et al. 1999). However, it is not yet known how a similar variable mechanism proceeds in detail, especially why the peak flow decreases when the roots are still under persisting (pulsing) pressure treatment, when root sensitivity decreases simultaneously with the flow rate. This behavior indicates an unfavorable effect of loading, i.e. the occurrence of some long-term functional deprivation. Further observation is needed to answer the question whether such an effect is irreversible or if the roots can regenerate again.

Root cutting clearly represents such an irreversible treatment. Flow response was to some extent similar to that observed in the shoots of reed and willow (Rychnovská et al. 1980; Čermák et al. 1984), but no peak occurred in shoots as in roots here. The sharp increase in flow visible in most treated roots (see Figs. 5, 7), reflects abrupt removal of root resistance below the cut end. Therefore water can move freely until there is some in the remaining part of conducting elements (Nadezhdina and Čermák 2000a, b; Nadezhdina et al. 2004). Somewhat flatter peak flow in roots following root severing (tree No. 433, data are not shown) or the near absence of such a peak (see tree 822, root SW in Fig. 6) probably reflects differences in root resistance. Flow peaks occurring in stems at distances of about 1 m above the cut ends of roots (or in large roots after severing their smaller branches) also varied significantly, from very sharp (see tree No. 885, Fig. 5) over less pronounced (tree No. 475, data are not shown) to rather flat ones (see trees 822, 522, Figs. 6, 7).The repeated appearance of flow peaks after subsequent cutting of the very same root (tree No. 715, data are not shown) can probably be explained the same way. However, a more detailed study is needed to arrive at a clear conclusion.

The time period during which the flow was decreasing (20–40 min) (see Figs. 5, 6, 7) evidently corresponds to free water content in the root segment between its cut end and the sap-flow measuring point, as was observed earlier (integrated water flow after branch severing corresponded to measured changes in branch water content before and after the treatment—Čermák et al. 1984). The exponential course of water depletion probably reflects a gradual outflow of water from conducting elements of decreasing diameter, which corresponds to Hagen–Poiseuille law.

Sap-flow dynamics and fractions of total flow

Responses of flow at different sapwood depths in root and in stem were different and depend first of all on the magnitude of contribution of a particular root to the total flow in the larger root at the point of sap-flow measurement. We first focused on flow dynamics in this part of the study, in order to clarify the sequences of events, which can assist in understanding the processes. It seems that the total latent injury (that which occurred

underground and was not visible on the surface) was directly caused only to a relatively small part of the root systems. However, if even a small part of the root system is damaged, it is big enough to open tree tissues to fungal infection, which subsequently can cause much larger damage in the following years (Ronnberg 2000).

General evaluation of root damage

Flow rate which lowered on an average by about 8%, compared to the untreated state, does not seems significant. However, flow values decreased to approximately 40%, when we considered the magnitude of root damage as the integrated difference in flow rates between its levels at different sapwood depths before the treatment and that after the stabilization of flow after loading, compared this difference to the flow rate after root severing. Such a level need not necessarily be zero, because of the water supply from deep undamaged root branches, but it was considered as a "relative zero" for a particular treated root (see Eqs. 2, 3). Such a decrease in sap flow occurring in large coarse roots attached to directly damaged roots indicates serious injury to the conducting system.

Sap flow in those parts of the coarse roots situated close to the stems, root buttresses and in the stems themselves responded to treatment by heavy skidders only if (a) a significant part of the coarse roots (with projected area well over 500 cm^2) occurred under the heavy load, and (b) these roots were situated in surface soil layers down to a depth of about 10 cm at the same time. Sap flow did not respond if (c) roots were situated in deeper soil layers then indicated or (d) if only an insignificant part of the roots (characterized by a small projected area—below 200 cm^2) were actually damaged (Fig. 8).

We can understand from the significant part of treated roots, the coarse roots of a certain projected area (approximately amounting over 500 cm^2 of projected area), e.g. a root with a diameter of 2 cm and a total treated length of 250 cm or in similar combinations (see Fig. 8). In reality, this can be represented by several parallel root branches, connected to a larger root or a stem (where the sap-flow sensors was installed). The importance of the diameter is related to the treated fractions of the root systems and the importance of the root length can be interpreted in terms of seriousness of the damage (roots are not cut at one point by loading, but probably less serious lesions caused by high pressure evidently accumulated along the root length until they became substantial). Rather, shallow upper soil layers were evidently sufficient to protect roots against heavy mechanical load. This leads to rather optimistic conclusions for forestry. Deeply rooting species should be resistant against such damage. It seems technically possible to arrange artificial root protection whenever necessary, e.g., using the bed from tree branches on the trails or a special technical mat.
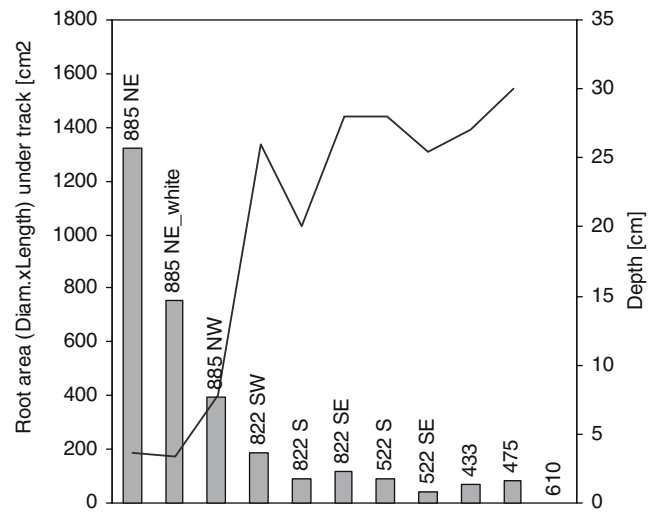
Fig. 8 Loaded area of the measured roots situated under the wheels of heavy machinery and their depth under soil surface

Conclusions

1. The physical parameters of the soil changed significantly during the first movement of logging machines; the changes became more pronounced after further movements. Therefore, it is necessary to minimize tractor movement in forest stands outside of specified lines.
2. The application of low-pressure tires (and also their low-pressurization) in logging machines was found useful, the magnitude and duration of pressure in soils caused by machine movement decreased.
3. The application of spruce slash on places where logging machines are going to move, helps to protect tree roots and root-buttresses, provided the layer is originally at least 40 cm deep and large wooden parts of branches (which may even increase local specific pressure) are excluded.
4. Experiments based on sap-flow responses to any treatment should be performed under high evaporation demands and correspondingly high transpiration/sap-flow rates.
5. Sap flow in coarse roots actually treated by a heavy moving load clearly and immediately responded with a sharp increase followed by a similar decrease (creating peak) after several minutes.
6. When the maximum influence of loading was recorded, the flow rate was lowered on average by about 8% compared to an untreated state after the first treatment, and remained the same after passing the peak during the second. However, the decrease amounted to about 40%, when compared to "relative zero flow" occurring after root severing. This indicates serious local damage to the conducting system.
7. Flow in stem sections oriented in the opposite direction to the trail and also flow in stem sections and root buttresses oriented to the trail, but where roots

were not actually growing below the trail (or occurred there in very limited amount only) or deeper in the soil did not response to the treatment or responded insignificantly.

8. Sap flow only responded in surface roots below trails, occurring down to a depth of about 10 cm below the original soil (litter) surface and this, only when a significant part of the roots (with total projected area of treated root branches more then 500 cm^2) occurred under the tires. This indicates the protective ability of soils and also, possible artificial root-protection mechanisms.

9. Even when loading directly damages rather small fractions of the total root systems, it opens tree tissues to subsequent fungal infection, whose impact could be much more serious in coming years.

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