Original scientific paper

Nutrient Concentration on Skid Trails under Brush-Mats – Is a Redistribution of Nutrients Possible?

Herbert Borchert, Christian Huber, Axel Göttlein, Johann Kremer

Abstract

In mechanized timber harvesting, it is common practice to build brush mats from logging residues on skid trails. Protective effects of brush mats against soil compaction are documented by several studies. On the other hand, a large quantity of nutrients is concentrated on the skid trail. Fully mechanized harvesting has been criticized frequently for this reallocation of nutrients. Is there really a risk of nutrient leaching below skid trails or imbalances? Are the nutrients redistributed through nutrient uptake by roots of adjacent trees? Effects of fully mechanized thinning on soil, water and nutrient balance were examined in a seventy years old spruce stand on a nutrient poor site in Bavaria. Sections of the trails were covered with brush mats, while other sections remained uncovered. For five replications, soil physical properties, soil chemistry, matter and water balances and the density of fine roots were measured in the middle of the trail, under the tire tracks, at the transition of trail and stand and inside the stand over a period of two years. Logging operation caused soil compaction. The macropore volume decreased and both hydraulic conductivity and air permeability were severely reduced. The nutrients were largely kept in the forest ecosystem. Results of the soil moisture monitoring indicate that, within the sections covered by a brush mat, tree roots extracted water from the soil between the tracks. Without cover, the trees scarcely extracted water from this area. Hence, building a brush mat can facilitate water availability and thus enable redistribution of nutrients.

Keywords: soil compaction, brush mat, nutrient balance

1. Introduction

When opening up forest stands with skid trails, traffic of heavy machinery is concentrated on these lanes. Severe changes of the structure and aeration may occur below tracks. In order to reduce such changes, skid trails are often covered with logging residues. Thus the pressure on the soil surface is supposed to be reduced. Many studies have proved the protective effect of brush mats. Schäfer and Sohns (1993) detected a decreasing penetration resistance according to the thickness of a brush mat. Also Becker et al. (1989) found a positive effect of the brush mat on the penetration resistance. Jacke et al. (2008) proved experimentally a wider distribution of the load below a brush mat. Eliasson (2005), Labelle and Jaeger (2012) and Jaeger et al. (2012) determined reduced soil compaction if the track was covered with a brush mat.

However, if slash is displaced from inside the stand to the skid trail, lot of nutrients will also be relocated. The slash comes mainly from the top of the tree, where the nutrient concentration is high. According to Weis and Göttlein (2012), the concentration of many nutrients is e.g. in needles up to twenty times of that in wood. It is not clear to which extent and how quickly tree roots can grow into the compacted area and collect the deposited nutrients. In the case of poor nutrient supply, spruce can have an extensive root system (Schmidt-Vogt 1991). However, on skid trails soil compaction may hamper rooting (Kremer 1998, Gaertig et al. 2001, Eppinger et al. 2002, Schäffer 2005). There is little knowledge on the dynamics of slash decomposition. Due to the high nutrient concentration, the rate of mineralization is higher than that of litter (Lundmark-Thelin and Johansson 1997). An accumulation of slash and deadwood (e.g. after a clear cut or a dieback caused by bark beetles) can cause nitrate leaching, if the nutrient uptake by plants is insufficient (Emmet et al. 1991, Weis et al. 2001, Blumfield and Xu 2003, Huber et al. 2004, Huber 2005, Weis et al. 2006). Also, other nutrients deposited with the brush mat can be leached. Potassium and phosphor in needles and twigs are mineralised quickly (Ouro et al. 2001, Huber et al. 2004, Thiffault et al. 2006, Palviainen et al. 2005). According to a study carried out in Finland, 49% of P and 90% of K were set free from needles, twigs and fine roots three years after a clear cut (Palviainen 2005). Moreover K is very mobile in the soil. So the risk of leaching is high, if there is no plant uptake (Olsson 1999, Huber et al. 2004, Huber 2005). P can cause an eutrophication of lakes and rivers if there is surface runoff (Palviainen et al. 2004). It is not clear how far these processes also apply to brush mats, because the insolation is much less than in the cited case studies. Insolation is a main driver for mineralisation (Huber et al. 2004, Palviainen 2005).

Due to rising energy prices, slash is intensively extracted and then chipped and used for energy purposes. The use as brush mat and processing for wood chips compete with each other. Von Teuffel (2012) claims that, if biomass is deposited on skid trails, nutrients are permanently out of reach of the trees. For this reason, he suggests the use of biomass for energy purposes and the return of the extracted nutrients with treated wood ash.

Practitioners of forestry are not really sure how to deal with the slash. Therefore, the Centre for Forest Nutrition and Water Resources, the Chair of Forest Work Science and Applied Informatics, both Technical University of Munich and the Bavarian State Institute of Forestry conducted a study on the dislocation of biomass and nutrients in harvesting. The focus of the study was: Does nutrient leaching occur after mineralization of slash deposited on skid trails or is a reallocation possible by taking up nutrients by roots of adjacent trees?

2. Materials and methods

A stand about 70 years old in the community of Eslarn in the region of Upper Palatinate was thinned at the end of March 2007. Skid trails were cut by a harvester, equidistant at 30 meters. Thinning was carried out in a combined method of fully mechanized cutting by harvester and felling of trees that were out of crane reach by forest workers. The harvester was a Valmet 901.3 6WD, weight of about 13 t, inflation pressures in front tires between 1.6 and 2.7 bar and in rear 1.6 bar. The timber was logged by a Timberjack 1110 8WD forwarder, bare weight of about 15 t and a load capacity of about 11 t. The inflation pressure in the front tires was between 2.0 and 3.4 and in the rear 2.5 to 4.2 bars. During logging, the soil water content was about 30 Vol.%.

The stand stocks on a brown soil developed from gneiss. The mineral soil of sandy loam or loamy sand is covered by an organic layer of moder and has a skeleton fraction up to 14%. The base saturation between 6–11% indicates a very poor soil. With a mean temperature of 6.5 °C the climate is cool compared to the Bavarian average. The yearly precipitation of 800 mm (1971–2000) is slightly below average. In spite of poor nutrient stocks in the soil, the stand grows vigorously. The diameter in breast height (*dbh*) of the stem of mean basal area was 23.7 cm before thinning, top height 30.7 m, stand density 1162 trees and the growing stock 670 m^3 standing gross volume. 335 trees/ha or 132 m^3/ha were cut during the first thinning. With four replications, skid trail sections were covered with a brush mat and others were kept free of slash.

2.1 Measuring the brush mat

At four sections covered with brush mat, the height profile was measured over a width of 4 m at three spots before the first crossing and after logging again. From each replication in the area of the tire tracks, samples of the brush matt were taken in a square of 1 m^2. The samples structure and weight were determined.

2.2 Soil physical investigations

Four replications of soil samples were taken at three spots in the tracks and in the adjacent stand (reference) immediately after thinning, and two years later again. Core samples were taken in four depths (5–10 cm; 15–20 cm; 25–30 cm; 35–40 cm). Bulk density, pore volume, pore size distribution, air permeability and hydraulic conductivity were measured in the laboratory. In addition, one soil column was taken from a track of each replication, covered with a net, scanned in a computer tomography and replaced precisely at the same place. Two years later, the same samples were taken, scanned again, and the roots which grew into the columns in the meantime were counted.

2.3 Chemical and hydrological investigations

The chemical and hydrological investigations were conducted in each case in the middle of the skid trail, in the tire track, in the transition zone to the adjacent trees and inside the stand. These four locations form a transect. At one section of the skid trails covered with a brush mat and one section without a brush mat, two transects were established. Thus five replications could be analyzed, one more than in case of soil physics.

2.4 Element input from mineralization

Immediately after thinning, samples of needles and twigs were collected and wrapped in bags of nylon. At each of the five replications and four sampling locations litterbags were placed on the ground. During the following two years at different times litterbags were collected, the losses in mass and the nutrient mineralization were determined after HNO_3 pressure digestion.

2.5 Element input from precipitation

At all sampling locations and in the open field, precipitation collectors were established. The samples were collected monthly. The element concentration was determined from composite samples.

2.6 Changes in soil chemistry

Two years after thinning, soil samples were taken from all five replications at all sampling locations. In the laboratory, the pH value, the C and N content, the cation exchange capacity (*CEC*) and the exchangeable cations in a NH_4CL extract were measured separately for the organic layer and the soil depth of 0–10 cm, 10–20 cm and 20–40 cm.

2.7 Nutritional state of the trees

During thinning, from ten trees at each replication, needles aged 1–3 were collected from the 7th whorl. Separate samples from inside the stand and from trees standing adjacent to the skid trail were collected. Three years later, needles were collected again. The element contents of C, N, P, K, Ca, Mg, Al, Fe, Mn, Na, Cu and Zn were determined from composite samples.

2.8 Chemistry of seepage water

At each sampling location, a pore water sampler was installed in a depth of 40 cm. Water samples were collected in intervals of one to two months between May 2007 and the end of 2009. The pH value, HCO_3^-, dissolved organic carbon, total nitrogen, NH_4^+, NO_3^-, $H_2PO_4^-$, SO_4^{2-}, Cl^-, Al, Fe, Mn, Ca, Mg, K und Na of the pore water was determined. The water fluxes were calculated by means of a water balance model. Some meteorological input data were measured directly, some were taken from a forest climate station 25 km away. The element losses were calculated from the substance concentration and the modeled water fluxes.

2.9 Soil water content

At all sampling points, ECH_2O soil moisture sensors were installed detecting the water content in the upper 20 cm of mineral soil hourly.

2.10 Forest growth

Changes of the lightning conditions by thinning, and changes of the water and nutrient supply can affect forest growth. The growth of the stand was investigated on two plots. One plot was established on both sides of a skid trail section covered with a brush mat, the other along a section without a brush mat. On both plots (30×25.5 m and 25×25 m) the *dbh* was measured with a circumference measuring tape before thinning and after each following four growing seasons. All trees were numbered and the coordinates of the stem base recorded.

3. Results of the study

3.1 Brush mat

Fig. 1 shows one brush mat profile, typical for all measured profiles. The uneven distribution of the brush mat is noticeable. The maximum height is in the middle of the skid trail. An even distribution of the slash would have been preferable. Prior to machine traffic, the mean thickness of the brush mat was on average 37 cm in the area of the left track and 24 cm on the right side with variation coefficients of 47% and 64%. After compaction, only 9 cm remained on average on the left side and 8 cm on the right. Thus the mat was compacted to a quarter or a third of its former height.

The weight of the brush mat ranged from 14 to 48 kg/m² with an average of 27 kg/m².

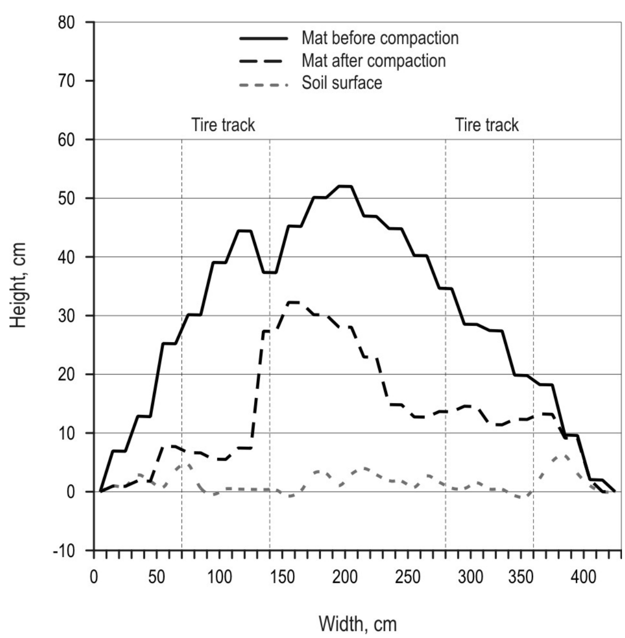

Fig. 1 The profile of a brush mat before compaction by forest machinery and after compaction

Table 1 Comparison of soil parameters between different locations after logging in 2007

Parameter	Depth, cm	Inside stand	Track without brush mat	Track with brush mat
Bulk density, g/cm^3	5–10	1.05 a	1.44 b	1.37 c
	15–20	1.33 a	1.53 b	1.44 b
	25–30	1.3 a	1.51 b	1.39 a
	35–40	1.39	1.51	1.47
Porosity,%	5–10	57% a	40% b	47% c
	15–20	48% a	37% b	46% a
	25–30	49% a	38% b	47% a
	35–40	45% a	38% b	44% a
Large macropores, ≥50 μm	5–10	16% a	4% b	5% b
	15–20	12% a	4% b	7% b
	25–30	15% a	5% b	10% b
	35–40	11% a	8% ab	8% b
Small macopores, 10–<50 μm	5–10	13% a	6% b	6% b
	15–20	10% a	5% b	7% c
	25–30	8% a	6% b	7% b
	35–40	8%	6%	7%
Residual pores, <10 μm	5–10	28% a	30% a	36% b
	15–20	27% a	27% a	32% b
	25–30	25% a	24% a	30% b
	35–40	26% a	23% a	29% b
Air permeability of macropores (k_a), μm^2	5–10	441 a	39 b	110 c
	15–20	224	76	105
	25–30	304 a	137 b	191 ab
	35–40	216	114	109
Hydraulic conductivity (K_{sat}), m/d	5–10	12.4	5.4	0.4
	15–20	4.8	2.8	0.6
	25–30	4.2	1.3	1.1
	35–40	1.5	11.0	0.6

a, b, c – data indicate significant differences between locations at the level of 95% as a result of a *t* test

3.2 Soil physics

In Table 1, the data of the samples collected inside the stand represent the reference. The soil bulk density increased significantly under the track without a brush mat down to a depth of 30 cm and under the brush covered track to a depth of 20 cm. Down to a depth of 10 cm without a brush layer, the increase was significantly higher than with cover. The porosity decreased significantly in the track without brush mat down to the depth of 40 cm. With a brush mat, the porosity decreased only to a depth of 10 cm. In both tracks, the volume of the macropores was reduced to great depth. Here only little differences between both tracks were observed. The volume of the residual pores in the track with a brush mat increased compared to the reference. Apparently, there was a movement of macropores to residual pores. The volume of the residual pores did not shift significantly below the track without a brush mat. The results show that the traffic of forest machinery caused a soil compaction for both tracks covered with a mat and bare ground. Without a brush mat, the degree of compaction was at a higher level.

The air permeability was significantly reduced in the upper soil layer. The reduction was higher in the track without a brush mat compared to the covered track. In greater depth, only the track without a brush mat had significantly lower air permeability. In spite of the reduction, the air permeability is still slow to medium even in the track without a brush mat in the upper soil layer, according to the Bruggenwert (1966) classification.

The data regarding the hydraulic conductivity were not normally distributed. There were many low and few high values. Thus a *t* test was not possible in this case. The Mann-Whitney *U* test was performed instead. This test shows significant differences between the reference and both tracks. In contrast, the samples of both the track with and without a brush mat can belong to the same population. There were significant differences only in the depth of 35–40 cm. Sampling was repeated two years later. Then a K value of 0.7 m/d was measured in the track without a brush mat in the same depth and no significant differences to the track with a brush mat.

The functionality of the soil has been limited to some degree due to compaction.

Two years after compaction, the bulk density did not change significantly neither in the tracks with a brush mat nor the tracks without it. Only in the second depth below the track without a brush mat, the average of 1.61 g/cm^3 was significantly higher. The porosity was significantly higher in the upper soil layer below the track without a brush mat (5%) and below the track with cover (6%) than immediately after logging. Below the track without a brush mat, the porosity rose significantly at a depth of 25–30 cm and 35–40 cm.

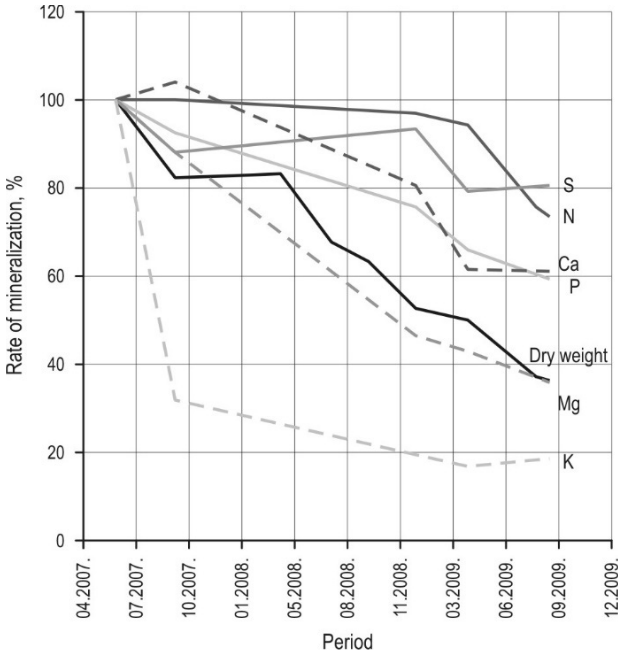

Fig. 2 The rate of mineralization of dry matter and different elements in litterbags filled with needles deposited inside the stand

The air permeability did not change significantly during the two years. The hydraulic conductivity only changed significantly in the depth of 35–40 cm below the track without a brush mat and was then at the same low level as in the track with a brush mat.

3.3 Element input from mineralization

After about two years, 36% of the needles (Fig. 2) and about 60% of the twigs (dry weight) remained in the litterbags. The mineralization of K was remarkably fast in both cases, whereas N decomposed only slightly (needles) or was even accumulated in the twigs.

Sulfur was also mineralized only slightly. The needles delivered phosphor and calcium only slowly, too. The mineralization of Mg was similar to that of dry matter. The needles were mineralized faster inside the stand and at the transition of trail and stand than on the operating trail. Significantly more dry matter remained in the litterbags placed in the middle of the skid trail and on the tracks (95% level). In case of the twigs, only marginal differences in mineralization were observed referring to the location. Remarkable differences occurred in mineralization of N from needles. N has been mineralized inside the stand and at the transition to the trail, whereas N was accumulated in needles placed on the skid trail. These differences were significant as well. The location did not affect the mineralization of K, Ca, Mg and P significantly. Only the litterbags placed in the middle of the trails contained significantly more Ca at the end than those inside the stand.

3.4 Element input from precipitation

Element input from precipitation was larger in the middle of the skid trail compared to the open field (Table 2). Thus it is also affected by the surrounding forest stand. The N input was slightly above the Bavarian average. The sulfur input was comparatively low. The deposition of Mg and K was average, and of Ca very low.

Table 2 Average throughfall deposition in 2007 to 2009

Measuring point	H_2O	N	S	Ca	Mg	K
	mm	kg ha^{-1} y^{-1}				
Open field	932	10.9	3.7	1.8	0.7	3.0
Inside stand	633	20.7	5.6	4.1	1.2	15.2
Edge of skid trail	647	21.0	5.7	4.3	1.4	15.6
Middle of skid trail	765	15.2	4.5	3.2	1.0	10.2

3.5 Changes in soil chemistry

The potassium stocks were highest in all depths in the middle of the skid trail covered with a brush mat (Table 3). In some cases, they were significantly higher compared to the reference, in others compared to the skid trail without a brush mat. This is in good agreement with the high mineralization rates of K in needles and twigs. Also, the Ca and Mg stocks were highest in the organic and upper soil layer on skid trails with a brush mat. However, the differences were only significant in case of Ca in the upper soil layer. The Ca stock was significantly lower at a depth of 20–40 cm below the trail with a brush mat compared to those without a mat. The N stocks were significantly lower in depths of 10–20 and 20–40 cm on skid trails with a brush mat than those without a mat. The N stock inside the stand was significantly lower in a depth 20–40 cm than at the skid trail without a brush mat.

3.6 Nutrition state of trees

At the beginning, the element contents of needles were low in case of N, P, Ca and Mg when compared to other regions of Bavaria (Weis and Göttlein 2012). They were very low in case of Fe and slightly above average for Mn. Three years after thinning, there were hardly any differences between treatments and locations. Three-year needles from trees along skid trails

Table 3 Total C and N pool and the stock of different elements at the cation exchanger in soil samples from inside the stand and in the middle of the skid trail measured three years after thinning

Depth	Location	C	N	K	Ca	Mg	Al	Mn	Fe	CEC
		t ha^{-1}		kmol ha^{-1}						
Organic layer	Inside stand	62.5	2.5	0.9 ab	4.6	1.6	2.7	0.9	1.2	17.4
	Skid trail with mat	72.8	3.0	1.3 a	7.2	2.8	3.9	1.6	1.5	23.7
	Skid trail without mat	58.6	2.3	0.6 b	4.0	1.8	3.2	0.9	1.4	17.1
0–10 cm	Inside stand	30.5	1.7	0.6 a	0.8 a	1.1	27.1	0.6	6.9	43.6
	Skid trail with mat	32.9	1.8	1.2 b	2.2 b	2.0	30.9	0.7	6.1	49.7
	Skid trail without mat	35.2	2.1	0.6 ab	1.4 ab	1.6	30.4	0.9	9.8	52.0
10–20 cm	Inside stand	14.8 ab	1.5 a	0.7 ab	0.8	1.0	22.7	1.3	0.4	32.3
	Skid trail with mat	15.5 a	1.2 b	0.9 a	0.9	1.0	25.1	0.8	0.6	34.5
	Skid trail without mat	11.3 b	1.5 ab	0.5 b	0.9	0.9	21.5	1.3	0.6	30.1
20–40 cm	Inside stand	13.1	2.7 ac	1.4 ab	1.6 ab	1.7	34.4	2.1	0.2	51.6
	Skid trail with mat	13.0	2.0 b	1.9 a	1.5 a	1.9	49.3	2.0	0.3	68.5
	Skid trail without mat	11.3	3.1 c	1.0 b	2.2 b	1.8	37.8	2.2	0.4	54.8

a, b, c – data indicate significant differences between locations at the level of 95% as a result of a *t* test

with a brush mat had significantly lower concentrations of N and Mg compared to trees from inside the stand.

3.7 Chemistry of seepage water

The nitrate concentration of seepage water was very low during the investigation period, both inside the stand and below the skid trails. A very high nitrate concentration was measured only on one of five skid trails covered with a brush mat. In this case, the concentration of Ca Mg and K was high as well. Without this outlier, the concentration of N, Ca, Mg and K did not differ significantly between skid trails with and without a brush mat.

3.8 Element losses with seepage water

The water fluxes increased on skid trails because of reduced interception (Table 4). The soil in Eslarn is not nitrogen saturated. Thus, the nitrogen losses were very low inside the stand. On skid trails with a brush mat the nitrogen losses (mainly nitrate) and the losses of other nutrients were very high in one case. In the other four cases, the nutrient losses were similar to those of skid trails without a brush mat, but slightly higher than inside the stand. These additional losses are marginal referring to the whole stand because the area affected is small. The nutrients transferred to the skid trails remained largely in the ecosystem except for one case.

Table 4 Material flow with the percolating water in a soil depth of 40 cm on average of 2007 to 2009

Measuring point	H_2O	N	Ca	Mg	K
	mm	kg ha^{-1} y^{-1}			
Inside stand	301	0.7	2.5	2.2	4.9
Skid trail with brush mat, without outlier	487	1.4	4.2	5.4	5.8
Skid trail with brush mat, only outlier	487	76.8	9.4	12.5	15.0
Skid trail without brush mat	487	1.4	3.5	4.2	6.8

3.9 Development of soil water content

The curve of the water content of soils on skid trails with a brush mat and inside the stand is conspicuously similar. After rainfall, the water content rises considerably. The maxima do not differ between the treatments, because the porosity in the middle of the skid trails was not affected. After rainfall, the water

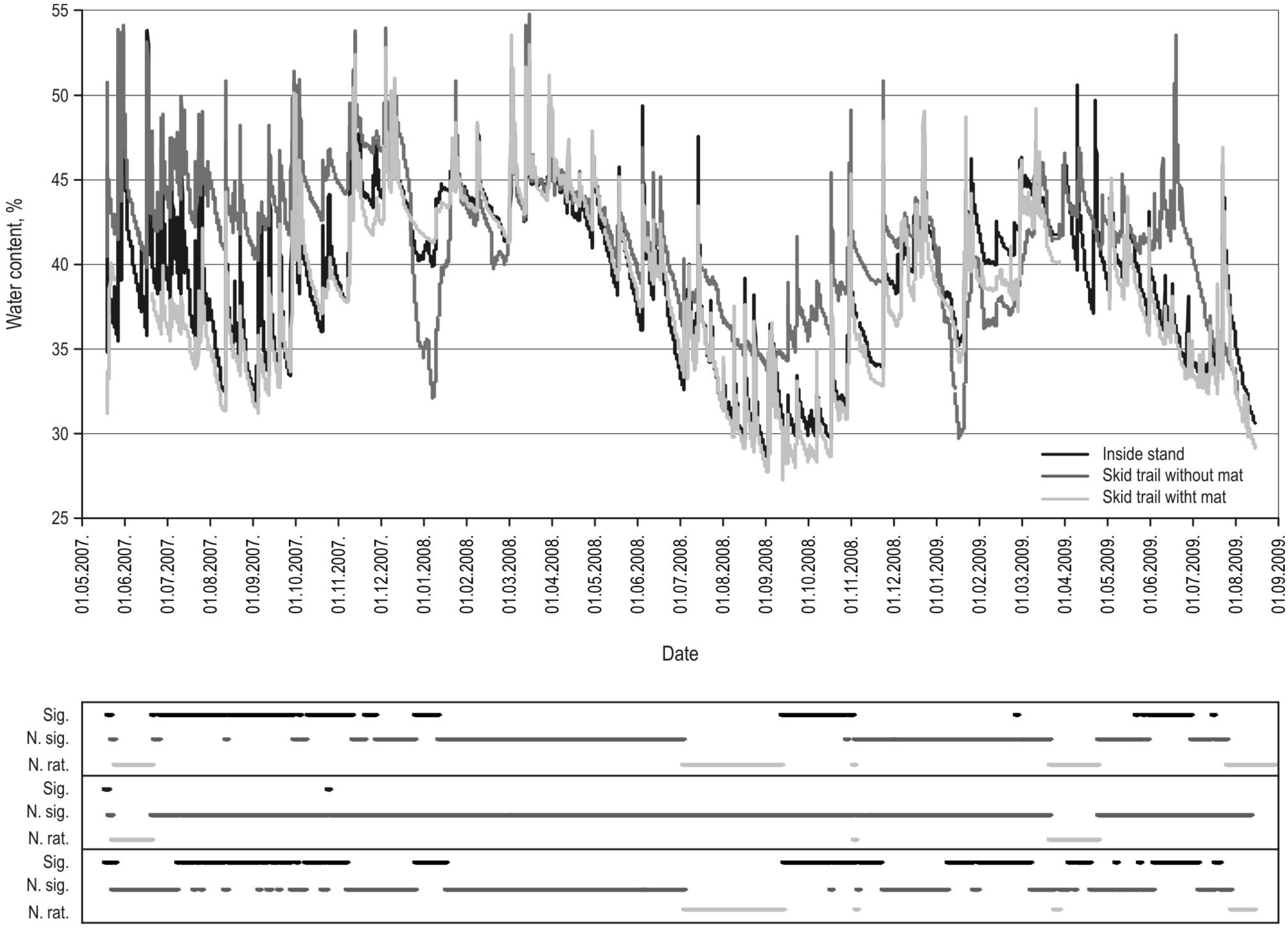

Fig. 3 The development of the volumetric water content inside the stand (reference), in the middle of the skid trail with and without a brush mat

content decreases again rapidly due to the drainage of macropores. Afterwards, the water content decreases further inside the stand and on skid trails covered with a brush mat during the growing season. In contrast, on skid trails without a brush mat, the water content hardly decreases.

The bars below Fig. 3 show periods with significant (Sig.) and with no significant (N. sig.) differences and periods not ratable (N. rat.). The upper bars show differences between both skid trails, the bars in the middle between the skid trail with brush mat and the reference and that below differences between the skid trail without a mat and the reference.

The differences were significant for a long period particularly during the first growing season. In the second year, some instruments failed during summer, thus significance could not be calculated in July and August. Afterwards, the differences were significant till November. In the third year, the time period ended already at the end of July for the skid trails without a mat. During winter, there are periods when the soil is dryer on skid trails without a brush mat. These periods coincide with frost periods. The

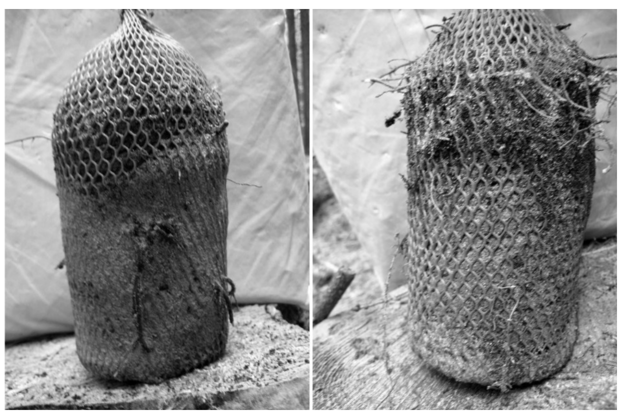

Fig. 4 The rooting of soil columns below tire tracks covered with a brush mat (right) and without a mat (left) two years after passing of forest machinery

soils were frozen on skid trails without a brush mat, and for this reason the instruments recorded wrongly dryer soils.

3.10 Rooting

Two years after logging, five to six times more roots grew in soil columns of tracks covered with a brush mat than in the soil below bare tracks (Fig. 4).

3.11 Forest growth

After thinning, an improved lightning can particularly be expected for trees along new skid trails. All trees with a distance up to 4 m from the middle of the skid trail were defined as edge trees. Neither a *t* test nor a Mann-Whitney *U* test showed significant differences of the average *dbh* between both plots and between edge trees and the other trees before thinning. The Mann-Whitney *U* test was performed because the *dbh* distribution of the stand was not normal. Even four growing seasons later no significant differences of the *dbh* were found between the plots. The mean diameter increment of edge trees of 0.47 cm /year at the plot along the skid trail with a brush mat was significantly higher than that of the other trees (0.31 cm/year). The edge trees on the plot without a brush mat did not differ significantly from the others. It could be possible that the edge trees along the trail with a brush mat had an improved competitive situation after thinning. Then the increased growth could be due to a better lightning. Thus a competition index *C* was calculated for each tree. The index is the sum of the quotient of *dbh* difference and distance of the next three neighbor trees:

$$C_1 = \frac{dbh_1 - dbh_{\mathrm{N1}}}{distance_{\mathrm{N1}}} + \frac{dbh_1 - dbh_{\mathrm{N2}}}{distance_{\mathrm{N2}}} + \frac{dbh_1 - dbh_{\mathrm{N3}}}{distance_{\mathrm{N3}}} \quad (1)$$

Where:

N1, *N2* and *N3* are the next neighbor trees.

No significant differences could be found between the edge trees and the other trees on both plots, neither immediately after thinning nor at the end.

4. Discussion

As the results show, CTL harvesting can cause an accumulation of nutrients in the area of skid trails in case the slash is deposited on the trail. The nutrients are decomposed at different pace. Potassium was mineralized very quickly. This is in accordance with other studies mentioned before. Hence, the potassium content was elevated considerably in soils below skid trails covered with brush. Phosphor was mineralized rather slowly in difference to the results of Palviainen (2005). The nutrient losses by leaching were low except for one case. The high nutrient losses on one skid trail must not have been caused by depositing the slash there. The nutrient reallocated to the skid trails remained mostly within the ecosystem.

The brush mats were rather thick. Almost everywhere they had more than 15 kg/m², and because of that they should have a considerable protective impact according to Jacke et al. (2008). On average they were heavier than 20 kg/m², a weight causing a significant reduction of measurements exceeding the 80% standard Proctor density threshold as Jaeger et al. (2012) observed. However, the soil was compacted below the brush mat. As shown by the bulk density and porosity, the compaction was not as severe as without a brush mat. The functionality of the soil regarding aeration and drainage was reduced but still existed.

The level of water content in Fig. 3 seems to be high compared to porosity (Table 1). After rapid drainage following rainfall, the water content is about 43% during periods of wet soils. The porosity less the large macropores is about 39% in the upper 20 cm. Probably Fig. 3 overvalues the water content up to 10%. However, important are the differences between the curves. The increased moisture in the soil on the skid trail not covered with a brush mat might be partly due to higher infiltration, because there is less interception. However, it can also indicate a hindered water uptake of the tree roots. Although the soil was not deformed seriously, the roots of the trees adjacent to the skid trail without a brush mat apparently were crushed or sheared. At least for three years, the tree roots recolonized only a little the space between the tire tracks. In case of skid trails with a brush mat, the trees could still take water. Thus nutrients from the skid trail could be transferred back inside the stand. As the nutrients mineralize in parts slowly, the relocation will be slow as well. Generally, relocation is possible from the investigated skid trails with a brush mat.

Dietrich (2011) observed a correlation between soil moisture and the height of a brush mat on skid trails as well. He assumed a mulching impact of the slash and therefore expected higher water content below a brush mat. The measurement showed the opposite: The higher the brush mat, the dryer was the soil.

Apparently, the trees adjacent to skid trails without a brush mat could not benefit from the better lightning after thinning. Maybe their growth was limited by nutrient or water supply, because soil compaction below tracks hindered rooting. As forest growth was observed only at one skid trail with and one without a brush mat, the results are valid only for these plots. The observed growth reactions are plausible. We should not expect this reaction each time. Increment differences could be expected only if nutrient or water supply limits tree growth.

A growth surplus of the trees growing along skid trails with a brush mat could explain the lowered N and Mg concentrations in the needles. Here, a dilution may have occurred. An increased growth could also explain the lower nitrogen content in the soil covered with a brush mat. Possibly the nitrogen uptake from the soil increased. Concurrently nitrogen was mineralized very slowly, so that at least temporarily a depletion of nitrogen below skid trails with a brush mat could occur. Furthermore, a depletion of nitrogen could have been caused by a nitrogen blockade. Microbial decomposition of the slash requires finally much nitrogen.

5. Conclusion

Soil deformations by machinery traffic are largely irreparable, at least in the foreseeable future. As the investigation shows, rooting of the soil can already be hindered by soil compaction even if no rutting occurs. Thus the uptake of water and nutrient by trees is hampered. This can have an impact on tree growth, if water or nutrients are in short supply. Particularly on dry and nutrient poor sites, the skid trails should be treated with care so that the soil can serve as a reservoir of water and nutrients. If forest machinery drives off road, the soil can be protected (1) by applying low ground pressure, (2) choosing periods of dry conditions or (3) covering the soil with a brush mat of sufficient thickness. Hence, we suggest continuing to lay a brush mat.

The statement of von Teuffel (2012), according to which the biomass deposited on the skid trail means that nutrients are permanently out of reach of the trees, is not true. If the machinery operates carefully, a relocation of nutrients remains possible.

The situation becomes critical if soil deformation hinders rooting in spite of a brush mat coverage. In this case the accumulated nutrients are scarcely available for the trees. Unfortunately, hampered rooting is not visible by means of the track shape. Methods should be developed for measuring the rooting on skid trails easily. At least returning of the slash from skid trails by machinery should be considered in case of hampered rooting on poor sites.

6. References

Becker, G., Hofmann, R., Roeder, A., Eisenbarth, E., Hanewinkel, M., 1989: Bodenschäden durch Forstmaschinen auf Tonstandorten? – Entstehung, Messung, Begrenzung. Forst und Holz 10: 507–512.

Blumfield, T.J., Xu, Z.H., 2003: Impact of harvest residue on soil mineral dynamics following clearfall harvesting of a hoop pine plantation in subtropical Australia. Forest Ecology and Management 179(1–3): 55–67.

Bruggenwert, M.G.M., Janse, A.R.P., Koenigs, F.F.R., 1966: Algemene Bodemkunde. Handleiding kandidaatspraktikum Landbouwhogeschool, Wageningen, 162 p.

Dietrich, K., 2011: Auswirkungen einer Reisigauflage auf die Bodenfeuchte einer Rückegasse. Masterarbeit an der Fakultät Forst, Geo und Hydrowissenschaften der Technischen Universität Dresden, 82 p.

Eliasson, L., 2005: Effects of forwarder tyre pressure on rut formation and soil compaction. Silva Fennica 39(4): 549–557.

Emmett, B.A., Anderson, J.M., Hornung, M., 1991: The controls on dissolved nitrogen losses following two intensities of harvesting in a Sitka spruce forest (N. Wales). Forest Ecology and Management 41(1–2): 65–80.

Eppinger, M., Schack-Kirchner, H., Hildebrand, E., 2002: Rückegassen als Wurzelraum? AFZ/Der Wald 10: 489–491.

Gaertig, T.H., Schack-Kirchner, H., Hildebrand, E.E., 2001: Steuert Gasdurchlässigkeit im Boden Feinstwurzeldichte und Vitalität der Eiche? AFZ/Der Wald 25: 1344–1347.

Huber, C., Baumgarten, M., Göttlein, A., Rotter, V., 2004: Nitrogen turnover and nitrate leaching after bark beetle attack in Mountainous Spruce Stands of the Bavarian Forest National Park. In: Wieder, R.K., Novak, M. and Vile, A. (Ed.): Biogeochemical Investigations of Terrestrial, Freshwater and Wetland Ecosystems Across the Globe. Water, Air, and Soil Pollution: Focus 4, 391–414.

Huber, C., 2005: Long lasting nitrate leaching after bark beetle attack in the highlands of the Bavarian Forest National Park. Journal of Environmental Quality 34(5): 1772–1779.

Jacke, H., Sengpiel, A., Brokmeier, H., 2008: Zur Druckverteilung unter Reisigmatten. Forst u. Technik 10: 22–27.

Jaeger, D., Labelle, E.R., Poltorak, B.J., 2012: Soil disturbances by off-road traffic of forwarders, magnitude, persistence and mitigation. Proceedings 45th FORMEC conference, October 8–12, Dubrovnik, Croatia.

Kremer, J., 1998: Befahrungsbedingte Strukturveränderungen von Waldböden und ihre Auswirkungen auf das Wachstum von Fichten, Kiefern und Buchen auf ausgewählten Standorten. GCA-Verlag (Forschen und Wissen Forstwirtschaft), Herdecke, 177 p.

Labelle, E.R., Jaeger, D., 2012: Quantifying the use of brush mats in reducing forwarder peak loads and surface contact pressure. Croatian Journal of Forest Engineering 33(2): 249–274.

Lundmark-Thelin, A., Johansson, M.B., 1997: Influence of mechanical site preparation decomposition and nutrient dynamics of Norway spruce (*Picea abies* (L.) Karst.) needle litter and slash needles. Forest Ecology and Management 96(1–2): 101–110.

Olsson, A., 1999: Effects of biomass removal in thinnings and compensatory fertilization on exchangeable base cation pools in acid forest soils. Forest Ecology and Management 122(1): 29–39.

Ouro, G., Perez-Battalon, P., Merino, A., 2001: Effects of silvicultural practices on nutrient status in a *Pinus radiata* plantation: Nutrient export by tree removal and nutrient dynamics in decomposing logging residues. Ann. For. Sci. 58: 411–422.

Palviainen, M., 2005: Logging residues and ground vegetation in nutrient dynamics of a clear-cut boreal forest. Dissertationes Forestales 12. Faculty of Forestry, University of Joensuu, Finland, 38 p.

Palviainen, M., Finér, L., Mannerkoski, H., Piirainen, S., Starr, M., 2005: Changes in the above and below ground biomass and nutrient pools of ground vegetation after clear cutting of a mixed boreal forest. Plant and Soil 275(1–2): 157–167.

Schäfer, T., Sohns, D., 1993: Minderung der Bodenverdichtung durch eine Reisigauflage. AFZ/Der Wald 9: 452–455.

Schäffer, J., 2005: Bodenverformung und Wurzelraum. Teuffel et. al. (Hrsg.) Waldumbau für eine zukunftsorientierte Waldwirtschaft, Springer, 345–361.

Schmidt-Vogt H., 1991: Die Fichte, Band II/3. Paul Parey, Hamburg-Berlin, 781 p.

Thiffault, E., Paré, D., Bélanger, N., Munson, A., Marquis, F., 2006: Harvesting intensity at clear felling in the boreal forest: Impact on soil and foliar nutrient status. Soil Science Society of America Journal 70(2): 691–701.

Von Teuffel, K., 2012: Nachhaltigkeit und Holznutzung. AFZ-Der Wald 4: 8–9.

Weis, W., Huber, C., Göttlein, A., 2001: Regeneration of mature Norway spruce stands. The impact of clear cutting and selective cutting on seepage water quality and soil fertility. In: Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection. The Scientific World Journal 1: 493–499.

Weis, W., Rotter, V., Göttlein, A., 2006: Water and element fluxes during the regeneration of Norway spruce with European beech: Effects of shelterwood cut and clear cut. Forest Ecology and Management 224(3): 304–317.

Weis, W., Göttlein, A., 2012: Nährstoffnachhaltige Biomassenutzung. LWF aktuell 90: 44–47.

Received: April 30, 2014
Accepted: January 14, 2015

Authors' address:

Herbert Borchert, PhD.*
e-mail: Herbert.Borchert@lwf.bayern.de
Bavarian State Institute of Forestry
Hans Carl von Carlowitz Platz 1
GERMANY

Prof. Christian Huber, PhD.
e-mail: christian.huber@hswt.de
University of Applied Science
Am Hofgarten 4
GERMANY

Prof. Axel Göttlein, PhD.
e-mail: goettlein@forst.tu-muenchen.de
Forest Nutrition and Water Resources
Technical University of Munich
Hans Carl von Carlowitz Platz 2
GERMANY

Johann Kremer, PhD.
e-mail: kremer@wzw.tum.de
Forest Work Science and Applied Informatics
Technical University of Munich
Hans Carl von Carlowitz Platz 2
85354 Freising
GERMANY

* Corresponding author