

# Nitrogen mineralization and vegetation along skidding tracks

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**Abstract** – Forest management requires a dense forest road system which combines truck roads and skidding tracks. However, harvesting machines cause damage to forest stands and soils. The aim of this study is to examine the consequences skidding tracks have on net nitrogen mineralization and vegetation composition compared to adjacent forest stands. A beech forest on limestone as well as beech and Norway spruce forests on acidic soils were investigated in south Lower Saxony, Germany. Along the wheel tracks the net nitrogen mineralization is markedly reduced compared to the undisturbed stands. Although nitrogen mineralization is found to be low especially along the wheel tracks, ruderal plants with high nitrogen indicator values have established themselves. Along the skidding tracks, numerous species from fringe and ruderal communities, grasslands and wet sites occur while the stands are dominated by typical forest plant species. Therefore, species diversity is higher along the skidding tracks than in the adjacent stands.

**skidding track / beech forest / spruce forest / species diversity / nitrogen mineralization / indicator values**

**Résumé** – **Minéralisation d’azote et végétation le long de lignes de débardage.** Une gestion forestière durable nécessite un système de desserte forestière dense par des chemins et des lignes de débardage. La circulation d’engins forestiers lourds cause des dégâts parfois importants au sol et aux peuplements forestiers. Une hêtraie calcicole ainsi qu’une hêtraie et une pessière sur des stations acidiclinales ont fait l’objet de la présente étude dont l’objectif est l’appréciation des conséquences de la circulation sur la minéralisation d’azote ainsi que sur la végétation. Par rapport à des peuplements voisins non perturbés, la minéralisation d’azote nette dans les ornières est sensiblement ralentie. Malgré ce fait, de nombreuses espèces des ourlets et des milieux ouverts (“espèces rudérales”), présentant un besoin élevé d’azote, apparaissent le long des lignes de débardage. Les peuplements fermés sont caractérisés par des espèces forestières typiques. Ainsi, on constate une plus grande diversité d’espèces le long des lignes de débardage.

**ligne de débardage / hêtraie / pessière / diversité d’espèces / minéralisation d’azote / valeurs indicatrices selon Ellenberg**

## 1. INTRODUCTION

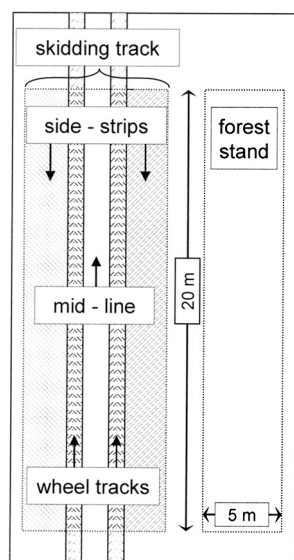
In many situations forest soils are compacted [34, 61] and the ground vegetation is disturbed or even destroyed as a result of travelling and skidding action of harvesting machinery [60, 47]. This is especially obvious along permanent skidding tracks. These are primitive roads without an artificial surface, running through the forests 15–60 m apart from each other [17]. In the last few years logging with harvesters and skidders has increased because it seemed more economic, more comfortable and safer for workers [6, 13, 33]. Most German forests are subdivided by dense forest road and track systems [5, 17, 25], of which the consequences are harvesting damage to stand and soil as well as area loss for timber production [3, 17, 62]. However, ecological aspects of skidding tracks on herb layer vegetation have hardly been considered [11, 12, 30]. Also net nitrogen mineralization which is an important factor in ecosystem functions [19] might be influenced along skidding tracks. Nitrogen mineralization allows the estimation of nitrogen sup-

ply to plants and is an indicator of biological activity in the soil [19, 56]. Therefore the aims of this study are to prove the following hypotheses:

1. Along skidding tracks soil compaction leads to a reduction of net nitrogen mineralization.
2. Plant species richness is higher along skidding tracks than in the undisturbed forest stands nearby.
3. Plant species composition changes along skidding tracks in comparison to the undisturbed adjacent stands.

Soil compaction due to heavy machinery strongly depends on the soil type [7, 36]. In addition, tree species composition influences ecosystem functions, such as nitrogen mineralization, soil characteristics, transmission of light [4, 20, 41] as well as ground vegetation [31, 58, 68]. Hence, harvesting traffic may lead to different effects depending on the tree species composition, nutrition as well as the naturalness of the vegetation [8, 9, 20, 55]. Therefore the investigations took place at two different sites and on three vegetation types. A species

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**Figure 1.** The four experimental plots have been created as illustrated. Skidding tracks consist of side-strips, wheel tracks and mid-line. The undisturbed forest stand is separated from the skidding track by a distance of 5 m.

rich beech (*Fagus sylvatica*) forest on limestone is compared with a species poor beech (*Fagus sylvatica*) forest on acidic sandstone. On the sandstone site, the close-to-nature beech forest is also compared with an artificial Norway spruce (*Picea abies*) forest.

## 2. STUDY AREA AND METHODS

### 2.1. Study area

The research areas are in the Solling uplands and in the Göttingen forest, located in the south of Lower-Saxony, Germany. Both sites are characterised by a subatlantic climate with a moderate altitude between 300–400 m above sea-level. In the Göttingen forest mean annual temperature is about 8.5 °C [64]. The annual rainfall is 680 mm, of this 340 mm falls during the vegetation period (May–September). In the Solling uplands the climate is cooler and moister (mean annual temperature: 7.5 °C, annual rainfall: 900 mm, of which 420 mm falls during the vegetation period) [38, 46]. The shelly limestone in the Göttingen forest weathered to shallow rendzina soils of the carbonate buffer system while the Solling uplands, a sandstone region covered with a loess overlay, are characterised by acid brown earths of the aluminium buffer system. According to amelioration liming, increased pH values are recorded in the Solling beech forest. Three vegetation types of mature stands were selected where logging had taken place one year previous to the start of the investigations. In the Göttingen forest, a beech forest on limestone belonging to the *Hordelymo-Fagetum* [15] was examined while in the Solling uplands the beech forest belongs to the *Luzulo-Fagetum* [28, 65, 67]. Both beech forests correspond to the potential natural vegetation [40, 63]. However, throughout history the woods had been used intensively. In the Solling the beech forests were often replaced by planting of Norway spruce, which is today distributed over a wide area [23, 28, 46, 67]. This third stand type of examination belongs to the semi-natural *Galio harcynici-Culto-Piceetum* [65, 67].

**Table I.** Number of plots ( $n$ ) and average plot size ( $\emptyset$  size [m<sup>2</sup>]) for all transect units: these are forest stand, side-strips, wheel tracks and mid-line. In the Göttingen forest a beech forest on limestone, and in the Solling uplands beech and spruce forests on acidic soils were investigated.

	Stand		Side-strips		Wheel tracks		Mid-line	
	$n$	$\emptyset$ size [m <sup>2</sup> ]	$n$	$\emptyset$ size [m <sup>2</sup> ]	$n$	$\emptyset$ size [m <sup>2</sup> ]	$n$	$\emptyset$ size [m <sup>2</sup> ]
<b>Göttingen,</b>								
beech forest	15	100	15	42.4	12	23.6	12	19.8
<b>Solling,</b>								
beech forest	14	100	26	41.1	9	30.4	9	19.3
spruce forest	9	100	18	36.1	10	33.0	10	28.2

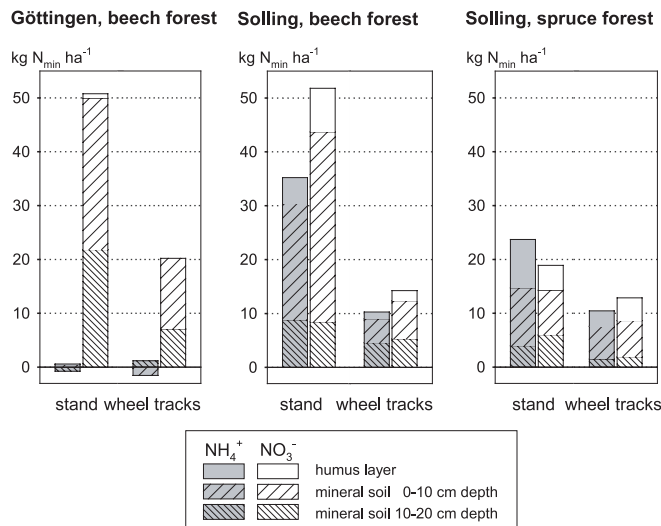
### 2.2. Methods

The nitrogen mineralization, bulk density and the vegetation composition were measured along the skidding tracks in comparison to the nearby undisturbed stands. Data was collected from 20 m long transects parallel to the skidding tracks. The skidding track was divided into three sections of different disturbance intensities (Fig. 1). The wheel tracks with heavily compacted soils are mainly influenced by the harvesting machines. The mid-line is the area between the wheel tracks where the disturbance intensity is lower. The side-strips extend up to the first line of trees, looking very similar to the closed forest as they are barely effected by the machines. As a reference site the undisturbed adjacent stands were recorded. In the stands a constant size of 100 m<sup>2</sup> per plot was chosen, whereas the plot size along the skidding tracks differed depending of their width (Tab. I).

Forest soils are rich in organic nitrogen (up to 9 t N ha<sup>-1</sup>) [47], however, plants assimilate nitrogen only in its inorganic forms, ammonium and nitrate [19]. Therefore net nitrogen mineralization of the soil was investigated along the wheel tracks and the adjacent stands with an incubation method lasting from March to November 2001 (30 weeks) [43, 69]. Soil samples (two samples per plot) were taken with a soil scorer (diameter 8 cm) to avoid soil disturbance [27, 43, 44]. For an incubation period of six weeks these samples were buried at their original place in polyethylene bags to avoid plant assimilation and leaching [22]. In the laboratory the soil monoliths were separated into three layers: the humus layer and the mineral soil at a depth of 0–10 cm and 10–20 cm. The material was sieved through a 4 mm sieve. Ammonium and nitrate were determined by a distillation method described by Gerlach [27] and Mrotzek [44]. The difference between the initial concentration of mineral nitrogen and after incubation indicates the mineralization rate within six weeks [43]. As nitrogen mineralization fluctuates seasonally [43, 66] the summed mineral nitrogen ( $N_{\min}$ ) values [kg  $N_{\min}$  ha<sup>-1</sup> 30 weeks<sup>-1</sup>, up to 20 cm soil depth and ppm  $N_{\min}$  respectively] are presented here.

In order to calculate the values in kg  $N_{\min}$ , the weight of fine soil per unit area [t ha<sup>-1</sup>] has been measured in the humus layer and the mineral soil as well as bulk density, which is an important parameter of soil compaction. Nitrification rate is expressed by the rate of nitrate at the total amount of nitrogen mineralization [10]. Two transects for each of the three stand types were investigated. Hence, an arithmetic mean will be given, but it is not possible to calculate differences between them.

Vegetation relevés were recorded on a larger data basis (Tab. I). All vascular plants and mosses were identified working through tree, shrub, herb and moss layer. Plant cover was estimated in percent. Plot



**Figure 2.** Net mineralization of ammonium and nitrate [ $\text{kg N}_{\text{min}} \text{ha}^{-1}$ ], measured from March to November (30 weeks) in the humus layer and the mineral soil for a depth of 20 cm. The diagrams show the means of two samples from the forest stands and the wheel tracks of the Göttingen beech forest and Solling uplands (beech and spruce forests). For total amounts of nitrogen mineralization see Table II.

size differs between the relevés, but the minimum area for the different vegetation types was used sufficiently [16].

The mean and total number of herb layer species was calculated for the different transect units shown in Table I. The indicator values formed by Ellenberg et al. [21] permit quick estimates of the ecological site conditions for vegetation relevés. The arithmetic mean of indicator values for light, soil reaction and nitrogen were calculated for the herb layer species in the different transect units (Tab. I). The phytosociological behaviour following the grouping introduced by Ellenberg et al. [21] was calculated for all plant species occurring in one transect unit.

### 3. RESULTS

#### 3.1. Nitrogen mineralization and soil compaction

The net nitrogen mineralization is higher in the forest stands than along the wheel tracks which only have a low rate of mineralization (Fig. 2). In many cases the soil in the wheel tracks is compacted compared to the soil which was observed in the undisturbed stands (Tab. II), especially in the upper mineral soil in 0–10 cm depth. The humus rich clay on limestone in the Göttingen forest has a lower bulk density than the sandy soils found in the Solling uplands. In the spruce forest, soil compaction along wheel tracks is rather low, perhaps because of the thick humus layer and the high stone content in 10–20 cm depth (Tab. II) which partly prevent the soil from soil compaction.

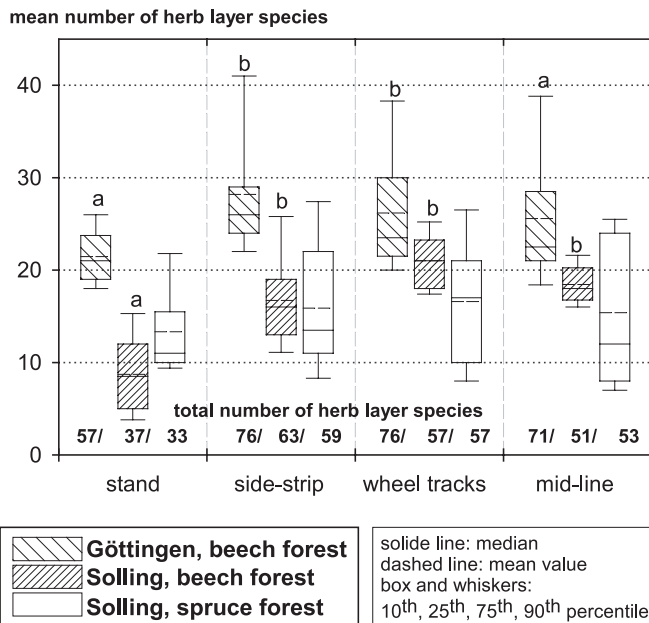
In the Göttingen forest on alkaline soil, the nitrification rate is around 100% (Fig. 2). The nitrogen supply in the stands (*Holdelymo-Fagetum*) is relatively low with  $51 \text{ kg N ha}^{-1}$ , however the wheel tracks have still a markedly smaller mineralization rate (Tab. II). In the forest stand the humus layer on

**Table II.** Data of soil and nitrogen mineralization of the litter layer and the mineral soil in depths of 0–10 cm and 10–20 cm.  $n$  = number of samples, given for the forest stands and the wheel tracks on the three study sites.  $\pm s$  = standard deviation.

	Göttingen, beech forest		Solling, beech forest		Solling, spruce forest	
	stand	wheel tracks	stand	wheel tracks	stand	wheel tracks
$n$	8	10	10	10	10	10
Weight per unit area (fine earth fraction) [ $\text{t ha}^{-1}$ ]						
Litter	4.2	–	33.7	60.6	60.9	60.3
0–10 cm	516.1	624.1	1055.9	1212.5	801.4	734.8
10–20 cm	566.7	486.7	1067.2	1137.8	584.9	698.4
Bulk density (fine earth fraction) [ $\text{g cm}^{-3}$ ]						
Litter	0.09	–	0.14	0.26	0.11	0.15
0–10 cm	0.55	0.67	1.10	1.29	0.90	0.87
10–20 cm	0.61	0.59	1.12	1.19	0.78	0.90
Stone content [%]						
0–10 cm	13.8	23.4	3.9	5.9	11.0	15.0
10–20 cm	8.3	21.7	4.7	4.8	26.6	22.3
Thickness of the humus layer [cm]						
Mean	0.7	–	2.5	2.5	5.7	4.4
$\pm s$	0.6	–	1.0	1.1	1.6	1.8
Nitrogen mineralization [ $\text{ppm N}_{\text{min}} 30 \text{ weeks}^{-1}$ ]; $n = 2$						
Litter	233.4	–	381.8	51.7	223.7	117.5
0–10 cm	55.3	17.7	53.8	9.5	23.7	17.5
10–20 cm	37.2	17.0	16.2	8.7	17.1	5.0
Total	325.9	34.7	451.8	69.9	264.5	140.0
Nitrogen mineralization [ $\text{kg N}_{\text{min}} \text{ha}^{-1} 30 \text{ weeks}^{-1}$ ]; $n = 2$						
Total	50.6	19.9	87.0	24.5	42.6	23.3

the nutrient rich soils is very productive in nitrogen mineralization but thin and is missing along the wheel tracks (Tab. II). As a result the nitrogen mineralization is most effective in biologically very active mineral soil (Fig. 2).

In the beech forest of the Solling site the nitrification rate is near 60%. The nitrogen mineralization in the stand is the highest measured during this study, a total of  $87 \text{ kg N ha}^{-1}$ . The mineralization rates of the humus layer and the upper mineral soil are very high (Tab. II and Fig. 2). They become lower in the mineral soil between 10 and 20 cm depth. In contrast along the wheel tracks the mineralization rate is much lower, a total of just  $25 \text{ kg N ha}^{-1}$  which means only 28% of the nitrogen mineralization [ $\text{kg N}_{\text{min}} \text{ha}^{-1} * 30 \text{ weeks}^{-1}$ ] measured in the stands and 16% of the nitrogen mineralization [ $\text{ppm N}_{\text{min}} 30 \text{ weeks}^{-1}$ ] respectively. This difference in percentage is



**Figure 3.** Mean and total numbers of herb layer species in the stands, side-strips, wheel tracks and mid-lines of the Göttingen beech forest and Solling uplands (beech and spruce forests). Significant differences within one forest type are differentiated by use of small letters. They were calculated with u-Test (Mann-Whitney),  $p > 0.05$ .  $n$  see Table I.

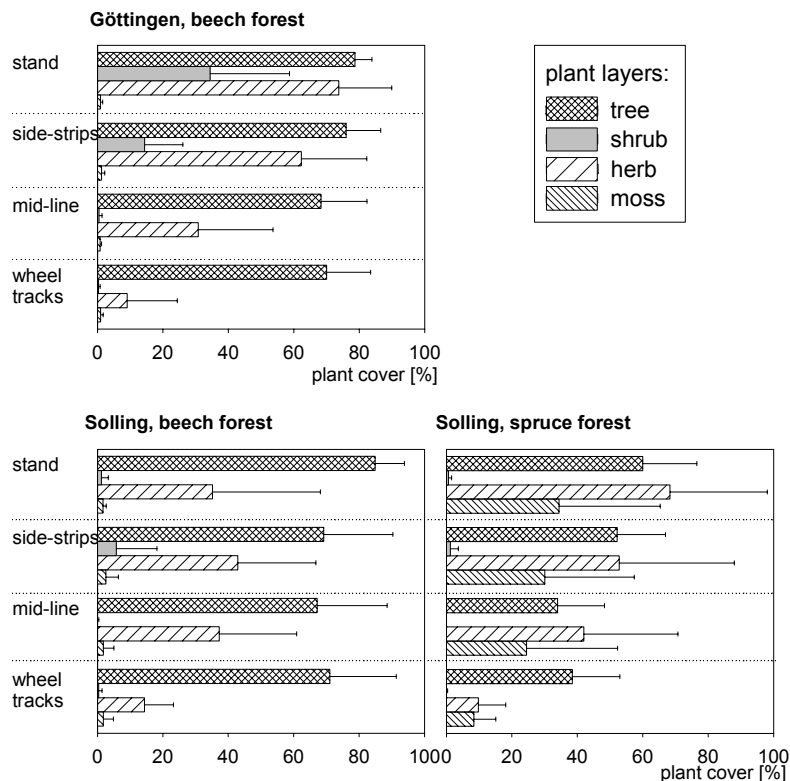
caused by the higher soil bulk density along the wheel tracks which compensate the lower nitrogen mineralization rates [ $\text{ppm N}_{\text{min}} 30 \text{ weeks}^{-1}$ ].

In the spruce forest the difference between the stand and the wheel tracks is not as big as those of the Solling beech forest; the reduction constitutes 54%. More than a quarter of the nitrogen is mineralised in the thick humus layer (Fig. 2 and Tab. II). In the stand only  $48 \text{ kg N ha}^{-1}$  is mineralised of which 44% is nitrate.  $23 \text{ kg N ha}^{-1}$  is found along the wheel tracks, having a nitrification rate of 55%.

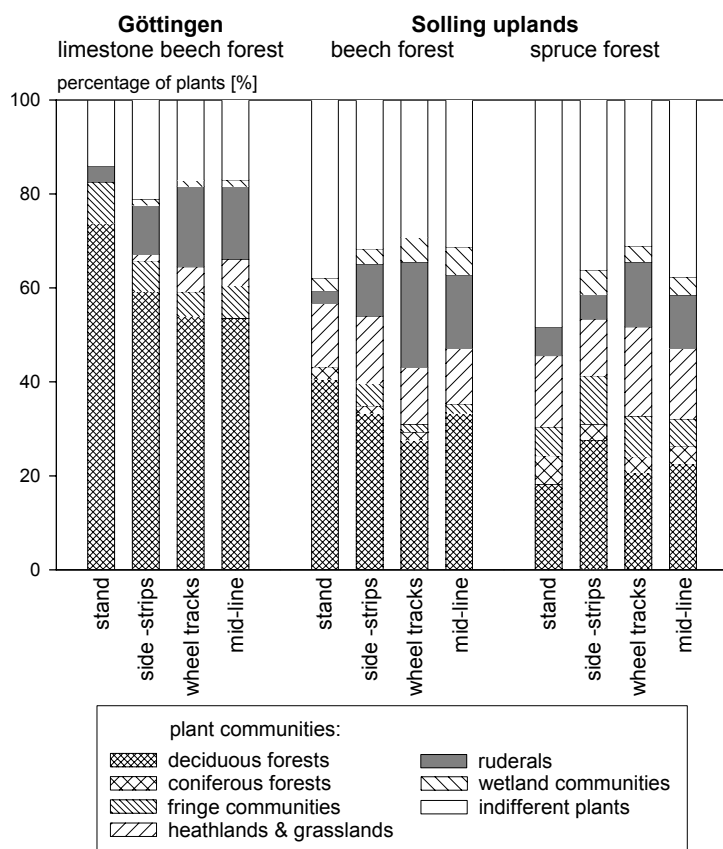
### 3.2. Species diversity, phytosociological behaviour and site ecology

The total number of herb layer species in the different stands of beech and spruce is considerably lower than along the skidding tracks (Fig. 3). The beech forest on limestone has a total of 57 herbaceous species, a higher species richness than that of the beech and spruce forests of the Solling uplands (37 and 33 herbaceous species). In the three different stand types most plant species are found along the side-strips (59–76 herbaceous species) and even in the wheel tracks a large number of species occur. However, the herbaceous plants along the wheel tracks have a markedly lower cover (Fig. 4). Along the mid-line the total numbers of species are a little smaller than in the wheel tracks. Along the mid-line the plant cover in the beech forests is reduced compared with the undisturbed stands. The mean numbers of species (Fig. 3) show significant differences between the species richness in the stands compared with the skidding tracks in the beech forests. In the spruce forest, however, species richness along the skidding tracks only shows a slight increase.

Phytosociological spectra according to Ellenberg et al. [21] (Fig. 5) show that in the stands of the Göttingen forest most



**Figure 4.** Average plant cover [%] with standard deviation of tree, shrub, herb and moss layer in the three forest types, divided into forest stands, side strips, mid-lines and wheel tracks.  $n$  see Table I.



**Figure 5.** Spectra of the plant communities formed by Ellenberg et al. [21]. Shown are the three different stand types. Each spectrum is calculated for all plants occurring in the forest stands, along side-strips, wheel tracks and mid-lines, respectively.

species belong to plant communities of deciduous forests, some originate from fringe communities and very few are ruderals. Along the skidding tracks the percentage of deciduous forest plant species decreases, whereas ruderals as well as plants from grasslands increase, e.g. species like *Alliaria petiolata*, *Geranium robertianum*, *Plantago major* and *Prunella vulgaris*. In the beech forest of the Solling uplands the percentage of forest plant species is a little smaller and even in the stand 14% of the plant species belong to plant communities of the open landscape (*Carex pilulifera*, *Juncus effusus*). Again along the skidding tracks the percentage of ruderals (*Stellaria media*, *Persicaria minor*, *Rumex obtusifolius*) and of wet sites (*Stellaria alsine*) increase.

In the spruce forest stand phytosociological behaviour is more mixed. 31% of the herbaceous species are closely related to the forest communities, numerous plant species like *Galium saxatile* and *Carex pilulifera* are related to heathlands and grasslands, to clear cuttings (*Epilobium angustifolium*, *Digitalis purpurea*) and ruderal communities (*Urtica dioica*, *Mycelis muralis*). Along the side-strips the percentage of deciduous forest species (*Festuca gigantea*, *Impatiens noli-tangere*) and fringe communities increase while wheel tracks and mid-line were characterised by increasing numbers of ruderals. Plant species of wetland communities occur along the skidding tracks only.

Site factors are characterised by Ellenberg's indicator values [21] (Tab. III). The average light values of the herb layer indicate much higher light intensities in the spruce forest than in the beech stands where shade plants are quite frequent. In

general, the tree layer is lower along the skidding tracks than in the adjacent stands independent of the tree species (Fig. 4). In the beech forests this effects a slight increase of light demanding plants and therefore in the mean light indicator values (Tab. III).

**Table III.** Arithmetic mean indicator values [21] for light, soil reaction and nitrogen figures. Given are the three forest types divided into stand, side strips, wheel tracks and mid-line. *n* see Table I.

<b>Göttingen, beech forest</b>			
	Light	Reaction	Nitrogen
Stand	3.5	6.8	6.1
Side-strips	3.8	6.8	6.2
Wheel tracks	4.3	6.7	6.3
Mid-line	3.9	6.8	6.3
<b>Solling, beech forest</b>			
Stand	4.1	3.8	4.9
Side-strips	4.8	4.2	5.2
Wheel tracks	5.0	5.3	6.3
Mid-line	5.0	5.2	6.3
<b>Solling, spruce forest</b>			
Stand	5.2	3.2	4.1
Side-strips	5.2	3.4	4.4
Wheel tracks	5.2	3.8	4.7
Mid-line	5.2	3.7	4.5

As expected, in the beech forest on limestone, indicator plants of weak acid to weak basic conditions dominate. No changes along the skidding tracks are visible. In contrast, the Solling stands are characterised by plant species mainly found on acid soils. Besides, acidity indicators are more common in the spruce stands than in the close-to-nature beech stands. In both Solling sites the mean soil reaction indicator values are higher along the skidding tracks than in the undisturbed forest stands. These results apply also for the mean nitrogen indicator values with increasing figures from the side-strips to the wheel tracks and mid-line area. However, the differences between the three sites are not as clear as those regarding the soil reaction indicator values. In the Göttingen forest, plants often found in places rich in available nitrogen indicate better nutrient supply than in the sites of the Solling uplands where indicator plants of intermediate nitrogen availability dominate.

#### 4. DISCUSSION

Net nitrogen mineralization in beech forests on limestone is assumed to be higher than in beech forests on acid soils [19]. However, Leuschner [41] and Schmidt [56] found that the net nitrogen mineralization in beech forests is not very variable between nutrient poor and nutrient rich forest soils. Sometimes it can be lower in a *Hordelymo-Fagetum lathyretosum* than in a *Luzulo-Fagetum*. The nitrogen mineralization activity [ $\text{ppm N}_{\text{min}} 30 \text{ weeks}^{-1}$ ] in the Göttingen forest was nearly as high as in the Solling beech forest, but the lower bulk density and the shallow soils caused low amounts of net nitrogen mineralization according to the area [ $\text{kg N}_{\text{min}} \text{ ha}^{-1}$ ]. Schnieder [59] also measured a low nitrogen mineralization of  $64 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  in the Göttingen forest while according to Schmidt [56] net nitrogen mineralization of the *Hordelymo-Fagetum lathyretosum* varied between 100 and  $150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and did clearly correlate with the degree of disturbance. In coniferous forests the mineralization is mostly lower than in deciduous forests [2, 39, 65, 66], which is also true in the Solling stands. However, this is not only an effect of the change in vegetation composition [4] but also dependent on the site factors. Moreover, the nitrogen mineralization activity is changing on small scale [65], so generalisations have to be taken with care. The spruce stand was found to be a little lower in pH values and richer in stone content than the beech forest on the Solling site. In long terms, nitrogen cycling of forest communities is well balanced [1, 19]. Therefore net nitrogen mineralization measured in the undisturbed stands can be used as a reference for comparison with skidding tracks.

Along the wheel tracks the net nitrogen mineralization, especially the ppm values, are much lower than in the stands at all three sites. Soil compaction due to travelling of heavy machinery restricts soil aeration [48, 49, 61] so that the activity of mineralization by soil microorganisms is inhibited. On the other hand, Gerlach [27] found on experimentally disturbed soil samples higher rates of nitrogen mineralization than in undisturbed samples, because of better soil aeration. Low mineralization rates can be induced by the disturbance of the humus layer. By harvesting traffic the litter layer is compacted and mixed with the surface mineral soil, or it is even missing in the beech forests. This again may cause lower aeration. In the spruce forest

the inhibition of nitrogen mineralization along wheel tracks is not as distinctive. The forest floor is probably much better protected by branch mats which are often used in coniferous forests as a buffer between harvesters and soil surface. These branches protect the soil against deformation and soil compaction, if the layer is over 25 cm thick [12, 26, 50, 51]. Also the higher stone content may protect against soil deformation. Therefore, the mineral soil under the wheel tracks of the spruce site is not as compacted as the beech sites. This is indicated by a lower bulk density and increasing nitrification rate, whereas poor aeration would inhibit nitrification [19, 35]. The slight increase of soil pH measured in the humus layer and the decrease of plant species mainly found on acid soils support this explanation. At all sites investigated, the nitrogen supply offered to plants has been reduced along the wheel tracks and might become a limiting factor in plant nutrition.

Contrasting to this the mean nitrogen indicator values increase from the forest stands towards the skidding tracks. This might be explained by the better light conditions in the beech forests (see below), as light-demanding species can be nitrogen indicators at the same time [21]. Schaffers and Sykora [52] found that “the N-values appeared to be only weakly correlated with soil parameters including N-mineralization and available mineral N” (p. 225), but were strongly correlated with biomass production. Furthermore, many of the plant species often found in places rich in available nitrogen are mainly ruderals or indicators of disturbance [32, 60]. Apart from this, along the skidding tracks, soil conditions have been so severely changed, that Ellenberg’s indicator values should be viewed with caution [37]. Especially the nitrogen figures of the plant species recorded do not correlate with low net nitrogen mineralization measured in the wheel tracks. Instead they reflect the change in vegetation composition between the undisturbed stands and skidding tracks.

The mean indicator values calculated in the forest stands for light, soil reaction and nitrogen are more reliable. These reveal the different site conditions which also have different plant species richness [14, 20, 41, 55, 58]. Beech forests on limestone have a higher plant diversity than beech forests on acidic soils [14]. Instead of the close-to-nature beech forest, the planted spruce stands of the Solling uplands contain on average more plant species than the *Luzulo-Fagetum*. Increasing species diversity of the spruce stands (*Galio harcynici-Cultopiceetum*) is related to an increase of plant species originating from natural spruce forests, clear cuttings, grasslands and ruderal communities while typical plant species of the *Luzulo-Fagetum* still remain [58, 67].

Along the skidding tracks species richness is higher than in the undisturbed forest stands, although the plot size is smaller (cf. Chap. 2.2). This is effected by numerous species of non-forest communities, similar to the effect of substituting the close-to-nature beech forest by spruce plantation [58, 65, 67]. Some of these species (e.g. *Prunella vulgaris*, *Ranunculus repens*, *Plantago major*) are more resistant to mechanical stress or destruction than many forest plants [20, 60]. Most of the non-forest plant species (e.g. *Juncus spec.*, *Poa annua*, *Prunella vulgaris*) produce a permanent seed bank, are wind-dispersed, but also used forest harvesting machines for dispersal [24, 54]. Some are only able to germinate in bare mineral soil as created along wheel tracks [8, 12, 24]. Some may benefit

from the better light conditions caused by the opening of the beech canopies along the skidding tracks [20, 24, 57, 58]. In spruce stands, however, the thinning of the canopy along skidding tracks seemed to be of small importance. Light intensity in mature spruce stands is already much higher than in closed beech stands [42, 65].

The results are in agreement with other comparative investigations between almost unmanaged and managed forests. In managed forests, harvesting as well as soil disturbance and compaction due to heavy machinery increase species diversity [8, 9, 12, 30, 55]. Schall [53], Glowienka [29] and Mrotzek et al. [45] compared the vegetation along forest roads with the adjacent stands. They found high species numbers along the forest roads, caused by different site conditions and disturbance effects.

Increasing species diversity of herbaceous plants increases the food and habitat resources for many animal species such as insects, e.g. butterflies [18], birds and deer [53]. However, the increase in species diversity is clearly related to a decrease of naturalness. In general, plant species colonising the skidding tracks are not rare, e.g. on lists of endangered species, but they are common in open habitats and rare in unmanaged or virgin forests [55].

Skidding tracks are a result of human interference and cause disturbances within forest ecosystems which influence the properties of soils and therefore indirectly have an impact on the vegetation. Close-to-nature forests like beech forests are one of the most natural vegetation types found in Central Europe [20]. Therefore it can be concluded, to minimise the invasion of non-forest species in these forests and to reduce soil compaction, harvesting traffic should be restricted to a few permanent skidding tracks.

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