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Methods for the assessment of soil deformation in forest stands: interrelationships and ecological relevance

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(With 10 Figures and 7 Tables)

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Bodenverdichtung, Zeigerpflanzen, Boden-CO_2-Konzentration, Bodenverformung, Bodenbelüftung, Rückegassen.

1. INTRODUCTION

Since the middle of the last century, vehicle movement for timber harvesting has continually increased (HAMBERGER, 2003). Vehicle movement strongly affects soil structure. The pore volume and pore continuity are reduced and can lead to various alterations in soil functions (GAERTIG et al., 2000; HERBAUTS et al., 1996; HILDEBRAND, 1983; HORN et al., 2007; KOZLOWSKI, 1999; LEUTZ et al., 1980; LÖFFLER, 1985; SCHACK-KIRCHNER, 1994; ZANDER et al., 1988). In particular, insufficient soil aeration has a harmful effect on soil ecology. Oxygen consumption in a well-aerated soil averages 10–20 l/m²/day during the growing season and is primarily used for root respiration (BRUNOLD et al., 1996). In forests, root respiration alone is thought to consume 25% to 50% of the carbon fixed in a growing season (LAMBERS et al., 1996; QI et al., 1994). Oxygen for root respiration must be acquired from the free atmosphere, and carbon dioxide must be discharged. As aeration is primarily controlled by diffusion (GLIŃSKY and STĘPNIEWSKI, 1985), it depends on the air-filled pore space and pore continuity. Low pore volume or discontinuity of pores lead to restricted gas exchange. The structure of the soil surface is of particular importance because the inter-aggregate pore space is the most important pathway for subsoil aeration. If the soil surface is smeared, compacted or sealed, soil aeration is restricted. The result is anoxia in the soil, which has various detrimental effects on soil ecology. The following attributes may help to identify compacted soils.

1.1 Morphological changes in the soil caused by redox reactions

A marbled appearance, with rust blotches and bleached zones, are characteristic signs of anoxia. Under hypoxic conditions, specialised microorganisms decompose the organic matter in the soil. During these processes, nitrate is denitrified and metal ions, such as Mn(III,IV) or Fe(III), are reduced to Mn(II) and Fe(II). The reduced ions generally exist as soluble metal organic complexes that can be dislocated in the soil. Iron free zones have a bleached aspect, while rust blotches mark the points where the oxidised iron precipitates. The oxidised manganese is visible as black points in the soil (CLEMENS, 2009; GAERTIG et al., 2000; LEUTZ et al., 1980; SCHEFFER and SCHACHTSCHABEL, 1992).

1.2 Accumulation of carbon dioxide in the soil

The concentration of CO_2 in the soil air is 10 to 100 times higher than in the atmosphere. This is caused both by the respiration of microorganism and the roots and by the reduced gas diffusivity of the soil towards the free atmosphere. Several investigations have indicated that soil CO_2 concentration decreases with increasing soil aeration, although soil respiration increases with increasing soil gas diffusivity. Therefore, elevated CO_2 concentrations in the soil atmosphere have been attributed to aeration deficiencies rather than to high respiration rates (GAERTIG, 2001; GAERTIG et al., 2002; QI et al., 1994; SCHACK-KIRCHNER, 1994).

Typical CO_2 concentrations in well-structured top soils range between 0.3% and 0.6%. CO_2 concentrations above 1% in top soils indicate insufficient aeration (GAERTIG et al., 2002; SCHACK-KIRCHNER and HILDEBRAND, 1998). Higher CO_2 concentrations could lead to reduced respiration and functional loss in the rooting space (BURTON et al., 1997; GAERTIG et al., 2002; MCDOWELL et al., 1999; QI et al., 1994).

1.3 Decrease in root growth and tree vitality

Soil compaction leads to a decline in roots and tree vitality. HETSCH et al. (1990) have described a beech decline (*Fagus sylvatica*) on a stagnosol after intensive vehicle movements. HILDEBRAND (1986) has observed degradation in spruce clones (*Picea abies*) with proceeding destruction of the soil structure, and a reduction in beech germination on soils with elevated bulk density (HILDEBRAND, 1983). Compaction hampers and decelerates root growth (GAERTIG et al., 1999; KOROTAEV, 1992; LÖFFLER, 1986) and decreases root density (EPPINGER et al., 2002; SAINJU et al., 1993). Some authors have found a decreasing respiration rate in fine roots with an

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increase in CO_2 concentrations in the rooting space (GAERTIG et al., 2002; MCDOWELL et al., 1999; QI et al., 1994). GAERTIG et al. (2002) have presumed that elevated CO_2 concentrations directly delay root metabolism. MANDL et al. (2006) have found that reduced rooting is related to anoxia and slaty soil structures.

1.4 Shifting in the natural range of plant species

In a forest with a certain climate, ground vegetation typical of the site establishes itself. The vegetation is adapted to site factors, such as soil moisture, nutrient supply, soil aeration, soil reaction and light conditions (ELLENBERG, 1986). Consequently, the competitiveness of species is affected by changes in the site factors due to timber harvesting. SMALL and MCCARTHY (2002) have documented the sensitivity of six herbaceous forest species towards changing soil structure and lighting conditions. GODEFROID and KOEDAM (2004) have observed that forest floor species respond in a specific way to soil compaction. A higher abundance of wetland species and ruderal species has been observed in skidding tracks and haul roads (ALBAN et al., 1994; BUCKLEY et al., 2003; EBRECHT and SCHMIDT, 2005; KLIMO, 1983; LEUTZ et al., 1980). Therefore, we expect that indicator plants for high moisture content, high radiation and basic soil reactions become more abundant in areas with vehicle movement.

Skidding tracks always imply a loss of production area. Because natural regeneration of soils is a process that occurs over decades or centuries (CORNS, 1988; FROEHLICH and MCNABB, 1984; KREMER, 2008, WILPERT and SCHÄFFER, 2006), it is important to reduce the rate of new soil deformation.

Installing the optimal density of forest tracks is a major aim of forest site planning (MLR, 2004; SCHMITZ et al., 2004). Systematic installation of skidding tracks at intervals of 20 or 40 m and a width of 4 m would occupy 20 % and 10 %, respectively, of the productive forest area. If forest management wants to reduce or minimise the extent of disturbed soil structure and protect undisturbed soil, sustainable skidding track management is necessary. Old skidding tracks must be integrated into future harvesting activities. This is often not possible because old tracks cannot be identified in the field by their micro-relief, and the potential of remote sensing tools for identification of former skidding tracks is limited (BACHER-WINTERHALTER and BECKER, 2009). A rapid chemical test used by CLEMENS (2009) to identify anaerobic conditions was only practical for soils with a high organic matter and ferric (II) oxide content.

Tab. 1
Characteristics of the investigation sites.
Merkmale der Untersuchungsstandorte.

Site no.	Site	Stand	Soil type + base material	Water supply	Nutrient supply*	Soil-texture	pH-values of topsoil**	Altitudinal belt	Mean annual temperature [° C]	Mean precipitation [mm/a]	Author
1	Solling	Mature beech	Cambisol of loess over new red sandstone	moderate	3	Silty loam	4.3 0.1 M KCl	submontane	8	1000	Schreiber, 2006
2	Sillium	Mature beech and oak	Stagnosol - Luvisol of Jurassic clay	good	4	Silt/ Clay	4.5 $H_20_{dest.}$	colline	9	650	Arens, 2007
3	Ebergötzen	Mature beech	Cambisol of loess over new red sandstone	good	3	Silty loam	3.6	colline	7.9	666	Dörr, 2007 Koch, 2008
4	Bösinghausen	Medium-aged beech and valuable broadleaved trees	Cambisol of shell limestone	moderate	5	Silty clay loam	4.5	submontane	7.5	709	Dörr, 2007 Becker, 2008
5	Falkenhagen	Mature beech	Luvisol of loess over new red sandstone	good	3	Silty loam	4.5	colline	7.9	669	Dörr, 2007
6	Nikolausberg	Mature beech and valuable broad-leaved trees	Luvisol of loess over shell limestone	good	4	Silty loam	4.2	colline	7.9	549	Dörr, 2007
7	Mackenrode	Mature beech	Vertisol of Röt-clay	good	4	Silty loam	4.1	colline	7.9	669	Dörr, 2007
8	Blankenheim	Mature sessile oak	Cambisol of loess over new red sandstone	good	3	Silt	4.5	submontane	8.6	450-500	Porzucek, 2008
9	Schieringen	Medium-aged beech	Stagnosol-Cambisol of glacial drift and sand	good/ dammed	3	Loam	4.0	planar	8.5	630	Mellin, 2009
10	Siemen	Medium-aged scotch pine	Podzol of glacial sand	good	1-2	Sand	4.0	planar	8	580	Mellin, 2009
11	Röthen	Mature scotch pine	Podzol of outwash plain	moderate	1-2	Sand	4.0	planar	8.5	630	Mellin, 2009

*5 levels: 5 = very good; 3 = moderate; 1 = very low; ** pH values were determined with indicator strips unless otherwise marked.

The aim of the present study is to find valid and practical methods to identify soil aeration deficiencies by consulting different investigations that deal with this topic. The following working hypotheses shall be tested:

1. Indicator plants for compacted soils and well-structured soils can be determined.

2. Old skidding tracks can be identified using a combination of the following parameters: micro-relief, soil deformation, soil CO_2 concentration, fine root density and indicator plants.

2. MATERIALS AND METHODS

2.1 Investigation sites

Seven studies covering eleven sites that represent the typical climate and soil types in Lower Saxony and Saxony-Anhalt, Germany were included in the present survey. The site characteristics are summarised in *table 1*.

In order to identify some principle process relations, data from additional examination sites have been included, e.g. for the relation between soil deformation and gas diffusivity as well as CO_2 concentrations from Heilbronn and Müllheim, Germany (GAERTIG et al., 2000) and for the reproducibility of soil CO_2 measurements from Göttingen, Germany.

2.2 Methods

The primary data for each of the studies surveyed were evaluated statistically to identify soil aeration deficiencies. Field soil science deformation parameters, topsoil CO_2 concentration, root density and vegetation composition have been analysed.

Each investigation took place during the growing seasons between 2005 and 2008. The objectives differed among the studies; therefore, not all parameters were assessed in all studies, and the sample design and number of replications varied. *Table 2* summarises the number of observations and sample designs implemented in each investigation.

In most studies, a 1x1-m grid was established for sample areas between 600 to 1100 m^2. Two authors conducted measurements along one to three transects per investigation site, with lengths of 25 to 50 m.

The traffic situation at each sample point was evaluated using the micro-relief, meaning visible traffic marks. In uncertain cases, estimates were made if the distance between matured trees allowed former passage of vehicles (GAERTIG et al., 2000). The authors used slightly different classes of traffic situations; therefore, the classes were reassigned to four groups (*Tab. 3*).

Tab. 2
Number of observations per investigation site.
Anzahl der Beobachtungen pro Untersuchungsstandort.

Author	Site	Assessment of:					Sample design*
		Traffic situation	Soil deformation	CO_2 conc.	Rooting	Vegetation	
Arens, 2007	2		950			1103	3
Becker, 2008	4	1127	921		920	1127	3
Dörr, 2007	3 - 7	284	227	279		284	1
Koch, 2008	3	675	643		643	675	3
Mellin, 2009	9 - 11	352	348	352		352	2
Porzucek, 2008	8	1066	1052		1052	1066	3
Schreiber, 2006	1	458	301			458	4
Total	1-11	3962	4442	631	2615	5065	

*Sample design:

1: 0.5-m intervals along 1 transect per site crossing skidding tracks and areas without vehicle movement (24.5–41 m length).

2: 1-m intervals along 3 transects per site at a distance of 30–50 m (40 m length).

3: grid of 1x1-m intervals (600–1127 m^2 extent).

4: grid of 2x2-m intervals, or 2x1-m intervals at densely covered sites (1700 m^2 extent).

Tab. 3
Classification of the traffic situation.
Einteilung der Befahrungssituation.

Group	Traffic situation
1	Skidding tracks
2	No traffic, i.e. vehicle movement could be excluded as much as possible
3	Vehicle movement outside of skidding tracks, visible by traffic marks
4	Traffic situation could not be clearly evaluated

To estimate soil deformation, a field classification tool was used that was based on three field soil science parameters: 1) the soil structure, in particular, the percentage of macro-aggregates, 2) the size of iron mottles or coats and 3) the size of bleached areas (*Fig. 1*).

The soil deformation level correlated significantly with top soil gas diffusivity and CO_2 concentration in the soil air (*Fig. 2*). The ecological relevance of the soil deformation level has been proven by a clearly negative correlation between the fine root density and the deformation intensity (GAERTIG et al., 2000).

In natural ecosystems, the gas-chromatographic analysis of CO_2 in soil air is considered to be rapidly assessable, relevant and an integrating indicator of soil aeration (AMPOORTER et al., 2010; GAERTIG et al., 2002; HILDEBRAND and WIEBEL, 1986; SCHACK-KIRCHNER and HILDEBRAND, 1998). Despite the difficulty in standardising values because of diurnal and annual variations in soil respiration, soil CO_2 concentration seems to have a high ecological relevance (GAERTIG et al., 2002; SCHACK-KIRCHNER and HILDEBRAND, 1998).

For CO_2 measurements, 5 ml of soil gas at a depth of 5 cm was aspirated through a probe (outer diameter of 3 mm) and analysed by a mobile gas chromatograph (Mikro GC 4900, Varian Inc.) (cf. GAERTIG et al., 2002). Because soil gas diffusivity is influenced by soil moisture, the data were assessed at least at field capacity so that the soil water might not be limiting for gas exchange.

To test the reproducibility of CO_2 measurements an independent study was conducted at a park in Göttingen, Germany. Top soil CO_2 concentration, soil temperature and moisture (Theta probe ML2X; ecoTech) were measured at the sites of three matured beech trees, which were growing one in a forest nearby the park, one at the lawn of the park and one at a playground in the park. Using a north facing sample grid, five sample points at each direction of the trees were measured twice within an interval of two weeks.

Based on the core-break method (BÖHM, 1979), the number of fine tree roots (root diameter < 2 mm) in the topsoil was counted at the breakage face of the soil samples and related to the breakage area. The fine root density was determined by the number of fine roots per area (dm^2) and classified into five groups (*Tab. 4*).

At each sample point, vegetation was assessed by estimating the coverage of each species in the forest floor vegetation with a frame of 400 to 600 cm^2. The nomen-

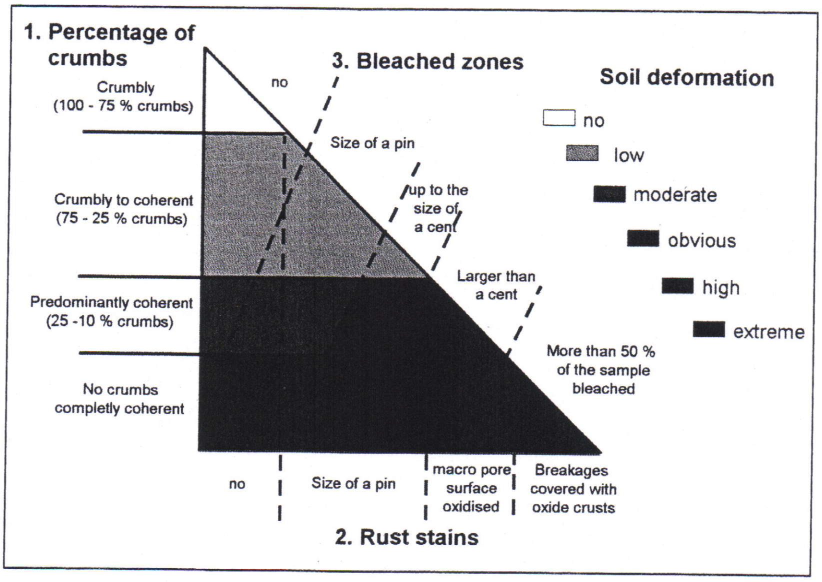


Fig. 1
Triangular key to detect soil deformation with field soil science parameters (GAERTIG et al., 2000).
Dreiecksschlüssel zur Bestimmung der Bodenverformung im Gelände (GAERTIG et al., 2000).

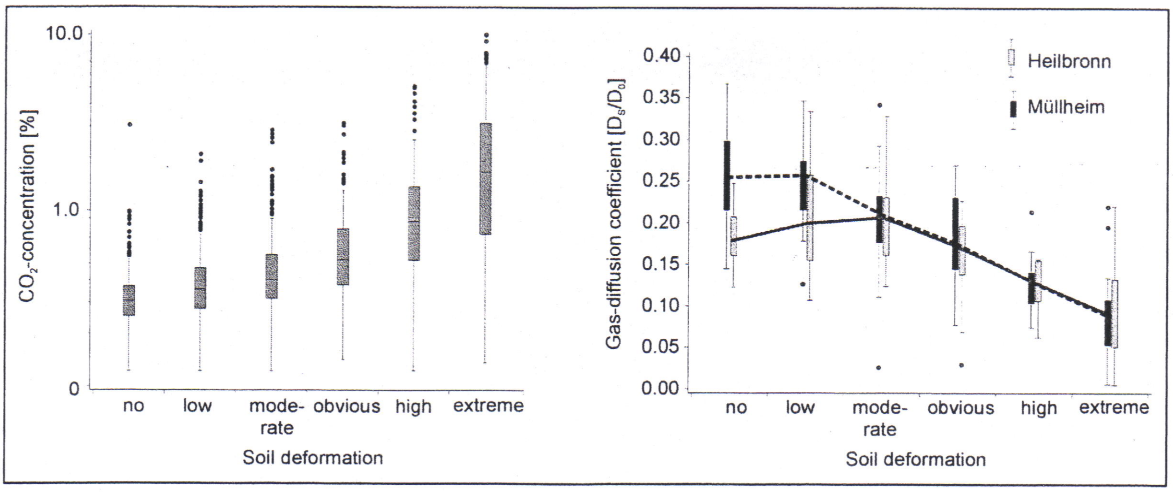


Fig. 2

Relationship between the soil deformation level and CO_2 concentration at 5 cm depth (left) and the gas-diffusion coefficient (right) (GAERTIG et al., 2000). The bottom and top of the box is the 25th and 75th percentile, and the band near the middle of the box is the 50th median. The ends of the whiskers represent 1.5 times the interquartile range from the box, and outliers are represented by points.

Zusammenhang zwischen dem Verformungsschaden und der CO_2-Konzentration der Bodenluft in 5 cm Tiefe (links), bzw. dem relativen scheinbaren Gasdiffusionskoeffizienten (rechts). Die Balken kennzeichnen jeweils das 25. und 75. Perzentil, die horizontale Linie im Balkeninneren den Median. Die vertikalen Verlängerungen der Boxen kennzeichnen die Beobachtungsbreite bis zu dem 1,5-fachen des Interquartilbereiches und die Punkte die Extremwerte außerhalb dieses Bereiches.

clature for the plant species is according to Rothmaler, as edited by JÄGER et al. (2000). Plant responses to soil deformation were analysed both separately for each investigation site and combined for all investigation sites, where the species was observed at least one time.

The data were analysed with the open source software R, version 2.9.2, and Microsoft Office Excel 2003. For nonparametric multiple comparisons with unequal sample sizes the Dunn-test with tied ranks according to ZAR (1999) was applied. The significance is shown for the significance level of $\alpha = 0.05$. The relationship between categorical variables (e.g. soil deformation level, soil texture, traffic situation) was examined by mosaic plots. The area of each cell is proportional to the number of cases in the cell. The dependency of categorical variables was tested with Pearson's chi-square test.

To ensure statistically the identification of indicator plants for soil deformation within the large data pool a cluster analysis of all plant species was conducted with Matlab 7.11.0 (R2010b). Clustering helps to make out new groups of similar observations. How well each object lies within its cluster, was controlled by the silhouette (data not shown). The new groups were analysed on the one hand regarding the relative accumulated plant coverage of each plant within each cluster, on the other hand regarding the relative distribution of the soil deformation levels at the sites of the plants, which were grouped into one cluster. The identification of indicator plants was than possible by an integrated interpretation of both results.

Tab. 4

Classification of root intensity.

Feinwurzelklassen.

Class	Rooting intensity	Number of fine roots/dm²
1	No living roots	0
2	Low	1-5
3	Medium	6-10
4	High	10-21
5	Very high	>21

3. RESULTS

3.1 Field soil science parameters

Marks of former traffic could not be accurately estimated by visible changes in the micro-relief at 47% of the sites (group 4, *Tab. 3*). Using a soil deformation key (GAERTIG et al., 2000), compacted soils that are typically attributed to the movement of heavy machines were readily identifiable. At 24% of the sample points, where the traffic situation could not be estimated by visible changes in the micro-relief, "obvious" to "extreme" soil deformation was assessed. In areas without forest traffic impacts (group 2, *Tab. 3*), more than 65% of the samples had only a low or moderate level of deformation. Alternatively, on skidding tracks 79% of the samples exhibited obvious to extreme soil deformation, whereby the majority of the data account for silty loam sites (*Fig. 3*). Deformation damage was detected for all soils with loamy, silty or clayey textures. At sites with sandy textures, soil deformation could not be detected or was detected at a low level. For these sites, compaction or redox characteristics were not even visible on skidding tracks (investigation sites "Siemen" [site 10] and "Röthen" [site 11]) (*Fig. 3*).

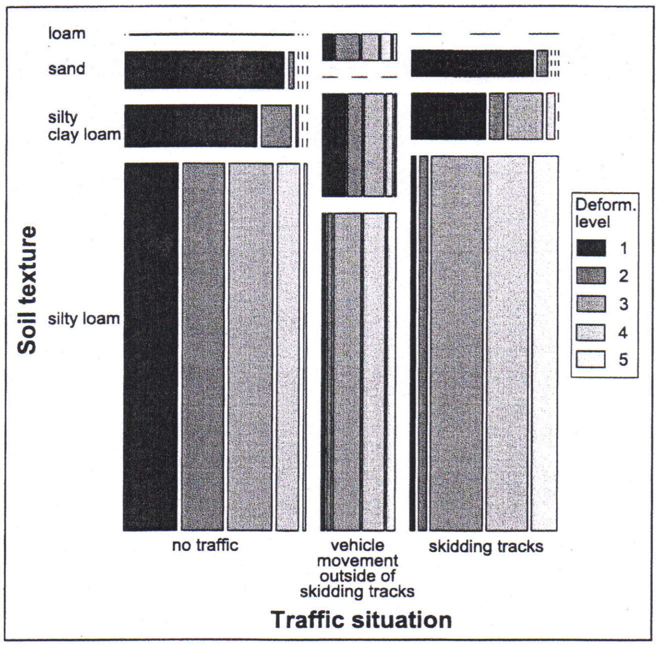


Fig. 3

Mosaic plot representing a three dimensional contingency table of deformation level, traffic situation and soil texture. The area of a piece of the plot correspond to the percentage of each soil deformation level at the investigation sites with different traffic situations and soil texture. Deformation level: 1 = low, 2 = moderate, 3 = obvious, 4 = high, 5 = extreme. Number of observations: 1858. Chi-squared test for given probabilities: p-value < 2.2e-16.

Mosaicplot einer dreidimensionalen Kontingenztabelle von Verformungsschaden, Befahrungssituation und Bodentextur. Die Fläche der Rechtecke entspricht dem Anteil der einzelnen Bodenverformungsstufen auf den Untersuchungsflächen mit unterschiedlicher Befahrungssituation und Bodentextur. Verformungsstufe: 1 = gering, 2 = mäßig, 3 = deutlich, 4 = stark, 5 = extrem. Anzahl der Beobachtungen: 1858. Chi-Quadrattest: p < 2.2e-16.

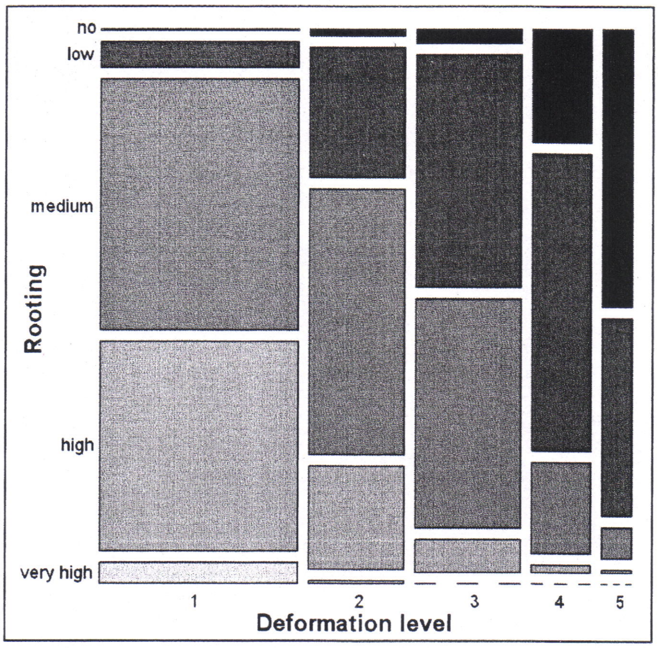


Fig. 4

Fine root density of trees in soils with different deformation levels. The areas of a piece of a plot correspond to the percentage of the different rooting classes at the specific soil deformation levels. Rooting level of fine roots: no = 0 roots/dm², low = 1-5 roots/dm², medium = 6-10 roots/dm², high = 10-21 roots/dm², very high = > 21 roots/dm². Deformation level: 1 = low, 2 = moderate, 3 = obvious, 4 = high, 5 = extreme. Number of observations: 2615. Chi-squared test for given probabilities: p-value < 2.2e-16.

Feinwurzeldichte von Bäumen in Böden mit verschiedenen Verformungsstufen. Die Fläche der Rechtecke entspricht dem Anteil, den die jeweilige Wurzelklasse in einer Verformungsstufe einnimmt. Stufen der Durchwurzelung: no = 0 Wurzeln/dm², low = 1-5 Wurzeln/dm², medium = 6-10 Wurzeln/dm², high = 10-21 Wurzeln/dm², very high = > 21 Wurzeln/dm². Verformungsstufe: 1 = gering, 2 = mäßig, 3 = deutlich, 4 = stark, 5 = extrem. Anzahl der Beobachtungen: 2615. Chi-Quadrattest: p < 2.2e-16.

3.2 Soil deformation level and rooting

Fine root density decreases with increasing soil deformation (*Fig. 4*). No roots, or only a few roots, were found at 81% and 93% of the sample points with high or extreme soil deformation (level 4 and 5), respectively.

3.3 Vegetation as an indicator of aeration deficiencies

Traffic impacts on the fine root distribution and occurrence of plant species were found on all silty and clayey soils. *Figure 5* exemplifies how the spatial distribution of herbal plants in forests varied according to changes in soil structure at the investigation site "Ebergötzen" (site 3). While *Carex remota* was concentrated in areas with high deformation levels (*Fig. 5* left), the distribution area of *Gymnocarpium dryopteris* was nearly transected by the traffic lane (*Fig. 5* right).

There were considerable differences in the percentage distribution of selected species across the different deformation levels (*Fig. 6*). The abundance of *Carex remota*, *Carex sylvatica*, *Deschampsia cespitosa* and *Juncus effusus* increases with rising deformation. *Gymnocarpium dryopteris*, *Melica uniflora*, *Fagus sylvatica* seedlings and *Fraxinus excelsior* seedlings grow primarily on soils with low deformation. However, some species, such as *Oxalis acetosella*, *Lamium galeobdolon*, *Rubus idaeus* and *Impatiens parviflora*, do not show a reliable reaction to compaction. The effect of soil deformation on the most frequent species is listed in the appendix.

Cluster analysis of the entire plant data set resulted in a clear separation of species growing on sandy soils (data not shown). Cluster analyses separated by soil texture showed for silty soils a significant relationship between the clusters and soil deformation level. About 90% of the data points of *Carex sylvatica* accumulated in cluster 2, where mainly plants were clustered growing at sites with a high deformation level. More than 80% of *Oxalis acetosella* were located in cluster 1, where primary plants were grouped growing at sites with a moderate deformation level (*Fig. 7*, *Tab. 5*).

For silty loamy soils, *Carex remota* were allocated to the cluster with a high deformation level, while *Fagus sylvatica* seedlings were allocated to a cluster with a low

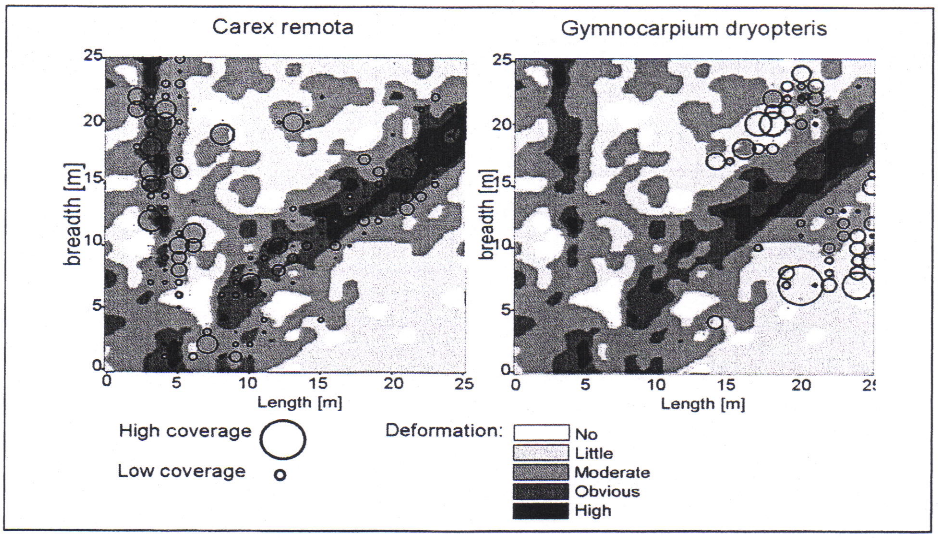


Fig. 5

Soil deformation level and occurrence of *Carex remota* (left) and *Gymnocarpium dryopteris* (right) at the site 'Ebergötzen' (site 3). Bubble diameters correspond to the coverage of observed plants.

Zusammenhang zwischen der Verformungsstufe und der Verbreitung von *Carex remota* (links) und *Gymnocarpium dryopteris* (rechts) auf dem Standort „Ebergötzen" (Standort 3). Der Durchmesser der Kreise entspricht dem Deckungsgrad der beobachteten Pflanzen.

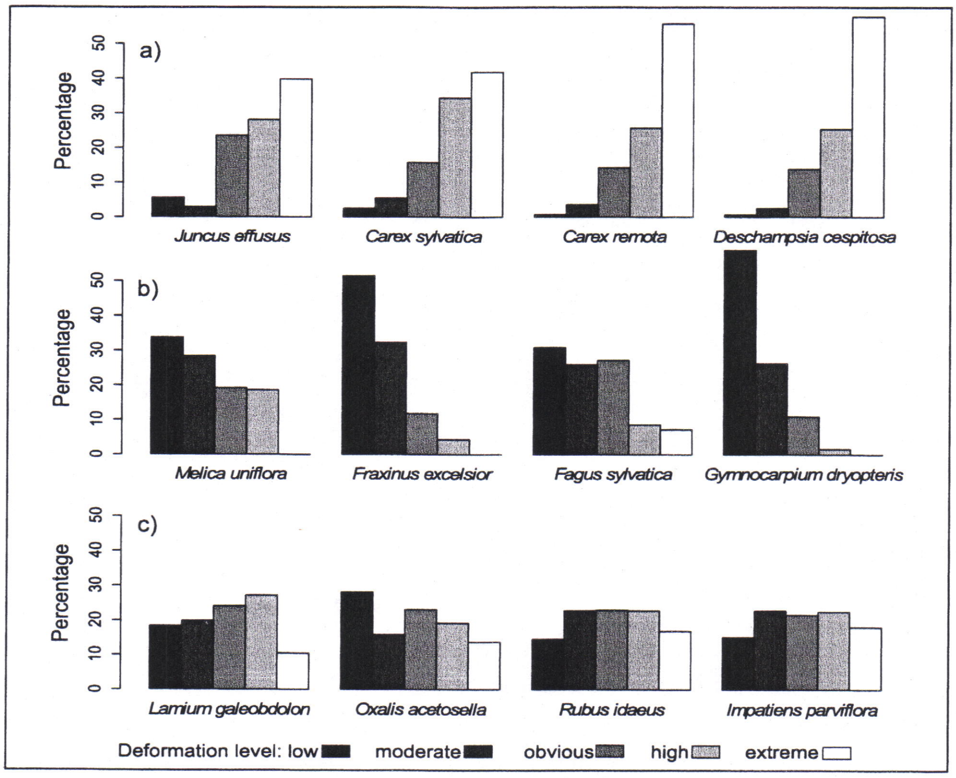
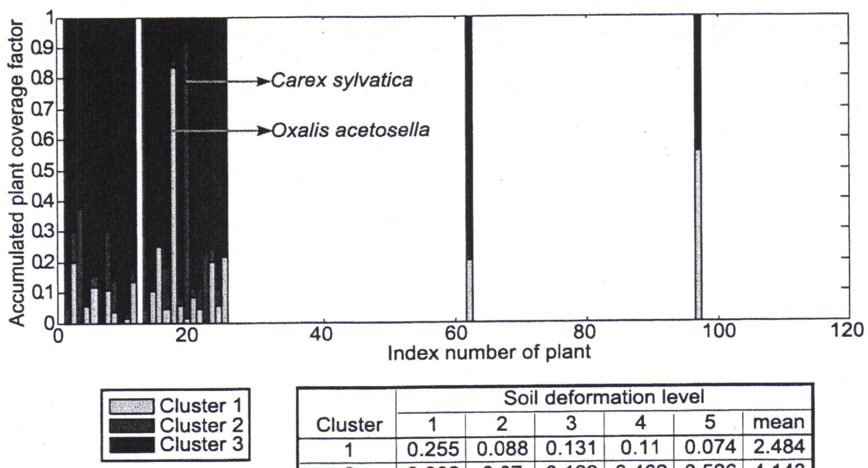


Fig. 6

Percentage distribution of the accumulated coverage of selected species across the different deformation levels. For each plant all the investigation areas are integrated, where the plant was observed at least one time. a) Indicators for compaction, b) indicators for well structured soils, c) species indifferent towards soil deformation. According to Pearson's Chi squared test, distributions of each species depend significantly on deformation level.

Prozentuale Verteilung des akkumulierten Deckungsgrades ausgewählter Pflanzenarten bezogen auf die unterschiedlichen Verformungsstufen. Integriert sind jeweils alle Aufnahmeflächen, auf denen die Pflanze wenigstens einmal vorgefunden wurde. a) Zeigerpflanzen für Verdichtung, b) Zeigerpflanzen für gut strukturierte Böden, c) neutrale Pflanzenarten gegenüber Bodenverformung. Der Pearson's Chi-Quadrattest zeigt einen signifikanten Zusammenhang zwischen dem Vorkommen der Pflanzenarten und der Verformungsstufe.



Cluster	Soil deformation level					
	1	2	3	4	5	mean
1	0.255	0.088	0.131	0.11	0.074	2.484
2	0.002	0.07	0.199	0.462	0.526	4.143
3	0.743	0.842	0.67	0.428	0.4	2.643
Total	1	1	1	1	1	

Fig. 7

Cluster analysis for silty soils. The graphic shows the relative accumulated plant coverage of each plant within each cluster. The contingency table shows the relative distribution of the soil deformation levels at the plant sites across the different clusters and the mean deformation level within each cluster. Number of observations: 950.

Clusteranalyse für schluffige Böden: Die Grafik zeigt den relativen summierten Deckungsgrad jeder Pflanze innerhalb der einzelnen Cluster. Die Kontingenztabelle zeigt die relative Verteilung der Verformungsstufen an den Pflanzenstandorten auf die einzelnen Cluster und den mittleren Verformungsschaden innerhalb der Cluster. Anzahl der Beobachtungen: 950.

Tab. 5

Summary of the cluster analysis. Included were only the most frequent plant species (number of observations >100) with a relative accumulated plant coverage within the cluster of >50% and the cluster had to be separated properly.

Zusammengefasste Ergebnisse der Clusteranalyse. Dargestellt sind die häufigsten Pflanzen (Anzahl an Beobachtungen >100), deren relativer aufsummierter Deckungsgrad innerhalb eines Clusters >50% ist und wo eine gute Separierung des Clusters besteht.

<table>
<tr><th>Soil texture</th><th>Total number of clusters</th><th>Cluster number</th><th>Mean deformation level</th><th>Plant species</th><th>Relative accumulated plant coverage</th><th>Number of observations</th></tr>
<tr><td rowspan="2">Silt</td><td rowspan="2">3</td><td>C1</td><td>2.484</td><td>Oxalis acetosella</td><td>83 %</td><td>870</td></tr>
<tr><td>C2</td><td>4.143</td><td>Carex sylvatica</td><td>90 %</td><td>419</td></tr>
<tr><td rowspan="4">Silty loam</td><td rowspan="4">5</td><td>C1</td><td>2.853</td><td>Rubus idaeus</td><td>75 %</td><td>323</td></tr>
<tr><td>C2</td><td>2.741</td><td>Impatiens parviflora</td><td>73 %</td><td>1562</td></tr>
<tr><td>C3</td><td>1.845</td><td>Fagus sylvatica</td><td>67 %</td><td>435</td></tr>
<tr><td>C4</td><td>4.479</td><td>Carex remota</td><td>72 %</td><td>403</td></tr>
<tr><td rowspan="3">Silty clayey loam</td><td rowspan="3">3</td><td>C1</td><td>2.029</td><td>Impatiens parviflora</td><td>60 %</td><td>1562</td></tr>
<tr><td rowspan="2">C2</td><td rowspan="2">2.361</td><td>Hedera helix</td><td>57 %</td><td>621</td></tr>
<tr><td>Fraxinus excelsior</td><td>55 %</td><td>476</td></tr>
</table>

deformation level. *Rubus idaeus* and *Impatiens parviflora* accumulated in further clusters with middle soil deformation. At sites with soils of silty clayey loam, only clusters with middle soil deformation could be separated. *Impatiens parviflora*, *Fraxinus excelsior* and *Hedera helix* were characteristic species in these clusters. For loamy and sandy soils, there was no significant relation between deformation level and the clusters.

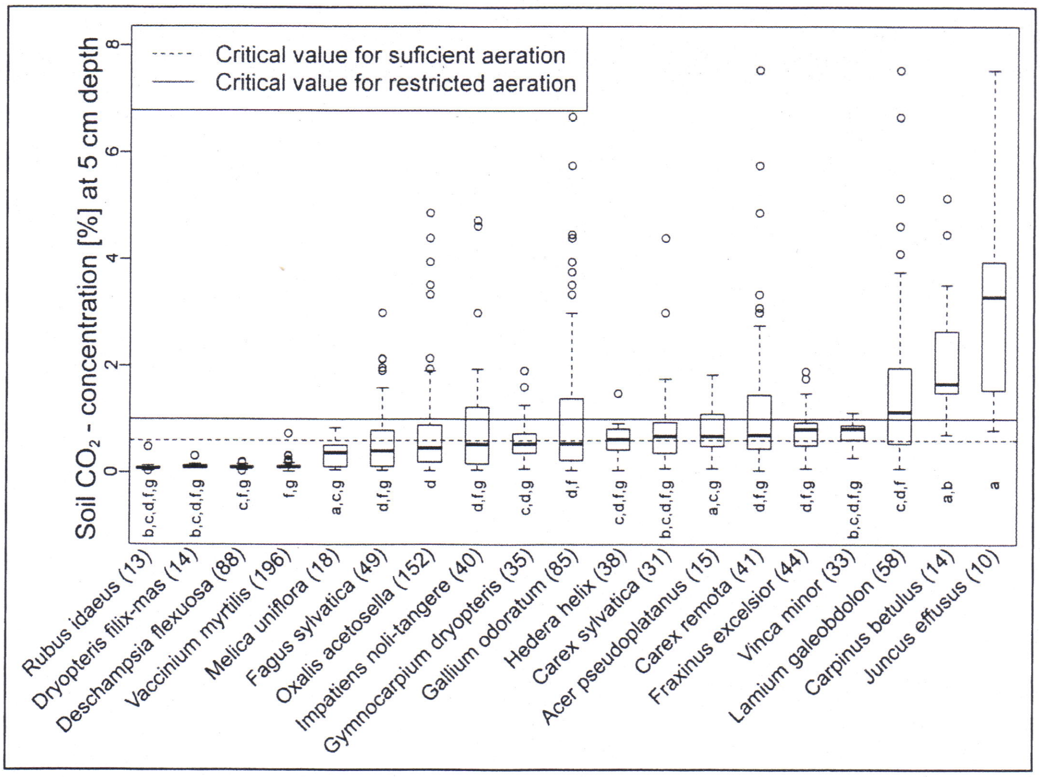


Fig. 8

Top soil CO_2 concentration (5 cm depth) beneath the most frequent species of the forest floor vegetation, where CO_2 concentration was assessed. The number of observations is shown in brackets. The horizontal lines represent the critical values of sufficient aeration for tree roots as found by GAERTIG et al. (2002) and SCHACK-KIRCHNER and HILDEBRAND (1998). Means with the same letters are not significantly different with 95 % probability. The bottom and top of the box is the 25th and 75th percentile, and the band near the middle of the box is the median. The ends of the whiskers represent 1.5 times the interquartile range from the box, and outliers are plotted with a circle.

CO_2-Konzentration in 5 cm Tiefe im Boden der häufigsten Pflanzenarten, wo die CO_2-Konzentration aufgenommen wurde. Die Anzahl der Beobachtungen steht in Klammern hinter den Artnamen. Die horizontalen Linien stellen die kritischen Werte für ausreichende Belüftung der Baumwurzeln da (GAERTIG et al., 2002; SCHACK-KIRCHNER und HILDEBRAND, 1998). Mittelwerte mit den gleichen Buchstaben sind mit einer Wahrscheinlichkeit von 95 % nicht signifikant verschieden. Der untere und obere Teil der Boxen repräsentieren das 25. und 75. Perzentil, die horizontale Linie im Balkeninneren den Median. Die vertikalen Verlängerungen der Boxen kennzeichnen die Beobachtungsbreite bis zu dem 1,5-fachen des Interquartilbereiches. Ausreißer außerhalb dieses Bereiches sind durch Kreise dargestellt.

Figure 8 shows that the CO_2 concentration of top soil at a depth of 5 cm differed between species in the forest floor vegetation. Top soil CO_2 concentrations at *Juncus effusus* and *Carpinus betulus* sites were up to 15 times higher than top soil CO_2 concentrations of the *Rubus idaeus*, *Dryopteris filix-mas*, *Deschampsia flexuosa* and *Vaccinium myrtilis* sites and exceeded the critical threshold of 0.6 % for restricted aeration (GAERTIG et al., 2002). The range of top soil CO_2 concentrations increased with increasing median.

A detailed evaluation of the tolerance towards soil deformation and soil carbon dioxide of the most frequently occurring species is provided in the appendix. The following species were considered indicator plants for well-structured soils: *Dryopteris carthusiana*, *Dryopteris dilatata*, *Euphorbia amygdaloides*, *Fagus sylvatica* seedlings, *Fraxinus excelsior* seedlings, *Geranium robertianum*, *Gymnocarpium dryopteris* and *Melica uniflora*. Indicator plants for compacted soils were the following: *Carex remota*, *Carex sylvatica*, *Deschampsia cespitosa*, *Holcus lanatus*, *Impatiens noli-tangere*, *Juncus effusus* and *Urtica dioica*. *Deschampsia flexuosa* and *Vaccinium myrtillus* were only found on sandy soils, which were generally not compacted. Some species showed different affinity at different sites, such as *Impatiens parviflora*, *Oxalis acetosella* and *Carex sylvatica*. For example, *Carex sylvatica* showed a clear preference for compacted soils at the site „Sillium“ (site 2), while it behaved indifferently towards soil compaction at the „Bösinghausen“ site (site 4) (Appendix).

Figure 9 shows the fine root density of trees beneath the most frequent forest floor species, where fine root density was assessed. The lowest root densities were found in soils where indicator plants for compaction grew, such as *Carex remota*, *Impatiens noli-tangere* and *Urtica dioica*. In contrast, the root density below plant

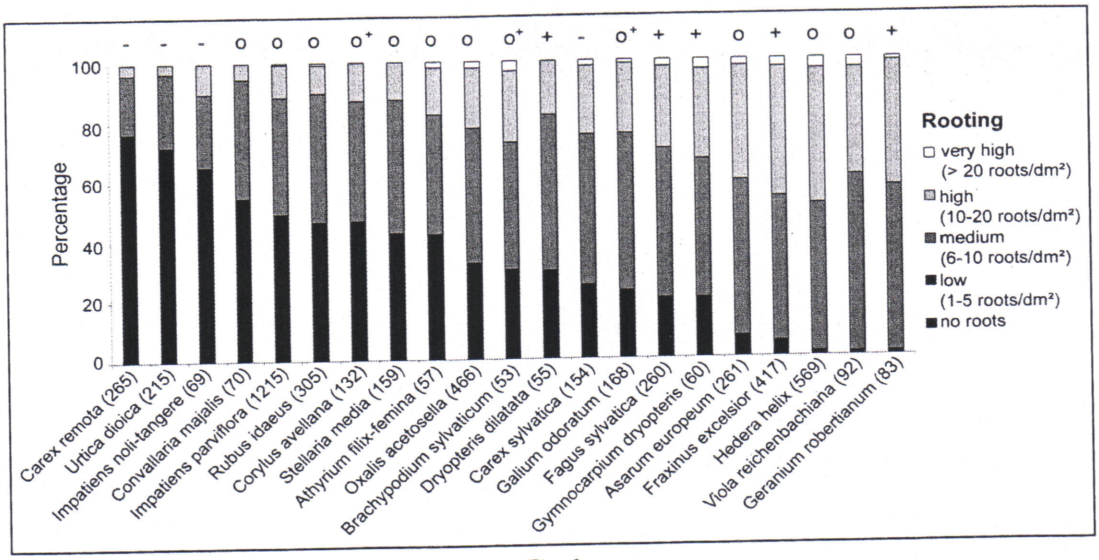


Fig. 9

Relative accumulated number of observations of the rooting classes beneath the most frequent species, where fine root density was assessed. The total number of observations is shown in brackets. [+] = Indicator of well aerated soils; [-] = Indicator for disturbed soils; [o] = indifferent.

Prozentuale akkumulierte Anzahl der Beobachtungen der Durchwurzelungsklassen im Boden der häufigsten Pflanzenarten, wo die Durchwurzelung aufgenommen wurde. Die Anzahl der Beobachtung pro Art steht in Klammern hinter dem Artnamen. [+] = Zeigerpflanze für gut durchlüftete Böden; [-] = Zeigerpflanze für verdichtete Böden; [o] = neutral.

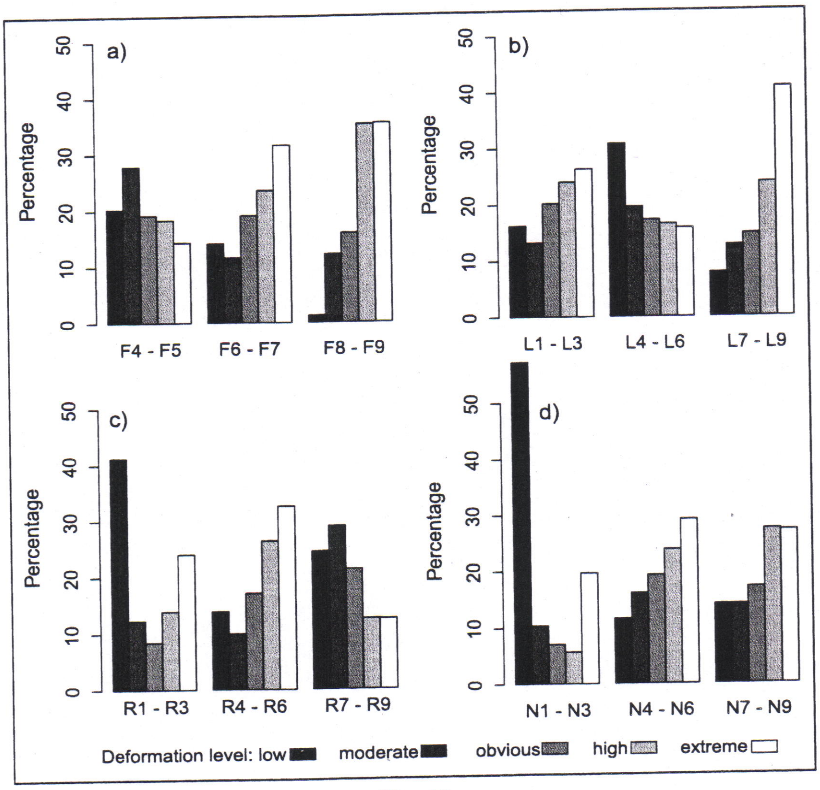


Fig. 10

Percentage distribution of most frequent species grouped by their indicator values according to ELLENBERG et al. (2001), and related to the different deformation levels. a) Indicator values for moisture, b) indicator values for light, c) indicator values for soil reaction, d) indicator values for nitrogen.

Prozentuale Verteilung der häufigsten Arten auf die unterschiedlichen Verformungsstufen. Die Pflanzen sind nach ihren Zeigerwerten nach ELLENBERG et al. (2001) in Gruppen zusammengefasst. a) Feuchtezahl, b) Lichtzahl, c) Reaktionszahl, d) Stickstoffzahl.

species that indicated well-structured soils was considerably higher, such as *Fagus sylvatica* and *Fraxinus excelsior* seedlings, *Geranium robertianum* and *Gymnocarpium dryopteris*.

The competitive behaviour of plants depends on various site factors. Some plant species are more sensitive or tolerant to specific site factors (e.g., soil reactions and light) than others. *Figure 10* shows the relative distribution of the most frequent species grouped by their indicator values and related to the different deformation levels, according to ELLENBERG et al. (2001). Obviously, there is a close relation between soil deformation and the abundance of indicator plants for moisture and radiation. The abundance of wetland species (F6–F9) and light-demanding (L7–L9) species increased with increasing deformation levels. In contrast, soil reaction and nitrogen levels seem to have no influence on the abundance of certain species (*Fig. 10*).

4. DISCUSSION

4.1 Forest floor vegetation as a compaction indicator

It is known that compacted soils or forest tracks are accompanied by specific flora (BARTSCH, 1987; EBRECHT and SCHMIDT, 2005; GODEFROID and KOEDAM, 2004; KLIMO, 1983). The competitive behaviour of plants depends on a combination of different site factors, and changes in site factors lead to a shift in forest floor vegetation. GODEFROID and KOEDAM (2004) have found a mixture of ruderal species, disturbance indicators, nitrogen indicators and plants indicating a basic soil reaction in soils with high compaction. Additionally, neophytes, such as *Impatiens parviflora* and *Impatiens glandulifera*, preferentially settle on forest tracks. EBRECHT and SCHMIDT (2005) found that ruderal species and open land species invade skidding tracks first because they are adapted to periodically recurring disturbances. They profit from the exposure of mineral soil rather than from changes in lighting conditions, soil reactions and nitrogen supply (EBRECHT and SCHMIDT, 2005; SCHMIDT, 2005).

The results of this study show that the forest floor vegetation can indicate the soil aeration status, and, therefore, the quality of the soil as a living space for roots. Wetland species find an ecological niche in compacted soils. A typical site factor for compacted soils is insufficient soil aeration. On badly aerated sites, species that are tolerant to a lack of oxygen supply become competitive. Species that are sensitive to anoxia will disappear; therefore, the observed dominance of species that are adapted to high soil moisture content in their natural distribution, such as *Juncus effusus*, *Deschampsia cespitosa* and *Carex remota* (ELLENBERG et al., 2001), is plausible. Those species are especially adapted to periodic anoxia by a porous transport tissue known as aerenchyma, which permits oxygen uptake from the free atmosphere (VARTAPETIAN and JACKSON, 1997).

The lack of oxygen leads to reductive processes in the soil, such as denitrification or the reduction of trivalent metal ions (GAERTIG et al., 2000; LEUTZ et al., 1980). Most of these reduction reactions consume protons and increase the pH, which should be reflected by the vegetation. However, plant species did not reflect the soil reaction status; therefore, the effect of soil reaction might be hidden by the effect of anaerobia.

Figure 10 shows an increase in light demanding plants with increasing soil deformation. Often, wetland species are exposed to direct radiation at their natural sites (e.g. *Juncus effusus*). Therefore, these species may profit not only from soil changes but also from higher radiation rates on skidding tracks. However, according to SCHMIDT (2005) and EBRECHT and SCHMIDT (2005), disturbance indicators recolonise the soil after clearings only if the soil is disturbed at the same time. Thus, it seems that soil degradation is a more important factor in shifting the vegetation compared to higher light intensity.

In *Tab. 6*, the results of the present study are compared with the results of other authors. Obviously, some species indicate soil compaction for all sites: *Carex remota*, *Deschampsia cespitosa*, *Impatiens noli-tangere* and *Juncus effusus*. In contrary to this study most other investigations focussed mainly on indicator plants for soil compaction, but not on indicator plants for well structured soils. Nevertheless, one indicator for well-structured soils, *Gymnocarpium dryopteris*, was also identified by others. A large number of species behaved neutral towards soil compaction at all sites. But the following species indicate different soil deformation levels under different site conditions: *Carex sylvatica*, *Circaea lutetiana*, *Deschampsia flexuosa*, *Dryopteris carthusiana*, *Dryopteris dilatata*, *Euphorbia amygdaloides*, *Fagus sylvatica* seedlings, *Geranium robertianum*, *Glechoma hederacea*, *Holcus lanatus*, *Impatiens parviflora*, *Melica uniflora*, *Stachys sylvatica*, *Stellaria media* and *Urtica dioica*. Therefore, the suitability of these plants for finding compacted areas in the field should be evaluated by screening the vegetation on the site.

4.2 Identification of soil compaction by soil CO_2 concentration and field soil science parameters

In this study, approximately half of the former wheeling tracks could be detected by visible changes in the micro-relief. By surveying soil deformation with the field deformation key, it was possible to evaluate soil compaction for nearly all sample points with silty or clayey soils. According to the results of GAERTIG et al. (2000), CO_2 concentration increases with increasing soil deformation level. Significantly lower CO_2 concentrations were found in soils with low soil deformation. The highest CO_2 concentrations were reached in finely textured soils, with a high level of soil deformation.

On sandy soils, there is a lack of experience in using the soil deformation key. In this study, very low CO_2 concentrations, which indicate good soil aeration, and low deformation levels were found on all sandy soils, including skidding tracks (GAERTIG et al., 2002). This might be attributed to the high air capacity of sands (Ad-hoc-Arbeitsgruppe Boden, 2005).

Soil compaction leads to ecological damage if fine root growth is hampered. The near complete absence of fine roots in “extremely deformed” soils, and the high fine

Tab. 6

Comparison of the indicator values with the literature.
[+] = Indicator of well aerated soils;
[-] = Indicator of disturbed soils; [o] = indifferent.

Vergleich der Zeigerwerte mit der Literatur.
[+] = Zeigerpflanzen für gut belüftete Böden;
[-] Zeigerpflanzen für Verdichtung; [o] = neutral.

Species	Own results	Ebrecht and Schmidt (2005)	Godefroid and Koedam (2004)	Others
Acer platanoides	o	o		
Acer pseudoplatanus	o	o		
Athyrium filix-femina	o		o	
Brachypodium sylvaticum	o^{+}	o	o	
Carex remota	-	-	-	
Carex sylvatica	o-	o	-	-*
Circaea lutetiana	o		+	
Convallaria majalis	o	o		
Deschampsia cespitosa	-		-	-***
Deschampsia flexuosa	+	o+	o	
Dryopteris carthusiana	+	o	o	
Dryopteris dilatata	+	o	o	
Dryopteris filix-mas	o+		o	
Euphorbia amygdaloides	+	o		
Fagus sylvatica	+	o		
Fraxinus excelsior	o+	o		
Galium odoratum	o	o		
Geranium robertianum	+	-	o	
Glechoma hederacea	o+		-	
Gymnocarpium dryopteris	+	o+		
Hedera helix	o+	o		
Holcus lanatus	-		o	
Hordelymus europaeus	o	o+		
Hypnum cupressiforme	+	o+		
Impatiens noli-tangere	-	-		
Impatiens parviflora	o	-	o	
Juncus effusus	-	o	-	-** -***
Lamium galeobdolon	o-	o	o	
Melica uniflora	+	o	o	
Mercurialis perennis	o+	o		
Oxalis acetosella	o+	o	o+	
Rubus fruticosus agg.	o+		o	
Rubus idaeus	o+	o	o	
Stachys sylvatica	o	-		
Stellaria media	o	-	-	
Urtica dioica	-	-	+	
Vicia sepium	o	o+		
Viola reichenbachiana	o	o		

* BARTSCH, 1987; ** KLIMO, 1983; *** LEUTZ et al., 1980.

root density in "not deformed" soils, may demonstrate the ecological relevance of field soil science parameters (*Fig. 4*). Beside the increasing mechanical impedance with increasing soil compaction, rooting might decline with increasing deformation level because high soil CO_2 concentrations, which are highly correlated with the deformation level, may affect root metabolism (GAERTIG et al., 2002). Although the detrimental effects of high carbon dioxide in soil air on roots are debated in the literature (BOUMA et al., 1997; BURTON and PREGITZER, 2002), there are several indicators that root growth is hampered by increasing soil CO_2 concentration (GAERTIG et al., 2002; MCDOWELL et al., 1999; QI et al., 1994; SMIT and STACHOWIAK, 1988).

Tab. 7

Mean and standard deviation of top soil CO_2 concentration, soil temperature and soil moisture for two measurement days.

Mittelwert und Standardabweichung der Boden-CO_2-Konzentration, Bodentemperatur und Bodenfeuchte an zwei Messtagen.

Investigation Site	Parameter	No. of investigations	First measurement	Replication	Significance
Compacted soil at playground	CO_2-conc.	20	3.28 ± 1.29	3.90 ± 1.52	
	Soil temperature	20	14.05 ± 0.74	16.53 ± 2.42	***
	Soil moisture	20	25.64 ± 10.06	19.50 ± 6.69	
Lawn	CO_2-conc.	20	1.12 ± 0.54	1.36 ± 0.45	
	Soil temperature	20	11.97 ± 0.24	16.57 ± 0.43	***
	Soil moisture	20	33.42 ± 4.53	21.77 ± 3.61	***
Well aerated forest soil	CO_2-conc.	20	0.32 ± 0.13	0.52 ± 0.31	
	Soil temperature	20	12.43 ± 0.19	17.35 ± 0.80	***
	Soil moisture	20	30.24 ± 7.44	20.81 ± 5.94	***

The use of soil CO_2 concentration as an indicator for aeration deficiencies is challenging because of the difficulty of standardisation of values. As integrating variable of soil respiration and gas diffusivity, soil CO_2 concentration depends on soil temperature and moisture (JASSAL et al., 2005). Nevertheless, an independent study has shown that the soil CO_2 concentration at a depth of 5 cm did not differ significantly when temperature increased by 4.6 °C and the concurrent moisture decreased by 11.6 % (investigation site "Lawn") (*Tab. 7*).

The range of CO_2 concentrations increases with increasing median. This indicates that species that prefer well-aerated soils (low top soil CO_2-concentration) are extremely sensitive to aeration deficiencies. Therefore, high CO_2 concentrations provide evidence of aeration deficiencies for some species. Consequently, despite the challenge of value standardisation, soil CO_2 concentration remains ecologically relevant and could be used as a parameter to detect aeration deficiencies if other methods fail.

A disadvantage of soil CO_2 analysis is that it requires analytical equipment and is quite time-consuming when analysing larger areas. Similarly, the assessment of the soil deformation level and identification of wheeling tracks by remote sensing (BACHER-WINTERHALTER and BECKER, 2009) or by rapid chemical testing (CLEMENS, 2009) are time consuming when analysing larger areas. Compared to these methods, the use of indicator plants for soil compaction is an adequate and efficient field method for practitioners to identify former wheeling tracks. The micro-relief, soil deformation, top soil CO_2 concentration and rooting provide additional information. These measurements can be used to support specific sites where the vegetation does not provide clear information.

One question is how these results could be implemented in practice. The protection and conservation of forest soils is a principle component of sustainable forestry. Vehicle movements during timber harvesting strongly influence several soil functions. Because soil regeneration is an extremely long-term process (EBRECHT and SCHMIDT, 2005; FROEHLICH and MCNABB, 1984; SCHACK-KIRCHNER, 1994; WILPERT and SCHÄFER, 2006), irregular vehicle movement leads to an accumulation of compacted soils. If the soil regeneration processes are unknown, then sustainable forestry needs effective skidding track management. This includes minimising the morphological damage caused by vehicle movement, and the attempt to identify former wheeling tracks and "recycle" compacted areas by including them in a new network of skidding trails. Permanent skidding tracks should be the standard in forest management; however, due to developments in forest technology, changing skidding track distances is required. Missing or unfavourable former skidding track nets lead to the creation of new tracks or new skidding track nets. To minimise damage to new areas, former wheeling tracks should be integrated into a new network of skidding tracks. In a field experiment, TRUMPA and GAERTIG (2008) were able to reduce the newly affected area by more than 50 % towards a trail network with a regular 20-m interval. Large soil areas could be protected using this approach.

5. ABSTRACT

Vehicle movement on forest soils affects important site factors. The typical consequences of soil compaction include soil aeration deficiencies, which cause a decrease in soil respiration and fine root growth and the loss of tree vitality; therefore soil protection is an important objective of sustainable forest management. One possibility for minimising the area of compacted soils is to use existing skidding tracks for future harvesting activities. This requires that old skidding tracks can be reliably identified.

The micro-relief, field soil science deformation parameters, top soil CO_2 concentration, root density and forest floor vegetation were investigated at eleven sites in Lower Saxony and Saxony-Anhalt, Germany to determine if the methods were suitable for identifying former skidding tracks or compacted soils.

Soil compaction can be identified by the field soil science deformation parameters and top soil CO_2 concentration. The composition of the forest floor vegetation changes with respect to soil structure. Wetland species

or ruderal species, such as *Carex remota*, *Carex sylvatica*, *Deschampsia cespitosa*, *Holcus lanatus*, *Impatiens noli-tangere*, *Juncus effusus* and *Urtica dioica* serve as indicators of soil compaction if they are found growing outside of their normal distribution area. Species that indicate well-structured soils are the following: *Dryopteris carthusiana*, *Dryopteris dilatata*, *Euphorbia amygdaloides*, *Fagus sylvatica* seedlings, *Fraxinus excelsior* seedlings, *Geranium robertianum*, *Gymnocarpium dryopteris* and *Melica uniflora*.

Using indicator plants of soil compaction is a valid and practicable method to identify compacted soils and old wheeling tracks. The micro-relief, deformation level and CO_2 concentration of soil can provide further evidence of soil compaction.

6. ZUSAMMENFASSUNG

Titel des Beitrages: *Methoden zur Beurteilung von Bodenverformung in Wäldern – Zusammenhänge und ökologische Relevanz.*

Durch die Befahrung von Waldböden ändern sich wichtige Standortseigenschaften. Insbesondere werden Belüftungsstörungen durch eine Verringerung des Luftporenvolumens und der Porenkontinuität verursacht, die zu einem Rückgang der Bodenaktivität, des Wurzelwachstums und der Baumvitalität führen. Bodenschutz muss daher ein zentrales Ziel nachhaltiger Forstwirtschaft sein. In der Praxis ändern sich mit neuen Holzernteverfahren bzw. neuen Befahrungsrichtlinien immer wieder die Anforderungen an die Feinerschließung. Häufig werden neue Rückegassen ohne Rücksicht auf die bestehende Feinerschließung angelegt, so dass es zu einer Akkumulierung von verdichteten Flächen kommt.

Eine Möglichkeit, die Neubefahrungsrate zu minimieren und so bislang ungestörte Waldböden vor einer Verdichtung zu schützen, ist die Integration alter Befahrungslinien in neue Erschließungskonzepte. Voraussetzung dafür ist das Auffinden alter Befahrungslinien.

Um zu prüfen, ob und wie bereits befahrene Flächen identifiziert werden können, wurde auf elf Untersuchungsstandorten in Niedersachsen und Sachsen-Anhalt geprüft (*Tab. 1*), ob strukturgestörte Böden über das Mikrorelief, die feldbodenkundliche Ansprache des Verformungsschadens, die CO_2-Konzentration in 5 cm Tiefe, die Durchwurzelung und die Bodenvegetation im Gelände von ungestörten Böden abgegrenzt werden können (*Tab. 2*).

Die Untersuchungen ergaben, dass anhand des Mikroreliefs nur an annähernd der Hälfte der Untersuchungspunkte die Befahrungssituation sicher angesprochen werden konnte. Durch eine feldbodenkundliche Ansprache des Verformungsschadens konnten besonders auf schluffigen und tonigen Standorten Bodenstrukturstörungen, die auf Befahrungen zurückzuführen sind, identifiziert werden (*Fig. 3*). Auch die etwas aufwendigere Analyse der CO_2-Konzentration in der Bodenluft eignet sich zur Bestimmung von Belüftungsengpässen, auch wenn Tages- und Jahresschwankungen berücksichtigt werden müssen (*Fig. 2*, *Tab. 7*).

Über den Vergleich von Bodenverformung, CO_2-Konzentration und Bodenvegetation konnte nachgewiesen werden, dass es auf strukturgestörten Waldböden zu einer Veränderung der Pflanzenartenzusammensetzung kommt: Auf strukturgestörte Bereiche weisen Nässe-/Feuchtezeiger und Ruderalarten wie *Carex remota*, *Carex sylvatica*, *Deschampsia cespitosa*, *Holcus lanatus*, *Impatiens noli-tangere*, *Juncus effusus* und *Urtica dioica* hin, wenn sie außerhalb ihres üblichen Vorkommensgebietes auftreten. Als Indikatorpflanzen für ungestörte Bereiche konnten hingegen folgende Arten identifiziert werden: *Dryopteris carthusiana*, *Dryopteris dilatata*, *Euphorbia amygdaloides*, Naturverjüngung von *Fagus sylvatica* und *Fraxinus excelsior*, *Geranium robertianum*, *Gymnocarpium dryopteris* und *Melica uniflora* (*Fig. 6*, *8*, *9* und *10*; *Tab. 5*, *6* und *9*; *Appendix*).

Mit der kombinierten Ansprache von Bodenvegetation, Mikrorelief und feldbodenkundlichen Verformungsschaden können alte Befahrungen schnell und sicher identifiziert werden. Die ebenfalls geeignete Methode der Bestimmung der CO_2-Konzentration der Bodenluft dürfte aufgrund des erforderlichen Equipments nur in Einzelfällen zur Anwendung kommen.

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9. APPENDIX

Evaluation of the most frequent species regarding their tolerance towards soil deformation (Def) and soil carbon dioxide (CO_2) and number of surveys. [+] = Indicator for well aerated soils; [-] = Indicator for disturbed soils; [o] = indifferent; Indicator values (ELLENBERG et al., 2001): L = radiation, F = moisture, R = soil reaction, N = nitrogen.

Toleranz der häufigsten Arten in Bezug auf Bodenverformung (Def) und erhöhte CO_2-Konzentration (CO_2) und Anzahl der Beobachtungen. [+] = Zeigerpflanzen für gut belüftete Böden; [-] = Zeigerpflanzen für Verdichtung; [o] = neutral; Zeigerwerte (ELLENBERG et al., 2001): L = Licht, F = Feuchte, R = Reaktion, N = Stickstoff.

	Indicator values				Siemen		Röthen		Falken-hagen		Schie-ringen		Eber-götzen		Bösing-hausen		Macken-rode		Nico-laus-berg	Blan ken-heim	Sil-lium	Total	
Species	L	F	R	N	Def	CO_2	Def	CO_2	Def	CO_2	Def	CO_2	Def	CO_2	Def	CO_2	Def	CO_2	CO_2	Def	Def	Def	CO_2
Acer platanoides	4	x	x	x											o 17							**o 17**	
Acer pseudoplatanus	4	6	x	7											o 172	o 15				+ 8		**o 180**	**o 15**
Asarum europeum	3	5	7	6											o 257					o 11		**o 268**	
Athyrium filix femina	3	7	x	6					- 6	+ 6	+ 2	+ 2	o 59							o 1	+ 4	**o 72**	**+ 8**
Avenella flexuosa	6	x	2	3																o^- 16		**o^- 16**	
Brachypodium sylvaticum	3	5	6	6									o 25		+ 38							**o^+ 63**	
Carex remota	3	8	x	x					- 7	- 6	o 20	o 20	- 158	o^- 5	o 10		- 9	- 10		- 107	- 92	**- 403**	**o^- 41**
Carex sylvatica	2	5	6	5					- 7	o 8			- 59	+ 3	o^- 123	o 3				o 1	- 229	**- 419**	**o 14**
Circaea lutetiana	4	6	7	7									o^- 5		o 36	- 6	o 6				o 16	**o 63**	**- 6**
Carpinus betulus	4	x	x	x													o 14	- 14			o 16	**o 30**	**- 14**
Convallaria majalis	5	4	x	4																o 75		**o 75**	
Corylus avellana	6	x	x	x																o^- 135		**o^+ 135**	
Deschampsia cespitosa	6	7	x	3											- 7				o^+ 8	- 27		**- 42**	**o^+ 8**
Deschampsia flexuosa	x	x	x	x	+ 48	+ 48	+ 41	+ 41														**+ 89**	**+ 89**
Dryopteris carthusiana	5	x	4	3					o 1				+ 5	o 5	o 1						+ 29	**+ 36**	**o 5**
Dryopteris dilatata	4	6	x	7					o 1				+ 61		o 2						o 9	**+ 73**	
Dryopteris filix-mas	3	5	5	6			+ 14	+ 14													- 13	**o 27**	**+ 14**
Euphorbia amygdaloides	4	5	8	5											+ 20							**+ 20**	
Fagus sylvatica	3	5	x	x					+ 18	+ 18	+ 4	+ 4	+ 167	+ 10	o^+ 69	o 8	+ 6	- 6	+ 4	o 45	+ 122	**+ 435**	**o^+ 50**
Festuca altissima	3	5	4	6																- 50	+ 11	**o^- 61**	
Fragaria vesca	7	5	x	6											o 33		+ 2					**o 35**	
Fraxinus excelsior	4	x	7	7									+ 1		+ 453	o 40	+ 1	- 1	+ 3	o 18		**+ 476**	**o 44**
Galium odoratum	2	5	6	5					o 23	+ 24	+ 32	+ 32	o^+ 86		o 96	- 10	o 17	- 17	+ 2		o 15	**o^+ 271**	**o 85**
Geranium robertianum	5	x	x	7									- 1		+ 88							**+ 89**	
Glechoma hederacea	6	6	x	7																	o^+ 178	**o^+ 178**	
Gymnocarpium dryopteris	3	6	4	5					o^- 6	o 6			+ 89	+ 29							+ 35	**+ 130**	**o^+ 35**
Hedera helix	4	5	x	x											o^- 587	o 4	+ 1	o 1	+ 33			**o^+ 621**	**+ 38**
Holcus lanatus	7	6	x	5																- 39		**- 39**	
Hordelymus europaeus	4	5	7	6									o^+ 6		o 38	o 4	o 1				o^- 3	**o 48**	**o 4**
Impatiens noli-tangere	4	7	7	6					o^- 26	+ 26			- 79	+ 10	+ 1		- 4	- 4			o^- 157	**o^- 267**	**+ 40**
Impatiens parviflora	4	5	x	6							+ 5	+ 6	o 287		+ 2					o 924	+ 344	**o 1562**	**+ 6**
Juncus effusus	8	7	3	4									- 3				o 10	- 10		- 5		**- 18**	**- 10**
Lamium galeobdolon	3	5	7	5									o 22	+ 4	o 126	o 19	o 34	- 35				**o 182**	**- 58**
Melica uniflora	3	5	6	6					o 9	+ 9			+ 6						+ 9		+ 34	**o^+ 58**	**+ 18**
Mercurialis perennis	2	x	8	7											o^+ 36							**o^+ 36**	
Oxalis acetosella	1	5	4	6					- 41	+ 41	o^+ 63	+ 63	o 228	+ 28	o 122	- 5	o 15	- 15		o 123	o 269	**o 870**	**+ 152**
Quercus petraea	6	5	x	x							+ 3						o 1			o 22		**o 26**	
Rubus fruticosus agg.	x	x	x	x	+ 3								o^+ 2		o^- 9							**o^+ 14**	

Appendix – Continue.
Anhang – Fortsetzung.

	Indicator values				Siemen		Röthen		Falken-hagen		Schie-ringen		Eber-götzen		Bösing-hausen		Macken-rode		Nico-laus-berg	Blan ken-heim	Sil-lium	Total	
Species	L	F	R	N	Def	CO_2	Def	CO_2	Def	CO_2	Def	CO_2	Def	CO_2	Def	CO_2	Def	CO_2	CO_2	Def	Def	Def	CO_2
Rubus idaeus	7	x	x	6	+ 3	+ 3	+ 9	+ 9					o 124		o$^-$ 9					o 176	- 1	**o 323**	**+ 12**
Rumex crispus	7	7	x	6									o 10									**o 10**	
Stachys sylvatica	4	7	7	7							- 2		- 8		o$^-$ 17						o$^+$ 17	**o 44**	
Stellaria media	6	x	7	8											+ 7					o 154		**o 161**	
Urtica dioica	x	6	7	9					- 1				- 184				- 2			o 36	o$^-$ 38	**- 261**	
Vaccinium myrtillus	5	x	2	3	+ 86	+ 86	+ 110	+ 110														**+ 196**	**+ 196**
Vicia sepium	x	5	6	5																	o 13	**o 13**	
Vinca minor	4	5	7	6											+ 66	o 33						**+ 66**	**o 33**
Viola reichenbachiana	4	5	7	6							o 2				o 96							**o 98**	

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