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Wild boar and red deer affect soil nutrients and soil biota in steep oak stands of the Eifel

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Abstract

In sloping oak forests of the German low mountain range high wild boar (*Sus scrofa*) and red deer (*Cervus elaphus*) population densities may affect soil ecological processes by grubbing, grazing, trampling and dunging. We simulated wild boar grubbing in a fenced exclosure and an unfenced replicate and established two adjacent control plots, one fenced, the other unfenced. We evaluated if repeated soil bioturbation and game exclusion by fencing influence soil texture, soil chemical and soil biotic properties in the upper soil over a time period of 2 years. Soil bioturbation was conducted in November 2000 and 2001 creating a grubbing pattern similar to that found in naturally grubbed areas. Soil and fauna sampling was performed in spring and fall of the years 2001 and 2002.

Soil bioturbation did not affect soil texture, pH and the contents of organic carbon and nitrogen. In contrast, the contents of potassium and magnesium, the microbial activity and the abundance of saprophageous and predatory soil arthropods were generally lower in grubbed plots compared to ungrubbed control plots ($p \leq 0.05$).

The exclusion of game did not improve soil quality. On the contrary, microbial activity and the contents of organic carbon and total nitrogen were elevated outside the fenced exclosure ($p \leq 0.05$) which may be related to the deposition of urine and dung.

Our study found that large mammals affect soil nutrient cycling in sloping oak forests either directly by the deposition of urine and dung or indirectly by accelerating nutrient leaching and disturbing the decomposer system in the soils.

Keywords: Bioturbation; Fencing; Wild boar; Red deer; Soil biota; Soil nutrients; *Quercus petraea*

1. Introduction

Mammals have varied influences on forest ecosystems. Many of these impacts affect forests directly such as seed dispersal (Heinken et al., 2002), tree browsing (Kuiters and Slim, 2002), bark peeling and fraying (Putman, 1996), others influence forests indirectly by modifying soil characteristics. Holtmeier (1999) described the ecological significance of mammals for soil processes over a broad range of processes and landscapes, while Whitford and Kay (1999) gave a detailed review on the consequences for biopedturbation by mammals in deserts.

In European deciduous forests large mammals may also have a great impact on the soil nutrient status and the soil biota by grazing (deer), grubbing (wild boar), trampling and dunging, but specific studies on these relationships remain scarce. In a previous study we found strong indications that high population densities of red deer (*Cervus elaphus*) enhance soil degradation in sloping oak forests (Mohr and Topp, 2001). The European wild boar (*Sus scrofa*) may also largely contribute to soil disturbances in temperate deciduous forests, especially when population densities are high. Wild boar grubbing is suspected to accelerate soil erosion, affect soil pH, decomposition processes and hence nutrient contents in the soil (Bratton, 1975; Singer et al., 1984).

In this study we aimed at evaluating the impacts of wild boar grubbing and red deer trampling and grazing on soil ecological characteristics in oak stands of steep terrain. The chosen investigation area (Ahr-Eifel; German low mountain range) is characterized by steep slopes and extremely high population densities of red deer and wild boar.

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To characterize the effect of grubbing both under the impact and without the impact of deer, we simulated wild boar grubbing within and outside a fenced exclosure. We intensely grubbed areas of 25×25 m twice, in November 2001 and 2002 and established ungrubbed control plots to address the following questions:

1. Does soil bioturbation affect soil texture, soil nutrient status and the soil biota?
2. Does exclusion of game by fencing result in an improvement of soil quality in fenced exclosures?

2. Material and methods

2.1. Study area

The study was conducted in the Ahr-Eifel (forestry district Adenau, Rhineland-Palatinate), a hilly region about 60 km south of Cologne in the German low mountain range. This eastern part of the Eifel is dominated by extended areas of semi-natural woodlands growing on devonic bedrock, mainly slate. Sessile oak (*Quercus petraea*) is the typical tree species at the dry and windward slopes exposed to the southwest. Leeward hillslopes are dominated by beech (*Fagus sylvatica*) and other hydrophilic deciduous tree species. Mean annual rainfall ranges from 600 to 800 mm and mean annual temperature varies between 6 and 9 °C, both depending on elevation and exposure. Game population densities at the forestry district of Adenau are extremely high. Red deer densities were calculated to be 20 individuals per 100 ha which is much higher than documented from most of the semi-natural and natural forests across Europe (2–5 ind./100 ha). Population densities of the European wild boar (*Sus scrofa*) are also high but there are no reliable calculations yet. The high game density results in visible damages to vegetation and soil. Red deer grazing and trampling and wild boar grubbing destroy the protective ground vegetation, mix soil layers, modify soil structure and change the surface microtopography. The degree of soil disturbance seems to be dependant on slope exposure, slope gradient and the frequency of game occurrence.

2.2. Patterns of wild boar grubbing

Wild boars find the majority of their diet on the soil surface or in the soil. To obtain their food they often grub in soil in the search for seedlings, saplings, roots, mushrooms and soil invertebrates, both on meadows and in forests. The patterns of grubbing may differ from location to location depending on the soil type, the vegetation cover, the food resources, the season and the herd size (Welander, 2000). Grubbing may be superficial, affecting only the litter layer, or breaking through the surface layer of vegetation and excavate soil to a depth typically ranging between 5 and 15 cm (Kotanen, 1995; Groot Bruinderink and Hazebroek, 1996). This often includes the mixing of organic topsoil with mineral soil. The displaced vegetation and soil may be left in place, or may be moved aside burying untouched vegetation or forming mounds. The area grubbed may extend for more than a hectare or be composed of many small (∼1 m^2), overlapping disturbed patches (‘feeding stations’—Vallentine, 1990). We simulated the two most distinctive patterns of wild boar grubbing in the investigation area: mixing of soil layers and displacement of vegetation. We thereby considered the average depth of soil excavation (10 cm) and the percentage of disrupted plants found in adjacent areas intensively grubbed by wild boars (100%). The grubbing pattern was created using rakes, which closely resemble the morphology of wild boar fangs.

2.3. Patterns of red deer

Red deer are less selective with their feeding preferences than roe deer and predominantly feed on grasses, herbs, mosses, buds, lichens and shoots or seedlings of shrubs and trees. In the study area a large part of their diet is taken from the shrub and herb layer so that locally both are heavily grazed. When the protective ground vegetation is missing large herds of red deer enhance wind and water erosion by trampling (Holtmeier, 1999). These effects appear to be pronounced at windward sites with inclinations higher than 20°. As known from a large body of literature erosion rates are highly influenced by the slope gradient. The regular distribution of faecal pellets at the unfenced plots of this investigation proves the presence of deer throughout the year.

2.4. Experimental plots

The bioturbation of the soil was performed twice, in November of the years 2000 and 2001. At this time wild boar grubbing activity is high because of the moist soil, the freshly fallen litter and seeds (especially acorn), the high abundance of soil and litter dwelling arthropods and the high number of fungi. We grubbed two plots (B1/B2) with an area of 25×25 m each. One plot was within a fenced exclosure (B1) to avoid additional disturbance by game, especially red deer, the second plot was outside the exclosure (B2) in a distance of 25 m to the fence. As pointed out above wild boar grubbing is highly variable in space, time and quality. Therefore we did not aim to create a mimic of a specific grubbing event observed in the field but rather to simulate the two most distinctive patterns of wild boar grubbing in the investigation area: mixing of soil layers and displacement of vegetation. We thereby considered the average depth of soil excavation and the percentage of disrupted plants in adjacent areas intensively grubbed by wild boars. These patterns are easily reproducible in the field and should result in similar effects as under ‘natural’ conditions.

The fence was built up in 1998. Adjacent (10 m) to the grubbed plots we established two control plots, fenced (C1) and unfenced (C2). The experimental site is exposed to the southeast and elevation is about 450 m with an average slope gradient of 25°. The dominant tree species is sessile oak. In contrast to the unfenced plots ground vegetation was well established inside the fenced exclosure. It was dominated by bramble (*Rubus fructiosus*). Oak saplings were also numerous. The soil type is a Ranker (FAO, A/C soil) with a shallow Ah horizon (≤5 cm).

2.5. Soil sampling

Soil samples were taken at random from the topsoil (0–5 cm) but not closer than 2 m to the fence to avoid edge effects. Ten replicates were taken at four sampling dates to attain a representative soil sample pool of 40 replicates for each plot. It had to be assured that repeated sampling never occurred at the same positions within a plot. Samples were taken in the spring following the bioturbation processes (April 2001/2002) and about 1 year after the bioturbation processes (October 2001/September 2002).

2.6. Soil chemical and microbial analyses

All soil samples were air-dried and sieved at a mesh size of 2 mm. Soil pH was determined according to Schlichting and Blume (1966) with a microprocessor pH-Meter (pH 320, WTW) after extraction with 1 M KCl. All the other chemical analyses were conducted with air dried soil. Content of organic carbon (C_{org}) was calculated from CO_2 measurements (Total Organic Carbon Analyser, Ströhlein Instruments) after combustion at 550 °C. Total nitrogen (N_t) content was analysed using the Kjeldahl method. The content of extractable phosphate-ions in soil was performed colorimetrically with the Vanadate-method as described in Steubing and Fangmeyer (1992). Ammoniumnitrate (1 M)-extractable base cations (Ca^{2+}, Mg^{2+}, K^{+}) were analysed with an Atomic Absorbance Spectrophotometer (AAS, Perkin–Elmer GmbH).

For microbial analyses soils were adjusted to 50% of the maximum water retention capacity of the sieved soils (WRC_{max}) and incubated at 20 °C. Potential microbial activity was determined using the method of Skambracks and Zimmer (1998), modified for soil samples. Microbial biomass was analysed using the fumigation–extraction method after Vance et al. (1987).

2.7. Litter and arthropod sampling

We collected the leaf litter within a 300 cm^2 metal frame taking eight replicates per plot and sampling date. After transportation in plastic bags the litter was placed in Tullgren funnels and the soil fauna extracted over a 2 week period. From all extracted arthropods we concentrated on saprophageous and predatory groups. Isopods as typical saprophagheous litter arthropods and spiders as an example of a predatory group were determined to the species level. After extraction the dry litter was cleaned and weighed.

2.8. Statistical analyses

We used the Kolmogoroff–Smirnoff-test to test for normal distribution of the data. Because not all data sets were normal distributed we present the median values with the median absolute deviation. We used the nonparametric Kruskal–Wallis-H-test and the Mann Whitney-*U*-test in succession to test for differences between data sets. The limit of significance was set at $p \leq 0.05$.

Three factorial analysis of variance (ANOVA) was conducted to specify the effect of bioturbation (grubbed/ungrubbed), fencing (fenced/unfenced) and season (spring/fall) on parameters distribution. Each factor appeared in a replicate number of $n=2$ and therefore the degree of freedom of the single factors was d.f. = 1. This experiment is a three factor randomised complete block design (RCBD). Adding ‘season’ as an ANOVA factor implies that repeated sampling never occurred at the same positions within the plots. All data were $\log(x+1)$ transformed to minimize violation of normal distribution. The limit of significance was set at $p \leq 0.01$. All statistical analyses were conducted with the computer program SPSS 11.0. In the ANOVA result tables the *F*-value, the significance-level and the R^2-value are presented. The R^2-value indicates the contribution of a specific factor to the total variance of the analysis. If a parameter’s distribution is exclusively influenced by the chosen factors then the R^2-value of the model is 1.0.

3. Results

3.1. Soil texture and soil chemistry

Soil pH ranged from 3.3 to 3.5 and the C/N ratio ranged from 14 to 16. The soil pH was slightly higher, the C/N ratio was slightly lower within the fenced exclosure compared to the plots outside the fence, but there were no significant differences between grubbed plots and control plots (Table 1). Soil texture (proportions of sand, silt and clay) was similar in all plots (Table 1). The WRC_{max} was significantly higher ($p \leq 0.05$) in unfenced plots and tended to be lower in the grubbed plots than in the control plots. The contents of organic carbon and total nitrogen always reached maximum values at the unfenced control plot (Table 1; Fig. 1). Values were significantly ($p \leq 0.001$) higher at the unfenced plots (C2/B2). Moreover, the contents of organic carbon and total nitrogen were generally higher at the control plots compared to the grubbed plots, but differences were not significant. Analysis of variance underlined the importance of fencing for the contents of organic carbon and nitrogen. Fencing contributed most to the model explanation for both elements (Table 2).

Contents of phosphate-P, potassium (K^{+}) magnesium (Mg^{2+}) and calcium (Ca^{2+}) were generally higher at

Table 1
Several soil properties of the experimental plots C1 (control, fenced), B1 (bioturbation, fenced), C2 (control, unfenced) and B2 (bioturbation, unfenced)

Site	N	Fenced		Unfenced	
		C1	B1	C2	B2
pH (1M KCl)	40	3.5 ± 0.1^{a}	3.5 ± 0.1^{a}	$3.4 \pm 0.1^{a,b}$	3.3 ± 0.1^{b}
C/N	40	14 ± 3^{a}	$14.0 \pm 3.0^{a,b}$	16 ± 2^{b}	16 ± 2^{b}
Litter (g/300 cm^2)	32	7.5 ± 3.1^{a}	5.4 ± 3.2^{a}	12.7 ± 4^{b}	$8.3 \pm 4.8^{a,c}$
WRC_{max} (%)	40	61.6 ± 3.1^{a}	57.8 ± 1.4^{b}	66.6 ± 2.6^{c}	65.7 ± 1.8^{c}
Nt (mg/g)	40	5.9 ± 0.9^{a}	5.3 ± 0.9^{a}	7.8 ± 1.3^{b}	7.4 ± 0.9^{b}
Ca^{2+} (mg/g)	40	0.9 ± 0.3^{a}	0.8 ± 0.3^{a}	1.3 ± 0.4^{b}	1.0 ± 0.2^{c}
Sand (%)	8	37.4 ± 4.1	38.9 ± 1.6	33.6 ± 1.5	34.9 ± 0.6
Silt (%)	8	42.3 ± 1.2	43.1 ± 1.1	52.0 ± 1.5	42.1 ± 2
Clay (%)	8	19.7 ± 1.0	17.9 ± 0.9	14.1 ± 1.2	22.9 ± 2.5

Presented are median and median absolute deviation ($n = 40$). Differences between the plots are indicated by different letters ($p \leq 0.05$; Mann Whitney-*U*-test).

the control plots than at the bioturbation plots (Table 1; Fig. 1). Differences for potassium and magnesium were significant ($p \leq 0.05$) at both the fenced and unfenced plots, whereas differences for phosphate were only significant ($p \leq 0.05$) inside the fenced exclosure and for calcium only outside the exclosure. The importance of bioturbation for these soil nutrients decreased in the order K ($r^2 = 0.24$) > Mg (0.07) > *P* (0.04) > Ca (0.04) according to analysis of variance (Table 2). Fencing only significantly ($p \leq 0.01$) influenced the latter three elements according to ANOVA: Mg (0.13) > Ca (0.12) > *P* (0.04).

Differences between spring and fall occurred for some of the properties but at grubbed and ungrubbed plots in the same way. Contents of nitrogen, magnesium and calcium were all significantly higher in fall compared to spring, reflected by highly significant ANOVA-results (Table 2).

3.2. Soil microbial properties

Microbial activity was significantly lower ($p \leq 0.05$) at grubbed plots compared to the control plots (Fig. 2). At the same time microbial activity was significantly higher ($p \leq 0.05$) at unfenced plots when comparing similar treatments, but according to analysis of variance bioturbation ($r^2 = 0.09$) contributed more to the model explanation ($r^2 = 0.19$) than the effect of fencing ($r^2 = 0.07$) (Table 2). The microbial biomass was only significantly lower at the control plot inside the fenced exclosure ($p \leq 0.01$). The season (spring/fall) had a greater impact on microbial biomass than bioturbation according to ANOVA ($r^2 = 0.29$). Higher C_{mic}-values were obtained in fall compared to spring. Fencing did not affect microbial biomass significantly according to analysis of variance. In contrast to microbial biomass, microbial activity was significantly correlated ($p \leq 0.001$; Spearman-rank-correlation) to the abundance of saprophageous soil arthropods.

3.3. Litter layer and litter arthropods

The amount of litter collected was significantly highest at the unfenced control plot (dry wt. 12.7 g/300 cm^2). At grubbed plots the amount of litter was lower than at the control plots, but the difference was only significant outside the exclosure (Table 1).

Three thousand four hundred and twenty-six individuals of the soil macrofauna were found in the litter, of which 1617 were saprophageous (Diptera Larvae, Isopoda, Diplopoda) and 1357 predatory (Arachnidae, Coleoptera, Chilopoda). For both saprophageous and predatory arthropods we obtained highest abundances at the ungrubbed control plots C1 and C2 (Fig. 3). Abundances at the corresponding grubbed plots B1 and B2 were significantly lower ($p \leq 0.05$) in all cases. In contrast, there were no consistent differences between fenced and unfenced plots regarding similar treatments. Abundances of saprophageous and predatory arthropods were significantly correlated to the amount of litter ($p \leq 0.001$; Spearman-rank-correlation).

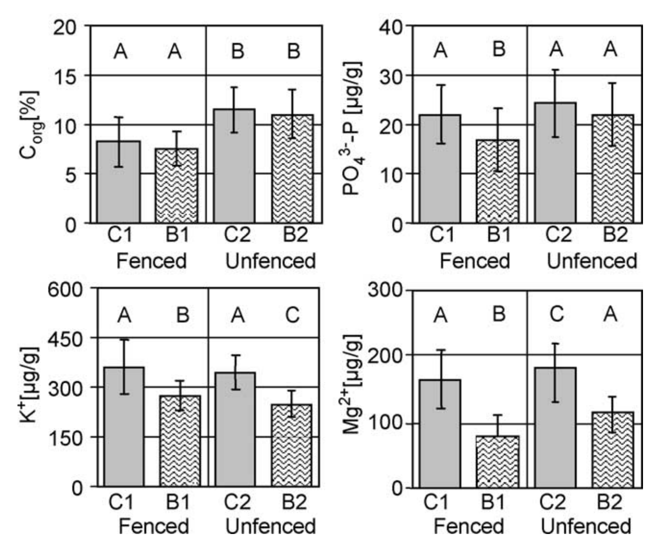

Fig. 1. Soil chemical properties (C_{org}, $PO_4^{3-} - P$, K^+, Mg^{2+}) in the topsoil of the experimental plots C1 (control, fenced), B1 (bioturbation, fenced), C2 (control, unfenced) and B2 (bioturbation, unfenced). Presented are median and median absolute deviation ($n = 40$). Mann Whitney-*U*-tests were conducted to test for differences between the plots. Different letters indicate significant differences between the plots ($p \leq 0.05$).

Table 2
Three-factorial ANOVA on the effects of bioturbation (grubbed/ungrubbed), fencing (fenced/unfenced) and season (spring/autumn) on the contents of soil nutrients

ANOVA 3-way	Bioturbation		Fencing		Season		Model		Interaction
	F	R^2	F	R^2	F	R^2	F	R^2	
d.f.	1		1		1		7		
$C_{org.}$	2.97 ns		59.98***	0.27	1.42 ns		9.65***	0.31	–
N_t	5.88 ns		82.07***	0.32	14.08***	0.06	14.73***	0.41	–
$PO_4^{3-}-P$	6.21**	0.04	6.14**	0.04	5.68 ns		2.65**	0.11	–
K^+	57.72***	0.24	5.92 ns		0.00 ns		12.55***	0.37	fen*seas
Mg^{2+}	16.81***	0.07	29.07***	0.13	25.71***	0.11	10.45***	0.33	–
Ca^{2+}	9.26**	0.04	28.33***	0.12	46.21***	0.20	12.11***	0.36	–
Micr. act.	17.45***	0.09	12.8***	0.07	3.38 ns		5.11***	0.19	–
C_{mic}	9.82**	0.04	1.37 ns		70.42***	0.29	12.68***	0.37	–
Saproph.	17.94***	0.12	3.27 ns		0.60		5.10***	0.23	bio*seas
Predators	16.20***	0.10	0.45 ns		24.36***	0.15	6.50***	0.28	
Isopoda	13.83***	0.07	45.68***	0.22	1.25 ns		12.19***	0.42	bio*fen
Aranaea	10.84***	0.08	0.90 ns		0.85 ns		2.32 ns		–

(C_{org}, N_t, $PO_4^{3-}-P$, K^+, Mg^{2+}, Ca^{2+}), soil microbial properties (microb. activity/biomass) and soil arthropod abundance at the experimental plots. ns, no significance; ** $p \leq 0.01$; *** $p \leq 0.001$. Only significant interactions are shown ($p \leq 0.01$).

Among those saprophageous individuals obtained quantitatively, isopods were the most abundant. Altogether we found 385 individuals. *Trichoniscus pusillus* was the dominant species at all sites. Additionally single specimen of *Oniscus asellus* and *Philoscia muscorum* were present. The vast majority of individuals was found in the control plot inside the fenced exclosure (C1, 342 ind.) with significantly higher abundances compared to all the other plots (Fig. 3). Outside the fenced exclosure isopods were almost absent. Accordingly, fencing contributed most to the model explanation of three way ANOVA (Table 2) but bioturbation and fencing significantly interacted ($r^2=0.07$).

Spiders as an example of a predatory arthropod group were less abundant at grubbed plots compared to control plots ($p \leq 0.05$; Fig. 3). At the unfenced and grubbed plot (B2) spiders were almost absent and thus significantly lower in abundance compared to all the other plots. ANOVA did not deliver a significant model explanation. The total number of individuals extracted from the litter samples were 57 at C1, 41 at B1, 101 at C2 and 8 at B2. About 60% of the individuals were juveniles. More than 50% of the species found at the plots belonged to the family Linyphiidae with *Walckenaeria incisa* as the most common species. Lycosidae (8 ind., e.g. *Trochosa terricola*), Theridiidae (6, e.g. *Robertus lividus*) and Agelinidae (4, e.g. *Coelotes inermis*) were less numerous. There were also single findings of Araneidae (ND), Hahniidae (*Hahnia Montana*) and Salticidae (ND). All the species found are common predators in the litter of deciduous forests. The numbers were too low to compare plots statistically on the species level.

4. Discussion

Soil bioturbation by vertebrates has diverse effects on soil properties. Burrowing of the subterranean rodent *Ctenomys talarum* (tuco-tuco) from South America was observed to increase sodium, potassium and magnesium contents in coastal grasslands of South America (Malizia et al., 2000). Other studies suggest that the digging activity in gopher or rabbit warrens enhance soil erosion (Yair, 1995; Gabet, 2000; Eldridge and Myers, 2001). Ford and Grace (1998) observed patterns of habitat destruction by nutria and wild boar which reduced belowground production in coastal marshes. In many German forests soil bioturbation by wild boars (*Sus scrofa*) predominates over other mammals' soil disturbances. Severely grubbed areas may extend for a hectare or more causing substantial damage to forests and neighbouring crops. However, little is known about the consequences of soil bioturbation for nutrient cycling in European deciduous forests. Aeration of the soil, incorporation of litter into the soil and mixing of soil layers could increase pH, enhance microbial activity and thus the release of nutrients into the soil. But grubbing could also disturb litter arthropods or accelerate nutrient leaching and soil

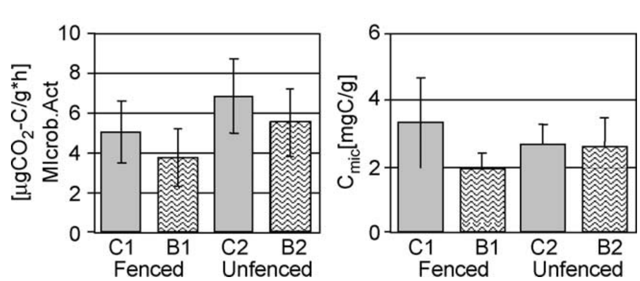

Fig. 2. Microbial activity and microbial biomass (C_{mic}) in the topsoil of the experimental plots C1 (control, fenced), B1 (bioturbation, fenced), C2 (control, unfenced) and B2 (bioturbation, unfenced). Presented are median and median absolute deviation ($n=40$). Mann Whitney-U-tests were conducted to test for differences between the plots. Different letters indicate significant differences between the plots ($p \leq 0.05$).

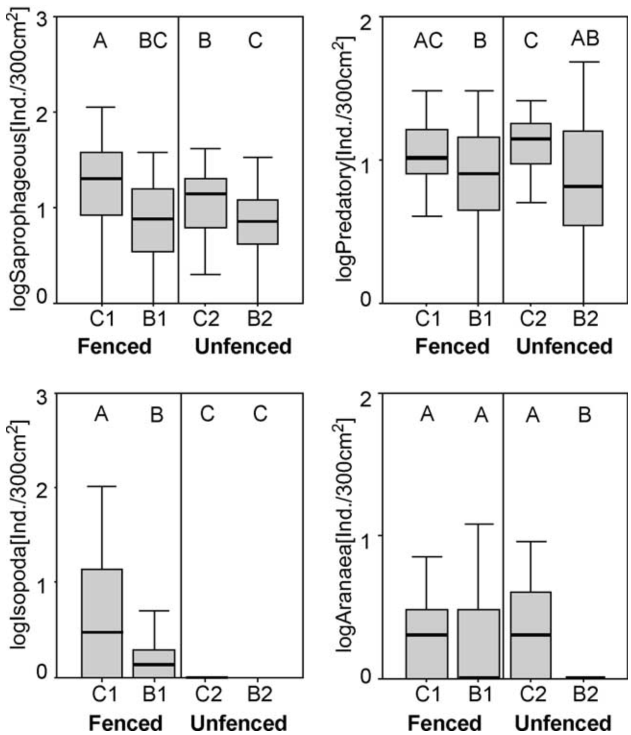

Fig. 3. Abundances of saprophageous and predatory soil arthropods and of isopods and spiders as examples of both groups (ind./300 cm^2) in the litter layer of the experimental plots C1 (control, fenced), B1 (bioturbation, fenced), C2 (control, unfenced) and B2 (bioturbation, unfenced). Presented are boxplots of the $\log(x+1)-$ transformed data ($n=32$). Mann Whitney-*U*-tests were conducted to test for differences between the plots. Different letters indicate significant differences between the plots ($p \leq 0.05$).

erosion, especially in steep terrain. Groot Bruinderink and Hazebroek (1996) did not find an effect of grubbing on organic matter, nitrogen and soil pH, even after 60 years of wild boar grubbing, but that was in lowland forests and on podzolic soils. In our study soil pH, organic carbon, total nitrogen the C/N ratio and soil texture were not affected by bioturbation either. Therefore, we can extend earlier findings by the fact that also in hilly woodlands with slope gradients up to 25° bioturbation does not seem to enhance soil erosion or loss of soil organic matter, at least for leeward (SE) exposed slopes.

The contents of phosphate, potassium, magnesium and calcium were always lower in grubbed plots compared to the ungrubbed plots. In a 3 year experiment at the Smokey Mountains Singer et al. (1984) also observed an accelerated leaching of P, Ca and Mg from soil after grubbing.

Reduced nutrient contents may also be the result of a reduction in microbial activity and biomass at the grubbed plots, because a significant proportion of available soil nutrients is derived from microbial transformations (Anderson and Domsch, 1980). It has been shown that factors like soil humidity, soil pH and the contents of organic carbon and nitrogen influence microorganisms (Wardle, 1992; McLaughlin et al., 2000). In our study those factors remained relatively constant and do not explain the variations in microbial activity and biomass among the plots. However, microbial activity was closely related to the abundance of saprophageous arthropods, a relationship which has already been documented in previous studies (Kandeler et al., 1994; Zimmer and Topp, 1999; Kautz and Topp, 2000). Consequently, soil bioturbation could have affected microorganisms indirectly by reducing the abundance of saprophageous arthropods. But also direct effects such as physical pressure or alterations in soil structure and soil microclimate may have been destructive for microorganisms.

Lower abundances of saprophageous and predatory arthropods at the grubbed plots compared to the control plots may be the consequence of soil horizon mixing and the incorporation of litter into the soil. Litter mass was clearly reduced in the grubbed plots (Table 1). Reduced resource availability has been reported to negatively affect soil invertebrates (David et al., 1991; Scheu and Schäfer, 1998). Physical manipulations to the soil have also been reported to affect the litter fauna (Jordan et al., 2000). Saprophageous and predatory arthropods were almost absent from the unfenced and grubbed plot but in contrast to the spiders, the isopods were also strongly reduced at the unfenced control plot. These results indicate that litter dwelling arthropods may not only be influenced by litter perturbations but also by physical disturbances resulting from soil bioturbation and trampling.

High red deer population densities were found to enhance soil degradation by lowering microbial activity and several soil nutrient contents (C, N, P) (Mohr and Topp, 2001). These effects were attributed to increased soil organic matter erosion by grazing and trampling and were most evident at windward sites with high slope gradients ($>20°$). In the present study such effects were not observed, contents of organic carbon and total nitrogen as well as microbial activity were even higher at unfenced plots compared to the fenced plots. Soil vegetation outside the fenced exclosure was almost completely removed by grazing but we did not find any indications for soil organic matter loss. We suppose that only at windward sites steeper than 25° game trampling intensifies soil organic matter loss by wind and runoff. At conditions chosen in this study (25°, SE-exposure) red deer may have even supported the increase of organic matter content and microbial activity in soil of the unfenced plots by the deposition of urine and dung. Mammalian excreta are reported to increase C, N and microbial activity in the soil (Lovell and Jarvis, 1996; Haynes and Williams, 1999; Willott et al., 2000).

None of the soil properties we observed showed differences between the sampling dates (spring/fall) that could only be attributed to a short-term effect of bioturbation on spring samples, nor did we find any differences between the years 2001 and 2002 which could only be attributed to the second bioturbation process in November 2001. Whenever changes between the sampling dates or years occurred they were found at all plots. Effects of soil bioturbation on soil properties occurred rapidly and sustained over at least a year. A repeated bioturbation after 1 year did not strengthen the observed effects, but the duration of the experiment was only 2 years, which may be inadequate to obtain clearer differences. Therefore, we believe that a higher grubbing frequency and a longer time period would further impede nutrient mineralisation and accelerate nutrient leaching.

5. Conclusions

Wild boar grubbing lowers the contents of several soil nutrients (P, Ca, Mg, K), impedes microbial nutrient mineralisation and reduces the abundances of soil arthropods in oak forests of the Eifel. Soil texture, pH and soil organic matter content (C, N) seem not to be affected by soil bioturbation. Deer grazing and game trampling do not affect soil characteristics at the given slope gradient and aspect (25°, SE), but the deposition of urine and dung may increase microbial activity and soil organic matter content. Isopods and spiders seem to be strongly disturbed by game trampling and soil bioturbation.

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