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Long Lasting Nitrate Leaching after Bark Beetle Attack in the Highlands of the Bavarian Forest National Park

Christian Huber*

ABSTRACT

During the past decade bark beetle (*Ips typographus*) attacks killed nearly all of the Norway spruce [*Picea abies* (L.) Karst.] stands in the unmanaged zone in the highlands of the Bavarian Forest National Park. This study was conducted to predict if and how long the catastrophic event might cause elevated nitrate (NO_3^-) concentration in seepage water, and if the presence of ground vegetation may reduce NO_3^- leaching. A chronosequence approach was used to investigate NO_3^- leaching before and after the death of trees. Additionally, the impact of ground vegetation coverage on NO_3^- leaching was determined. Flux weighted yearly NO_3^- concentrations were significantly elevated in the first 5 yr after the dieback compared with intact stands (27 μmol_c L^{-1}), with highest concentrations in the fifth year after the dieback (579 μmol_c L^{-1}). Lowest NO_3^- concentrations were observed 17 yr after the dieback (10 μmol_c L^{-1}). Suction cups in places without ground vegetation showed significantly higher NO_3^- concentrations of 163 to 727 μmol_c L^{-1} (Year 2–5 after the dieback) than suction cups without vegetation. However, net uptake of N by ground vegetation observed during the first 7 yr after the dieback was low on a plot scale. Compared with other severe disturbances in forests, NO_3^- concentrations were elevated for a longer period. Due to high rates of precipitation, NO_3^- dilution occurred and concentrations remained mostly below the European critical level for drinking water. Part of the observed heterogeneity in NO_3^- concentrations could be attributed to different patterns of ground vegetation coverage.

During the last decade a combination of mild winters, warm summers, and storm events promoted the development of large populations of bark beetles (*Ips typographus*) in the Bavarian Forest National Park, especially in the mountainous spruce ecosystem of the highlands (1100–1450 m altitude). Because natural processes have priority in the national park, no counter measures against the bark beetle attack were undertaken except for the creation of a border zone of 500 to 1000 m wide to prevent further outbreak expansion into private forests. As a result, nearly all stands (mostly Norway spruce) in the unmanaged zone of the highlands of the national park were killed. An increase in NO_3^- concentrations in seepage water after clear-cutting (Likens et al., 1969; Borman and Likens, 1979; Vitousek et al., 1979; Weis et al., 2001; Huber et al., 2004b) and storm events (Mellert et al., 1996) is often described. The magnitude varies widely (Mellert et al., 1996; Weis et al., 2001) and depends on the N status, fertility, and productivity of the ecosystem (Ring, 1995; Berden et al., 1997; Katzensteiner, 2003). Mineralization and nitrification are usually enhanced after cutting and cause "excess nitrification" (Dahlgren and Driscoll, 1994). The herbaceous vegetation and regenerating trees may reduce soil solution NO_3^- in disturbed ecosystems (Stevens and Hornung, 1990; Emmett et al., 1991; Mellert et al., 1996; De Keersmaeker et al., 2000; Weis et al., 2001; Parfitt et al., 2002; Fiala et al., 2005; Mellert et al., 1996; Huber et al., 2004b). However, a slow "dieback" may be different from instantaneous events such as clear-cuts. After the dieback, the whole biomass remains on the site; the dead trees remain standing for several years until they break down; and radiation, air temperature, and interception remains relatively unchanged for a long time (Huber et al., 2004a).

The dramatic dieback was discussed during a hearing in the Bavarian parliament about the potential of NO_3^- contamination of ground water resources in the highland area, as well as to the expansion area of the national park, where mechanical counter measures will be conducted against bark beetles until 2017. Due to the lack of investigations in the area, or appropriate models to evaluate the risks of NO_3^- leaching after the dieback in the highlands of the national park, the following study was conducted.

The purpose of this article is to answer the following questions:

1. Are there changes in the total N supply and C/N ratios of the soil?
2. How long are NO_3^- concentrations in seepage water (40-cm depth) elevated?
3. Do peak and flux weighted yearly NO_3^- concentrations exceed the European limit of drinking water quality?
4. Does ground vegetation have a significant influence on NO_3^- leaching?

MATERIALS AND METHODS

Site and Stand Description

The Bavarian Forest National Park is situated 150 km east of Munich along the border of the Czech Republic (Fig. 1a, b). The park was founded 1970 as the first national park in Germany to protect the forest landscape in the low mountain range. The park was expanded in 1997 ("expansion area") from an area of approximately 10 000 ha to 24 250 ha (Fig. 1b). According to the "leaving nature alone" directive of the World Nature Protection Organization (IUCN), natural processes are given priority in the national park despite intensive protest of the residents in this area. The park exhibits the largest un-

Fachgebiet für Waldernährung und Wasserhaushalt, Department für Ökologie, Wissenschaftszentrum Weihenstephan, TU-München, Am Hochanger 13, D-85354 Freising, Germany. Bayerisches Staatsministerium ELF with the projects V50B and V58. Received 28 May 2004.
*Corresponding author (huber@forst.tu-muenchen.de).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: BS, base saturation of the action exchange capacity; CEC, cation exchange capacity; IUCN, World Nature Protection Organization; L, litter layer; Of, fermentation layer; Oh, humus layer.

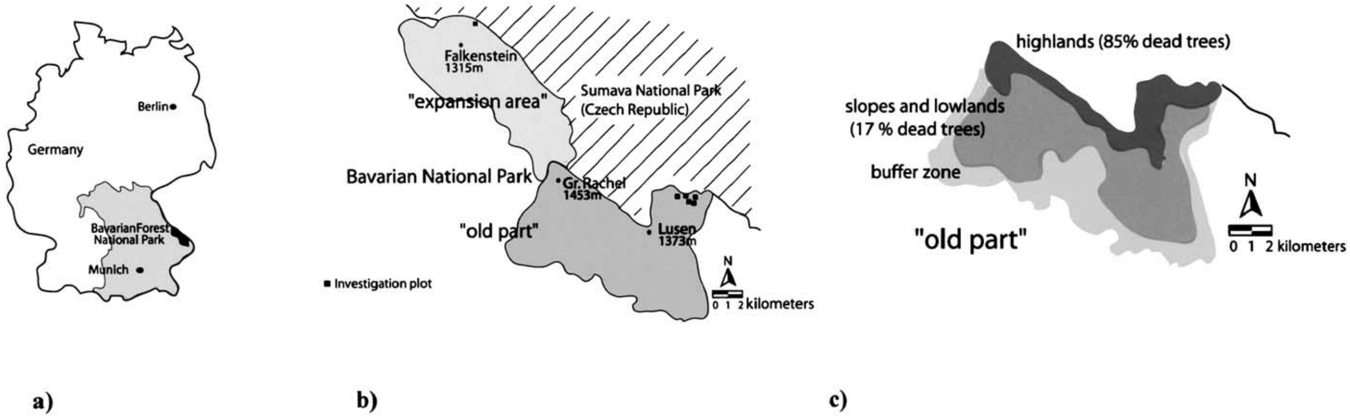

Fig. 1. Bavarian Forest National Park location map. (a) The Bavarian Forest National Park is situated 150 km northeast of Munich. (b) The Park is divided into two parts: (i) the unmanaged "old part" (Rachel-Lusen area), and (ii) the managed expansion area (Falkenstein-Rachel area). Five investigation plots are located in the east part of the Rachel-Lusen area, and one plot in the northwest of the Falkenstein-Rachel area. (c) In the old part of the park, 85% of the trees died after the dieback and 17% of trees in the slopes and lowlands. In a buffer zone infested trees were cut.

managed forested area in Central Europe. The extensive unmanaged zone is concentrated in the old part of the park (Rachel-Lusen area), which compromises 75% of this area. In the expansion zone (Falkenstein-Rachel area), however, most of the area will be managed until 2017. In a 500-m buffer zone (see Fig. 1c) infested trees were cut to prevent further bark beetle infestation into private forests (Rall, 1999). More than 85% of the forested area (1922 ha) in the highlands (1060–1450 m above sea level) and 17% (1764 ha) in the lower parts (690–1060 m above sea level) were killed by 2001 due to the bark beetle attack (Heurich et al., 2001). Before the bark beetle attack, a mountainous Norway spruce forest uniformly covered the highland area (plant community: *Soldanello-Picetum barbilophoietosum*). Trees were 80 to 300 yr old and sporadically mixed with mountain ash (*Sorbus aucuparia* L.) The ground flora was dominated by hairy reed grass (*Calamagrostis villosa* Chaix) and waify hair grass (*Deschampsia flexuosa* L.). Other species present were bilberry (*Vaccinium myrtillus* L.), greater wood rush (*Luzula sylvatica* Huds.), wood sorrel (*Oxalis acetosella* L.), different sphagnum mosses (*Sphagnum* ssp.), broom moss (*Dicranum scoparium* Hedw.), and polytrichum moss (*Polytrichum attenuatum* Menz.). The mean annual air temperature in the highlands is 3.0 to 4.5°C, mean annual precipitation (of which 50% is snow) is around 1600 mm with a maximum of >2000 mm in some years. The growing season is short with an average snow cover of 7 mo (October–May). The soil is an acidic brown earth (FAO, Dystric Cambisol), rich in humus, with indications of podzolization, and is strongly acidified in the topsoil. A 10- to 18-cm organic layer (raw humus), subdivided into LOf1, Of2, and Oh covers the mineral soil. pH values are low with a minimum in the Oh horizon (2.6 in $CaCl_2$). The base saturation of the mineral soil is between 2 and 10%. Approximately 8000 kg N ha^{-1} are stored down to the 40-cm soil depth (Huber et al., 2004a). Nitrogen fluxes in throughfall of intact stands were in the range of 12 to 16 kg ha^{-1} yr^{-1}.

Study Plots

The plots listed in Table 1 have been under investigation since May 1999. Five of the six plots are located on a plateau in the area of the Reschbachklause (48.933° N lat; 13.583° E long; altitude 1150 m above sea level) in the unmanaged Rachel Lusen area ("old part"). Additionally, the plot Buchenau (49.033° N lat; 13.333° E long; 1100 m above sea level) is investigated, which is situated in the managed Falkenstein Rachel area ("expansion area"), where bark beetle prevention will be conducted until 2017 (see Fig. 1c).

Within the investigation period, a chronosequence from the beginning of the dieback (Year 0) to the 7th year after the dieback and the 16th to 18th year after the dieback was established. The scheme of the chronosequence is presented in Table 1. The criteria for selecting the plots and more information about the plots are given in Huber et al. (2004a).

Soil Water Samples

Soil water samples were collected with 10 to 20 subsamples per plot with ceramic tension lysimeters (SKL 100, UMS,

Table 1. Scheme of the chronosequence from before the dieback (Intact, and Year 1), to the beginning of the dieback (Year 0) until 18 yr after the dieback listed are the corresponding plot including a short description and the year of the investigation.

Description	Plot	Year of investigation												
Wind thrown 1983	83											1999	2000	2001
Dieback 1994, storm thrown in winter 1999–2000	94								1999	2000	2001			
Dieback 1996, dead wood still standing	96						1999	2000	2001					
Dieback 1999, dead wood standing	99			1999	2000	2001								
1999 alive, dieback 2000, dead wood standing	00		1999	2000	2001									
Managed intact stand in the Expansion zone of the park	E	1999–2001												
		Intact	−1	0	1	2	3	4	5	6	7	16	17	18
		Year after the dieback												

Munich) with an tension of 60 kPa at a 40-cm depth from the top of the soil (below the main rooting zone). These soil water samplers were installed vertically, in hand-augered holes. Disturbance was kept to a minimum during installation by use of mats, and when complete, access to the sampler areas was restricted. A self-made portable 12-V vacuum pump is used to partially evacuate glass bottles attached to the samplers. The first two samples after the installation were rejected to eliminate installation disturbance effects. The glass bottles are protected against light by plastic buckets. For all samples, ground vegetation coverage by species was determined once a year. Samples were taken after the snowmelt (April, May) on a biweekly to monthly basis. Soil water samples were filtered using membrane filters with a pore size of 0.45 μm (Schleicher and Schuell, NC45) and stored until they were analyzed at 4°C. Nitrate was measured with ion chromatography (Dionex, IC2020I).

Estimation of Water and Nutrient Fluxes

Water fluxes were calculated with computer model BROOK90 (Federer, 1997). Air temperature, relative humidity, and radiation were measured on each plot in hourly intervals. Precipitation fluxes were determined on the site with five open polyethylene collectors on each plot at 1 m above the ground (sampling time at 2- to 4-wk intervals). From December until the end of April precipitation was collected with five polyethylene drums. Additionally, meteorological standard data such as maximum and minimum air temperature, water vapor pressure, wind speed, and precipitation were available from the weather station Waldhäuser (945 m above sea level), operated by the German Weather Service and the National Park Administration. This data were used for modeling after modifications were made with the data collected on the site. Soil density, depths of horizons, and organic C content were directly determined on the site. Data about soil texture were taken from earlier investigations of comparable stands. Parameters like yield and growth data were taken from stands close to the investigation plots (Jehl, 2001). Flow-weighted yearly elemental concentrations were obtained by weighting element concentrations with their respective periodic water fluxes.

Estimation of Nutrient Stores in Soil and Ground Vegetation

In the summer of 2000 three random samples were collected within each plot at four measuring points. The organic layer was sampled using a 400 cm^2 frame, the upper mineral horizons (depth of 0–5, 5–10 cm) with a 100-cm^2 frame, and samples of deeper horizons (10–20, 20–40 cm) with an auger (1.5 cm diam.). Slash, roots, and stones were removed from the samples, and the coarse and fine roots were separated by hand. Fresh weights and oven-dry weights of the subsamples were determined. pH was determined in 0.01 *M* $CaCl_2$ solution of fresh samples.

Nitrogen accumulation in the aboveground biomass of ground vegetation was determined in 1999, 2000, and 2001. Coverage of different species of ground vegetation was measured on 10 to 20 subplots (1 m^2) directly at the suction cups on each plot. Aboveground biomass and nutrient storage of ground vegetation were determined on each plot at separate subplots nearby. Nitrogen storage was calculated by the multiplication of coverage, biomass, and nutrient content. Carbon and N were measured with CHN (Leco) on dried samples. The analyzed species were in order of their average coverage: waify hair grass, hairy reed grass, "other mosses" (mainly broom moss), bilberry, polytrichum moss, red respberry (*Rubus idaeus* L.), stiff clubmoss (*Lycopodium annotium* L.), hairy wood rush (*Luzula pilosa* L.), spinulose wood fern (*Dryopteris carthusiana* Vill.), *Oxalis acetosella*, and broad leaved willowherb (*Epilobium montanum* L.).

Statistical Analysis

Statistical calculations were done using the statistics package SPSS 11.5 for Windows. Significance of the regression lines was tested using an *F* test. The significance of the differences in NO_3^- concentrations and C/N ratios were tested using a one-way ANOVA. A Bonferroni test was used as a post-hoc test, and Thamhane's T2 was used when variances were not equal according to Levene statistics. A critical probability level of 0.05 was used to indicate significant differences.

RESULTS

Total Nitrogen in the Soil and Carbon/Nitrogen Ratios

The total N pool in the soil (Table 2) was similar for all plots and ranged from 746 to 792 kg N m^{-2}. The highest soil N pools were found in the first year after the dieback. However, the standard deviation was in all cases higher than the differences between the plots.

A statistically significant decrease in the C/N ratio from the beginning of the attack to 17 yr after the dieback could be detected for the humus layers (Table 3). Relatively low C/N ratios (18.0–18.8) were observed in Year 4 (4 yr after the dieback) for the upper mineral soil horizons (depth of 0–5, 5–10, and 10–20 cm). This may be due to the elevated NH_4^+ fluxes in the first 4 yr after the dieback in the humus leachate (data not presented).

Chronosequence of Nitrate Concentration (below the Main Rooting Zone in 40-cm Depth)

Figure 2 shows the time series of the mean quarter year NO_3^- concentrations in seepage water (40-cm depth) in a chronosequence from the beginning to Year 7 after the dieback of a stand and in the Years 16, 17, and 18. Ammonium was mostly below the detection limit; therefore, the data is not presented. Before the dieback, NO_3^- concentrations were low (<50 μmol$_c$ L^{-1}) in the intact stands (expansion area and old part). After the dieback, the lowest concentrations were regularly found

Table 2. Amount of total N in the soil (means ± SD) estimated within a chronosequence before the dieback (0) to 17 yr after the dieback. Investigations were made in summer 2000 with four replicates at each plot.

	Year after dieback				
Soil layer	0	1	4	6	17
Humus layer + 0–5 cm	315 ± 34	334 ± 43	328 ± 48	321 ± 39	287 ± 33
5–40 cm	437 ± 73	467 ± 47	418 ± 117	424 ± 93	465 ± 103
Total	752 ± 107	792 ± 88	746 ± 165	745 ± 132	754 ± 136

Table 3. Carbon/nitrogen ratios in the different horizons in a chronosequence of the Years 0, 1, 4, 6, and 17 after the dieback. Year 0 was estimated few months before dieback. The humus layers are abbreviated according to the German soil classification. L, litter layer; Of, fermentation layer; Oh, humus layer. Soil samples were collected in 2000 with four replicates on each plot. Significance of the differences were tested using a one-way ANOVA. Bonferroni test was used as a post-hoc test when variances were equal according to Levene statistics, Thamhane's T2 when variances were not equal. A critical probability level of 0.05 was used to indicate significant differences. Means ± SD followed by different letters within each row are significantly different at $P < 0.05$.

	Year after dieback				
Soil layer	0	1	4	6	17
LOf1	32.2 ± 4.1 a	27.5 ± 1.9 ab	28.2 ± 4.8 ab	26.0 ± 1.11 b	22.9 ± 1.9 b
Of2	26.0 ± 0.3 a	24.5 ± 0.7 ab	23.6 ± 1.0 b	25.2 ± 0.4 ab	23.0 ± 1.9 b
Oh	24.4 ± 2.8 ab	27.7 ± 1.7 a	22.7 ± 1.0 bc	24.1 ± 0.8 ab	19.8 ± 0.3 c
0–5 cm	22.0 ± 1.6 a	20.5 ± 1.2 ab	18.0 ± 1.7 b	20.6 ± 0.8 ab	18.3 ± 0.9 b
5–10 cm	20.8 ± 2.5 a	21.5 ± 0.8 a	18.2 ± 1.7 a	19.5 ± 0.9 a	21.2 ± 0.5 a
10–20 cm	22.1 ± 1.3 bc	23.5 ± 0.9 ab	18.8 ± 1.2 d	20.7 ± 0.7 cd	24.9 ± 0.6 a
20–40 cm	24.3 ± 2.3 a	20.7 ± 1.5 a	20.0 ± 4.7 a	20.7 ± 0.7 a	20.9 ± 1.2 a

after the snowmelt and the highest after the growing season. Nitrate concentrations were elevated from the first year until Year 7 after the dieback. The maximum average 3 mo mean NO_3^- concentration of 934 μmol_c NO_3^- L^{-1} was reached 5 yr after the dieback sampled after the growing season. Because of the relatively high precipitation in this area, NO_3^- concentrations were rarely above the European level for drinking water. For the Years 16 to 18 after the dieback, NO_3^- concentrations were low (<50 μmol_c L^{-1}) again. Figure 3 shows the flux weighted yearly NO_3^- concentrations of the chronosequence. Concentrations directly after snow melting had a high weight for the calculated flux weighted concentrations due to the high water fluxes in this period. During this time the concentrations were lower than the rest of the year (see Fig. 2) and as a result, the yearly flux weighted concentrations never exceeded the European limit for drinking water of 805 μmol_c L^{-1}. In the intact stands the average concentrations were relatively low with 75 μmol_c L^{-1} in the expansion area, and 27 μmol_c L^{-1} in the "old part." A significant elevation was estimated for the Years 1 to 5 after the dieback. The highest flux weighted yearly concentrations was reached in the fifth year after the dieback (579 μmol_c L^{-1}). The lowest concentrations were found from 16 to 18 yr after the dieback (10–14 μmol_c L^{-1}).

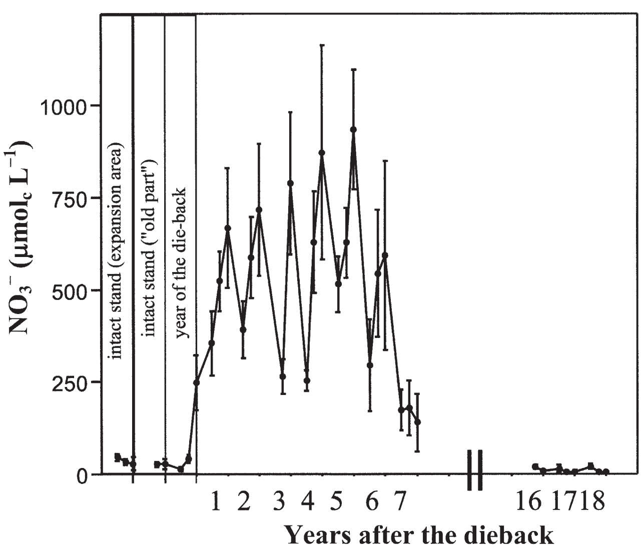

Fig. 2. Chronosequence of the NO_3^- concentration in seepage water at the 40-cm depth (means ± 95% confidence intervals) before and after the bark beetle attack. Each point was determined from a minimum of 10 suction cups. The scheme of the chronosequence is presented in Table 1.

Nitrogen Storage by Ground Vegetation

Table 4 shows the percent coverage and the N accumulation in aboveground parts of ground vegetation. In the intact stand the coverage by ground vegetation was in total 74% with mosses dominating (43%). This resulted in relatively high values of N storage (6.49 g N m^{-2}). After the dieback the coverage of ground vegetation and the N storage is slightly reduced (minimum 4.94 g N m^{-2} in the year of the dieback), then it increased again with a relative maximum in the fourth year (6.96 g N m^{-2}), later decreased values (4.41 g N m^{-2}) in the seventh year and higher values in Years 16, 17, and 18.

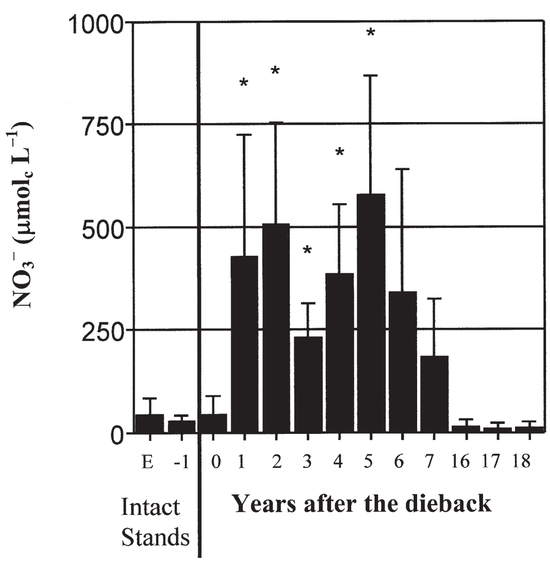

Fig. 3. Yearly mean flux-weighted NO_3^- concentration (means and 95% confidence intervals) before and after the dieback of the stand. Significant differences between the intact stand (−1) and the relevant year are marked with asterisks. E, intact stand in the expansion area; −1, intact stand 1 yr before the attack; 0, year of the dieback; 1, 1 yr after the dieback; and so on. Each point was determined from a minimum of 10 suction cups. The scheme of the chronosequence is presented in Table 2. Significance of the differences were tested using a one-way ANOVA. Thamhane's T2 test was used as a post-hoc test because variances were not equal according to Levene statistics. A critical probability level of 0.05 was used to indicate significant differences.

Table 4. Chronosequence of coverage by ground vegetation and the amount of N stored in the ground vegetation in aboveground parts from intact stands (Year 1) to Year 7 and for the Years 16 to 18 after the dieback (means ± SE) Desflex, waify hair grass; Calvilo, hairy reed grass; Rubidea, red raspberry; Σ, sum; cover, coverage by the respective species.

	Desflex		Calvilo		Mosses		Rubidea		Other species		Σ	
Year	Cover	N	Cover	N	Cover	N	Cover	N	Cover	N	Cover	N
	%	$g\ m^{-2}$	%	$g\ m^{-2}$	%	$g\ m^{-2}$	%	$g\ m^{-2}$	%	$g\ m^{-2}$	%	$g\ m^{-2}$
						Intact						
Year −1	1 ± 1	0.0 ± 0.0	9 ± 2	0.7 ± 0.2	43 ± 6	4.7 ± 0.7	0	0	21 ± 4	1.1 ± 0.3	74 ± 7	6.5 ± 0.4
						Years after the dieback						
Year 0	12 ± 4	0.7 ± 0.3	6 ± 1	0.3 ± 0.1	27 ± 4	3.1 ± 0.5	0	0	19 ± 4	0.9 ± 1.6	64 ± 6	4.9 ± 0.5
Year 1	23 ± 7	2.5 ± 0.8	6 ± 1	0.6 ± 0.1	9 ± 3	0.9 ± 0.3	0	0	21 ± 4	1.3 ± 0.2	59 ± 6	5.4 ± 0.7
Year 2	40 ± 9	4.7 ± 0.3	6 ± 2	0.5 ± 0.2	3 ± 2	0.3 ± 0.2	0	0	21 ± 5	1.0 ± 0.2	70 ± 8	6.6 ± 1.0
Year 3	25 ± 7	0.8 ± 0.7	18 ± 6	1.1 ± 0.4	14 ± 3	1.5 ± 0.4	0	0	12 ± 4	1.2 ± 0.4	69 ± 10	4.5 ± 0.6
Year 4	28 ± 8	2.8 ± 0.9	27 ± 6	2.7 ± 0.7	6 ± 3	0.7 ± 0.3	0	0	8 ± 4	0.7 ± 0.3	68 ± 12	7.0 ± 1.2
Year 5	23 ± 7	1.7 ± 0.5	28 ± 6	2.5 ± 0.5	2 ± 1	0.2 ± 0.1	0	0	12 ± 4	0.4 ± 0.2	65 ± 8	4.7 ± 0.6
Year 6	17 ± 10	2.0 ± 1.2	36 ± 12	3.8 ± 1.2	1 ± 1	0.1 ± 0.1	0	0	8 ± 4	0.1 ± 0.1	62 ± 11	6.0 ± 1.2
Year 7	10 ± 6	0.8 ± 0.4	27 ± 9	3.3 ± 1.1	1 ± 1	0.1 ± 0.1	0 ± 0	0.1 ± 0.1	8 ± 5	0.2 ± 0.1	47 ± 10	4.4 ± 0.9
Year 16	27 ± 10	2.4 ± 0.9	28 ± 10	2.3 ± 0.8	2 ± 2	0.2 ± 0.2	25 ± 10	7.4 ± 3.2	7 ± 5	0.2 ± 0.2	88 ± 8	12.6 ± 2.7
Year 17	25 ± 9	2.6 ± 0.9	25 ± 9	1.3 ± 0.5	4 ± 2	0.4 ± 0.2	21 ± 10	6.8 ± 3.2	8 ± 4	0.3 ± 0.3	83 ± 4	11.5 ± 2.5
Year 18	23 ± 8	1.8 ± 0.6	18 ± 7	1.3 ± 0.5	3 ± 2	0.4 ± 0.2	19 ± 9	6.2 ± 3.1	10 ± 5	0.4 ± 0.2	73 ± 7	10.1 ± 2.7

Deschamspsia flexuosa and (or) Calamagrostis villosa were the most important species for N accumulation from Year 1 to 7 after the dieback. In the Years 16 to 18, Rubus ideaus was responsible for the fact that N accumulation increased (12.58 g N m^{-2} in Year 16). Net storage (storage of N after the dieback in comparison with the year when the stand was intact) is relatively low for the first 7 yr. Partial to totally uncovered patches of ground vegetation are created by forest residues that have fallen from the dead trees and reduce the coverage of the ground vegetation over time.

Coverage of Ground Vegetation and Nitrate Concentration

Figure 4 shows the influence of ground vegetation coverage for different years after the dieback. In the intact stands in the year of the dieback, and in the first year after the dieback, no significant effect of coverage on NO_3^- concentration was detected. Significant effects could be observed for the Years 2, 3, 4, and 5. Nitrate concentrations are high when the coverage of the ground vegetation is low, mostly on places with high amounts of wood debris from the dead trees. On places uncovered by vegetation, leachate of NO_3^- was approximately 400 $\mu mol_c\ L^{-1}$ higher than on fully covered ones. The first pulse of NO_3^- released by mineralization is completed after about 3 yr, during which most of the dead wood is still standing. However, after further disturbances, especially when the standing dead boles break due to white rot and/or storm events, more woody debris accumulates on the ground, the stands open up, and the mineralization pulse starts again with highest NO_3^- concentrations on uncovered places.

DISCUSSION

Massive disturbances of forest vegetation due to clear-felling or other harvesting methods (Vitousek et al., 1979), storm events (Mellert et al., 1996), or insect outbreaks (Swank et al., 1981) can lead to N leaching losses and temporarily elevated NO_3^- concentrations in the soil solution. The fact that NO_3^- concentrations in the study of bark beetle attacks in an unmanaged forest ecosystem generally remained below the European level for drinking water and is predominantly attributed to the relatively high levels of precipitation in that region. Elevated NO_3^- peak concentrations were often found after catastrophic events in Bavarian forests. After clear-cutting the N-saturated Höglwald site average concentrations up to 2750 $\mu mol_c\ L^{-1}$ occurred (Huber et al., 2004b) and after storm events concentrations raised up to 3500 $\mu mol_c\ L^{-1}$) (Mellert et al., 1996). Nitrate concentrations were moderately elevated in case studies in the Austrian Alps (Katzensteiner, 2003), in Northern Bavaria (Weis et al., 2001), Southern Bavaria (Rothe and Mellert, 2004), and in the clear-cut experiment of the Hubbard Brook Experimental Forest (Dahlgren and Driscoll, 1994), though in all experiments the NO_3^- concentration remained below the European limit for drinking water. However, in contrast to these, NO_3^- concentrations in many studies of such catastrophic events remained on a much lower level. In a study of Johnson and Todd (1988) maximum NO_3^- concentrations of ~25 $\mu mol_c\ L^{-1}$ were measured. Relatively low NO_3^- concentrations were observed after clear-cutting a N-limited mixed coniferous stand in Finland (<20 $\mu mol_c\ L^{-1}$; Piirainen et al., 2002), in an Irish catchment study (~40 $\mu mol_c\ L^{-1}$; Cummins and Farrell, 2003), and in the majority of sites clear-felled in Great Britain (Reynolds and Edwards, 1995; Neal et al., 1998). Especially on N-limited or non–N-saturated sites, where forest growth is enhanced by N deposition or fertilization, leaching of NO_3^- after clear-cutting can be very low (Ring, 1995; Berden et al., 1997). Huber et al. (2004a) came to the conclusion that despite the fact that a lot of research has been done, the nitrate and nutrient losses after disturbances of the forest vegetation are difficult to predict for forest managers, as there are no practicable and accurate computer based model predictions available.

In the present study of a "natural dieback" the highest concentrations occurred in the fifth year after the dieback. In other case studies, NO_3^- peaks occurred much earlier. An increase in NO_3^- was observed in Hubbard Brook 1 yr following whole tree harvesting and reached

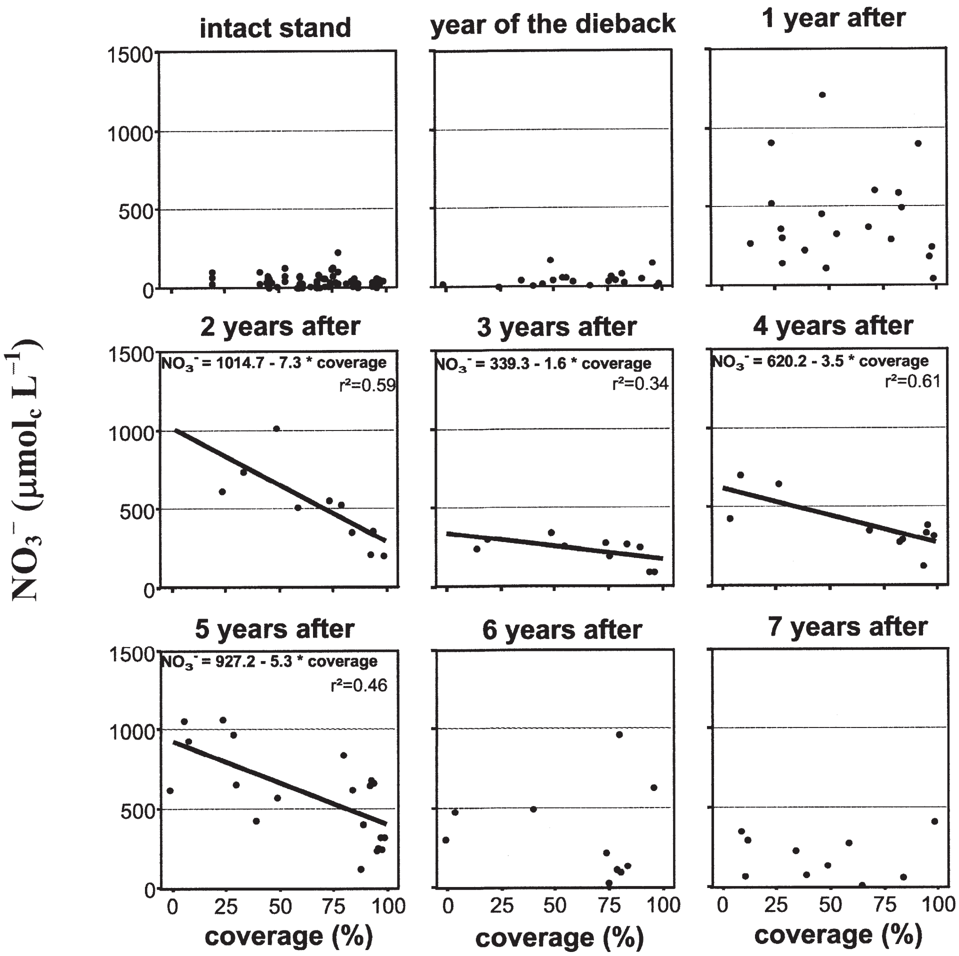

Fig. 4. Impact of coverage by ground vegetation (%) on NO_3^- concentrations (yearly means) before and after the dieback of the stands. A significant regression is marked with a regression line, regression equation, and stability index (r^2).

the maximum in the next year. A decline to near reference concentrations was recognized after 4 to 5 yr (Dahlgren and Driscoll, 1994). In the clear-cut at the N-saturated Höglwald site, the year following the clear cut had the highest NO_3^- concentrations. However, just 2 yr after the clear-cutting, NO_3^- concentrations were below the control plot (Huber et al., 2004b). The delay in NO_3^- peak concentrations in the present study may be explained by the shading effect of standing dead trees in the first years, and by the break down of the stems, and also the addition of organic material to the soil in the following years. Likewise, in the Hubbard Brook experiment, a distinct delay in the release of NO_3^- to the soil solutions could be detected. Borman and Likens (1979) explained the delay by a temporary immobilization of N due to increasing populations of microorganisms consuming organic material with a high C/N ratio. As the C/N ratio decreases and demand by microorganisms for N declines, excess N is released by decomposition and may be leached. In the present study a decrease in the C/N ratio of the humus horizons could also be detected.

In the bark beetle–infested stands, NO_3^- concentrations were higher in autumn, due to lower precipitation (therefore less dilution) and the end of the growing season for the ground vegetation. A lot of disturbed stands also exhibited a seasonal NO_3^- peak after the growing season (Mellert et al., 1996; Weis et al., 2001; De Keersmaeker et al., 2000).

Between Years 2 and 5 after the dieback, I observed a significant reduction of NO_3^- concentrations in seepage water on plots covered by ground vegetation (mostly hairy reed grass and waify hair grass) in comparison with uncovered ones. Hairy reed grass communities reduced NO_3^- leaching significantly in deforested sites in the Beskidy Mountains, Czech Republic (Holub, 2003; Fiala et al., 2005). Also, in the studies of Vitousek et al. (1979), Stevens and Hornung (1990), Emmett et al. (1991), Mellert et al. (1996), and Weis et al. (2001) it was supposed that ground vegetation is an effective sink to reduce NO_3^- concentrations in seepage water.

However, no relevant net N uptake by ground vegetation could be observed when comparing the N storage in ground vegetation from an intact stand with the N storage in Year 7 after the dieback. Due to a mulch effect of wood, bark, twigs, and needles from the dead trees a mosaic is generated with bare to fully covered places. Therefore, the coverage by ground vegetation is from Year 0 to 7, sometimes lower than in an intact stand. In Years 1, 6, and 7 after the dieback, the NO_3^- concentration was independent from coverage by ground vegetation. Compared with the high yearly N losses with seepage, the storage potential by ground vegetation in our study is very limited on a plot scale (see Huber et al., 2004a). A very limited influence of the herb vegetation was also observed in investigations made by Schmidt (2002) in experimentally created canopy gaps in beech forests (*Fagus sylvatica* L.).

Despite the high NO_3^- losses with seepage (500–600 kg N ha^{-1} within 7 yr after the dieback) no significant changes in the total N content of the soil could be detected. The amount of N stored in the residues left on the site equal the losses of seepage water (Huber et al., 2004a), plus an unknown amount due to the emission of N trace gases. The NO_3^- losses, though significant in respect to drinking water quality, are lower than the standard deviation of total N stores in the soil (40-cm depth). When N storage of the soil is high, it is impossible to make conclusions from the parameters total N to other processes of the N cycle.

CONCLUSIONS

The results observed show an example of what may happen after disturbances (in our case bark beetles) in an unmanaged forest ecosystem. The on-site findings are valid for the N-saturated spruce [*Picea abies* (L.) Karst] ecosystems in the highlands of the Bavarian Forest National Park with their specific site conditions and may serve as decision support for the expansion area of the national park (managed until 2017). After the natural dieback, a long period of NO_3^- leaching of >7 yr occurred, and was statistically significant for 5 yr. The highest NO_3^- concentrations were reached after 4 to 5 yr at the end of the growing season. This is in contrast to catastrophic events in managed forests (clear-cut, storm throw), where maximum NO_3^- losses generally occur within the first 2 or 3 yr. The elevated NO_3^- concentrations in seepage water may exhibit a worsening, but not a severe risk for the deterioration of drinking water quality of springs and ground water in the highlands of the Bavarian Forest National Park. The negative effect of NO_3^- leaching were alleviated due to the high precipitation in this region and NO_3^- concentrations usually remained below the European level for drinking water quality (806 $\mu mol_c\ L^{-1}$), but were higher than in a lot of disturbed, but managed forest ecosystems. Studies with tension lysimeters below the main rooting zone are used as indicators for the maximum potential risk of ground water contamination, since denitrification may occur in the further flowpath and reduce NO_3^- concentrations in ground and surface waters. This is a great uncertainty. On the one hand, denitrification in deeper forest soil horizons is thought to be much lower than in surface soils due to a low quantity and quality of organic C. On the other hand, a continuous interaction of subsurface sediments with ground water may compensate for the lower denitrification rates (Hill and Cardaci, 2004).

After the natural dieback, important nutrients stored within slash and wood can remain on the site. However, part of the nutrients (especially K^+ and Mg^{2+}) will also be leached and accompany NO_3^- in seepage water (see results in Huber et al., 2004a).

I also observed a very high heterogeneity in the NO_3^- concentrations. This was seen, at least in part, due to a mosaic of covered and uncovered patches by ground vegetation and slash. However, the ground vegetation did not effectively reduce average NO_3^- concentrations at a plot scale.

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