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Impact of prescribed burning on the nutrient balance of heathlands with particular reference to nitrogen and phosphorus

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Abstract

Question: Can prescribed winter burning compensate atmospheric nutrient loads for dry heathlands? What effects does prescribed burning have on nutrient balances, particularly as regards the limiting nutrients N and P?

Location: Lueneburg Heath, NW Germany.

Methods: In two burning experiments (in 10/15 year old *Calluna*-stands) nutrient balances (for N, Ca, K, Mg, P) were calculated by analysing nutrient inputs (atmospheric deposition, ash deposition), nutrient stores (above-ground biomass, organic horizon) and nutrient outputs (biomass combustion, leaching).

Results: Atmospheric nutrient deposition amounted to 22.8 $kg.ha^{-1}.a^{-1}$ for N and < 0.5 $kg.ha^{-1}.a^{-1}$ for P. Nutrient stores in the above-ground biomass were 95/197 $kg.ha^{-1}$ for N and 5/13 $kg.ha^{-1}$ for P (first/second experiment, respectively). From these stores 90/53% (for N) and 25/14% (for P) were removed by burning. Effects of leaching on nutrient balances were low. In the first two years after burning, leaching rates of N increased by about 4/6 $kg.ha^{-1}$, whereas leaching rates of P did not change significantly. Input/output-ratios showed that prescribed burning leads to positive nutrient balances for N, Ca and Mg in the long term. For example, the amounts of N removed by prescribed burning are equivalent to ca. five years of atmospheric inputs. Applied in ten-year cycles, this measure alone cannot prevent N accumulation in the long term.

Conclusion: Regarding 10/15 year old *Calluna*-heaths, we assume that prescribed burning cannot compensate for atmospheric N inputs, thus making long-term changes in the nutritional state inevitable. Therefore, prescribed burning should be applied in combination with high-intensity management measures.

Keywords: Above-ground biomass; Atmospheric nutrient deposition; *Calluna vulgaris*; *Deschampsia flexuosa*; Heathland management; Leaching; Nutrient removal.

Abbreviation: TEP = Theoretical Effective Period.

Introduction

Heathlands were recognized as an important habitat by the European Union Habitats Directive in 1986 (Webb 1998; Marcos et al. 2003) and are considered one of the most important cultural landscapes in Europe. Conservation of heathlands has become a major issue (Diemont 1996; Terry et al. 2004) and projects have been started at national and international levels aiming at preserving and restoring existing heathlands and re-creating them within their original distribution area (Marcos et al. 2003; Dorland et al. 2003, 2004, 2005).

Traditional land use has perpetuated ecosystems of a low nutrient status in which plant succession is arrested (Webb 1998). Inputs, losses and turnover of nutrients in heathlands, where nutrients are present at low levels, are important in both the functioning and management of habitats (Chapman et al. 1989).

The increasing amount of nutrient input by atmospheric deposition in recent decades and the abandonment of traditional land use has led to an invasion by the grass *Deschampsia flexuosa* or other plant species of less ecological value and, thus, to a transition from *Calluna vulgaris* dominated heathland to grassland (Marrs 1993; Uren et al. 1997; Kirkham 2001; Roem et al. 2002). Such changes in heathlands have been observed in many European countries (Britton et al. 2001; Dorland et al. 2003; Marcos et al. 2003). In order to preserve these landscapes, the employment of management practices to remove nutrients has increased in importance (Erisman & de Vries 2000; Power et al. 2001). Prescribed burning, alongside grazing, is still the predominant measure in the management of lowland heaths (Pakeman et al. 2003). Consequently, the important role of fire in restoring and conserving heathland has been repeatedly documented (e.g. Mallik & Gimingham 1985; Forgeard 1990; Adams et al. 1994; Gimingham 1992; Allchin et al. 1996; Valbuena & Trabaud 2001).

From a nature conservation point-of-view, it is important to know to what extent prescribed burning may counterbalance atmospheric nutrient loads, or whether combinations with high-intensity management measures are needed to preserve a low nutrient status. The main objective of our study was to investigate the effects of fire on the nutrient balances of heathlands in order to assess whether prescribed burning is a sufficient measure for the removal of nutrients added to heathlands by atmospheric deposition. As N and P are known to be the most important nutrients limiting growth of heathlands (Koerselman & Meuleman 1996; Gerdol et al. 2000; Tessier & Raynal 2003), we focused particularly on the effects of prescribed burning on the budget and balance of these nutrients. In addition, balances were calculated for Ca, K and Mg. The following questions have been addressed in our study: 1. Can prescribed winter burning counterbalance atmospheric nutrient loads in dry heathland ecosystems? 2. What effects does prescribed burning have on nutrient balances of heathlands, particularly as regards the limiting nutrients N and P? 3. What impact does the amount of above-ground biomass have on the effectiveness of prescribed burning?

Methods

Study area

The study area is located in the northern part of the nature reserve Lüneburger Heide, Lueneburg Heath (Lower Saxony, NW Germany, 53°15' N, 9°58' E, 105 m a.s.l.). It is characterized by Pleistocene sandy deposits. Prevailing soil types are nutrient-poor Podzols or podzolic soils, with pH_{H2O} values in the topsoil ranging between 3.3 and 3.5. The climate is of a humid suboceanic type. Mean precipitation values amount to 811 $mm.a^{-1}$ and the mean temperature amounts to 8.4 °C (Müller-Westermeier 1996).

Sample plots and prescribed burning procedure

In the study area, two burning experiments were carried out on two randomly selected sample plots, which differed in the age of the dwarf shrub (*Calluna vulgaris*) vegetation. The first sample plot (first experiment) was dominated by about ten-year-old *Calluna vulgaris* stands (with negligible amounts of grasses and cryptogams). The second sample plot (second experiment) was characterized by ca. 15-year-old *Calluna vulgaris* stands, in which *Deschampsia flexuosa* and cryptogams (forming an understorey layer under the dwarf shrub canopy) were co-dominant. Owing to the fact that *Calluna vulgaris* was older, above-ground biomass was expected to be higher in Experiment. 2. In each sample plot (0.8 ha in size) eight experimental plots (20 m × 20 m in size) were selected at random. Four experimental plots were burned (treatment plots), and the remaining four served as controls (control plots; i.e. four replicates per experiment). In the Lueneburg Heath, prescribed burning is generally applied during the winter. Important prerequisites for prescribed burning are periods of fine weather and low wind velocities. Winter burns are low-temperature fires and, thus, do not affect the organic horizon (Niemeyer et al. 2004). Treatment plots in the first experiment were burned in late winter (16.02.2001), and in Experiment 2 in early autumn (18.10.2001). The two sample plots were neither managed nor grazed during the past decade.

Analysis of atmospheric nutrient inputs

Atmospheric nutrient input was measured by means of 12 bulk samplers (type Münden 200; Inst. of Forest Hydrology, Hannoversch Münden, DE) installed 100 cm above ground (six samplers per experiment). To avoid contamination by birds or insects, samplers were protected by a surrounding ring and a synthetic sieve inside. Samples were collected biweekly for a period of two years in the first experiment, and for one year in Experiment 2 (starting immediately after the burning of treatment plots). Samples were kept in a fridge (< 4 °C; for a maximum of three months) until analysis. Ca-, K-, Mg- and P-concentrations were determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES; Optima 3300 RL; Perkin Elmer, Burladingen, DE). For analysing N-concentrations samples were dissolved in a K_2SO_4-NaOH solution according to the Koroleff method (Grasshoff et al. 1983), and afterwards subjected to microwave digestion (MLS-ETHOS; MLS-GmbH, Leutkirch, DE). Total N was measured with an ion chromatograph (IC-DX 120 Dionex; Idstein, DE). The analysis procedure described above makes chemical conservation of samples unnecessary (Grasshoff et al. 1983).

In experiments over a period of six years, Gauger et al. (2000) compared bulk – and total (wet and dry) – deposition data. The authors found that bulk deposition samplers underestimate total N-, Ca-, K-, and Mg-deposition by about 23.2%, 35.3%, 25.0% and 35.7%, respectively. In order to estimate the total deposition, bulk deposition of N, Ca, K and Mg was corrected by the factors 1.30, 1.54, 1.33 and 1.55, respectively (according to Gauger et al. 2000; Bleeker et al. 2000).

Analysis of nutrient losses by leaching

Nutrient loss by leaching was determined by means of a lysimeter consisting of intact soil cores (100 cm in length and 10 cm in diameter) and tension controlled porous cup soil water samplers (PE-sinter/0.45 µ nylon-membrane; Umwelt-Geräte-Technik, Müncheberg, DE). Soil water samplers were installed at depths of 100 cm. In the first experiment, the leachate was analysed over a period of two years in two treatment and two control plots ($n = 2$). The leachate in Experiment 2 was analysed in all treatment and all control plots ($n = 4$). Samples were taken simultaneously and at the same intervals as deposition samples. Digestion and analysing procedures were the same as for the deposition samples.

Analysis of the nutrient stores in the above-ground biomass and organic horizon

In order to determine nutrient stores in the above-ground biomass, above-ground plant material in the treatment plots was harvested on randomly selected 1-m^2 patches before and immediately after burning ($n = 4$). Harvested plant material was separated into three groups: dwarf shrubs (i.e. *Calluna vulgaris*), graminoids (i.e. *Deschampsia flexuosa*) and cryptogams. Dried material (105 °C) was weighed, cut with a cutting mill (SM 100 S; Retsch, Haan, DE) and afterwards ground with a ball mill (pulverisette 7; Fritsch, Idar-Oberstein, DE).

In the treatment plots the organic layer was harvested on square areas (10 m × 10 cm in size) located at the intersection points of a 10 m × 10 m grid (points spaced 2 m apart). A total of 36 samples were obtained and thoroughly mixed (i.e. one sample per plot, $n = 4$ per experiment). This procedure was repeated immediately after burning in order to determine the level of nutrient input as a result of ash deposition. Organic material was treated in the same way as the above-ground biomass.

The N-content of ground material from plants and the O-horizon was analysed with a C/N-analyser (Vario EL; Elementar, Hanau, DE). In order to determine the Ca-, K-, Mg- and P-contents in plants and the O-horizon, ground material was dissolved in an HNO_3/HCl/H_2O_2-solution using microwave digestion (Lamble & Hill 1998; Wong et al. 1997). Digests were analysed with Inductively coupled plasma optical emission spectroscopy, ICP-OES.

Calculation of nutrient balances

For the calculation of nutrient balances, net nutrient inputs were compared with net nutrient outputs. We defined the annual net input of nutrients as the difference between the annual deposition and the annual leaching measured in the control plots. Nutrient losses from the above-ground biomass were calculated by comparing nutrient contents of the above-ground biomass and the unburned remainder. Nutrient losses during the burning procedure are due to the emission of gaseous compounds and ash particles (Diemont 1996). Ash particles are partly deposited and thus remain in the system (Allen et al. 1969; Evans & Allen 1971; Gimingham 1972). The nutrient deposition by ash and possible combustion of organic material (of the O-horizon) was calculated by comparing the nutrient contents of the O-horizon (of treatment plots) before and immediately after burning.

It is likely that leaching rates increase after burning due to increased mineralization rates in the O-horizon (Mallik 1986; Berendse 1990; Kirschbaum 1995; Schmidt et al. 2002) and decreased transpiration rates of the vegetation (Mallik & FitzPatrik 1996; Anderson & Hetherington 1999). With the regeneration of vegetation, leaching rates decrease continuously whilst evapotranspiration and nutrient uptake rates of the regenerating vegetation increase (Gimingham 1972; Forgeard 1990). According to Forgeard (1990), Maltby et al. (1990) and Sedláková & Chytrý (1999) it takes about six years for the vegetation cover (particularly as regards the dwarf shrubs) to achieve the situation as it was prior to prescribed burning. Hence, it is likely that increased leaching rates take place mainly within six years after burning, due to the effects described above. In order to calculate the increase of leaching rates after burning in approximation, we presume that nutrient outputs by leaching are maximal within two years after burning (Experiment 1: measured; Experiment 2: calculated according to the results of Experiment 1). With the vegetation recovery in the third year after burning, nutrient losses by leaching decrease continuously (linear decrease) until the status quo ante is achieved after six years. Thus, the total amounts of nutrient loss in a heath due to increased leaching after burning, may be calculated according to the following equation:

$$\begin{aligned} L_{(6yr)} &= L_{(1yr)} + L_{(2yr)} + {}^{4}/_{5}\, L_{(2yr)} + {}^{3}/_{5}\, L_{(2yr)} + {}^{2}/_{5}\, L_{(2yr)} + {}^{1}/_{5}\, L_{(2yr)} \\ &-6\, L_{(control)} = L_{(1yr)} + 3L_{(2yr)} - 6\, L_{(control)} \end{aligned} \tag{1}$$

where:

$L_{(6yr)}$ = increase in leaching due to the application of prescribed burning (i.e. within six years after heathland burning);

$L_{(1yr)}$ = amount of leaching in the treatment plots in the first year;

$L_{(2yr)}$ = amount of leaching in the treatment plots in the second year;

$L_{(control)}$ = amount of annual leaching in the control.

Calculation of the theoretical effective period (TEP)

Total nutrient loss (due to the combustion of the above-ground biomass and increased leaching rates) was related to the annual net input (annual atmospheric nutrient deposition minus leaching rates in the control). This relationship provides a term of reference that describes the period of time (in years) to which the amount of nutrients removed due to prescribed burning and atmospheric nutrient input is equivalent (Britton et al. 2001). We call this the Theoretical Effective Period (TEP).

The TEP for a particular nutrient element is calculated according to the following formula:

$$\mathrm{TEP}_{(\mathrm{N,P,Ca,Mg,K})} = \frac{\text{output biomass} + \text{output increased leaching}}{\text{annual net nutrient input}} \qquad (2)$$

where:
output biomass = differences between the amounts of nutrients in the above-ground biomass in treatment plots before and after burning minus ash deposition;
output increased leaching = differences in leaching levels between the treatment and corresponding control plots (within six years after burning);
annual net input = annual nutrient deposition minus annual leaching in the control plots.
For the calculation of the TEP we assumed that deposition rates remain unchanged over the subsequent years.

Statistics

Measurement results from atmospheric deposition, leaching, above-ground biomass and the O-horizon were subjected to one-way ANOVA (SPSS 11.5 for Windows) and Tukey's post-hoc test. Log-transformation of leaching data and arcsine-transformation of data from atmospheric deposition, nutrient contents of the above-ground biomass and O-horizon were performed prior to ANOVA.

Table 1. Annual total nutrient deposition (wet and dry deposition; means and ± 1 SD in brackets, $n = 12$) in the Lueneburg Heath. Deposition rates for P were below the analytically detectable threshold value. They thus amount to less than 0.5 kg.ha^{-1}.a^{-1}.

	N	Ca	K	Mg	P
Bulk deposition	17.5	3.3	2.7	1.8	<0.5
Estimated total deposition	22.8 (0.59)	5.1 (0.32)	3.6 (0.37)	2.8 (0.15)	<0.5

Results

Atmospheric nutrient inputs and net input rates

A comparison of the atmospheric nutrient deposition revealed no significant differences between the 12 bulk samplers ($p > 0.05$). Thus, atmospheric nutrient deposition was considered to be equal for all the experimental plots. Table 1 gives an overview of the annual amounts of nutrient deposition (means and SD) with respect to the nutrient elements considered. The N-input amounted to 22.8 kg.ha^{-1}.a^{-1}. P-deposition rates fell below the analytically detectable threshold value (0.0326 mg.L^{-1}). Deposition rates are, thus, below 0.5 kg.ha^{-1}.a^{-1}. With the exception of K, annual net input rates were in a comparable range for both experiments (e.g. for N 20.8 kg.ha^{-1}.a^{-1} and 21.0 kg.ha^{-1}.a^{-1};Table 2).

Leaching

Leaching rates in the treatment plots were elevated during the two years following burning (Figs. 1 and 2). They were particularly high for N, Ca and K immediately after burning and varied in a nutrient typical pattern during the course of the two years investigated (first experiment, Fig. 1). Amounts of leached nutrients were significantly higher in treatment plots than in controls for N, Ca, K and Mg in the first year, and for N, Ca and K in the second year. No significant differences were found for Mg in the second year or for P in either year. However, it should be mentioned that leaching rates of P were close to the analytically detectable threshold value. The second burning experiment yielded similar results (Fig. 2). Significantly increased leaching was found in the treatment plots for N, Ca and Mg, in which, again, the increase of nutrient losses was highest for N and Ca.

Nutrient stores in the above-ground biomass and O-horizon before and after burning

In the first experiment, above-ground biomass of *Calluna vulgaris* amounted to 11 806 kg.ha^{-1}. 84% of this biomass was burned. In Experiment 2, the above-ground biomass ratios of *Calluna* : *Deschampsia* : cryptogams amounted to 12 179 : 466 : 5311 kg.ha^{-1}. Of these groups ca. 28 : 88 : 81% of the above-ground biomass remained after burning. Table 2 summarizes the results with respect to the nutrient stores in the above-ground biomass and the O-horizon and the outputs due to burning. In the first experiment between 90-98% of the nutrients that were fixed in the above-ground biomass were removed. For example, only 10.3% (= 9.8 kg.ha^{-1}) of the N remained in the unburned above-ground biomass (N-content before burning: 95.3 kg.ha^{-1}).

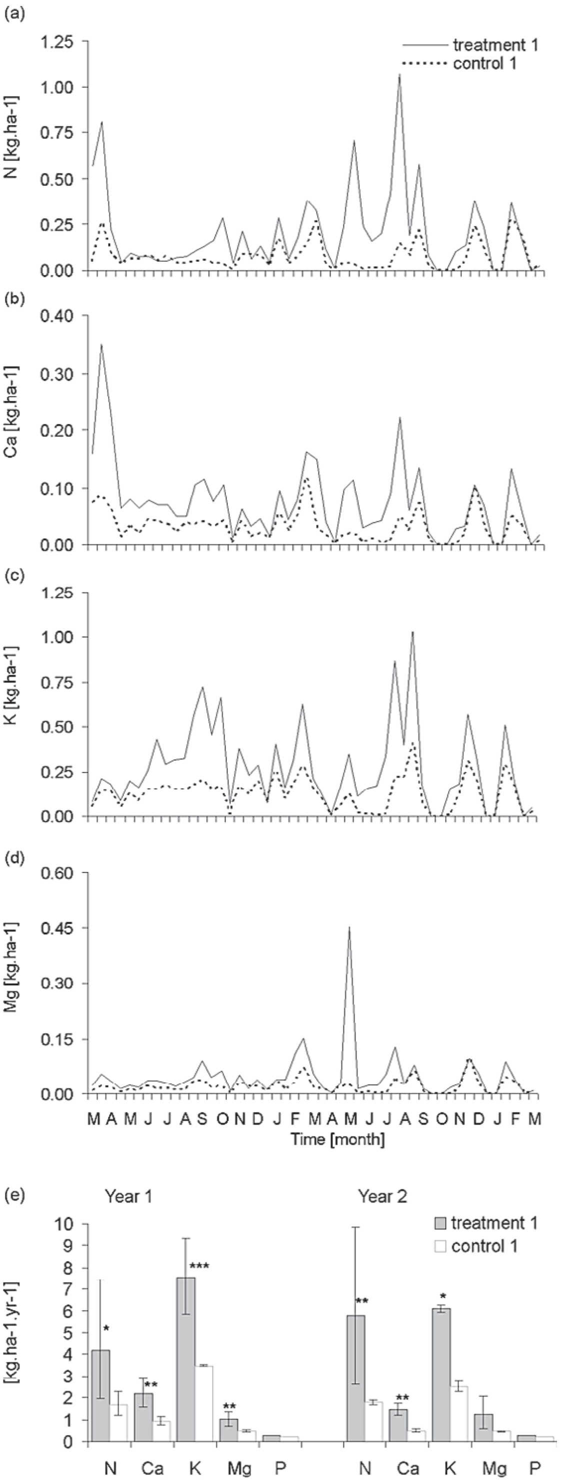

Fig. 1. Annual course (two-year period) of leaching of N (**a**), Ca (**b**), K (**c**) and Mg (**d**) (treatment plots: solid line; control plots: thin line) and annual amounts of nutrients leached (**e**) in the treatment plots (closed columns) and the control plots (open columns) in the first and the second year after burning (Experiment 1); **a-d:** Means of two samples, *n* = 52 measurements; **e:** Means, max. and min. values; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

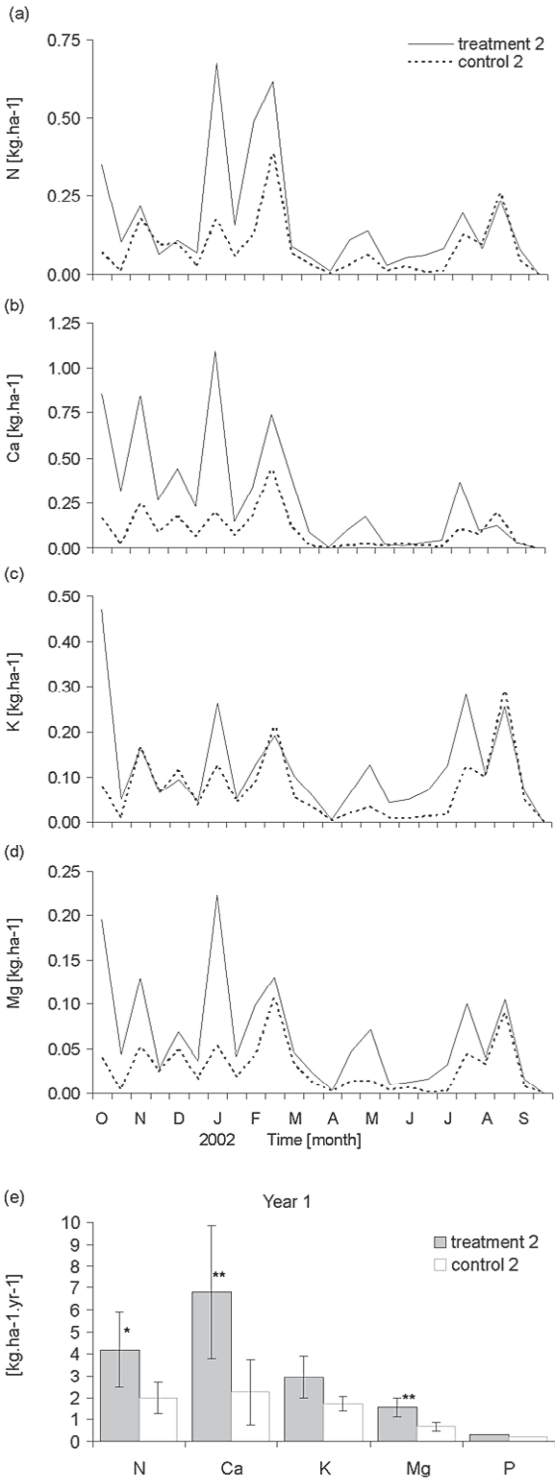

Fig. 2. Annual course (one year period) of leaching of N (**a**), Ca (**b**), K (**c**) and Mg (**d**) (treatment plots: solid line; control plots: thin line) and annual amounts of nutrients leached (**e**) in the treatment plots (closed columns) and the control plots (open columns) one year after burning (Experiment 2); **a-d:** Means of four samplers, *n* = measurements; **e:** Means ± 1 SD; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

Table 2. Impact of prescribed burning on nutrient balances of heathlands (studied in the Lueneburg Heath in two burning experiments); values are given for the input, stores and output of nutrients; mean values of: $n = 4$ (+) or $n = 12$ (++) and ± 1 SD (in brackets) in kg.ha^{-1}; Theoretical Effective Period (TEP) in years; significant differences in the nutrient stores of the O-horizon due to ash deposition are marked with: * = $p < 0.05$; ** = $p < 0.01$; ns = not significant; nc = not calculated; calculation of the increase of leaching after burning, see text.

		Experiment 1					Experiment 2				
		N	Ca	K	Mg	P	N	Ca	K	Mg	P
Calculated input	Annual atmospheric deposition^{++}	22.8	5.1	3.6	2.8	<0.5	22.8	5.1	3.6	2.8	<0.5
	Annual leaching control plot^{+}	1.8	0.7	3.0	0.5	<0.2	2.0	2.0	1.7	0.7	<0.2
		(0.5)	(0.3)	(0.8)	(0.1)	(nc)	(0.2)	(0.6)	(0.1)	(0.1)	(nc)
	Annual net input	21.0	4.4	0.6	2.3	<0.3	20.8	3.1	1.9	2.1	<0.3
Nutrient stores	Above-ground biomass^{+}	95.3	34.3	26.6	9.6	4.8	196.9	67.4	56.3	18.2	12.9
		(10.7)	(2.3)	(3.1)	(0.8)	(0.2)	(28.3)	(7.5)	(10.3)	(1.2)	(1.4)
	Unburned remainder^{+}	9.8	1.5	0.5	0.3	0.4	92.7	28.2	13.0	6.2	4.9
		(3.5)	(0.6)	(0.2)	(0.1)	(0.1)	(10.5)	(5.2)	(5.3)	(1.2)	(0.7)
	Burned biomass	85.5	32.8	26.1	9.3	4.4	104.2	39.2	43.3	12.0	8.0
	O-horizon before burning^{+}	771.8	77.8	30.6	17.8	25.4	736.1	56.1	31.2	16.9	23.5
		(89.0)	(12.6)	(7.6)	(1.9)	(3.1)	(95.4)	(11.1)	(5.1)	(3.4)	(5.1)
	O-horizon after burning^{+}	766.5 ^{ns}	103.8 ^{ns}	49.7*	26.8**	28.8 ^{ns}	741.3 ^{ns}	91.6**	49.3**	27.8**	29.9 ^{ns}
		(148.6)	(28.4)	(17.7)	(3.0)	(4.1)	(13.1)	(139.0)	(13.4)	(6.4)	(4.5)
	Ash deposition	–5.3	26.0	19.1	9.0	3.4	5.2	35.5	18.1	10.9	6.4
Output	Due to burning (smoke)	90.8	6.8	7.0	0.3	1.0	99.0	3.7	25.2	1.1	1.6
	Due to leaching	12.4	3.3	12.2	2.5	<0.2	11.1	9.3	2.9	4.1	<0.3
	Total output	103.2	10.1	19.2	2.8	<1.2	110.1	13.0	28.1	5.2	<1.9
	TEP (years)	4.9	2.3	32.2	1.2	nc.	5.3	4.2	14.8	2.5	nc

With the exception of N in Experiment 1, the nutrient stores of the O-horizon increased as a result of ash deposition. The nutrient contents in the O-horizon after burning were significantly higher for K and Mg (in Experiment 1) and for Ca, K, and Mg (in Experiment 2). Although the percentage of nutrient losses from the above-ground biomass in Experiment 2 (53-77%) was lower than in the first, the total amounts of nutrients removed in Experiment 2 were clearly higher (e.g. for N: 104.2 kg.ha^{-1}; Table 2). With the exception of N, the amounts of nutrients returned to the system due to ash deposition are related to the amounts of nutrients fixed in the above-ground biomass.

Comparison of the TEPs

In order to calculate the TEP with respect to a particular nutrient, the input, stores, and output rates were compared (Table 2). The TEP for a particular nutrient element is shown in the bottom row of Table 2. As regards nitrogen, for example, prescribed burning removed the amount of N that corresponds to 4.9 and 5.3 years of atmospheric input (Experiments 1 and 2, respectively). The shortest TEP was found for Ca, and amounts to 2.3 a (Experiment 1) and 4.2 a (Experiment 2). TEP for P was not calculated, as P-concentrations in the deposition and the leachate fell below the analytically detectable threshold value.

Discussion

Atmospheric nutrient inputs

The rates of atmospheric nutrient deposition found in our study area are in good agreement with other records in NW Germany (Meeseburg et al. 1995; Mück 1998; Gauger et al. 2000; Anon. 2000). They are also in the range reported in studies from the British Isles (Power et al. 1998, 2001; Kirkham 2001), and are somewhat lower than deposition rates in the Netherlands (Bakema et al. 1994; Erisman & de Vries 2000). This indicates that our study area is exposed to deposition rates which are representative for quite a number of heaths in northwestern Central Europe.

Leaching

Comparisons of leaching data are difficult due to the lack of corresponding analyses. Leaching values for N reported for heaths in NW Germany are in a comparable range to our findings (Matzner & Ulrich 1980; Engel 1988; Schlieske 1992), but these were based on rough calculation rather than on direct measurements. Mück (1998) analysed N leaching rates under *Calluna vulgaris* stands in the Lueneburg Heath, which amounted to 7.3 kg.ha^{-1} in 1989 and to 2.9 kg.ha^{-1} in 1990. The author assumed that the high values found in

1989 resulted from high summer temperatures leading to increased N-mineralisation rates and, thus, to increased leaching. Allen (1964) and Allen et al. (1969) reported on burning experiments and effects on leaching in heathlands in the UK. They found nutrient losses (Ca, K, Mg and P) by leaching after heather burning ranging from 0.01 to 1 kg.ha^{-1}.a^{-1}. Discrepancies between these and our results may be explained by different atmospheric deposition rates, differences in soil conditions, different temperatures and precipitation rates during the summer and different nutrient contents in the burned biomass. However, the impact of the above-ground biomass available for combustion was comparatively low in our experiments. For example, although the N-store in the biomass in Experiment 2 was about twice that of Experiment 1, leaching rates for N after burning were in a comparable range in both experiments (Table 2). Thus, we assume that the major impacts on leaching (particularly for N) are deposition rates and soil surface temperatures (of the O-horizon) affecting the litter mineralization.

In our experiments, differences in leaching between treatment and control plots were particularly high immediately after burning and during the summer, as the removal of a shading dwarf shrub layer led to significantly increased soil surface temperatures in the treatment plots (Niemeyer et al. 2004). The distinct increase in leaching of Ca may be due to the high Ca-concentrations in the ash (26.0 and 35.5 kg.ha^{-1}, respectively). High amounts of Ca mobilised after burning remain unused by the regenerating vegetation, and thus were to be found to a high proportion in the leachate. In addition, it is likely that high NH_4^+-concentrations (appearing after heathland burning) may lead to a replacement of cations (Mg, Ca and K) at exchange sites in the soil (Brady & Weil 1996). This process may also explain increased leaching rates for Ca, Mg and K, as these ions are replaced by NH_4^+.

In our experiments, the course of post-management leaching rates was calculated in approximation. Thus, uncertainties in the calculation of leaching rates may affect the outcomes for the TEP. However, the amount of nutrient loss due to leaching after heathland burning is very low compared to the nutrient losses from the above-ground biomass. For example, if the increase of leaching rates for N in Experiment 2 is underestimated by about 50% (i.e., 11.1 instead of 16.6 kg.ha^{-1}), TEP will increase only by about 3.8% (from 5.3 to 5.5 a). Leaching, thus, has negligible effects on the nutrient balances, and uncertainties in its calculation have only slight effects on TEP outcomes.

Nutrient output from the above-ground biomass

Although the above-ground biomass within the experimental plots was variable within a wider range, the mean values of nutrient stores (for N and P) were in good agreement with findings of other authors (Matzner & Ulrich 1980; Engel 1988; Aerts 1993; Alonso et al. 2001; Kirkham 2001). Hence, the stands investigated in this study may be considered as representative of many heaths in northwestern Central Europe as regards both their structure and the nutrient stores of the above-ground biomass.

As our experiments showed, the amounts of nutrient loss due to burning increase with increasing above-ground biomass available for combustion. Nevertheless, the effectiveness of a fire at removing nutrients (expressed in percentage of removed nutrients) may not increase with increasing biomass. For example, in Experiment 1 ca. 90% of the N fixed in the biomass was removed (compared to only 53% in Experiment 2), although the ratio of the biomass N-content in the experiments amounted to 95.3 : 196.9 kg.ha-1. This finding may apply to winter burns in particular, as a complete combustion of high standing stocks is unlikely in the winter months, due to low burning temperatures (Power et al. 2001; Terry et al. 2004). In addition, with increasing burning intervals (and thus increasing age of stands), *Calluna vulgaris* stems sometimes remain unburned (Nilsen et al. 2005). This is in agreement with our results, as in Experiment 1 84%, and in Experiment 2 only 72% of *Calluna*-biomass was burned. The reduced quantities of nutrient losses in Experiment 2 also can be attributed to the high proportion of *Deschampsia flexuosa* and cryptogams in the above-ground biomass. More than 80% of the biomass of these groups remained unburned in the treatment plots. The amounts of nutrients removed by prescribed burning are also affected by stochastic parameters such as the water content of the vegetation, soil humidity, and effects of wind (Gimingham 1972; Hobbs & Gimingham 1984). Owing to a missing layer of cryptogams protecting the O-horizon in Experiment 1, it is likely that this horizon was slightly affected by burning. This may explain the negative balance for N as regards the O-horizon in Experiment 1. However, pre-/post-treatment differences in the N-content of the O-horizon are not significant at the level of $p = 0.05$. In our experiments, the nutrient losses from the above-ground biomass are in a range well comparable with that calculated in other studies (Diemont 1996; Terry et al. 2004), but they may be distinctly higher with increasing fire temperatures (Diemont 1996). In summary, the amounts of nutrients removed from heathlands by means of prescribed burning may vary due to the effects of all the parameters mentioned above

(Robertson & Davies 1965; Chapman 1967; Allen et al. 1969; Terry et al. 2004).

Our results show that prescribed burning has the potential to remove comparatively high amounts of N fixed in the above-ground biomass. By contrast, Ca, K, Mg and P were found in high amounts in the ash and, thus, remain in the system. This may be attributed to the fact that N-removal by prescribed burning is due to both losses of gaseous N and losses through small ash particles (Allen et al. 1969; Chapman 1967; Diemont 1996). Assessing the effectiveness of management measures as regards their potential to mitigate atmospheric nutrient loads, prescribed burning is as efficient as low-intensity mowing (Power et al. 2001; Sieber et al. 2004; Terry et al. 2004). However, compared to high-intensity management measures (e.g. sod-cutting) the amounts of nutrients removed by winter burns are low (Chapman 1967; Sieber et al. 2004; Terry et al. 2004), because in most cases O-horizons with high nutrient stores (cf. Table 2) remain unaffected since combustion temperatures are low. Our results suggest that the effectiveness of prescribed winter burning on removing N from heathland ecosystems increases with shorter management cycles (i.e. the burning of heath at 10-year rather than 15-year intervals).

Nutrient balances and TEP

As regards the TEP for the nutrient elements considered, in both experiments only TEPs for K exceed values of 10 years (Table 2, bottom row). As prescribed burning is generally not applied within a cycle of less than 10-15 years, due to the period of time that vegetation needs for recovery (Miller & Miles 1970; Terry et al. 2004), stands subjected to prescribed winter burning will accumulate N, Ca and Mg in the long term.

These findings must be interpreted in the light of the fact that heathland ecosystems are considered to be N-(co-)limited on the vegetation level (Koerselman & Meuleman 1996; Roem & Berendse 2000; Tessier & Raynal 2003). Hence, habitat management can mitigate some effects of atmospheric nutrient loads, particularly by maintaining a long-term balance of N-budgets. Our results suggest that prescribed winter burning as a low-intensity measure (Power et al. 2001, 2004) cannot compensate the present-day atmospheric N-loads within an application cycle of ca. 10 years. As burning procedures of heaths have many positive effects on heathland dynamics (e.g. rejuvenation of *Calluna vulgaris*; Gimingham 1992; Allchin et al. 1996; Valbuena & Trabaud 2001), they should be applied in combination with more intensive techniques (e.g. high-intensity mowing, sod-cutting) in order to preserve balanced budgets for growth-limiting and competition-controlling nutrients in the long term. It remains unclear to what extent atmospheric nutrient loads (particularly for N) will accelerate vegetation growth (Berendse et al. 1994; Power et al. 1998), which would allow for shorter management cycles (Diemont 1996). This would increase the effectiveness of management measures as regards the nutrient output.

Outcomes of TEP are affected by some other soil chemical processes that have not been quantified in this study, but need to be addressed when interpreting TEP outcomes. One source of uncertainty in our calculation of the TEPs for N are losses caused by denitrification. Such losses would increase the output rates and thus the TEP. As denitrification takes place primarily in wet heathlands (Troelstra et al. 1997), the underestimation of the TEP in our study may be comparatively low regarding this process. In addition, an interpretation of TEP outcomes must also consider the fact that small amounts of K, Ca and Mg may be released from soils due to weathering of minerals (Brady & Weil 1996). In the sandy podzols of the study area, Ca-, Mg- and K-contents of the C-horizons are below 0.1%, 0.1%, and 1.1%, respectively (Scheffer & Schachtschabel 2002). These stores are very low compared with stores in the above-ground biomass and humus-horizons. Weathering of minerals thus may have slight effects on the TEP calculated for K, but is negligible for Ca and Mg (regarding podzols). Uncertainties in the calculation of the TEP due to difficulties in estimating post-management leaching rates have been discussed above (see section on leaching).

In summary, our study provides evidence that low-intensity (winter) burns are not sufficient to compensate present-day atmospheric N-deposition. In this context, it may be important that effects of N on shoot growth of *Calluna vulgaris* are lower in those heaths which had received more intensive management treatments (Barker et al. 2004). However, in order to preserve a balanced N-budget on a long-term basis, high-intensity measures, which may be applied in combination with low-intensity measures (prescribed burning, grazing), will be an indispensable instrument in heathland preservation.

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