Nährstofflimitierung in *Calluna*-Heiden Nordwestdeutschlands

am Beispiel von extensiven und intensiven Pflegeverfahren

vorgelegt von
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Einleitung

Zwergstrauchheiden zählen zu den ältesten Kulturlandschaften Europas. Ihre Entstehung lässt sich aufgrund pollenanalytischer Befunde in die Jungsteinzeit datieren (Volksen 1993; Lütkepohl & Kaiser 1997; Härdtle 2004). Bestimmende Faktoren für die Entstehung und den Erhalt der Heiden waren neben klimatischen Voraussetzungen eine ganzjährige Weidenutzung und der Einsatz von Feuer. Im Zuge der historischen Heidebauernwirtschaft entwickelten sich Landnutzungssysteme, die durch einen räumlichen Nährstofftransfer von den weiten Heiden (outfields) als Nährstoffquelle zu den hofnahen Gärten und Äckern (infields) als konzentrierende Nährstoffsenke gekennzeichnet waren (Kaland 1986; Küster 1999; Haaland 2002; Webb 2002; Prüter 2004).

Sowohl eine veränderte traditionelle Landnutzung als auch erhöhte atmogene Nährstoffeinträge griffen massiv in den Nährstoffhaushalt der Heiden ein. Dies führte insbesondere während der letzten Jahrzehnte zu einem europaweiten Rückgang von Heideflächen. Vor allem erhöhte atmogene Stickstoffeinträge werden ursächlich in Zusammenhang mit einer verstärkten Vergrasung der Heiden gebracht. In den Niederlanden beispielsweise führte dies zu einem Flächenverlust von mehr als 35% von ehemals *Calluna* dominierten Heiden (Van der Eerden et al. 1991; Aerts 1993; Bobbink & Heil 1993; Berendse et al. 1994; Barker et al. 2004). Auch in der Lüneburger Heide wurden Verluste an Heideflächen beobachtet; heute umfassen trockene Sandheiden nur noch etwa 19 % des Naturschutzgebietes (Keienburg et al. 2004).

Deshalb zählen Zwergstrauchheiden sowohl auf nationaler (§2 und §30 BNatschG; §2 und §28a NNatG) als auch auf europäischer Ebene (FFH-Richtlinie der Europäischen Union) zu den besonders schützenswerten Kulturlandschaften Europas. Das moderne Management von Heiden hat neben der Verjüngung der Heidebestände in zunehmendem Maße die Aufgabe, die Wirkung von Nährstoffeinträgen auf die Vegetation zumindest teilweise zu kompensieren. In den meisten Ländern Mittel- und Westeuropas wird dies heute öffentlich finanziert und von Naturschutzorganisationen und/oder der öffentlichen Hand, häufig innerhalb von Schutzgebieten umgesetzt.

Im NSG Lüneburger Heide werden zur Heidepflege vor allem die Beweidung mit Heideschnucken, maschinelle Pflegemaßnahmen wie Mähen, Schoppern oder Plaggen und der kontrollierte Feuereinsatz im Winterhalbjahr durchgeführt. Diese Pflegemaßnahmen orientieren sich in ihrer Wirkung an historischen Bewirtschaftungsverfahren. Die Kombination verschiedener Verfahren bewirkt einen erheblichen Austrag von Nährstoffen aus den Heideflächen und sorgt für die notwendige Verjüngung der Besenheide.

Stickstoff (N) und Phosphor (P) gelten für die terrestrischen Ökosysteme als die überwiegend wachstumslimitierenden Elemente (Koerselman & Meuleman 1996; Kirkham 2001; Tessier & Raynal 2003; Güsewell 2004). In den sauren, nährstoffarmen Heideökosystemen Nordwest-Europas wird in der Regel N als das alleinige wachstumslimitierende Nährelement betrachtet. Das hängt damit zusammen, dass die Mineralisationsrate in solchen Systemen gering ist und die Nährstoffe in Form von komplexen organischen Verbindungen fixiert sind (Read 1991; Genny et al. 2000). Als dominierende Arten dieser Systeme gelten *Erica tetralix, Calluna vulgaris* und *Empetrum nigrum* (Aerts & Heil 1993). Diese Arten leben in Symbiose mit Mykorrhiza-Pilzen, welche die Fähigkeit haben, den organisch gebundenen Stickstoff in mineralische Verbindungen umzuwandeln und den Pflanzen für ihre Ernährung zu Verfügung zu stellen. Damit sind diese von der Mineralisation organischer Substanzen weniger abhängig.

Die Vegetation in diesen Heiden umfasst auch Gräser wie z.B. *Deschampsia flexuosa* und *Molinia caerulea,* die - nur bei einem hohen Niveau pflanzenverfügbarer Nährstoffe - hohe Konkurrenzfähigkeit besitzen. Da diese Arten keine bzw. nur eine begrenzte Kapazität haben, die organischen N-Quellen zu verwenden, sind sie unter nährstoffarmen Bedingungen gegenüber den mykorrhizierten Arten stark benachteiligt. Diese stabile Konkurrenzsituation kann durch die erhöhten atmosphärischen N-Einträge gestört werden (Aerts & Chapin 2000). Dies führte dazu, dass es zu einer zunehmenden Vergrasung mit *Deschampsia* (Sandheiden) und *Molinia* (Moorheiden) kam (Marrs 1993; Uren et al. 1997; Kirkham 2001; Roem et al. 2002; Dorland et al. 2004).

Die N-Vorräte in der oberirdischen Biomasse stellen weniger als 20% des gesamten N-Haushaltes im Heidesystem dar (Power et al. 1998). Die größten Vorräte dieses Elementes befinden sich im Boden. Eine gründliche Standortsanierung mit dem Ziel eines erheblichen N-Austrages kann durch einen Abtrag der Rohhumusschicht erreicht werden (De Graff et al. 1998). Im Hinblick auf den N-Haushalt wirken sich die derzeit praktizierten Verfahren der Heidepflege sehr unterschiedlich aus. Durch extensive Mahd und kontrollierten Winterbrand kann nur ein großer Teil der oberirdischen Biomasse entfernt bzw. verbrannt werden. Dagegen werden beim Schoppern die oberirdische Biomasse und der überwiegende Teil der O-Lage und beim Plaggen die oberirdische Biomasse, die O-Lage und eine variable Menge des A-Horizontes entfernt. Aus diesem Grund wirken sich die jeweiligen Pflegeverfahren je nach Art und Anwendungszyklus nicht nur auf die Vegetation, sondern auch in unterschiedlichem Maße auf die Stickstoffvorräte im System aus.

Im Rahmen dieser Arbeit werden Ergebnisse aus verschiedenen Feldstudien vorgestellt, die zusätzliche Erkenntnisse zur Erhaltung von *Calluna*-Heiden liefern bzw. eine Optimierung des Heidemanagements ermöglichen. Zu diesem Zweck wurden am Beispiel der Lüneburger Heide die Auswirkungen extensiver und intensiver Heidepflegeverfahren auf die Nährstofflimitierung als Triebkraft der Ökosystemdynamik bzw. -entwicklung untersucht.

Die vorliegende kumulative Dissertationsschrift umfasst vier Beiträge. Die Ergebnisse basieren auf Forschungsarbeiten, die im Rahmen eines BMBF-Projektes von 2001 bis 2004 im NSG Lüneburger Heide durchgeführt wurden. Nachfolgend werden die Fragestellungen und die Methoden für die einzelnen Beiträge dargestellt. Abschließend werden die wichtigsten Ergebnisse vorgestellt und diskutiert.

Fragestellungen und Methoden

Beiträge I, II und III

I. **Auswirkungen von Brand und Mahd auf die Ernährungssituation von *Calluna vulgaris* und *Deschampsia flexuosa* in Heideökosystemen**
II. **Effects of prescribed burning on plant available nutrients in dry heathland ecosystems**
III. **Impact of prescribed burning on the nutrient balance of heathlands with particular reference to nitrogen and phosphorus**

Das kontrollierte Brennen wurde zur Pflege von Heideflächen in Naturschutzgebieten Mitte der 50er Jahre des 20. Jahrhunderts erstmals empfohlen und wird seit 1993 mit Erfolg als Pflegemaßnahme im NSG Lüneburger Heide angewendet (Lütkepohl & Stubbe 1997; Niemeyer et al. 2004). Um die negativen Auswirkungen auf Flora und Fauna zu minimieren, wird das kontrollierte Brennen fast ausschließlich im Winterhalbjahr durchgeführt (Gimingham 1992). Als Anwendungszyklus wird für das kontrollierte Brennen ein Zeitraum von 10-12 Jahre angesetzt (Terry et al. 2004). Gegenüber den anderen Pflegemaßnahmen hat das kontrollierte Brennen den Vorteil, dass sich die erhöhten Temperaturen während des Brandes positiv auf die Keimung der *Calluna*-Samen auswirken können (Müller et al. 1997).

Als weiteres extensives Verfahren wird im NSG Lüneburger Heide die extensive Mahd seit den 80er Jahren des 20. Jahrhunderts praktiziert. Heiden werden in der Regel nach 10 Jahren gemäht, je nach Regeneration der Vegetation auch häufiger (Sieber et al. 2004).

In diesen Beiträgen wurde die Wirkung extensiver Heidepflegeverfahren (Winterbrand: **Beiträge I-III** und Mahd: **Beitrag I**) auf die Verfügbarkeit pflanzlicher Nährstoffe und die Ernährungssituation der in Heiden konkurrierenden Arten *Calluna vulgaris* und *Deschampsia flexuosa* untersucht. Zu Grunde lag die Hypothese, dass sich durch Winterbrand das Verhältnis der für Heiden maßgeblich limitierenden Elemente N und P zu Gunsten eines verbesserten Stickstoffangebotes verschiebt und somit P zunehmend limitierendes Nährelement wird. Leitfrage dieser Beiträge war, wie sich die Nährstoffkonzentrationen in der Biomasse in *Calluna* und *Deschampsia* (Betrag I) und im Oberboden (Beiträge I und II) sowie im Sickerwasser (**Beitrag III**) infolge eines Brandereignisses bzw. extensiver Mahd verändern. Im Einzelnen wurde folgenden Fragestellungen nachgegangen:

- In welchem Umfang akkumuliert die Besenheide (*Calluna vulgaris)* die wachstumslimitierenden Nährelemente N und P im Vergleich zur Drahtschmiele (*Deschampsia flexuosa)*?
- Wie ist die Ernährungssituation von *Calluna* und *Deschampsia* in Abhängigkeit von extensiven Pflegemaßnahmen?
- Wie ändert sich der Gehalt an pflanzenverfügbaren Nährstoffen im Boden nach einem Winterbrand?
- Können die gegenwärtigen N-Depositionen im Ökosystem Heide durch kontrollierten Winterbrand kompensiert werden?

Alle Untersuchungsflächen (**Beitrag I-III**) befanden sich im NSG Lüneburger Heide (NW-Deutschland). Im nördlichen Teil des NSG liegt eine ca. 100 ha große Heidefläche („Auf dem Töps“). Dort wurden im Februar 2001 zwei Flächen ausgewählt, auf denen die miteinander konkurrierenden Pflanzen *Calluna vulgaris* und *Deschampsia flexuosa* wuchsen **(Beitrag I)**. Die ausgewählten Heideflächen waren miteinander vergleichbar. Damit ist gewährleistet dass für die Untersuchung möglichst identische Bedingungen (geologische, zeitliche geografische Gegebenheiten) gelten. Eine der beiden Flächen wurde abgemäht und die andere abgebrannt. Zwischen beiden Untersuchungsflächen wurde eine Referenzfläche eingerichtet, auf der keine Pflegemaßnahme durchgeführt wurde. Um die Ernährungssituation beider Arten (*Calluna* und *Deschampsia*) im Hinblick auf das

Heidemanagement zu untersuchen, wurden am Ende der Vegetationsperiode (September 2002) sowohl die Maßnahmeflächen (Brand und Mahd) als auch die Referenzfläche beprobt. Dabei wurden 5 cm der jüngsten Triebe von *Calluna* abgeschnitten. Bei *Deschampsia* wurde die oberirdische Blattmasse beerntet. Bodenproben wurden nach dem Brand monatlich genommen.

Im Februar 2003 wurden zusätzliche Flächen abgebrannt. Dort wurden die Nährstoffsituation im Boden (O-Lage und A-Horizont), sowie der Nährstoffaustrag durch das Sickerwasser unter Einfluss vom kontrollierten Brennen untersucht **(Beitrag II)**. Während die Nährstoffdynamik im Boden durch monatliche Bodenprobennahme für ein Jahr ermittelt wurde, ließ sich der Nährstoffaustrag bei zweiwöchiger Sickerwasserbeprobung mittels Lysimetern und tensionsgesteuerten Saugkerzen für zwei Jahre erfassen **(Beitrag III)**.

Neben den oben genannten Parametern wurden im Rahmen der Untersuchungen weitere erhoben; zum einen wurden die Temperaturen während des Brennens in unterschiedlichen Höhen über dem Erdboden bzw. Tiefen in der Humusauflage gemessen und zum anderen wurden die Temperaturen auf der Bodenoberfläche über einen Zeitraum von zwei Monaten auf gebrannten und nicht gebrannten Flächen jeweils vier Mal täglich aufgezeichnet. Als weitere Parameter wurden die Nährstoffeinträge (atmogener Eintrag, Ascheniederschlag) ermittelt.

Beitrag IV

IV. Impact of sod-cutting and choppering on nutrient budgets of heathlands

Das maschinelle Plaggen oder Schoppern ist derzeit vor allem dort notwendig, wo in den vergangenen Jahrzehnten die Heidepflege nicht intensiv genug betrieben wurde und sich folglich in der mächtigen Rohhumuslage große Nährstoffmengen angereichert haben. Erst wenn diese Nährstoffspeicher entfernt und der Mineralboden wieder weitgehend freigelegt worden ist, kann die Heide sich von Grund auf verjüngen (Keienburg et al. 2004).

Heutzutage gelten beide modernen Heidepflegemaßnahmen als wirksame Instrumente, um den hohen atmogenen N-Einträgen entgegen zu wirken (Power et al. 2001; Terry et al. 2004). Nachteil beider Verfahren sind die hohen Kosten, die durch große Mengen anfallenden Abfallmaterials, welches abtransportiert und entsorgt werden muss, entstehen. Die Kosten variieren im Untersuchungsgebiet zwischen 2800 und 3500 Euro ha^{-1} beim Plaggen und zwischen 1500 und 2000 Euro ha^{-1} beim Schoppern (Müller 2004).

Da das Heidemanagement durch Plaggen bzw. Schoppern relativ neu ist - beispielsweise wurde das Schoppern erstmals Mitte der 90er Jahre des 20. Jahrhunderts im NSG Lüneburger Heide angewendet (Sieber et al. 2004) -, sind Kenntnisse über die Einflüsse dieser Verfahren auf den Nährstoffhaushalt bzw. die Nährstofflimitierung im Ökosystem Heide von großer Bedeutung.

Der **Beitrag IV** befasst sich insbesondere mit dem Unterschied der beiden intensiven, maschinellen Pflegeverfahren im Hinblick auf die Nährstoffdynamik. Im Rahmen dieses Beitrages wurde folgenden Fragestellungen nachgegangen**:**

- Welche Menge an Nährelementen (insb. N und P) kann das Plaggen im Vergleich zum Schoppern aus dem System entfernen?
- Welche Auswirkungen haben beide Verfahren der Heidepflege im Hinblick auf Nährstoffausträge (insb. N und P) über das Sickerwasser?
- Können diese Pflegeverfahren langfristig die gegenwärtigen atmogenen N-Einträge kompensieren?

Um die untersuchten Pflegeverfahren im Hinblick auf ihre Effizienz für einen Nettoentzug von Nährstoffen aus Heideökosystemen vergleichen zu können, wird der Begriff der „Theoretischen Wirkungsdauer“ (TEP) eingeführt und definiert (Härdtle et al. 2006). Die TEP beschreibt den Zeitraum, in dem die entzogene Menge an Nährelementen in Form atmogener Einträge wieder in das System gelangt. Alle anderen Methoden bzw.

Beschreibungen des Untersuchungsgebietes entsprachen der Vorgehensweise der Beiträge I-III.

Ergebnisse und Diskussion

Atmogene Nährstoffeinträge

Deposition

Die vorliegenden Ergebnisse zeigten im Untersuchungszeitraum N-Einträge in Höhe von 22,8 kg ha^{-1} a^{-1} (**Beitrag I-IV**). Der ermittelte P-Eintrag lag unter 0,5 kg ha^{-1} a^{-1}. Diese Werte stimmen mit anderen Untersuchungen aus Deutschland und Großbritannien überein (Sutton und Fowler 1995; Bleeker et al. 2000; Gauger et al. 2000; Schmidt et al. 2004; Herrmann et al. 2005). Modelle aus den Niederlanden, die sich mit der Konkurrenzsituation von verschiedenen Heidearten befassen, zeigten, dass N-Einträge von 15-20 kg ha^{-1} a^{-1} als *critical-load* gelten, um in Sandheiden die Zwergsträucher durch Gräser zu ersetzen (Heil &

Bobbink 1993; Bobbink et al. 2003). Vor diesem Hintergrund gewinnt die Entwicklung eines Management–Systems an Bedeutung, das auf einer erheblichen N-Reduktion basiert, und damit zu einem langfristig stabilisierten N-Haushalt beitragen kann.

Nährstoffausträge

Oberirdische Biomasse und Boden

Im Gegensatz zu den extensiven Pflegemaßnahmen (kontrolliertes Brennen; **Beitrag III** und Mähen; **Beitrag I**), entfernen die intensiven Pflegemaßnahmen (Plaggen und Schoppern; **Beitrag IV**) die gesamte oberirdische Biomasse. Bei diesen Maßnahmen wurden die höchsten Nährelemententzüge erzielt (86 bzw. 155 kg N ha^{-1} a^{-1} und 4 bzw. 10 kg P ha^{-1} a^{-1}). Durch das kontrollierte Brennen konnten dagegen nur 72/84% *Calluna vulgaris* Sträucher (15/10-jähriger Bestand) entfernt werden.

Die Temperaturmessungen über dem Erdboden (**Beitrag II und III**) zeigten, dass während des Brennens maximale Temperaturen von 500 bis 800°C erreicht werden. Jedoch war die Erwärmung der Rohhumusauflage durch das Feuer in einer Tiefe von mehr als 1 cm nicht mehr messbar, da der Boden zum Brandzeitpunkt gefroren war. Winterbrände werden gegenüber den Sommerbränden aus naturschutzfachlicher Sicht bevorzugt, da die Brandtemperatur (>450°C) zwar hoch genug ist, um den gebundenen Stickstoff in gasförmige Verbindungen zu überführen, aber nicht zu hoch, um die Regenerationsknospen von *Calluna vulgaris* oder das Edaphon nachhaltig zu beeinträchtigen (Gimingham 1972; Mallik & Gimingham 1985).

Die Ergebnisse zeigten auch, dass das kontrollierte Brennen im Gegensatz zu den intensiven Maßnahmen (Plaggen und Schoppern) die Vorräte im Boden nicht bzw. kaum beeinträchtigt (**Beträge III und IV**). Nach allen drei Maßnahmen kann jedoch eine Akkumulation von Ammonium im Oberboden beobachtet werden. Dies erklärt sich zum einen durch die fehlende bzw. stark reduzierte Nährstoffaufnahme durch die Pflanzen (Dorland et al. 2003), zum anderen durch die erhöhte Mineralisation der im Boden verbliebenen, abgestorbenen Wurzeln und anderem organischen Materials (Berendse 1990; Mitchell et al. 1999) als Folge der Veränderung des Mikroklimas im Oberboden (**Beitrag II**). Die ermittelten Vorräte (**Beiträge I-IV)** an oberirdischer Biomasse, O-Lage und A-Horizont sowie die Nährelementgehalte in Vegetation und Boden, zeigten eine gute Übereinstimmung mit anderen Arbeiten (Matzner & Ullrich 1980; Rode & Schmitt 1995; Alonso et al. 2001; Kirkham 2001; Dorland et al. 2003).

Sickerwasseraustrag

Nach allen drei Maßnahmen (kontrolliertes Brennen, Plaggen, Schoppern) waren die Auswaschungsraten mit dem Sickerwasser im Gegensatz zu den Kontrollflächen erhöht (**Beiträge II-IV**). Signifikant waren die Unterschiede insbesondere für N und zum Teil für Ca, K und Mg. Gründe für die erhöhte N-Auswaschung waren zum einen die erhöhten N-Konzentrationen im Oberboden und zum anderen die geringe N-Aufnahme der Vegetation nach der Maßnahme. Die generell niedrige P-Auswaschung nach den Maßnahmen (**Beiträge II-IV**) lässt sich so erklären, dass der P-Gehalt in den Podsolen der Heidelandschaften sehr gering ist und der Phosphor als Orthophosphat im O- und B-Horizont gebunden vorliegt (Chapman et al. 1989; Ollf & Pegtel 1994).

Eine maßnahmenbezogene Bilanzierung (**Beitrag IV**; Sieber et al. 2004) zeigte jedoch, dass der Sickerwasseraustrag gegenüber dem Austrag, der über Biomasse (Mähen, Brennen, Plaggen, und Schoppern) und Boden (Plaggen und Schoppern) erzielt werden kann, insbesondere für N, wenig ins Gewicht fällt; der prozentuale Anteil am Gesamtaustrag lag bei nur 3% (Mähen), 1,6 % (Plaggen) und 2,3 % (Schoppern). Zwar war die prozentuale N-Auswaschung in Folge eines Brandereignisses (10-12%; **Beitrag III**) höher als nach den maschinellen Pflegeeingriffen (Mähen, Plaggen und Schoppern), aber die erhöhte N-Auswaschung hatte insgesamt nur geringen Einfluss auf die TEP für N.

Theoretische Wirkungsdauern (TEP)

Da die atmogenen P-Einträge im Gegensatz zu den N-Einträgen gering sind (<0,5 kg P ha^{-1} a^{-1}, und 22,8 kg N ha^{-1} a^{-1}), hat das Entfernen des N-Reservoirs nachhaltige Konsequenzen für das System. Im Hinblick auf die Wirkung der Maßnahmen auf den N-Haushalt konnte im Vergleich zum kontrollierten Brennen durch das Plaggen ein bis zu 17-facher und durch das Schoppern ein ca. 10-facher N-Entzug erzielt werden. Die atmogenen N-Einträge werden daher nach der TEP-Berechnung nur bei den intensiven Maßnahmen (Plaggen; 61 und Schoppern; 90 Jahren) dauerhaft kompensiert (**Beitrag IV**). Das kontrollierte Brennen allein kann dies mit nur 5 Jahren TEP nicht langfristig gewährleisten (**Beitrag III**). Um dauerhaft eine nährstoffarme Situation in den Heideökosystemen aufrecht zu erhalten, ist eine Kombination extensiver und intensiver Maßnahmen notwendig.

Nährstofflimitierung

Im Hinblick auf die Ernährungssituation von *Calluna* und *Deschampsia* nach kontrolliertem Brennen zeigte sich (**Beiträge I und II)**, dass das Ammoniumangebot im Oberboden nach dem Brand für ein oder mehrere Jahre signifikant erhöht war. Die Verfügbarkeit anderer Nährstoffe war dagegen nur kurzfristig (P) oder nicht signifikant (NO_3^-, Ca, K, Mg) erhöht. Die C/N-Verhältnisse im Pflanzengewebe veränderten sich bei beiden Arten nach dem Brand nicht signifikant. Jedoch verschlechterte sich für *Deschampsia* die P-Versorgung deutlich (Tab. 1).

Tabelle 1: Einfluss des kontrollierten Brennens auf Gewebe-C/N-Verhältnisse, N/P-Verhältnisse und N- bzw. P-Gehalte von *Calluna vulgaris* und *Deschampsia flexuosa* (19 Monate nach dem Brennen). Signifikante Unterschiede sind fett gedruckt und mit einem Stern gekennzeichnet (* = p < 0,05, ** = p < 0,01); Mittelwerte (n=10) und STAB (in Klammern).

	Calluna vulgaris		*Deschampsia flexuosa*	
	ungebrannt	gebrannt	ungebrannt	gebrannt
C/Ca	125,5 (7,9)	107,6 (8,3)	309,2 (60,3)	***396,0** (98,4)
C/K	119,5 (21,0)	106,4 (7,2)	39,2 (3,8)	***57,4** (17,5)
C/Mg	345,7 (38,7)	355,0 (24,0)	725,9 (160,3)	****1041,1** (305,5)
C/P	631,3 (93,7)	594,9 (72,7)	560,8 (112,6)	****844,2** (277,3)
C/N	39,0 (2,7)	36,9 (4,0)	27,4 (1,7)	30,3 (4,5)
N/P	16,1 (1,6)	16,1 (0,7)	20,5 (4,1)	***28,7** (7,7)
N mg g^{-1}	13,5 (0,9)	14,4 (1,6)	17,4 (1,1)	17,2 (3,1)
P mg g^{-1}	0,9 (0,1)	0,9 (0,1)	0,9 (0,3)	***0,6** (0,1)

(Quelle: Mohamed et al. 2006)

Weltweit wird von zahlreichen Autoren die Verwendung von N/P-Verhältnissen in Feuchtgebieten als hilfreiches Instrument hervorgehoben, um Auskünfte über die Nährstofflimitierung im Ökosystem zu erhalten (Aerts et al 1992; Koerselman & Meuleman 1996; Güsewell & Bollens 2003; Tessier & Raynal 2003).

In europäischen Feuchtgebieten (Moore, Moorgrünland, Moorheiden, Feuchtgrünland) weisen N/P-Verhältnisse zwischen 14 und 16 auf eine Co-Limitierung von N und P hin, Werte <14 zeigen eine N-Limitierung und Werte >16 eine P-Limitierung an (Koerselman & Meuleman 1996). Allerdings konnten diese Grenzwerte von Koerselman & Meuleman (1996) bis jetzt noch nicht für Sandheiden bestätigt werden. Die im Untersuchungsgebiet ermittelten N/P-Verhältnisse (Tab. 1) von *Deschampsia flexuosa* weisen auf eine Verschiebung in Richtung P-Limitierung nach dem Brand hin (N/P-

Verhältnis: 20,5/28,7; ungebrannt/gebrannt). Grund dafür ist, dass das kontrollierte Brennen zu einer Verbesserung der N-Versorgung führt und gleichzeitig zu einer Verschlechterung der P-Versorgung. Dieser Befund unterstützt die Aussage von Aerts et al. (1992), dass sich unter zunehmenden N-Einträgen die Nährstofflimitierung zu einer P-Limitierung verschiebt. Demgegenüber hat das Brandereignis die Ernährungssituation bzw. das N/P-Verhältnis von *Calluna* nicht beeinflusst (Tab. 1; N/P-Verhältnis: 16,1/16,1; ungebrannt/gebrannt). Damit verbessert sich die Konkurrenzfähigkeit von *Calluna* gegenüber *Deschampsia*. Zusammenfassend lässt sich sagen, dass Winterbrand die Ernährungssituation für *Deschampsia* insbesondere im Hinblick auf die P-Versorgung verschlechtert. Winterbrand begünstigt somit die Konkurrenzfähigkeit von *Calluna*, indem sich für *Deschampsia* vor allem die P-Limitierung verstärkt.

Um festzustellen, ob das Wachstum von *Calluna* im NSG Lüneburger Heide durch N oder P limitiert ist, wurde im Jahr 2004 ein Düngungsversuch mit N, P und N+P gestartet (eigene, unpublizierte Daten). Dabei wurden 12 Flächen ausgewählt, die repräsentativ für das ganze NSG waren. Nach 2 Jahren Düngung während der Vegetationsperiode mit insgesamt 50 kg N ha^{-1} a^{-1}, 20 kg P ha^{-1} a^{-1} und mit N+P (d.h. 50 kg N ha^{-1} a^{-1} und 20 kg P ha^{-1} a^{-1}) zeigte sich, dass das Wachstum von *Calluna* nur auf den mit N gedüngten Flächen signifikant erhöht war. Dies war dagegen nach der Behandlung mit P bzw. N+P nicht feststellbar. Daher war das Wachstum von *Calluna* vor allem durch N beeinflusst.

Als weiterer Parameter beim Düngungsversuch wurde die Wirkung der Düngung auf das N/P-Verhältnis untersucht. Auch hier wurde nur auf den N-gedüngten Flächen eine Erhöhung des N/P-Verhältnisses in *Calluna* festgestellt (von 14 auf 17,3). Deshalb wird auf diesen Flächen (N-Düngung) eine Verschiebung hin zu einer P-Limitierung erwartet.

Unter diesen Umständen haben zwar die hohen N-Einträge im NSG Lüneburger Heide (22,8 kg N ha^{-1} a^{-1}; **Beitrag III**) eine positive Wirkung auf das Wachstum von *Calluna*, aber gleichzeitig werden dadurch Arten gefördert, die gut an P-limitierte Standorte angepasst sind, wie z.B. *Molinia caerulea* (Kirkham 2001). Außerdem wird *Calluna* durch die Störung in der Nährstoffdynamik benachteiligt. Daher scheint eine Reduzierung atmogener N-Einträge durch das Heidemanagement unverzichtbar, um die Heiden langfristig zu erhalten.

Schlussfolgerungen

- Im NSG Lüneburger Heide überschreiten die gegenwärtigen atmogenen N-Einträge (22,8 kg N ha^{-1} a^{-1}) den *critical-load* für Sandheiden (15-20 kg ha^{-1} a^{-1}).
- Für den langfristigen Erhalt der von *Calluna*-dominierten Sandheiden ist daher Heidemanagement unverzichtbar.
- Extensive Pflegeverfahren (Mahd, kontrollierter Winterbrand) sind nicht in der Lage, die aktuellen atmogenen N-Einträge zu kompensieren.
- Durch eine Kombination von extensiven und intensiven Verfahren wird ein erheblicher Austrag von Nährstoffen aus den Heideflächen bewirkt und für die notwendige Verjüngung der Besenheide gesorgt.
- Das Wachstum von *Calluna* im NSG Lüneburger Heide ist vor allem durch N beeinflusst.
- Mehr Kenntnisse über die Einflüsse der Pflegeverfahren (v.a. der intensiven) auf die Nährstofflimitierung der Pflanzenwachstums sind für die Optimierung des Heidemanagements im NSG Lüneburger Heide von großer Bedeutung.

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Beitrag I

Auswirkungen von Brand und Mahd auf die Ernährungssituation von *Calluna vulgaris* und *Deschampsia flexuosa* in Heideökosystemen

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Auswirkungen von Brand und Mahd auf die Ernährungssituation von *Calluna vulgaris* und *Deschampsia flexuosa* in Heideökosystemen

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1 Einleitung

Seit den 60er Jahren wird ein verstärktes Eindringen von Gräsern, insbesondere der Drahtschmiele (*Deschampsia flexuosa*), in die von Zwergsträuchern dominierten Sandheiden Norddeutschlands beobachtet. Diese Zunahme der Gräser wird unter anderem auf atmogene Stickstoffeinträge in Heiden zurückgeführt. In der Folge wird ein Rückgang charakteristischer Heidepflanzen wie *Calluna vulgaris* und *Erica tetralix* befürchtet (*Engel* 1988, *Steubing & Buchwald* 1989, *Mickel* et al. 1991, *Steubing* 1993, *Härdtle & Frischmuth* 1998).

Die wichtigste Ursache für die Ausbreitung der Drahtschmiele ist jedoch die Anreicherung von Rohhumus. Wegen des hohen Anteils von Flächen mit mächtigen Rohhumusauflagen im NSG „Lüneburger Heide“ müssen neben der Beweidung Verfahren eingesetzt werden, die einen intensiveren Austrag an Biomasse bewirken. Besenheide-Bestände, die sich noch in einem vitalen Stadium befinden, lassen sich mit Hilfe von kontrolliertem Feuer sowie Mahd gut verjüngen (*Koopmann & Mertens* 2004, *Fottner* et al. 2004, *Kaiser & Stubbe* 2004, *Lütkepohl & Kaiser* 1997).

Die vorliegende Studie verfolgt das Ziel, den Einfluss der Pflegemaßnahmen Brand und Mahd auf die Ernährungssituation der miteinander konkurrierenden Pflanzen *Calluna vulgaris* und *Deschampsia flexuosa* zu untersuchen. Hierzu wurden in den einjährigen Sprossen der beiden Pflanzenarten verschiedene Kohlenstoff/Nährelement-Relationen (C/N, C/P, C/Ca, C/Mg und C/K) ermittelt. Durch den Vergleich dieser Relationen sollte geprüft werden, ob sich die Pflegemaßnahmen Feuer und Mahd unterschiedlich auf die Ernährungssituation der Besenheide und der Drahtschmiele auswirken und demzufolge die Konkurrenzsituation zwischen beiden Arten beeinflussen.

* Die Untersuchungen wurden gefördert vom Bundesministerium für Bildung und Forschung im Rahmen des Verbundforschungsvorhabens „Feuer und Beweidung als Instrumente zur Erhaltung magerer Offenlandschaften in Nordwestdeutschland“.

2 Methode

2.1 Untersuchungsflächen

Die beiden Untersuchungsflächen befinden sich im Gebiet „Auf dem Töps“ im Nordteil des NSG „Lüneburger Heide“. Die jeweiligen Pflegemaßnahmen wurden auf den Flächen innerhalb des gleichen Zeitraums im Januar/Februar 2001 vorgenommen. Damit ist gewährleistet, dass für die Untersuchung möglichst identische Bedingungen (geologische, zeitliche und geographische Gegebenheiten) gelten.

Auf der westlich gelegenen Untersuchungsfläche wurde der Pflanzenbewuchs und die abgestorbene oberirdische Phytomasse auf Veranlassung des Vereins Naturschutzpark im Februar 2001 abgebrannt. Die östlich gelegene Fläche der beiden Untersuchungsflächen wurde abgemäht und das Mahdgut abgetragen. Zwischen beiden Untersuchungsflächen wurde eine Referenzfläche eingerichtet, die von den Pflegemaßnahmen ausgespart bleibt und als Nullfläche dient.

2.2 Nährstoffanalytik

Probennahme

Die Biomasse wurde am Ende der Vegetationsperiode im September 2002, eineinhalb Jahre nach den Pflegemaßnahmen geerntet. Je Fläche wurden 20 Proben *Calluna* und 20 Proben *Deschampsia* geerntet, wovon je zwei Proben zu einer Mischprobe zusammengefasst wurden. Die Probennahme erfolgte mit Hilfe eines Rasters, um eine räumliche Gleichverteilung der beprobten Pflanzen sicherzustellen. Die einzelnen Rasterpunkte lagen je fünf Meter in allen Richtungen voneinander entfernt. Für die Untersuchung wurden 5 cm der jüngsten Triebe der Heidepflanzen abgeschnitten. Bei der Drahtschmiele wurde die oberirdische Blattmasse beerntet.

Probenaufbereitung und Probenaufschluss

Im Labor wurde die geerntete Biomasse im Trockenschrank bei 105 °C getrocknet, anschließend geschreddert und in einer Kugelmühle staubfein gemahlen (*Bundesministerium für Ernährung, Landwirtschaft und Forsten* 1994: 110). Die aufgemahlenen Proben wurden bei 105 °C bis zur Gewichtskonstanz getrocknet und drei Stunden lang bei 550 °C verascht. Zur Asche wurden 10 ml HCl dazugeben und die Lösung wurde eingedampft. Der Rückstand wurde mit 2 ml HCl aufgenommen, in einen Messkolben überführt und auf 100 ml mit Reinstwasser aufgefüllt.

Messung der Aufschlusslösungen auf Ca, K, Mg, P

Die Messung der aufgeschlossenen Probelösung wurde mittels ICP-OES (Atomemissions-Spektrometer mit induktiv gekoppeltem Plasma als Anregungsquelle) durchgeführt.

Ermittlung des C/N-Verhältnisses

Die Messung der Biomassenprobe auf elementaren Kohlenstoff und Stickstoff erfolgte mit einem C/N-Analyser. Für die Analyse wurden die Pflanzenproben fein gemahlen und bis zur Gewichtskonstanz getrocknet. Die Proben wurden in Zinnschiffchen in den Analysator eingebracht und unter Sauerstoffzufuhr vollständig verbrannt. Die Konzentration der Gase wurde mit einem Wärmeleitfähigkeitsdetektor bestimmt (*Wieberneit* 2001: 18).

2.3 Statistische Methoden

Die Frage, ob es einen Unterschied im Nährstoffgehalt einer Pflanzenart auf zwei verschiedenen Flächen gibt, wurde durch die Berechnung von Mittelwertdifferenzen mit dem t-Test für zwei gepaarte Stichproben beantwortet. Die Fehlerwahrscheinlichkeit wird mit einem Signifikanzniveau von $\alpha = 5$ % angegeben. Die Berechnung der Mittelwertdifferenzen erfolgte durch das Softwareprogramm SPSS Vers. 10.0.

Die Ernährungssituation der Pflanzen wird in Bezug auf die Kohlenstoff/Nährelementgehalte diskutiert. Dieser Quotient gibt an, welche Menge eines Elementes bei einer bestimmten Photosyntheserate in die organische Substanz eingebaut wird.

3 Ergebnisse

Vergleich Feuerfläche –
Referenzfläche Feuer

Auf der Feuerfläche unterscheiden sich die Kohlenstoff/Nährelement-Relationen für die Besenheide für K, Mg, P und N nicht signifikant im Vergleich zur Referenzfläche (Abb. 1). Allerdings ist das C/Ca-Verhältnis auf der Feuerfläche mit einem Wert von 107 signifikant niedriger als auf der Referenzfläche mit einem Wert von 125.

Demgegenüber unterscheiden sich die Kohlenstoff/Nährstoff-Quotienten in *Deschampsia flexuosa* auf der Feuerfläche im Vergleich zur ungebrannten Referenzfläche sehr deutlich (Abb. 2). Alle Kohlenstoff/Element-Verhältnisse in *Deschampsia flexuosa* sind im Mittel auf der Feuerfläche größer als auf der Referenzfläche. Während der C/Ca-Quotient in der Drahtschmiele im Mittel auf der Feuerfläche 396 beträgt, ist er auf der Referenzfläche mit 309 signifikant enger. Das C/K-Verhältnis ist auf der Brandfläche mehr als 30 % größer als auf der Referenzfläche. Ebenso verhält es sich mit dem C/Mg- und dem C/P-Verhältnis. Der C/N-Quotient in den *Deschampsia*-Pflanzen auf der Feuerfläche ist mit einem Mittelwert von 30 wie bei den anderen Nährelementverhältnissen höher als das Verhältnis von 27 auf der Referenzfläche. Allerdings ist dieser Unterschied im Gegensatz zu den anderen Elementverhältnissen nicht signifikant.

Vergleich Mahdfläche –
Referenzfläche Mahd

Die C/Ca- und C/N-Quotienten in *Calluna*-Individuen, die auf der Mahdfläche wachsen, sind im Mittel signifikant enger als in den Pflanzen, die der dazugehörigen Referenzfläche entstammen. Das C/Ca-Verhältnis ist auf der Maßnahmefläche um 16 % und das C/N-Verhältnis um 11% enger als auf der unbehandelten Fläche. Die C/K-, C/Mg- und C/P-Verhältnisse im *Calluna*-Bestand unterscheiden sich nicht signifikant auf den beiden Flächen.

Der Mittelwert aus den Stichproben des C/Ca-, C/K-, C/Mg- und C/P-Quotienten in *Deschampsia flexuosa* auf der Referenzfläche ist signifikant enger als auf der Mahdfläche. Das bedeutet, dass die Nährstoffversorgung mit Calcium, Kalium, Magnesium und Phosphor für die Drahtschmiele nach der Pflegemaßnahme schlechter ist als auf der unbehandelten Referenzfläche. Die Mittelwerte weichen beim C/Ca-Verhältnis um 22 % voneinander ab, beim C/K-Verhältnis um 18 %. Das C/Mg-Verhältnis ist auf der Mahdfläche im Mittel 26 % weiter als auf der Referenzfläche und das C/P-Verhältnis im Mittel um 22 % bei der Referenzfläche enger. Nur der C/N-Quotient ist im Mittel auf beiden Flächen mit Werten von 28 auf der Mahdfläche und 29 auf der Referenzfläche ungefähr gleich hoch.

4 Diskussion

4.1 Vergleich der Auswirkungen der Pflegemaßnahmen Feuer und Mahd auf die Ernährungssituation von *Calluna* und *Deschampsia*

Die Nährstoffquotienten in *Calluna* und *Deschampsia* sind auf beiden Referenzflächen annähernd gleich. Daraus kann geschlossen werden, dass die Bodenverhältnisse beider Referenzflächen sich nicht signifikant voneinander unterscheiden. Daher wird davon ausgegangen, dass die Bodenverhältnisse auf der Feuer- und Mahdfläche, die direkt an den Referenzflächen liegen, ebenfalls gleich sind. Aus diesem Grund können

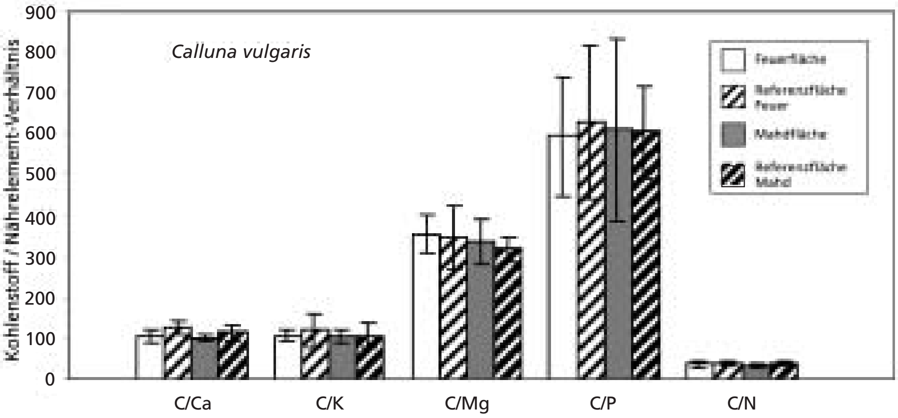

Abb. 1: Kohlenstoff/Nährelement-Verhältnisse für Calluna vulgaris auf den Untersuchungsflächen.

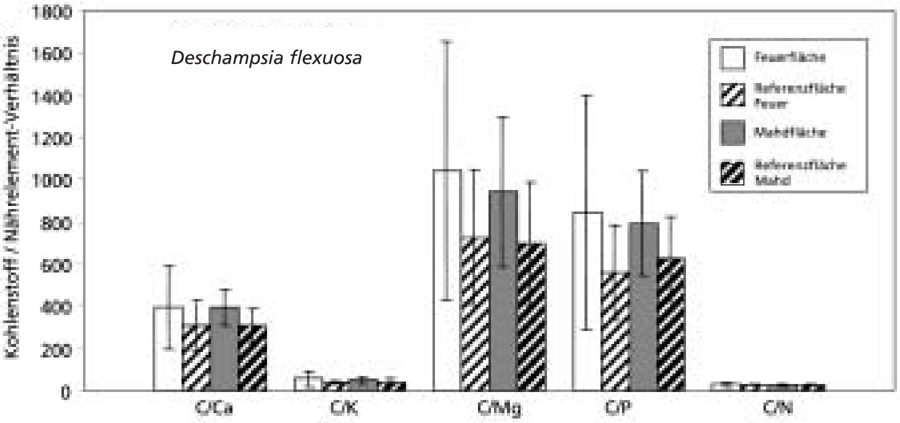

Abb. 2: Kohlenstoff/Nährelement-Verhältnisse für Deschampsia flexuosa auf den Untersuchungsflächen.

die auf der Feuer- und Mahdfläche wachsenden *Calluna*- und *Deschampsia*-Individuen hinsichtlich ihres Nährstoffquotienten miteinander verglichen werden.

4.2 Ernährungssituation von *Calluna* und *Deschampsia* in Abhängigkeit von Pflegemaßnahmen im Vergleich zu den Individuen auf den Referenzflächen

Die Ergebnisse zeigen, dass eine Verschlechterung der Nährstoffversorgung von *Deschampsia* ausschließlich auf Auswirkungen der Pflegemaßnahmen Feuer und Mahd zurückzuführen ist. Sie sollen im Folgenden unter verschiedenen Aspekten diskutiert werden:

Auswirkungen der Maßnahmen auf das Wurzelwerk

Zunächst könnte angenommen werden, dass eine Verschlechterung der Nährstoffversorgung von *Deschampsia* auf den Maßnahmeflächen auf eine Beschädigung der Wurzeln durch Brand oder Mahd zurückzuführen ist. Das Wurzelwerk von *Calluna* und *Deschampsia* befindet sich vorwiegend in der Rohhumusschicht (*Ellenberg* 1996: 372). Dennoch ist ein Absterben von Teilen der Wurzelmasse infolge des kontrollierten Brennens sehr unwahrscheinlich, da es in den oberen Bodenschichten zu einer Temperaturerhöhung von höchstens 1–2 °C kommt (vgl. *Schreiber* 1997: 60, in: *Falk* 2003: 57, *Niemeyer* et al. 2004). Auch bei der Mahd werden die Wurzeln nicht beschädigt, da der Kreiselmäher den Bewuchs oberhalb der Bodendecke abschneidet.

Auswirkungen der Maßnahmen auf die Verjüngung

Durch das kontrollierte Feuer wurden in der vorliegenden Untersuchung die *Calluna*-Sträucher abgebrannt, während der *Deschampsia*-Bestand trotz des Winterbrands weitestgehend stehen blieb. Durch die Mahd wurden die Heidesträucher abgeerntet, aber auch bei dieser Pflegemaßnahme blieben die *Deschampsia*-Individuen stehen. Es ist davon auszugehen, dass die bessere Nährstoffsituation der Besenheide auf den Maßnahmeflächen teilweise mit der Verjüngung der Pflanzen durch den Brand bzw. durch die Mahd zusammenhängt. Denn grundsätzlich zeigen *Calluna*-Pflanzen, die sich in der Pionierphase (bis 6 Jahre) befinden, eine bessere Ernährungssituation als Pflanzen, die sich in der Aufbauphase befinden (7–13 Jahre; Altersphasen eingeteilt nach *Barclay-Estrup & Gimingham* 1969: 756). Ebenso konnten *Miller & Miles* (1970) zeigen, dass die N-Gewebekonzentration von jungen *Calluna*-Pflanzen sehr hoch ist und auf ein niedriges Niveau nach ungefähr sechs Jahren abfällt. Auch bei den Untersuchungen von *Muhle & Röhrig* (1979: 56) lagen die Stickstoffgehalte in der jungen, gemähten Heide über denen der älteren. Die Ergebnisse von *Miller & Miles* (1969) und *Muhle & Röhrig* (1979: 56) stimmen mit den Befunden aus der vorliegenden Arbeit weitgehend überein.

Auswirkungen der Maßnahmen auf den Mykorrhizierungsgrad des Wurzelwerks

Ein möglicher weiterer Grund für die beobachteten Unterschiede in der Ernährunssituation der *Calluna*- und *Deschampsia*-Pflanzen ist an dem unterschiedlich hohen Mykorrhizierungsgrad des Wurzelwerks der beiden Arten auszumachen.

Die Mykorrhizierung von *Deschampsia* im Freiland und im Gewächshaus ist nach *Steubing* (1993) sehr niedrig (6 %), während sie bei *Calluna* auf dem Feld bei 28 % liegt. Somit hat *Calluna* durch die höhere Mykorrhizierung einen Konkurrenzvorteil gegenüber *Deschampsia*, indem die durch ein Brandereignis frei gewordenen Nährstoffe (vgl. *Niemeyer* et al. 2004, *Falk* et al. 2004) von *Calluna* vergleichweise gut genutzt werden können. Dieser Vorteil ist zudem bei jungen *Calluna*-Pflanzen stärker wirksam, da bei ihnen die Mykorrhizierung höher ist als bei den älteren (*Zijlstra & Berendse* 2001).

Auswirkungen der Maßnahmen auf das Mikroklima der Bestände

In beiden Pflegeverfahren ändert sich durch ein Entfernen der *Calluna*-Biomasse das Mikroklima im Bestandsinneren erheblich (vgl. *Niemeyer* et al. 2004). Insbesondere ist während der Vegetationszeit eine stark erhöhte Temperatur (bis zu 60 °C) unmittelbar auf der Vegetationsoberfläche zu beobachten. Dies hat zur Folge, dass sich auch die Transpirationsbeanspruchung der Vegetation erhöht. Solche Veränderungen dürften vor allem bei *Deschampsia* zu erhöhtem Wasserstress führen, während *Calluna* als Xerophyt solche Bedingungen besser toleriert. Als Folge ist bei *Deschampsia* ein verstärkter Schluss der Stomata zu erwarten, infolgedessen sich die Ernährungssituation für diese Art deutlich verschlechtert.

5 Zusammenfassung

Auf kontrolliert gebrannten und gemähten Heideflächen im NSG „Lüneburger Heide" sowie auf je benachbarten, nicht behandelten Referenzflächen wurden eineinhalb Jahre nach Durchführung der Pflegemaßnahmen frische Triebe von *Calluna vulgaris* und die oberirdische Biomasse von *Deschampsia flexuosa* auf ihre Kohlenstoff/Nährstoff-Relationen hin untersucht. Die Untersuchungen zeigen eine Verschlechterung der Nährstoffversorgung von *Deschampsia flexuosa*, die ausschließlich auf Auswirkungen der Pflegemaßnahmen Feuer und Mahd zurückzuführen ist.

Summary

One and a half year after prescribed burning and mowing of heaths in the "Lüneburger Heide" nature reserve young shoots of *Calluna vulgaris* and the above ground biomass of *Deschampsia flexuosa* from both treated and untreated plots were analyzed with respect to their carbon/nutrient relations. The investigations show a worsening of nutrient supply in *Deschampsia flexuosa* which can be solely linked to the management by prescribed burning and mowing.

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Beitrag II

Effects of prescribed burning on plant available nutrients in dry heathland ecosystems

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ORIGINAL PAPER

Effects of prescribed burning on plant available nutrients in dry heathland ecosystems

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Abstract Heathland management is an important tool with which to modify ecosystem impacts caused by atmospheric nutrient deposition. Since changes in nutrient availability as a result of management measures affect the outcomes of heathland succession and species competition, studies on this issue are important from both a nature conservation and management point of view. This study reports the effects of prescribed burning on nutrient availability in dry heathland soils and the nutrient content of the two competing heathland species *Calluna vulgaris* and *Deschampsia flexuosa*, with particular reference to N and P. We hypothesise that winter prescribed burning leads to additional N availability, which enhances the importance of P in the context of nutrient limitation in heathland ecosystems. In the nature reserve "Lueneburg Heath" (NW Germany) we examined the availability of nutrients in the humus horizons and in the leachate as well as the relevant C:element ratios in *Calluna* and *Deschampsia* before and after a burning experiment. Our results show that prescribed burning resulted in drastically increased NH_4^+ availability in the O-horizon. We observed only short-term effects (for NO_3^-, PO_4^{3-}, Mg) and insignificant effects on the availability of other nutrients (K, Ca). As a consequence of an increased nutrient availability in the humus horizons and a limited nutrient uptake by plants after burning, leaching increased significantly for N, Ca, K, and Mg after burning treatment. No significant changes were found in the foliar C:N ratios for either species after prescribed burning, although *Deschampsia* showed an increased deficiency for all the other nutrients, particularly for P, as expressed by increased foliar C:P and N:P ratios. By contrast, the nutrient content of *Calluna* did not change significantly, suggesting that prescribed burning favours the competitive capacity of *Calluna* as against *Deschampsia*. We assume that water shortage as a result of changes in the microclimate was mainly responsible for the deterioration of the nutrient content of *Deschampsia*. This gives *Calluna* a competitive advantage, enabling it to out-compete *Deschampsia* on burned heathlands, with respect to the key factor P-limitation.

Keywords *Calluna vulgaris* · *Deschampsia flexuosa* · Heathland management · Leaching · Nitrogen · N:P ratio

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Introduction

Heathlands were once a characteristic feature of the landscapes of NW Europe (Sutherland 2004). Their structure and species composition is characterised by the dominance of evergreen dwarf shrubs such as *Calluna vulgaris* (henceforth referred to as *Calluna*), *Empetrum nigrum, Vaccinium myrtillus* and other Ericaceous species. Heathlands were a product of both the natural site conditions and traditional management systems, including sod cutting, grazing and prescribed burning (Hulme et al. 2003; Pakeman et al. 2003). As a result of changes in land use practices and the introduction of artificial fertilizers, the area of heathlands has declined dramatically since the second half of the 19th century (Aerts and Heil 1993). In some countries nearly 90% of the heathlands have disappeared over the last 150 years (Sutherland 2004). Since the last third of the 20th century, policy has become more focused on possible measures for the conservation of the remaining heaths. As a consequence, heathlands are nowadays regarded as an internationally endangered habitat type of high conservation value, and conservation efforts are directed towards the preservation of heathland biodiversity (Alonso et al. 2001; Dorland et al. 2003).

In step with the loss of heathlands, many of the remaining areas have been subjected to changes in quality (e.g., species composition and vegetation structure) during recent decades. Such changes in the species composition of heathlands have been observed in many western and central European countries (Milligan et al. 2004). There is strong evidence that atmospheric nutrient deposition has contributed to the encroachment of grasses such as *Deschampsia flexuosa* (henceforth referred to as *Deschampsia*; Aerts and Berendse 1988; Pitcairn et al. 1991). Particularly competition between plants, and hence the vegetation dynamics, may be influenced by elevated nutrient levels in the essentially low-nutrient environment (Mickel et al. 1991; Alonso et al. 2001).

As a consequence, the employment of management measures to remove nutrients has increased in importance (Erismann and de Vries 2000; Power et al. 2001). Heathland management, primarily aiming at the prevention of scrub and tree establishment, is now considered necessary to address the ecosystem impacts caused by atmospheric nutrient loads. For example, the type and frequency of heathland management measures determines the quantities of nutrients removed from plant and humus components (Power et al. 2001). Management practices have, thus, an impact on the nutrient content of heathland ecosystems and, by reducing nutrient stores, have the potential to affect ecosystem responses to atmospheric nutrient loads. Whilst many recent studies have focused on the importance of interactions between heathland management and nutrient deposition (particularly of N, e.g., Calvo et al. 2005), little is known about the immediate impact of management measures on the nutrient availability in heathland soils and on the nutrient content of competing plant species, particularly as regards the effects of prescribed burning (Adams 2003). Winter is generally the preferred season for the application of prescribed burning; this, presumably, is derived from former farming practices in which heathland was burnt in the winter. Heathland can, of course, be burnt in the summer but this is usually prohibited by law. Furthermore, summer burning may have adverse effects on other wildlife such as breeding birds and reptiles, and might also affect the regeneration response. Since changes in nutrient availability as a result of management measures affect the outcomes of heathland succession and species competition, studies on this issue are helpful from a nature conservation and management point of view. Hence, the main objective of our study was to analyse the impact of prescribed burning on the nutrient availability in heathland soils and on the nutrient content of *Calluna* and *Deschampsia*. To this end we analysed changes caused by prescribed burning in the nutrient concentrations (of NH_4^+, NO_3^-, PO_4^{3-}, K, Ca, Mg) in upper soil layers (O-, A-horizon) and in the leachate. As nutrient availability is also related to microclimatic conditions (that may change due to the removal of the dwarf shrub canopy after prescribed burning; Schmidt et al. 2002), we investigated the soil surface temperatures in the stands during summer. In order to test whether prescribed burning affects the competitive performance of *Calluna* and *Deschampsia* (via nutrient availability), we determined the tissue nutrient contents of both species before and after a burning experiment.

The following questions have been addressed in our study: (i) What effects does prescribed burning have on the amounts of plant available nutrients (soils and leachate) in heathland ecosystems? (ii) Does prescribed burning affect the microclimate of the stands (expressed by soil surface temperature)? (iii) What effects does prescribed burning have on the nutrient content of *Calluna* and *Deschampsia*, particularly as regards their supply of N and P.

Methods

Study area

Our study area is the nature reserve ''Lueneburg Heath'' (Lower Saxony, NW Germany; 53°15′N, 9°58′E, 105 m a.s.l.), in which the largest complex of heathlands (about 5,000 ha) in NW Germany is located. The study area is characterised by Pleistocene sandy deposits. Prevailing soil types are acid and nutrient poor podzols or podzolic soils (for a more detailed description of their soil profiles see ''Sample plots''). The climate is of a humid, suboceanic type. Mean precipitation is 811 mm year^{-1} and the mean temperature is 8.4°C (Müller-Westermeier 1996).

Sample plots

Within a heathland area of 100 ha, 10 sample plots were randomly selected, each measuring 20 m × 40 m (species composistion and mean vegetation cover: dwarf shrubs (only *Calluna vulgaris*) 56%, graminoids (only *Deschampsia flexuosa*) 19% and cryptogams 42%). Each sample plot was divided into two subplots (20 m × 20 m; n = 20). The burning treatment was carried out in one subplot (treatment plot), and the second subplot served as a control (control plot). The sample plots were dominated by 10–12-year-old *Calluna* stands. This age was chosen because prescribed burning is carried out regularly on a 10–15 year cycle. None of the sample plots had been either managed or grazed during the last decade.

In all subplots the profile of the soils was examined. Soils were characterised by the following sequence of horizons (the mean thickness of a particular horizon is given in brackets, n = 20; data from Niemeyer et al. 2004 and Sieber et al. 2004): O-horizon (including O_L, O_f, O_h; 3.9 cm); A_{eh} + A_{he} (10.8 cm); B_{sh} + B_{hs} (8.1 cm); C (below 22.8 cm). In addition, in a complementary study, nutrient stores (for N, P, K, Ca, Mg) were determined in the above-ground biomass and the O-horizon before and immediately after the burning treatment, in four of the sample plots (i.e., four treatment and four control plots; data from Niemeyer et al. 2005). For a better interpretation of our findings, these results were considered in our study and are shown in Table 1.

Burning procedure

All treatment plots were burned (without adding extra fuel) in February 2001, and the vegetation was not cut before burning. Important prerequisites for the application of prescribed burning are periods of fine weather and low wind velocities. Since winter burns are low-temperature fires (max. burning temperature about 500°C at 3 cm above soil surface, lasting for 10–20 s; Niemeyer et al. 2004), in most cases the organic layer remains unaffected. About 75% of the above-ground biomass of *Calluna* was burned and 80% of the biomass of *Deschampsia flexuosa* and cryptogams remained unburned in the treatment plots. Therefore, *Calluna* regenerated mainly vegetative from the stem bases.

Determination of plant available nutrients and soil pH

Determination of plant available nutrients in the O- and A-horizons was carried out in five treatment plots and the corresponding control plots (i.e., 5 replicates, 10 subplots). In each subplot, soil samples (100 cm^3 each) were collected monthly for a period of 1 year at 20 randomly selected sample sites, starting immediately after

Table 1 Nutrient stores in the above-ground biomass, O- and A-horizon before and immediately after the subplots were subjected to prescribed burning; mean values (n = 4) and SD (in brackets); significant differences are indicated with an asterisk (* = $p < 0.05$); nutrient stores increased in the O-horizon in the treatment plots as a result of ash deposition (data from Niemeyer et al. 2005)

Nutrient stores in the		Nutrients (kg ha^{-1})				
		N	Ca	K	Mg	P
Above-ground biomass	Before	196.9 (28.3)	67.4 (7.5)	56.3(10.3)	18.2 (1.2)	12.9 (1.4)
	After	92.7* (10.5)	28.2* (5.2)	13.0* (5.3)	6.2* (1.2)	4.9* (0.7)
	Nutrient losses (from biomass)	104.2	39.2	43.3	12.0	8.0
O-horizon	Before	736.1 (95.4)	56.1 (11.1)	31.2 (5.1)	16.9(3.4)	23.5 (5.1)
	After	741.3 (139.0)	91.6* (13.1)	49.3* (13.4)	27.8* (6.4)	29.9* (4.5)
	Nutrients in ash	5.2	35.5	18.1	10.9	6.4
A-horizon	Not affected by burning	1782.3 (196.0)	156.8 (22.6)	298.2 (18.2)	70.6 (14.0)	114.0 (12.0)

the burning treatment (with the exception of the first sample, which was taken in February before burning). At each sample site both the O- and A-horizon were sampled. For each horizon, samples were thoroughly mixed in order to obtain one sample per horizon and subplot. The mixed samples were air dried and subsequently sieved with a 2 mm sieve. Samples were extracted with 0.0125 M $CaCl_2$ (VDLUFA 1980) and analysed immediately for plant available nitrogen (NH_4^+ and NO_3^-) using a cell test (Spectroquant VEGA 400; Merck, Darmstadt, Germany). Available PO_4^{3-}, Mg, and K were determined by extraction with calcium lactate, and available Ca by extraction with 0.01 M $MgCl_2$ (VDLUFA 1980). The extracted elements were determined using an ICP-OES (Optima 3300 RL; Perkin Elmer, Burladingen, Germany).

In the samples of the O-horizon pH_{H2}O/KCl{- values were measured before, immediately after and 1 year after burning (following Steubing and Fangmeier 1992). Values were determined using a glass electrode and a pH-meter (SenTix 97 T; WTW, Weilheim, Germany).

Nutrient losses by leaching

Nutrient losses by leaching were 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/0.45μ nylon-membrane; Umwelt-Geräte-Technik, Müncheberg, Germany). Soil water samplers were installed at depths of 100 cm, and samples were taken biweekly for a period of 1 year starting immediately after the burning treatment. In order to determine total N, 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, Germany). Total N was measured with an ion chromatograph (IC-DX 120 Dionex; Idstein, Germany). Concentrations of Ca, K, Mg, and P of samples were determined by means of an ICP-OES (see above). The annual rate of nutrient output was analysed in four treatment plots and the corresponding controls (i.e., four replicates).

Records soil surface temperature

Soil surface temperature was measured for a period of 2 months in summer 2002. Measurements were carried out directly on the soil surface of the treatment and the control plots by means of two thermocouples (NiCr-Ni; Dressel Temperatur-Meßtechnik, Biebertal, Germany). Temperature data were recorded with a data logger (C-Control; Conrad Electronic, Hirschau, Germany) four times a day (at 6.00 am, 12.00 am, 6.00 pm and 12.00 pm).

Nutrient content in *Calluna* and *Deschampsia*

In all subplots (n = 20), *Calluna* and *Deschampsia* plant material was sampled before and 19 months after the burning treatment (treatment and control plots). For each subplot, 20 samples (at least 50 g) of young shoots of *Calluna* and above-ground biomass (i.e., leaves) of *Deschampsia* (from randomly selected specimens) were mixed in order to obtain one sample per subplot and species (i.e., 10 replicates of the treatment plots and 10 of control plots). The harvested material was air dried, milled, dried again at 105°C and subsequently weighed (determination of oven dry weight). N- and C-contents were analysed with a C:N-analyser (Vario EL; Elementar, Hanau, Germany). Samples for determination of Ca, K, Mg, and P were dissolved in an HNO_3–HCl–H_2O_2 solution (Wong et al. 1997; Lamble and Hill 1998) and digested using a microwave (see above). Digests were analysed by means of ICP-OES (see above). From the data obtained we calculated the C:element and N:P ratios of the tissue of the two plant species.

Statistical analyses

One-way ANOVA with post-hoc Tukey's tests was performed to test for significant differences between both plant available nutrients, soil pH and the nutrient content of *Calluna* and *Deschampsia* in the treatment and the control plots. Log-transformation of data was performed in order to obtain normality of data (tested with a one-sample Kolmogorov–Smirnov test). All statistical analyses were carried out using the SPSS 11.5 package (SPSS Inc. Chicago, IL; USA).

Results

Effects of prescribed burning on plant available nutrients and soil pH

Concentrations of plant available nutrients in the course of the year following burning treatment showed very variable patterns (Fig. 1). Prescribed burning mostly affected the concentration of NH_4^+ in the O-horizon with maximum values during summer. The availability of NO_3^- increased significantly in the O-horizon immediately after burning and remained high from March to July. The concentrations of PO_4^{3-} and Ca were increased in March and April, and in October, respectively, and concentrations of K were not affected significantly. The availability of Mg, however, was significantly high in May and October, some months after the treatment. In contrast to the organic layers, nutrient concentrations in the A-horizon increased for NO_3^- only in April and May. In the subsequent period, no significant changes in nutrient concentrations were found in the A-horizon.

The pH-values in the O-horizon of the treatment plots did not change significantly ($P > 0.05$; means of $n = 5$; pre-treatment values: 3.5/3.1; post-treatment values immediately after burning: 4.0/3.3; post-treatment values 1 year after burning: 3.2/2.9. In the control plots, no significant changes in pH-values were observed either (values at the beginning of the experiment: 3.4/2.9; values after 1 year: 3.1/2.8).

Effects of prescribed burning on nutrient leaching

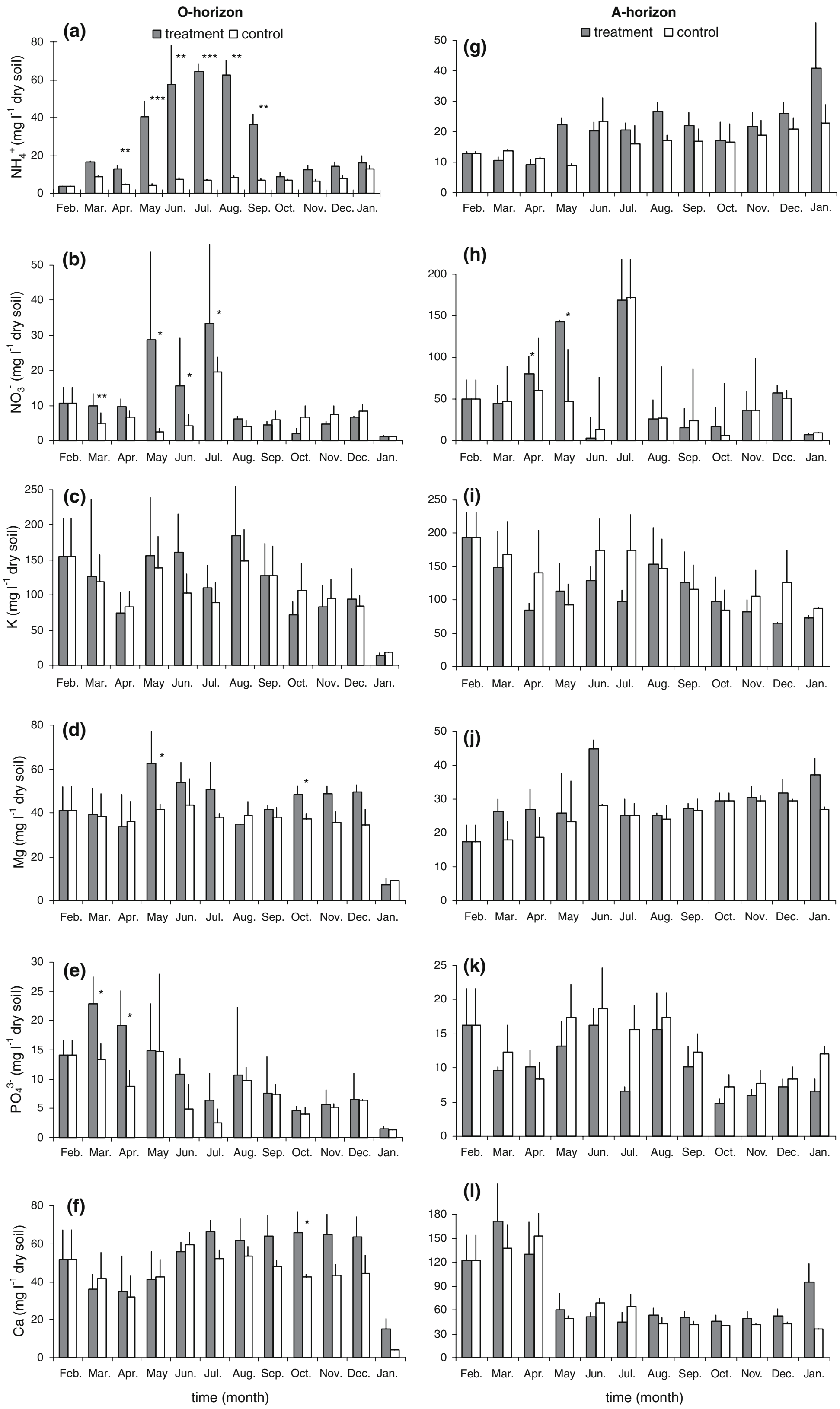
Leaching increased significantly for N, Ca, K, and Mg (Fig. 2). Compared to the control plots, post-treatment leaching for N increased by about 3.7 kg ha^{-1} $year^{-1}$. The quantities of leached P for all subplots were close to the analytically detectable threshold value. Leaching rates for P were thus below 0.5 kg ha^{-1} $year^{-1}$.

Soil surface temperature

Surface temperatures during summer 2002 ranged between 8°C and 60°C in the treatment plots, and between 10°C and 27°C in the control plots (Fig. 3). Day surface temperatures in the treatment plots always exceeded those of the control plots.

Effects of prescribed burning on plant tissue nutrient content

Before the burning treatment, the C:element ratios did not differ significantly between treatment and control plots (i.e., for each species C:element ratios were the same in control and treatment plots before burning).


O-horizon
A-horizon
treatment
control
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
NH_4^+ (mg l^{-1} dry soil)
NO_3^- (mg l^{-1} dry soil)
K (mg l^{-1} dry soil)
Mg (mg l^{-1} dry soil)
PO_4^{3-} (mg l^{-1} dry soil)
Ca (mg l^{-1} dry soil)
Feb. Mar. Apr. May Jun. Jul. Aug. Sep. Oct. Nov. Dec. Jan.
time (month)

◀**Fig. 1** Annual course of plant available nutrients (O-horizon: **a–f**, A-horizon: **g–l**) in the treatment plots (grey bars) and the control plots (blank bars) in the first year after burning treatment; mean values ($n = 5$) and SD; * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$. The first measurements were carried out in February 2001 (= Feb. on the x-axis) before burning treatment, all other measurements were carried out after burning treatment (March 2001–January 2002)

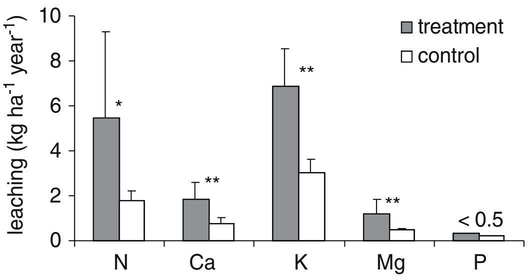


Fig. 2 Sum of the amounts of nutrients leached in the treatment plots (grey bars) and the control plots (blank bars) in the first year after burning treatment; mean values ($n = 4$) and SD; * = $P < 0.05$, ** = $P < 0.01$

Nineteen months after burning treatment, C:element ratios of *Calluna* showed no significant differences between plants in the treatment and the control plots (Table 2). By contrast, C:element ratios for *Deschampsia* increased significantly in the treatment plots. Only the C:N ratio remained unchanged.

The N:P ratio of *Calluna* did not differ significantly between plants in the treatment and the control plots, whereas the N:P ratio of *Deschampsia* was significantly higher for plants growing on the treatment plots (Table 2). With the exception of one sample, all the N:P ratios determined in the plant tissue of both species exceeded a value of 14 (not shown in Table 2).

Discussion

Effects of prescribed burning on nutrient concentrations in humus horizons and leachate

Our results revealed very variable patterns of nutrient concentrations following burning treatment. Burning particularly affects the availability of NH_4^+ in the O-horizon. Concentrations of NH_4^+ achieved highest values during summer (Fig. 1a). In our experiment, the removal of a former shading dwarf shrub canopy in particular led to distinctly higher soil surface temperatures (i.e., in the O-horizon) in the treatment plots (Fig. 3). This may explain the high concentrations of NH_4^+ found in the treatment plots. One important mechanism increasing NH_4^+ availability is the mineralisation of remaining roots and organic material in the humus horizons (Berendse 1990; Mitchell et al. 1999). As shown in Table 1, humus horizons represent huge stores for N, whilst only small quantities of N are located in the ash. Similar to our findings, excessive NH_4^+ production was also observed in heaths subjected to sod cutting (Dorland et al. 2003). We assume that both high N_{inorg} concentrations in the humus horizons (Fig. 1a) and limited N-uptake of the regenerating vegetation were responsible for the increased leaching of N (Fig. 2). It is likely that elevated N leaching following heathland burning

Fig. 3 Daily course of the soil surface temperature measured at 6 h-intervals from 06.06.2002 to 01.08.2002 (treatment plot: grey line; control plot: black line)

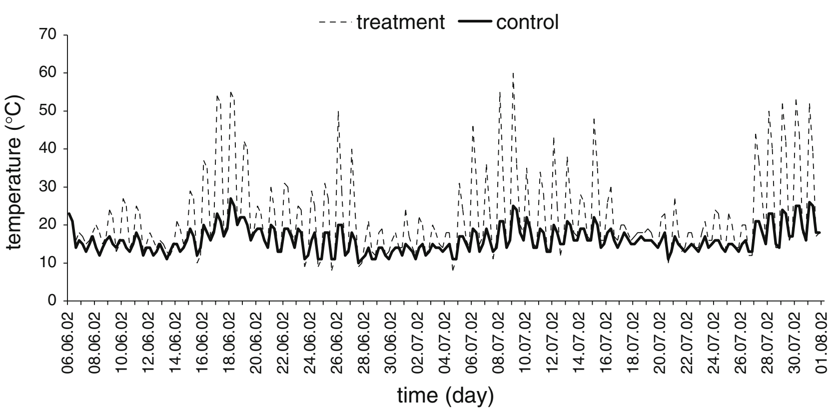


Table 2 Effects of prescribed burning on C:element ratios, N:P ratios and the tissue N- and P-contents of *Calluna vulgaris* and *Deschampsia flexuosa* (19 months after the subplots were subjected to prescribed burning)

	Calluna vulgaris		*Deschampsia flexuosa*	
	Control	Treatment	Control	Treatment
C:Ca	125.5 (7.9)	107.6 (8.3)	309.2 (60.3)	***396.0** (98.4)
C:K	119.5 (21.0)	106.4 (7.2)	39.2 (3.8)	***57.4** (17.5)
C:Mg	345.7 (38.7)	355.0 (24.0)	725.9 (160.3)	****1,041.1** (305.5)
C:P	631.3 (93.7)	594.9 (72.7)	560.8 (112.6)	****844.2** (277.3)
C:N	39.0 (2.7)	36.9 (4.0)	27.4 (1.7)	30.3 (4.5)
N:P	16.1 (1.6)	16.1 (0.7)	20.5 (4.1)	***28.7** (7.7)
N mg g^{-1}	13.5 (0.9)	14.4 (1.6)	17.4 (1.1)	17.2 (3.1)
P mg g^{-1}	0.9 (0.1)	0.9 (0.1)	0.9 (0.3)	***0.6** (0.1)

Significant differences are indicated in bold characters and with an asterisk (* $= P < 0.05$, ** $= P < 0.01$); mean values ($n = 10$) and SD (in brackets)

takes place over more than 1 year (Niemeyer et al. 2005), as vegetation needs about 5 years for recovery (Maltby et al. 1990; Sedláková and Chytrý 1999). Furthermore, soil surface temperatures remain increased throughout this period and thus may stimulate N mineralisation (Anderson and Hetherington 1999; Schmidt et al. 2002). Concentrations of NH_4^+ found in the O-horizon of the treatment plots (up to 64.53 mg l^{-1}) suggest that vegetation here is oversupplied with N. In these plots, values are about eight times higher than for the control plots. According to the experiments of Dorland et al. (2003), high concentrations of ammonium in the field as a result of sod cutting were responsible for the low germination and thereby may hamper the establishment of many heathland target species.

In contrast to NH_4^+, concentrations of plant available NO_3^- and PO_4^{3-} in the O-horizon showed a distinct, but short-term increase (Fig. 1b, e). We suppose that the peak of plant available NO_3^- can be attributed to nitrification following the burning procedure. Nitrification, and thus NO_3^- availability, distinctly increased in May in step with increasing soil temperatures (Fig. 1b). This interpretation may be supported by the finding that pH-values showed no significant change. Although one would expect elevated pH-values, owing to the deposition of basic ash (Forgeard 1990), nitrification and, thus, liberation of protons may have compensated for a pH-increase (Brady and Weil 1996). As NO_3^- is easily leached, elevated concentrations were also found in the A-horizon in April and May. The short-term increase in plant available P may be attributed to the liberation of P fixed in the burned biomass, and P appears in considerable amounts (6.4 kg ha^{-1}; Table 1) in the ash deposited after burning (Diemont 1996; Niemeyer et al. 2005). The quantities of leached P fell below the analytically detectable threshold value (Fig. 2). We assume that P, generally appearing in low concentrations in heathland soils, is prevented from leaching by the sorption of ortho-phosphate in the humus- and B-horizons (Chapman et al. 1989; Olff and Pegtel 1994).

The question remains as to why some of the nutrients with higher concentrations in the ash (Ca, Mg, K; Table 1) were evidently not plant available or, if plant available, then only in amounts slightly higher than in untreated plots. Several reasons may account for this. As shown by Diemont (1996), nutrients in the ash deposited after heathland burning are not quantitatively plant available, and their availability increases depending on their liberation as a result of mineralisation processes. In addition, NO_3^-, Ca, K, and Mg are easily leached with percolating soil water (Brady and Weil 1996). As the nutrient uptake by plants (through the existing roots, as the plants regenerate from the stem bases) is very limited after burning (Forgeard 1990; Maltby et al. 1990; Mallik and Fitzpatrick 1996), we found significantly increased concentrations of these nutrients in the leachate (Fig. 2). Thus, most of the plant available cations liberated after burning treatment are not fixed by the cation exchange system in the upper soil, but are leached, as they cannot be taken up by plant roots (Mallik and Fitzpatrick 1996). This process may be intensified by an excessive liberation of NH_4^+ (see above). High concentrations of NH_4^+ may lead to a replacement of cations (Mg, Ca and K) at the soil exchange sites (Brady and Weil 1996) and, hence, to an increased leaching of Ca, Mg and K.

Effects of prescribed burning on the nutrient content of *Calluna* and *Deschampsia*

The nutrient contents of *Calluna* and *Dechampsia* showed different responses to prescribed burning. Whilst C:element ratios in *Calluna* did not change significantly, ratios increased significantly for *Deschampsia* after heathland burning (with the exception of the C:N ratio). Furthermore, N:P ratios increased for *Deschampsia*, but remained unchanged in *Calluna*. These results suggest that burning negatively affects the nutrient content of *Deschampsia*. High burning temperatures in general favour *Calluna* regeneration, but depend on the amount of organic matter available for combustion and the water content of the above-ground biomass subjected to burning (Miller and Miles 1970). Prescribed burning, however, is an inappropriate management measure in stands dominated by grasses (these stands should be subjected to sod cutting if management aims at the reestablisment of heather). Thus, regeneration success after burning treatment mainly depends on the structural and vegetation patterns of heaths at the beginning of the treatment. We assume that changes in the microclimate were mainly responsible for the deterioration of the nutrient content of *Deschampsia*. In the stands of the control plots, *Deschampsia* formed a low grass layer protected by a shading dwarf shrub canopy. Hence, soil surface temperatures in the control ranged within a small interval (during summer, Fig. 3). The removal of the dwarf shrubs drastically changed the microclimate for *Deschampsia*, as shown by the increase in soil surface temperatures up to 60°C. This may have led to deficiencies in the water supply and, thus, to reduced transpiration and nutrient uptake rates. Effects of water shortage on the nutrient content of heathland plants were also reported by Tomassen et al. (2004). The oversupply with N on the treatment plots may explain why C:N ratios remained unchanged in *Deschampsia*, whilst the other C:element ratios increased. This interpretation is supported by the finding that the mean N content of *Deschampsia* did not change significantly after burning treatment (Table 2). By contrast, *Calluna*, as a pyrophytic and xerophytic species (Webb 1998), was hardly affected by burning and did not suffer from changes in the microclimate. In experiments analysing the below-ground competition between *Calluna* and grass roots it was shown that *Calluna* was the superior competitor for nutrients, probably because of its ability to concentrate root growth in the upper organic layer (Genney et al. 2000).

In our experiment, prescribed burning particularly aggravates the P-supply of *Deschampsia*. Leaf P-content for this species decreased significantly after burning, whilst the mean N-content remained unchanged (Table 2). Prescribed burning thus increased the P limitation for *Deschampsia* at the plant species level (Tomassen et al. 2004). However, the high N availability on the treatment plots may raise the question as to why N:P ratios of *Calluna* did not change significantly. We assume that *Calluna* is co-limited by P on the sites studied. This is supported by the fact that N:P ratios of *Calluna* ranged between 14 and 17 (in all sample plots), indicating an N–P-co-limitation (Kirkham 2001; Roem et al. 2002; Tomassen et al. 2004). Hence, both the N- and the P-content of *Calluna* increased after burning, whereas the N:P ratio remained unchanged.

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Beitrag III

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

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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:

$$L_{(6yr)} = L_{(1yr)}+L_{(2yr)}+{}^{4}/_{5}\,L_{(2yr)}+{}^{3}/_{5}\,L_{(2yr)}+{}^{2}/_{5}\,L_{(2yr)}+{}^{1}/_{5}\,L_{(2yr)} - 6\,L_{(control)} = L_{(1yr)}+3L_{(2yr)}-6\,L_{(control)} \quad (1)$$

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:

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

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	5.1	3.6	2.8	<0.5
	(0.59)	(0.32)	(0.37)	(0.15)	

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 $kg.ha^{-1}$).

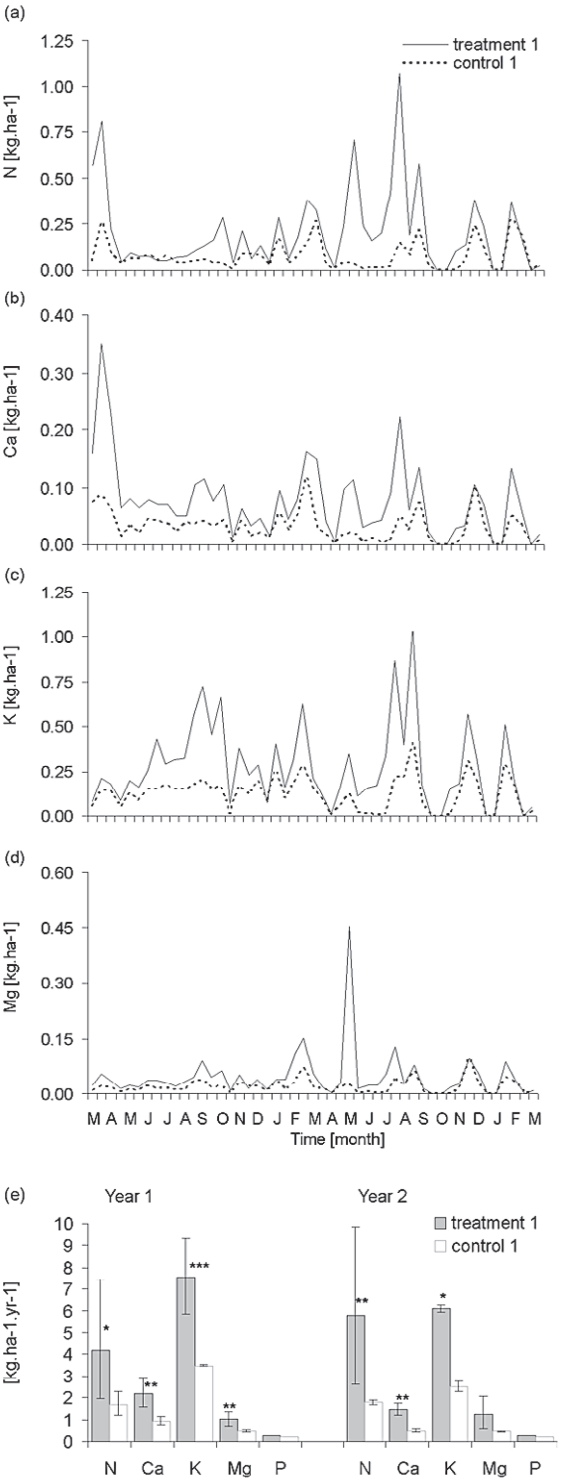

Fig. 1. Annual course (two-year period) of leaching of N (**a**), Ca (**b**), K (**c**) and Mg (**d**) (treatment plots: solid line; control plots: thin line) and annual amounts of nutrients leached (**e**) in the treatment plots (closed columns) and the control plots (open columns) in the first and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

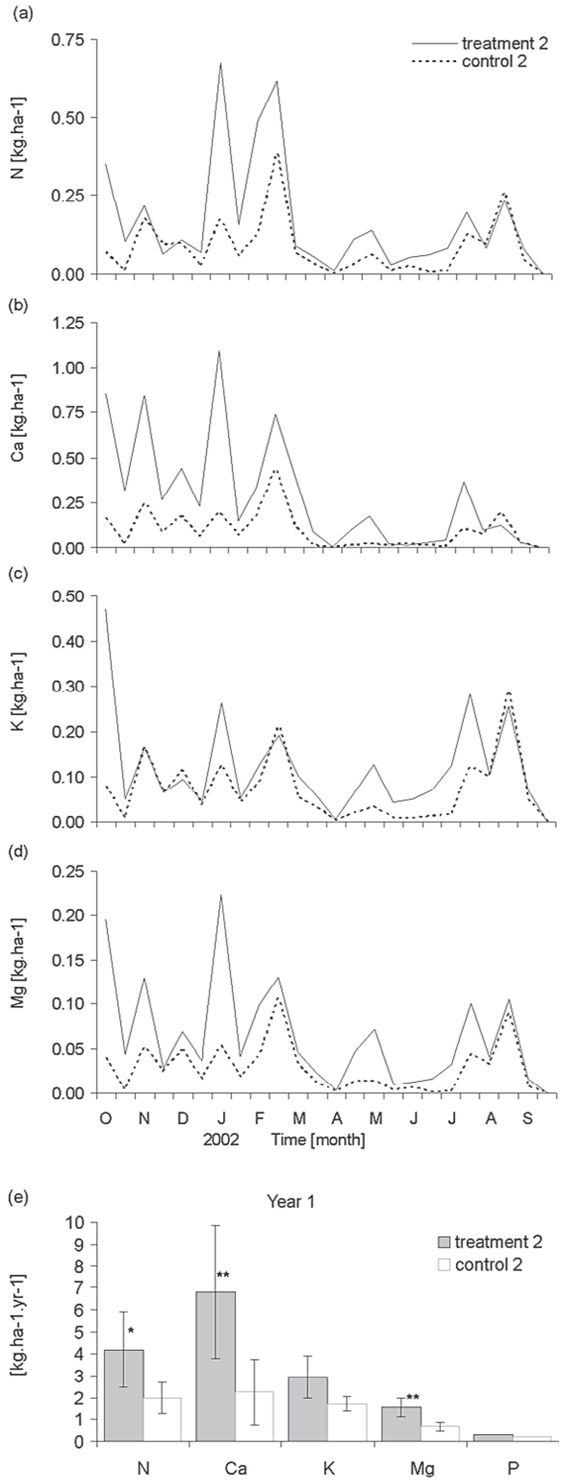

Fig. 2. Annual course (one year period) of leaching of N (**a**), Ca (**b**), K (**c**) and Mg (**d**) (treatment plots: solid line; control plots: thin line) and annual amounts of nutrients leached (**e**) in the treatment plots (closed columns) and the control plots (open columns) one year after burning (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 (0.5)	0.7 (0.3)	3.0 (0.8)	0.5 (0.1)	<0.2 (nc)	2.0 (0.2)	2.0 (0.6)	1.7 (0.1)	0.7 (0.1)	<0.2 (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 (10.7)	34.3 (2.3)	26.6 (3.1)	9.6 (0.8)	4.8 (0.2)	196.9 (28.3)	67.4 (7.5)	56.3 (10.3)	18.2 (1.2)	12.9 (1.4)
	Unburned remainder^{+}	9.8 (3.5)	1.5 (0.6)	0.5 (0.2)	0.3 (0.1)	0.4 (0.1)	92.7 (10.5)	28.2 (5.2)	13.0 (5.3)	6.2 (1.2)	4.9 (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 (89.0)	77.8 (12.6)	30.6 (7.6)	17.8 (1.9)	25.4 (3.1)	736.1 (95.4)	56.1 (11.1)	31.2 (5.1)	16.9 (3.4)	23.5 (5.1)
	O-horizon after burning^{+}	766.5^{ns} (148.6)	103.8^{ns} (28.4)	49.7* (17.7)	26.8** (3.0)	28.8^{ns} (4.1)	741.3^{ns} (13.1)	91.6** (139.0)	49.3** (13.4)	27.8** (6.4)	29.9^{ns} (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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Beitrag IV

Impact of sod-cutting and choppering on nutrient budgets of dry heathlands

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Biological conservation, in press

Impact of sod-cutting and choppering on nutrient budgets of dry heathlands

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Abstract

Heathlands are endangered by both atmospheric nutrient deposition and natural succession. High-intensity management measures are considered necessary, as low-intensity measures (e.g. mowing, prescribed burning) are not able to compensate for atmospheric nutrient loads. Choppering (i.e. the near-complete removal of the O-layer) has several advantages over sod-cutting, including less waste material, faster vegetation recovery and lower costs. This raises the question addressed in this study as to the extent to which choppering and sod-cutting affect nutrient budgets in dry heathlands.

We compared the quantities of N, Ca, K, Mg, and P removed by choppering and sod-cutting in the Lueneburg Heath (NW Germany). Nutrient balances were calculated by analysing atmospheric inputs, elevated leaching rates following management, and output due to the removal of above-ground biomass and humus horizons.

Nutrient loss was particularly high after removal of O- and A-horizons. In contrast, increased leaching after management was of minor importance for nutrient budgets. Although considerably more nutrients were removed by sod-cutting than by choppering (e.g. N: 1712/1008 $kg.ha^{-1}$), nutrient output by choppering was still sufficient to compensate for 60.7 years of net N-input. Choppering was able to remove more N per volume unit than sod-cutting due to higher N-contents in the organic layer than in the A-horizon. For this reason, choppering is more economical than sod-cutting and, thus, should be considered the preferable method at sites not dominated by *Molinia caerulea.* A combination of high-intensity measures with prescribed burning would appear to be suitable as this would ensure more selective removal of N.

Keywords: atmospheric nutrient deposition, *Calluna vulgaris*, *Deschampsia flexuosa*, leaching, nitrogen, nutrient removal

Introduction

Heathlands have been designated one of the most important cultural landscapes in the category of endangered habitat types in Europe (EC Habitats Directive 92/43/EEC; Webb, 1998) and it is against this background that the conservation of heathlands has become a major issue in European nature conservation.

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However, not only has the area covered by heathlands decreased throughout Europe in the course of the last few decades but the structural and functional qualities of heathlands have also seen changes (Aerts and Heil, 1993; Marrs, 1993; Rose et al., 2000). The major problems involve the transition from heathlands to grasslands, decreasing biodiversity, the accumulation of soil organic matter, the increase of heather beetle attacks and a reduced resistance of *Calluna vulgaris* (L.) Hull (henceforth referred to as *Calluna*) to frost and drought (Marrs and Le Duc, 2000; Roem and Berendse, 2000). Natural succession resulting from the cessation of traditional land use as well as elevated nutrient deposition have both been held responsible for these changes (Bobbink et al., 1998; Webb, 1998; Bakker and Berendse, 1999).

Modern management measures have become increasingly important in the preservation of heathlands. Primarily aiming at the regeneration of dwarf shrubs and the prevention of tree establishment, modern heathland management is now considered an important tool with which to modify ecosystem impacts caused by atmospheric nutrient deposition (Power et al., 2001; Terry et al., 2004). The necessity for high-intensity management practices is pointed out by several authors in this connection, since low-intensity management such as prescribed winter burning and mowing are not sufficient to counterbalance atmospheric nutrient loads on a long-term basis (Power et al., 2001; Barker et al., 2004; Terry et al., 2004; Härdtle et al., 2006).

Sod-cutting is regarded as highly effective at reducing nutrient pools and hence is considered the most suitable means of recreating degenerated heaths (Diemont and Linthorst Homan, 1989; Bakker and Berendse, 1999; Britton et al., 2000). This management measure - in some countries also known as sod removal, turf cutting/removal/stripping or plaggen - follows historical models from the 18^{th} and 19th centuries. In the past this was, and indeed still is today, most common in the Netherlands and Germany. In the course of this measure, the complete above-ground biomass, the O-layer and part of the A-horizon are removed. Traditionally, sods were cut by hand, spread out in barns, where they became mixed with the faeces of the sheep, and finally used to fertilise the arable fields on nutrient-poor sandy soils (Webb, 1998). Nowadays, this work is performed in most regions by specially developed sod-cutting machines. However, sod-cutting is cost-intensive and produces a large amount of waste material, dependent on the cutting depth (Britton et al., 2000; Koopmann and Mertens, 2004; Müller, 2004).

It was for this reason that an alternative management measure was introduced. So-called "choppering" removes the complete biomass and the largest part of the O-layer, without affecting the A-horizon (Maes et al., 2004). The result is the creation of bare soil, with only a thin layer of organic material (about 0.5 cm) remaining on the surface. In terms of the intensity with which it enables the removal of soil and plant material from heaths, choppering represents a medium between sod-cutting and high-intensity mowing (Power et al., 2001; Terry et al., 2004). Frequently, no clear distinction is made between the terms sod-cutting and choppering. A less intensive sod-cutting procedure (understood here as choppering) was applied for the first time in the Netherlands in the 1980s (Diemont and Linthorst Homan, 1989). Choppering was introduced into our current study area in the middle of the 1990s and has henceforth been successfully applied in regenerating dry heaths where *Deschampsia flexuosa* (L.) Trin. (in the following referred to as *Deschampsia*) had become (co-) dominant. By contrast, choppering is not suitable for a restoration of sites dominated by *Molinia caerulea* (L.) Moench (henceforth referred to as *Molinia*), since the tussock is not removed completely by this means and therefore vegetative regeneration of *Molinia* can not be prevented. Choppering has several advantages over sod-cutting. Firstly, the machine used in our choppering experiment works faster and is smaller than the one used for sod-cutting; hence, there is less mechanical impact. Secondly, smaller amounts of waste material are produced which can be composted (Koopmann and Mertens, 2004). Thirdly, vegetation regenerates faster after choppering than after sod-cutting (Sieber et al., 2004), an aspect which was viewed in a positive light by visitors to the area (Müller, 2004). And finally, costs of choppering amount to barely half those of sod-cutting (Müller, 2004).

There is as yet scant information on the extent to which nutrient budgets are affected by choppering and sod-cutting in relation to current atmospheric nutrient deposition. In particular, little is known about the effect of these management measures on leaching rates. Hence, in order to further understanding of nutrient dynamics resulting from mechanical high-intensity management in dry lowland heaths, we addressed the following research questions in our study: i) What is the nutrient input from atmospheric deposition in the study area and what quantities of nutrients can be removed from above-ground biomass and soil by choppering and sod-cutting (N, Ca, K, Mg and P)? ii) What quantity of nutrient loss can be attributed to leaching rates following the management measures? iii) How sustained is the effect of nutrient removal in relation to atmospheric nutrient deposition (nutrient output/input ratios resulting from management measures and atmospheric nutrient loads)?

Materials and methods

Study area

The experiments were carried out in the nature reserve Lueneburg Heath, Lower Saxony, NW Germany (53°15' N, 9°58' E, 105 m a.s.l.), where the largest complex of heathlands in NW Germany (about 5000 ha) is located. Pleistocene sandy deposits and nutrient-poor podzols or podzolic soils characterise the study area. In the topsoil pH(H_2O) values range between 3.2 and 3.6. The climate is of a humid suboceanic type with mean annual precipitation of 811 mm and a mean annual temperature of 8.4 °C (Müller-Westermeier, 1996). The study area was chosen to represent both the typical structure and edaphic conditions of dry lowland heaths in NW Germany.

Experimental design and management procedures

Within a heathland area of 100 ha in size a total of 18 treatment plots was randomly selected; 9 of these served for the choppering and 9 for the sod-cutting experiment. On all treatment plots (9 + 9) the nutrient pools in above-ground biomass and soil were analysed before and after the management procedure. A leaching experiment was also carried out both on 4 of the 9 choppering treatment plots and on 4 of the 9 sod-cutting treatment plots (4 + 4). That means we had 9 replicates for biomass and soil analyses and 4 replicates for leaching analyses. Each treatment plot was 20 m x 20 m in size. For the leaching experiment, control plots where no management measures were performed were also needed. These control plots (4 + 4) also measured 20 m x 20 m and were adjacent to the treatment plots used for the leaching experiment.

The sites selected for sod-cutting and choppering were dry heathlands with *Calluna*, *Deschampsia* and *Molinia* as dominant species (see Table 1). Sample plots were comparable as regards the thickness of the organic layer, vegetation structure and the age of *Calluna* (10-12 years). All sample plots had been unmanaged during the past decade.

Choppering (in the following referred to as "ch") and sod-cutting (in the following referred to as "sc") were carried out in Dec 2001/Jan 2002. Choppering created bare soil by removing the above-ground biomass and most parts of the O-layer, with only a thin layer of organic material remaining on the surface (Table 2). A machine equipped with sledges was used in the choppering process. Sod-cutting created bare soil by removal of the above-ground biomass, O-layer and parts of the A-horizon (Table 2). After this management measure, mineral soil formed the surface of the site.

Table 1
Mean cover of prevailing plant species in the choppered (ch) and sod-cut (sc) plots before management measures were carried out (n = 9 (ch) and n = 9 (sc)).

	Prevailing species	ch Mean cover (%)	sc Mean cover (%)
Dwarf shrubs	*Calluna vulgaris*	40	38
Graminoids	*Deschampsia flexuosa*	66	26
	Molinia caerulea	< 1	36
	Graminoids (total)	66	62
Cryptogams	*Hypnum cupressiforme*	30	49
	Dicranum scoparium	23	6
	Cryptogams (total)	53	55

Atmospheric nutrient deposition

Nutrient input from atmospheric deposition was determined using 12 bulk deposition samplers (type Münden 200, Inst. of Forest Hydrology, Han. Münden, Germany). Samplers were installed 100 cm above ground in the close vicinity of the treatment plots. Samples were collected biweekly for a period of one year (from Dec 2001 - Jan 2003) starting immediately after the management measures had taken place.

Concentrations of Ca, K, Mg, and P were determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, Optima 3300 RL, Perkin Elmer, Burladingen, Germany). In order to analyse total N-concentrations, we dissolved samples using $K_2S_2O_8$-NaOH solution according to the Koroleff-method (Grasshoff et al., 1983). Subsequently, samples were subjected to microwave digestion (MLS-ETHOS, MLS-GmbH, Leutkirch, Germany). Total N was analysed by means of an ion chromatograph (IC-DX 120, Dionex, Idstein, Germany).

In a six-year-long experiment, Gauger et al. (2000) compared bulk and total (i.e. 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 calculate total deposition input, our bulk deposition data were corrected by the factors 1.30 (N), 1.54 (Ca), 1.33 (K), and 1.55 (Mg) (according to Bleeker et al., 2000; Gauger et al., 2000).

Nutrient pools in plants and soil

Above-ground biomass: Above-ground plant material was harvested from randomly selected 1 m² patches in each treatment plot. Harvested plant material was separated into three groups: dwarf shrubs, graminoids and cryptogams. No above-ground biomass was left after the choppering and sod-cutting experiments.

Dried material (105 °C) was weighed for each group, cut with a cutting mill (SM 100 S, Retsch, Haan, Germany) and subsequently ground with an agate ball mill (Pulverisette 7, Fritsch, Idar-Oberstein, Germany).

Organic layer: In all treatment plots a grid of 10 m x 10 m with intersection points spaced 2 m apart was marked out. At each intersection point (n = 36) we determined the thickness of the organic layer and took a soil sample comprising the entire horizon. In addition bulk density of the horizon was determined by means of a 100 cm³ sample. All samples from one treatment plot were thoroughly mixed, so that we obtained 9 mixed samples per management experiment. Samples of the organic layer were treated in the same way as biomass material. After choppering, the thickness of the remaining organic layer was determined using the 36 intersection points of the grid. After sod-cutting there was no organic material left.

A-horizon: Samples of the A-horizon were taken and treated according to the procedure described above for the organic layer. After sod-cutting, the thickness of the remaining A-horizon was determined using the 36 intersection points of the grid. Choppering did not affect the A-horizon.

Chemical analyses: N-contents of above-ground biomass, organic layer and A-horizon were analysed with a C/N analyser (Vario EL, Elementar, Hanau, Germany). Samples for Ca, K, Mg, and P determination were dissolved in an HNO_3-HCl-H_2O_2 solution using microwave digestion (Wong et al., 1997; Lamble and Hill, 1998). Digests were analysed by means of an ICP-OES (see above).

Nutrient loss by leaching (first year after management)

Nutrient loss by leaching was determined by means of lysimeters 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, Germany). Soil water samplers were installed at depths of 100 cm. The nutrient loss by leaching was determined on the 8 designated treatment plots (4 ch and 4 sc) and the 8 corresponding control plots (total n = 16). Samples were taken simultaneously and at the same intervals as deposition samples. Digestion and analysing procedures were the same as for the deposition samples.

Calculation of increase in leaching rates as a result of management measures

After the application of the management measures, it is to be expected that leaching rates increase in the treatment plots compared to the control plots (Berendse, 1990; Bakema et al., 1994). This is due to the removal of the vegetation, which leads to increases in both the amount of percolating soil water (as a consequence of reduced evapotranspiration rates in the treatment plots), and in the quantities of leached nutrients (as a consequence of the lack of nutrient uptake by vegetation; Gimingham et al., 1981; Sedláková and Chytrý, 1999). Compared to sites subjected to low-intensity management such as mowing or burning, leaching rates are expected to be higher in sites after high-intensity management like choppering or sod-cutting. This is due to the complete removal of the vegetation and the complete or partial removal of the humus horizons (Gimingham et al., 1981; Sedláková and Chytrý, 1999).

In order to calculate elevated leaching rates as a consequence of management measures, we followed the approach used by Niemeyer et al. (2005). This approach assumes a decrease in leaching rates in step with vegetation recovery after management as a result of increasing evapotranspiration and nutrient uptake rates of the regenerating vegetation (Gimingham et al., 1981; Sedláková and Chytrý, 1999). According to Bobbink et al. (1998) and Diemont and Lindhorst Homan (1989) vegetation recovery in choppered sites will achieve the situation prior to management after about 10 years, whilst in sod-cut sites vegetation recovery will take about 15 years. As above-ground biomass of *Calluna* and organic matter in the O-layer increases almost linearly in the time span regarded (Gimingham et al., 1981; Berendse, 1990), we assume in approximation a linear decrease in leaching rates of 1/10 per year on the choppered plots and of 1/15 per year on the sod-cut plots.

Calculation of Theoretical Effective Periods

In order to provide nutrient balances for the heathland investigated, we calculated the ratio of the net output of nutrients (as a result of the management measures applied) and the annual net input. This ratio provides a term of reference that describes the period of time in which the quantities of nutrients removed due to a particular management measure are equivalent to atmospheric nutrient inputs (cf. Britton et al., 2000; Mitchell et al., 2000; Niemeyer et al., 2005). We call this the "Theoretical Effective Period (referred to as TEP)". For the calculation of the TEP we assumed that deposition rates remain unchanged for the subsequent years.

The TEP (unit: years) is calculated for each nutrient element according to the following formula:

TEP = net output (kg.ha-1.yr-1) / annual net input (kg.ha-1.yr-1);

where:

net output = nutrients removed by means of ch or sc + increased leaching (in: kg.ha-1.yr-1); and

annual net input = annual nutrient deposition – annual leaching under the control plots (in: kg.ha-1.yr-1).

Statistics

Measurement results from atmospheric deposition, leaching, above-ground biomass and soil were subjected to one-way ANOVA (SPSS 12.0 for Windows). Leaching data were log-transformed and the remaining data arcsin-transformed prior to ANOVA and the calculation of means and SD.

Results

Atmospheric nutrient deposition

There was no significant difference in atmospheric nutrient deposition ($p > 0.05$) between the 12 bulk samplers. Thus, we considered atmospheric nutrient deposition to be equal for all the experimental plots. Total N-input amounted to 22.8 kg.ha-1.yr-1 (Figure 1). P-concentrations in the samples were below the analytically detectable threshold value (0.0326 mg.l-1) and, hence, P-input below 0.5 kg.ha-1.yr-1.

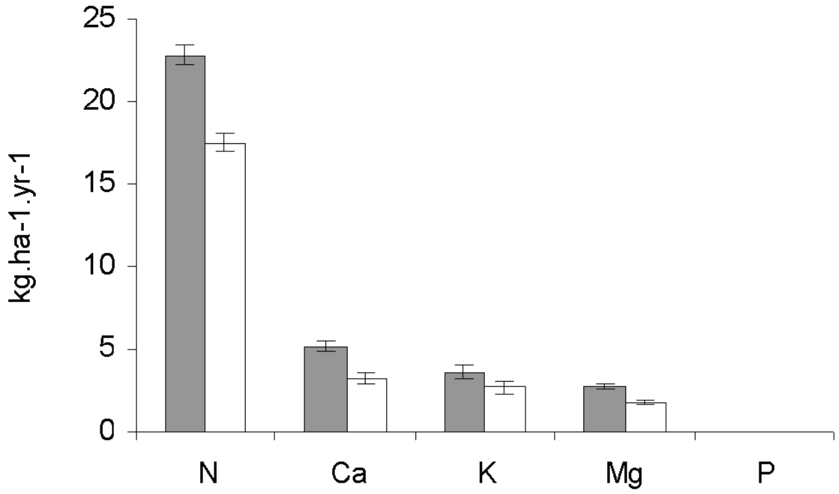

Figure 1
Annual atmospheric nutrient deposition in the study area in kg.ha-1; total deposition: filled columns; bulk deposition: open columns; mean values (*n* = 12) and ± 1 SD; Deposition rates for P were below the analytically detectable threshold value. They thus amount to less than 0.5 kg.ha-1.yr-1.

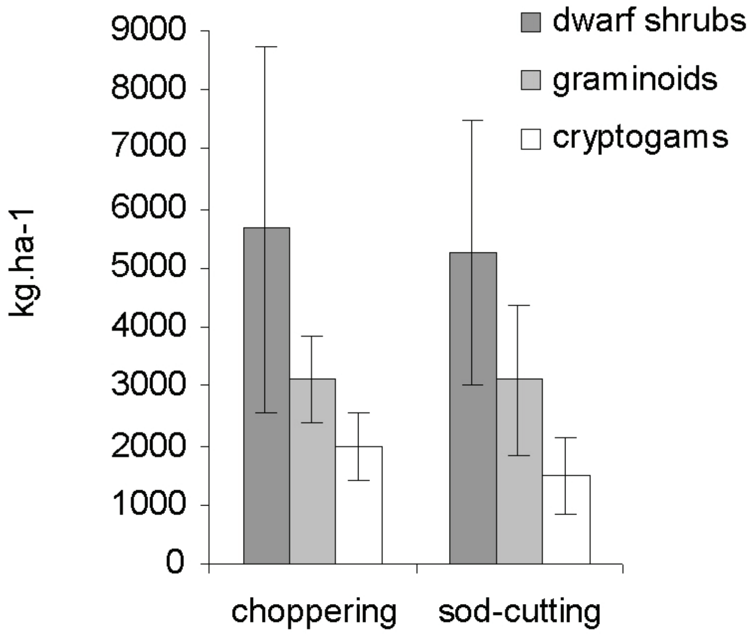

Figure 2
Above-ground biomass of dwarf shrubs, graminoids and cryptogams in the treatment plots before the management measures were carried out (mean values ± 1 SD; *n* = 9). Differences between the plots for choppering and sod-cutting were not significant.

Above-ground biomass, O-layer and A-horizon

Above-ground biomass amounted to 10 750.8 kg.ha-1 in the choppered plots and 9842.9 kg.ha-1 in the sod-cut plots (mean values). Dwarf shrubs had the highest share of above-ground biomass compared to graminoids and cryptogams (Figure 2).

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Above-ground biomass amounted to 10 750.8 kg.ha-1 in the choppered plots and 9842.9 kg.ha-1 in the sod-cut plots (mean values). Dwarf shrubs had the highest share of above-ground biomass compared to graminoids and cryptogams (Figure 2).

Table 2
Nutrient pools in above-ground biomass, organic layer and A-horizon before and after choppering/sod-cutting in kg.ha-1; thickness of organic layer and A-horizon in cm before and after management measure was carried out; mean values and ± 1 SD (in brackets); significant differences (before - after) are indicated by an asterisk: * = $p < 0.05$; ** = $p < 0.01$.

		ch						sc					
		Thick-ness	N	Ca	K	Mg	P	Thick-ness	N	Ca	K	Mg	P
Above-ground biomass	before	-	155.0 (37.2)	36.7 (12.5)	34.4 (7.8)	11.9 (3.8)	10.0 (2.6)	-	107.3 (29.3)	29.8 (9.0)	26.6 (9.9)	9.1 (2.9)	6.1 (1.9)
	after	-	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	-	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)
Organic layer	before	3.9 (0.5)	941.4 (181.9)	100.6 (42.4)	32.5 (8.2)	25.1 (7.1)	35.8 (7.6)	3.9 (0.5)	960.7 (166.3)	97.6 (23.1)	49.3 (10.4)	26.6 (4.8)	36.1 (7.0)
	after	0.5** (0.2)	108.4** (51.1)	11.6** (6.4)	3.9** (2.3)	3.0** (1.6)	4.2** (2.1)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)
A-horizon	before	10.1 (0.5)	1950.5 (460.8)	174.0 (32.2)	277.6 (48.5)	57.9 (10.3)	113.6 (22.3)	9.6 (2.6)	1850.9 (378.6)	201.2 (109.3)	281.3 (105.3)	62.9 (20.6)	92.2 (23.3)
	after	not affected						6.5* (2.2)	1239.9** (377.2)	137.9 (85.8)	192.8 (85.0)	42.9 (17.5)	62.4* (21.2)

Leaching

In the first year after the application of the management measures, leaching rates were elevated for all elements, compared with the control plots (Figures 3 and 4). They were particularly high during April and September. N-leaching was significantly increased ($p < 0.05$) after both management measures. Additionally, K-leaching after choppering and Mg-leaching after sod-cutting were significantly higher than in the control plots ($p < 0.05$).

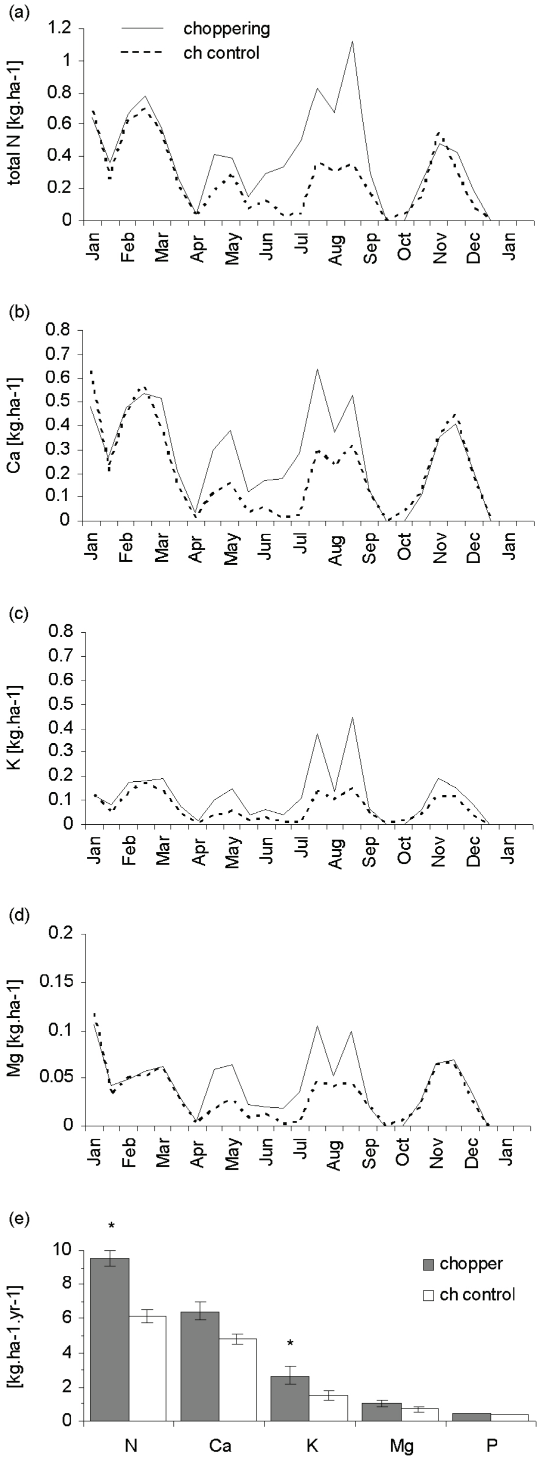

Figure 3
Annual course of leaching of N (a), Ca (b), K (c), and Mg (d) within the first year after the management experiment was carried out on the treatment plots (choppered plots: solid line; control plots: thin line); (e): annual quantities of nutrients leached within the first year after the management experiment was carried out on the treatment plots (choppered plots: filled columns; control plots: open columns); a-d: mean values (n = 4); e: mean values ± 1 SD (n of measurements = 48), significant differences between treatment and control are indicated by an asterisk: * $p < 0.05$, ** $p < 0.01$.

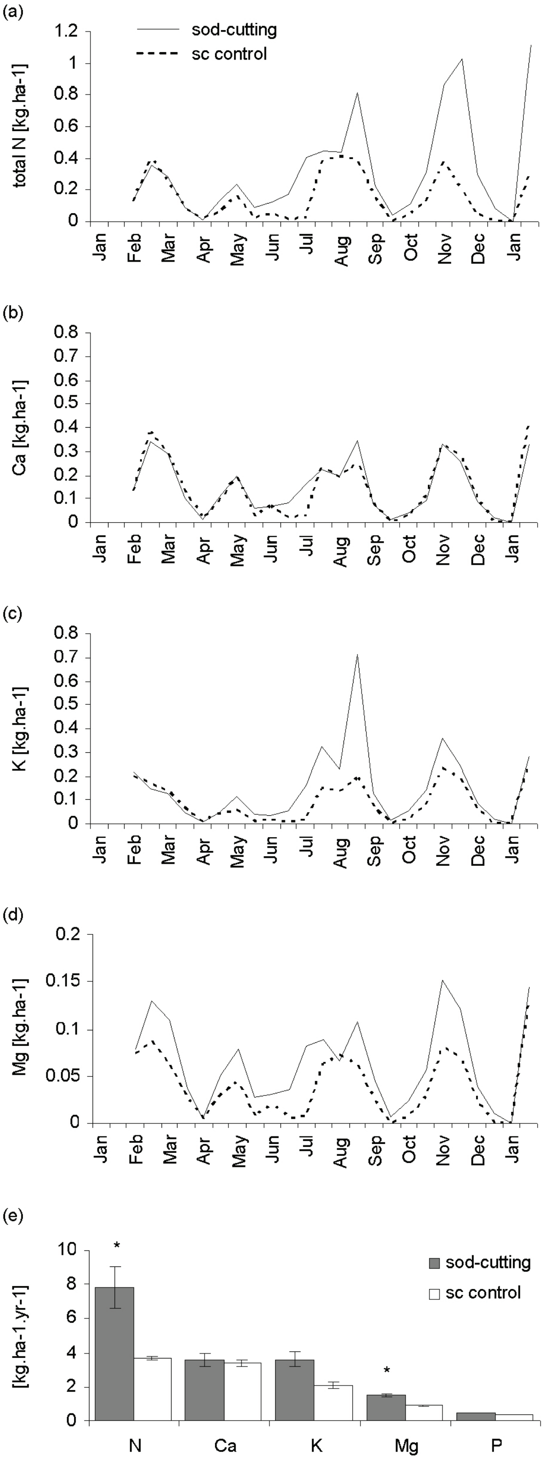

Figure 4
Annual course of leaching of N (a), Ca (b), K (c), and Mg (d) within the first year after the management experiment was carried out on the treatment plots (sod-cut plots: solid line; control plots: thin line); (e): annual quantities of nutrients leached within the first year after the management experiment was carried out on the treatment plots (sod-cut plots: filled columns; control plots: open columns); a-d: mean values (n = 4); e: mean values ± 1 SD (n of measurements = 48), significant differences between treatment and control are indicated by an asterisk: * $p < 0.05$, ** $p < 0.01$.

Table 3
Summary of the effects of choppering (ch) and sod-cutting (sc) on the nutrient budget of the heathland studied. Nutrient input and output are given in kg.ha-1; mean values (+: n = 12; ++: n = 9; +++: n = 4; SDs are shown in Fig. 2, Fig. 3 and Tab. 2). Theoretical Effective Period (TEP) in years; TEP for P was calculated in approximation for the following scenario: annual atmospheric deposition = 0.5 kg.ha-1; annual leaching control/increased leaching = 0/0 kg.ha-1.

		ch						sc					
		Thick-ness	N	Ca	K	Mg	P	Thick-ness	N	Ca	K	Mg	P
Above-ground biomass	before	-	155.0 (37.2)	36.7 (12.5)	34.4 (7.8)	11.9 (3.8)	10.0 (2.6)	-	107.3 (29.3)	29.8 (9.0)	26.6 (9.9)	9.1 (2.9)	6.1 (1.9)
	after	-	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	-	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)
Organic layer	before	3.9 (0.5)	941.4 (181.9)	100.6 (42.4)	32.5 (8.2)	25.1 (7.1)	35.8 (7.6)	3.9 (0.5)	960.7 (166.3)	97.6 (23.1)	49.3 (10.4)	26.6 (4.8)	36.1 (7.0)
	after	0.5** (0.2)	108.4** (51.1)	11.6** (6.4)	3.9** (2.3)	3.0** (1.6)	4.2** (2.1)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)	0.0** (0.0)
A-horizon	before	10.1 (0.5)	1950.5 (460.8)	174.0 (32.2)	277.6 (48.5)	57.9 (10.3)	113.6 (22.3)	9.6 (2.6)	1850.9 (378.6)	201.2 (109.3)	281.3 (105.3)	62.9 (20.6)	92.2 (23.3)
	after	not affected						6.5* (2.2)	1239.9** (377.2)	137.9 (85.8)	192.8 (85.0)	42.9 (17.5)	62.4* (21.2)

N-leaching after sod-cutting amounted to 7.8 kg.ha-1.yr-1 (53% more than in control plots) and after choppering to 9.5 kg.ha-1.yr-1 (35% more than in control plots). The quantities of leached P were close to the analytically detectable threshold value and thus below 0.5/0.4 kg.ha-1.yr-1 for the treatment and control plots, respectively.

Nutrient balances and Theoretical Effective Period (TEP)

Table 3 summarises output-input flows and gives the TEP for a particular element (last row in Table 3). With reference to N, for example, the application of choppering/sod-cutting removed quantities that corresponded to 60.7 and 89.6 years annual net input, respectively.

As P-concentrations fell below the analytically detectable threshold value, the TEP for P was calculated for the following scenario: maximal accumulation of P, assumption: deposition = 0.5 kg.ha-1.yr-1; leaching control = 0.0 kg.ha-1.yr-1; increased leaching = 0.0 kg.ha-1.yr-1. For this scenario the TEP for P was 83.2 years (ch) and 144.0 years (sc).

Discussions and Conclusions

Atmospheric nutrient deposition, nutrient pools, and leaching control plots

Atmospheric nutrient input in the study area was comparable to other regions in NW Germany (Bleeker et al., 2000; Herrmann et al., 2005). It was also in the range reported by studies conducted in the UK (Kirkham, 2001; Power et al., 2001; Schmidt et al., 2004), and was somewhat lower than deposition rates in many regions in the Netherlands (Bakema et al., 1994; Erisman and de Vries, 2000; Schmidt et al., 2004). By contrast, deposition rates reported from Denmark were somewhat lower than in our study area (Hansen and Nielsen, 1998; Schmidt et al., 2004). However, N-deposition in the study area exceeded critical load values for dry heathlands (10-20 kg.ha-1.yr-1; Achermann and Bobbink, 2003) by 2.8-12.8 kg.ha-1.yr-1. This emphasises the need for appropriate management prescriptions which aim at the removal of nutrients on a long-term basis. However, it should be considered that effects of atmospheric deposition may differ between regions depending on precipitation levels (Britton et al. 2001).

The amount of above-ground biomass was in the order of that reported by other authors, although it was highly variable within the treatment plots (SD in Figure 2; Engel, 1988; Diemont and Oude Voshaar, 1994). Our values were also in the range given by other authors for mean nutrient contents (N and P) in the prevailing plant species, *Calluna*, *Deschampsia* and *Molinia* (Aerts and Heil, 1993; Alonso et al., 2001; Kirkham, 2001).

The amount of organic matter in the O-layer was in good agreement with results reported by Engel (1988) and Diemont (1994). By contrast, lower humus accumulation (O-layer) is known from the UK (Chapman and Webb, 1978). N-pools in the O-layer and the A-horizon corresponded to the findings of Engel (1988). Comparable values for the nutrient content in the O-layer were also found by Rode (1995) and Mitchell et al. (2000), although the latter study focused on successional sites. We conclude that nutrient pools in above-ground biomass and soil were representative for many dry lowland heaths in NW Central Europe.

Some authors suppose that there is little N-leaching in heathlands (Berendse, 1990; Bobbink et al., 1998; Power et al., 2004). Taking data from Denmark, the UK, the Netherlands and Germany it appears that there is a wide range in the rate of N-leaching in lowland heathlands. Low leaching rates (0.4/<2.0 kg.ha-1.yr-1) were measured by Herrmann et al. (2005) and Nielsen et al. (2000), whilst the highest values (26.6/30.5 kg.ha-1.yr-1) were achieved in heathlands studied by Troelstra et al. (1997) and Schmidt et al. (2004). This wide range may be attributed to regional differences in atmospheric loads, soil properties, vegetation cover, and mineralisation rates caused by e.g. climatic influence. Leaching rates in our control plots were in the lower middle of the range represented by these data.

Nutrient output due to choppering and sod-cutting

The nutrient output resulting from mechanical management is primarily affected by the cutting depth and the nutrient pools in the above-ground biomass and soil. As expected, quantities of nutrients removed were highest in the sod-cut plots (Table 3). However, nutrient pools in the above-ground biomass in the choppered plots (e.g. N: 155.0 kg.ha-1; Table 3) exceeded those in the sod-cut plots (e.g. N: 107.3 kg.ha-1). This was caused by differences in the experimental plots at the beginning of the experiments (pools in above-ground biomass and species composition) and not by the treatments themselves.

However, compared to the above-ground biomass, the removal of the O-layer and the A-horizon caused much higher nutrient losses (Table 3). Nutrient pools in the A-horizon were even higher than those in the O-layer (Table 2). Practical demands on management measures brought up the question as to whether the amount of nutrient removal is related to the volume of O- and A-material. Therefore, we compared the volume of O-layer and A-horizon (Results section) to the corresponding nutrient content (Table 2). Our data showed that the O-layer contained more N per volume than the A-horizon, as N is primarily fixed in organic material. Consequently, N-budgets were more affected by the removal of a particular volume of O-layer than by removal of the same quantity of the A-horizon. By contrast, K-content in the A-horizon was distinctly higher than in the O-layer as K occurs (in sandy soils) mostly in silicates (e.g. feldspars). However, it is unlikely that K-removal leads to a deficiency in K for heathland plants, because K was found in similar amounts at all soil depths (own unpublished data). Hence, the effect of removing greater amounts of K with the A-horizon does not seriously affect the K-supply for plants. However, as costs for management depend on the volume of waste material (Müller, 2004), choppering is more efficient than sod-cutting with respect to N-removal.

Nutrient output due to increased leaching

Nutrient leaching after management was elevated in both the choppered and the sod-cut plots. Significant differences were observed in N- (ch and sc), K- (ch) and Mg-leaching (sc). This may be attributed to increased quantities of percolating soil water due to distinctly reduced evapotranspiration rates as well as to the lack of nutrient uptake by plants

(Gimingham et al., 1981; Sieber et al., 2004; Niemeyer et al., 2005). Additionally, it is likely that mineralisation rates increase after management (Berendse, 1990; Bakema et al., 1994). Two factors may account for this. Firstly, there are many dead plant roots and a considerable amount of other organic material remaining in the soil, all of which starts to decompose after vegetation has been removed (Berendse, 1990; Mitchell et al., 2000; Dorland et al., 2004). Secondly, elevated soil temperatures, attributed to the removal of shading vegetation, may lead to increased mineralisation rates (Anderson and Hetherington, 1999; Schmidt et al., 2002). As a consequence, more nutrients are mobilised and percolate. This interpretation can also be derived from the annual course of leaching rates (Figures 3 and 4). In the months with higher temperatures, i.e. from April to September, distinctly more nutrients percolated into the treatment plots. Furthermore, it is known that after sod-cutting, nitrifying activity decreases due to the removal of greater amounts of nitrifying bacteria and reduced soil moisture content. This leads to ammonium enrichment in the topsoil (Dorland et al., 2004). High NH_4^+-concentrations may lead to a replacement of cations at exchange sites in the soil (Brady and Weil, 2002). This process may explain the fact that elevated quantities of K and Mg were leached through the treatment plots, since these ions were replaced by NH_4^+.

Our calculation of increased leaching rates must be considered an approximation. There are some uncertainties as to how post-management leaching rates develop after the first year. Since vegetation cover has a considerable influence on leaching rates, all irregularities in the process of regeneration (time span, pattern, species composition) may affect the outcome of the calculation. Furthermore, immobilisation of nutrients by microbes or by sorption processes in the soil (Meiwes et al., 1998; Nielsen et al., 2000; Power et al., 2004) may influence the assumed decrease pattern. However, as Table 3 shows, the total nutrient loss due to leaching was always very low compared to the output caused by the removal of above-ground biomass and soil. For example, increased N-leaching amounted to only 2.0% (ch) and 1.9% (sc) of total N-output, respectively. An underestimation of increased N-leaching by 100% would prolong the TEP by 2%, which corresponds to 1.2 (ch) or 1.7 (sc) years, respectively. Thus, we conclude that choppering and sod-cutting caused increased nutrient losses through leaching, but that the overall effect on the nutrient budget of heathlands is of minor importance.

Nutrient balances and Theoretical Effective Period (TEP)

This study clearly shows that the effect of sod-cutting on nutrient balances (N, K, Mg, P) is of much longer duration than the effect of choppering. TEP for sod-cutting was prolonged by between 48% (N) and 254% (K) of the TEP for choppering (Table 3). The removal of high nutrient pools in the A-horizon by sod-cutting was primarily responsible for these differences, whilst the effect of higher nutrient leaching after sod-cutting can only explain a negligibly small proportion. By contrast, it is conspicuous that TEP for Ca was much higher after choppering (448 years) than after sod-cutting. This is explained by the very low net input rates of Ca caused by high Ca-leaching in the control plots (4.8 kg.ha-1.yr-1), probably due to slightly higher loam contents in the control plots.

In summary, we derived the following consequences for conservation management (with regard to N and P):

i) The effect of N and P removal after both choppering and sod-cutting will be of much longer duration than one life-cycle of *Calluna* and even longer than humus re-accumulation would take (Gimingham, 1972; Berendse, 1990). Hence, high-intensity measures should be followed by low-intensity management measures which affect only above-ground biomass, in order to rejuvenate overaged dwarf shrubs, and to remove trees and shrubs. We recommend the application of prescribed burning, since this management measure not only induces successful vegetative and generative regeneration of *Calluna* (Mallik and Gimingham, 1985; Nilsen et al., 2005), but also prevents an increasing P-shortage, due to more selective removal of N (Niemeyer et al., 2005). Moreover, a mix of several management measures on a small scale is important in order to preserve spatial and temporal heterogeneity in heathlands (Webb, 1998; Vandvik et al., 2005).

ii) Although the effect of nutrient removal after sod-cutting is longer-lasting than in the case of choppering, TEPs for N and P still amount to more than 60 and 83 years, respectively, for the choppered plots. Choppering was shown to be able to remove more N per volume unit, due to higher N contents in the organic layer. Hence, amongst other advantages (e.g. faster in application, less waste material, faster vegetation recovery) choppering is more economical than sod-cutting. Consequently, at sites with *Deschampsia* encroachment, choppering should be viewed as the preferred method as far as nutritional and economic demands are concerned.

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