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Modellierung und Kartierung räumlich differenzierter Wirkungen von Stickstoffeinträgen in Ökosysteme im Rahmen der UNECE-Luftreinhaltekonvention

Teilbericht IV: Der Einfluss anthropogener Stickstoffeinträge auf die Diversität und Funktion von Bodenorganismen

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Modellierung und Kartierung räumlich differenzierter Wirkungen von Stickstoff-einträgen in Ökosysteme im Rahmen der UNECE-Luftreinhaltekonvention

Teilbericht IV: Der Einfluss anthropogener Stickstoffeinträge auf die Diversität und Funktion von Bodenorganismen

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Im Auftrag des Umweltbundesamtes

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Teilbericht I: Simulationen ökosystemarer Stoffumsetzungen und Stoffausträge aus Waldökosystemen in Deutschland unter Berücksichtigung geänderter Stoffeinträge und Klimabedingungen

Teilbericht II: Das BERN-Modell - ein Bewertungsmodell für die oberirdische Biodiversität

Teilbericht III: Modellierung der Wirkung der Stickstoff-Deposition auf die biologische Vielfalt der Pflanzengesellschaften von Wäldern der gemäßigten Breiten

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Zusammenfassung der vier Teilberichte

Naturnahe Ökosysteme sind seit mehreren Jahrzehnten hohen atmogenen Fremdstoffeinträgen ausgesetzt. Im Gegensatz zu den Schwefeleinträgen, welche durch Maßnahmen zur internationalen Luftreinhaltung in den letzten Dekaden drastisch reduziert werden konnten, bleiben die luftgebundenen Einträge von reduziertem und oxidiertem Stickstoff weiterhin auf einem sehr hohen Niveau mit im Mittel 40 kg N ha^{-1} $Jahr^{-1}$ für Waldstandorte in Deutschland. Das FuE-Vorhaben „Modellierung und Kartierung räumlich differenzierter Wirkungen von Stickstoffeinträgen in Ökosysteme im Rahmen der UNECE-Luftreinhaltekonvention“ wurde gemeinschaftlich von vier Partnern bearbeitet, mit der zentralen Fragestellung, wie sich atmogene Stoffeinträge in Waldökosysteme gemeinsam mit der Klimaänderung auf die physiko-chemischen Eigenschaften von Waldböden, Nährstoffspeicherung und -austrag (Karlsruher Institut für Technologie, IMK-IFU) sowie auf die Biodiversität von Pflanzen (ÖKO-DATA und Waldkundeinstitut Eberswalde) und Bodentieren (Universität Gießen) auswirken.

Im Rahmen der Arbeiten, die am IMK-IFU durchgeführt wurden, musste zunächst das Versauerungsmodell SAFE in die am IMK-IFU bereits entwickelte biogeochemische Modellumgebung MoBiLE implementiert werden. Auf Grundlage verschiedener Depositions- und Klimaszenarien wurden mit Hilfe des biogeochemischen Forest-DNDC-SAFE Modells (realisiert aus der Modellumgebung MoBiLE) Prognosen für das Kohlenstoff/Stickstoff (C/N) Verhältnis des Bodens, sowie für die Austräge von Stickstoff in die Atmosphäre in Form des Treibhausgases N_2O als auch für den Nitrataustrag in die Hydrosphäre erstellt. Außerdem wurde die Veränderung der Basensättigung und des pH-Wertes für den Zeitraum 1920-2060 d.h. sowohl retrospektiv als auch prognostisch simuliert. Die Ergebnisse der Modellanwendung für 62 Level II Standorte Deutschlands zeigen, dass mit Rückgang der SO_4 Deposition die Versauerungsproblematik weitgehend entschärft werden konnte, jedoch erholen sich Standorte mit hoher N-Deposition (> 40kg N ha^{-1} $Jahr^{-1}$) vergleichsweise langsamer. Der Rückgang der N- Deposition hat an den meisten Standorten noch zu keiner Erholung der Waldökosysteme bezüglich des Nährstoffstatus (signifikante Änderung des C/N Verhältnis) und des Stoffaustrags (NO_3^- und N_2O) geführt. Sensitivitätsstudien mit verschiedenen N-Depositionsszenarien zeigen, dass bei einem Rückgang auf 15 kg N ha^{-1} $Jahr^{-1}$ (entspricht im Mittel dem Maximum Feasible Reduction = MFR Szenario von IIASA, Stand 2003) eine mäßige Erholung einiger, bei einem Rückgang auf 5 kg N ha^{-1} $Jahr^{-1}$ eine schnellere Erholung aller untersuchter Waldstandorte zu verzeichnen ist.

Zur Erfassung der durch atmogene Stoffeinträge möglichen Veränderung der Pflanzenbiodiversität wurden die Ergebnisse der biogeochemischen Modellsimulationen (Zeitreihen der Basensättigung, pH-Wert sowie C/N Verhältnis und Wasserverfügbarkeit)

nachfolgend an zwei verschiedene Bewertungsmodelle für die oberirdische Biodiversität weitergegeben. Die hierzu verwendeten Modelle BERN (Bioindication for Ecosystem Regenerarion towards Natural conditions, ÖKO-DATA) und das Modell des Waldkundeinstitutes Eberswalde (W.I.E.) sind in der Lage, aufgrund umfangreicher empirischer Erhebungen und statistischer Auswertung, die zukünftige Entwicklung der Vegetation in Abhängigkeit veränderter abiotischer Parameter, wie Boden und Klima, zu prognostizieren. Im Rahmen dieses Forschungsvorhabens wurden beide Biodiversitäts-modelle weiterentwickelt und präzisiert. Im Rahmen des Modellansatzes des W.I.E. wurden vier verschiedene Klassen der Gefährdung der pflanzlichen Biodiversität in Wäldern und Forsten abgeleitet. Mit Hilfe eines neu entwickelten statistisch abgesicherten Zeigerwertmodells wurden für die wichtigsten Wald- und Forstökosystemtypen im grundwasserfreien Standortsbereich des ostdeutschen Tieflandes Grenzwerte für eintragsinduzierte Veränderungen im Oberbodenzustand abgeleitet. Mit den gekoppelten Simulationen des biogeochemischen Forest-DNDC-SAFE Modells und den Vegetationsmodellen lassen sich Aussagen bezüglich der Gefährdung der Vegetationsvielfalt treffen und daraus Critical Loads für Stickstoff ableiten. Neu in dem Forschungsvorhaben ist, dass sich neben dem Schutzgut Biodiversität auch Aussagen zur Gefährdung anderer Schutzgüter wie der Atmosphäre (Treibhausgase) und Hydrosphäre (Eutrophierung) treffen lassen. Dies ist wichtig, da die Simulationen zeigen, dass höhere N-Austräge mit einer Verengung des Boden-C/N d.h. der Zunahme der N-Verfügbarkeit teilweise antikorrelieren, woraus sich, je nach Eigenschaften der Standorte, bei gleicher Deposition unterschiedliche Wirkungen auf die Schutzgüter Atmosphäre, Hydrosphäre und Biodiversität ergeben. Neben den stofflichen Auswirkungen auf die Biodiversität wird zukünftig auch mit klimatisch induzierten (Zunahme von Trockenstress, Verlängerung der Vegetationsperiode) Veränderungen der Artenzusammensetzung von terrestrischen Ökosystemen zu rechnen sein. Wie ausgeprägt die Änderungen der Temperatur und/ oder der Wasserverfügbarkeit aber auch die Zunahme von Extremereignissen sein werden, hängt stark vom gewählten Klimaszenario ab. Hier besteht zukünftig erheblicher Forschungsbedarf insbesondere auch im Hinblick auf die Frage, wie sich Änderungen der Umweltbedingungen wie z.B. Temperatur und Feuchte, aber auch Extremereignisse auf die Vegetation und die mikrobiell getriebenen C- und N- Umsetzungsprozesse und damit auf die Nährstoffverfügbarkeit und den Stoffaustrag in terrestrischen Ökosystemen auswirken. Wie die Studie der Universität Gießen zeigt, sollte in diese Betrachtungen zukünftig auch der Zusammenhang zwischen Strukturen und Funktionen von Ökosystemen und Diversität des Bodenlebens inklusive Rückkopplungen auf z.B. Bodenfunktionen wie die Mineralisierung mit eingeschlossen werden. Jedoch ist in diesem Forschungsfeld verglichen zur Pflanzenbiodiversität noch wenig bekannt. Dennoch zeigt die Auswertung der derzeit verfügbaren Daten, dass eine

negative Auswirkung der Stickstoffdeposition auf die Diversität einiger Bodenorganismen bereits absehbar ist. Eine mangelnde Datengrundlage, sowie die nicht immer optimale Qualität der vorhandenen Studien, lassen aber allgemeine Schlüsse über die Auswirkung auf die Bodenfauna noch nicht zu.

Im Rahmen der Weiterentwicklung der verwendeten Modellen zeigt das Forschungsvorhaben auch auf, dass die Verfügbarkeit von Daten aus dem forstlichen Umweltmonitoring teilweise limitiert ist und hier insbesondere Verbesserungen bezüglich der Abstimmung von gemessenen und den von Modellen nachgefragten Input- und Validierungsdaten dringend notwendig erscheint. Aus der Unsicherheit der Datenlage, insbesondere auch im Hinblick auf die zeitliche Rekonstruktion der atmosphärischen Stoffeinträge, und der sich hieraus ergebenden eingeschränkten Modellvalidierung, ergibt sich weiterer Forschungsbedarf, um eine regionale und letztendlich auch deutschlandweite Anwendung des gekoppelten Modellansatzes zwischen dem biogeochemischen Forest-DNDC-SAFE Modell und den Bewertungsmodellen zur Biodiversität wie BERN (ÖKO-DATA) und dem Modell auf der Grundlage des Ökosystemtypenkonzeptes (W.I.E) zu verwirklichen. Prinzipiell wird jedoch nachgewiesen, dass sich aus den Ergebnissen der Modellkopplung sowohl im nationalen Rahmen (BERN) als auch auf regionaler Ebene (BERN, W.I.E) die aktuellen Regenerierungspotenziale von Vegetation und Standort ablesen, Zielzustände bestimmen sowie der Abweichungsgrad der aktuellen Zustände zu diesen Zielzuständen für spezifische Waldstandorte darstellen lassen. Ebenso wie bei den Schutzgütern Atmosphäre und Hydrosphäre kann der Verlauf des Gefährdungspotentials auch für die pflanzliche Biodiversität und die Existenzmöglichkeiten von Arten oder Gesellschaften aufgezeigt werden.

Summary of the four parts of the report

Semi-natural ecosystems are exposed to high atmospheric deposition for decades. In contrary to sulphur deposition which could be significantly reduced due to international conventions on air pollution prevention during the last decades, deposition of both, reduced and oxidized nitrogen is still on a very high level in average 40 kg N ha^{-1} yr^{-1} in forest ecosystems in Germany. The FuE-Project "Modelling and mapping of spatial differentiated impacts of nitrogen input to ecosystems within the framework of the UNECE – Convention of Air Pollution Prevention" was jointly conducted by 4 partner institutions and studied impacts of atmospheric nitrogen deposition and climate change on physico-chemical properties of forest soils, nutrient storage and nutrient export (Karlsruhe Research Centre, IMK-IFU) as well as biodiversity of vegetation (ÖKODATA and Waldkundeinstitut Eberswalde) and soil organisms (Gießen University).

Work carried out at IMK-IFU initially concentrated at the implementation of the soil acidification model SAFE into the biogeochemical model framework MoBiLE already developed at IMK-IFU. Based on different deposition and climate scenarios prediction of the soil C/N ratio, nitrogen losses (N_2O emissions) into the atmosphere and via nitrate leaching into the hydrosphere were made using the biogeochemical Forest-DNDC-SAFE model (realized from the MoBiLE framework). Additionally changes in base saturation and pH values were simulated for the period 1920-2060. Simulation results for 62 Level II sites in Germany show, that with the decline of the SO_4^- deposition soil acidification could be mitigated, although sites with high nitrogen deposition (> 40 kg N ha^{-1} yr^{-1}) do recover slower than others with lower nitrogen deposition. At most sites the decline in nitrogen deposition did not yet lead to a regeneration concerning nutrient status (significant re-widening of the C/N ratio) and nitrogen losses (NO_3^- und N_2O).

Sensitivity studies regarding different nitrogen deposition scenarios show, that a decline of nitrogen deposition to 15 kg N ha^{-1} $year^{-1}$ (it averages the maximum feasible reduction = MFR deposition scenario , IIASA 2003) show a moderate, a decline of nitrogen deposition to 5 kg N ha^{-1} $year^{-1}$ show a faster recovery of the forest sites investigated.

For assessing impacts of nitrogen deposition on plant biodiversity time series of base saturation, pH value, C/N ratio and water availability provided by the biogeochemical model served as input in two different plant biodiversity models. In dependency of changes in abiotic parameters i.e. soil and climate the biodiversity model BERN (Bioindication for Ecosystem Regeneration towards Natural conditions, ÖKO-DATA) and the model of the Waldkundeinstitut Eberswalde (W.I.E.) are able to predict future vegetation development based on extensive empirical data collection and derived statistical relations.

In the framework of this project both biodiversity models were further developed and specified. For the model approach of the W.I.E. four different classes of endangerment of plant biodiversity in forests were derived. Due to the help of a newly developed statistical verified indicator value system, thresholds for deposition induced changes of top soil conditions for the most important forest ecosystems of the East German Lowlands were derived.

Based on the coupled simulations of the biogeochemical Forest-DNDC-SAFE model and the biodiversity models predictions concerning the endangerment of vegetation diversity can be assessed and hence Critical Loads for nitrogen can be derived. A new aspect of this project is that not only predictions about the endangerment of plant biodiversity but also about other subjects of protection like the atmosphere and the hydrosphere can be made. This is of great importance, since simulations show that depending on specific site conditions higher N losses via N_2O or nitrate leaching partly anti-correlate with a narrowing of the soil C/N ratio i.e. increased N availability, resulting in different impacts on the subjects of protection atmosphere, hydrosphere and biodiversity.

In addition to the biogeochemical induced impacts on plant biodiversity, in the near future also impacts of climate change (increase of drought stress, extension of the vegetation period), on the species composition in terrestrial ecosystems have to be accounted for.

The climate induced changes highly depend on the chosen climate scenario. Further research is needed especially towards the question how changing environmental conditions, like temperature and moisture, as well as extreme weather events, do effect the vegetation and the microbial C and N transformation having impacts on ecosystem nutrient availability and nutrient losses. Furthermore, the study of Gießen University could demonstrate that the relation between structures and functions of ecosystems and biodiversity of soil organisms, including feedback mechanisms to soil functions e.g. decomposition, should be considered especially given that relatively little is known about this topic compared to plant biodiversity. Due to the information of available data a negative effect of nitrogen deposition on the diversity of several soil organisms can already be noticed. However, due to the lack of reliable data as well as the inferior quality of some studies general conclusions about effects of elevated nitrogen deposition on soil fauna composition can´t be drawn at present.

In the framework of the further development of the applied models, the project also shows, that the data availability from forest monitoring programs is partly limited and that an improvement especially with regard to the coordination of field measurements and the demand of required model input and validation data is crucial.

Concerning the uncertainty and incompleteness of input (in particular site specific time series of atmospheric deposition) and validation data further research is needed especially with

regard to the combined model applications of Forest-DNDC-SAFE and BERN/ ecosystem type model of W.I.E on regional and national scale.

However, for specific forest sites the project demonstrates that the coupled model approach is capable to derive actual regeneration potentials of the vegetation, assign target states as well as the degree of deviations of the present situation on regional (BERN, W.I.E.) as well as on national (BERN) scale. Furthermore, changes of the risk potential over time for the subjects of protections like atmosphere and hydrosphere as well as for plant biodiversity and possible existence of plant species and communities could be demonstrated.

Berichts-Kennblatt

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Teilbericht IV:

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Anhang mit 1457 Publikationen welche bei der Erstellung der Meta-Analyse berücksichtigt wurden.</td></tr>
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16. Zusammenfassung

Naturnahe Ökosysteme sind seit mehreren Jahrzehnten hohen atmogenen Fremdstoffeinträgen ausgesetzt. Im Gegensatz zu den Schwefeleinträgen, welche durch Maßnahmen zur internationalen Luftreinhaltung in den letzten Dekaden drastisch reduziert werden konnten, bleiben die luftgebundenen Einträge von reduziertem und oxidiertem Stickstoff weiterhin auf einem sehr hohen Niveau mit im Mittel 40 kg N ha^{-1} $Jahr^{-1}$ für Waldstandorte in Deutschland. Das FuE-Vorhaben „Modellierung und Kartierung räumlich differenzierter Wirkungen von Stickstoffeinträgen in Ökosysteme im Rahmen der UNECE-Luftreinhaltekonvention“ wurde gemeinschaftlich von 4 Partnern bearbeitet mit der zentralen Fragestellung, wie sich atmogene Stoffeinträge in Waldökosysteme gemeinsam mit der Klimaänderung auf die physiko-chemischen Eigenschaften von Waldböden, Nährstoffspeicherung und -Austrag (Karlsruher Institut für Technologie, IMK-IFU) sowie auf die Biodiversität von Pflanzen (ÖKO-DATA und Waldkundeinstitut Eberswalde) und Bodentieren (Universität Gießen) auswirken.

Im Rahmen der Arbeiten, die am Institut für Tierökologie der Justus-Liebig-Universität Gießen durchgeführt wurden, konnte mittels einer Meta-Analyse die Wirkung von N-Deposition auf die Diversität von Bodenorganismen untersucht werden. Unter Berücksichtigung von 1457 Veröffentlichungen konnte gezeigt werden, dass vor Allem die Diversität von Bodenorganismen in naturnahen Ökosystemen durch N-Deposition bedroht ist. Ein experimenteller Stickstoffeintrag führt dabei oft zu einem negativen Einfluss auf die Diversität von Bodenorganismen in Waldökosystemen. Besonders stark betroffen ist dabei die Diversität von Pilzgemeinschaften, insbesondere Mykorrhiza-Pilz-Gemeinschaften nehmen durch Stickstoffeintrag in ihrer Artenzahl ab. Die N-Deposition scheint auch die Bodenfauna sowie bakterielle Gemeinschaften negativ zu beeinflussen, allerdings ermöglichen hier die Ergebnisse derzeit augrund kleiner Datensätze oder großer Datenstreuung kein abschließendes Ergebnis. Inwieweit die Abnahme der Diversität in Folge von zunehmender N-Deposition die Funktionen beeinflusst, welche durch die Bodenorganismen bereit gestellt werden, bleibt aufgrund der mangelnden Literaturlage ebenfalls offen.

17. Schlagwörter

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Biodiversität
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16. Abstract

Semi-natural ecosystems are exposed to high atmospheric deposition for decades. In contrary to sulphur deposition which could be significantly reduced due to international conventions on air pollution prevention during the last decades, deposition of both, reduced and oxidized nitrogen is still on a very high level in average 40 kg N ha^{-1} yr^{-1} in forest ecosystems in Germany. The FuE-Project "Modelling and mapping of spatial differentiated impacts of nitrogen input to ecosystems within the framework of the UNECE – Convention of Air Pollution Prevention" was jointly conducted by 4 partner institutions and studied impacts of atmospheric nitrogen deposition and climate change on physico-chemical properties of forest soils, nutrient storage and nutrient export (Karlsruhe Research Centre, IMK-IFU) as well as biodiversity of vegetation (ÖKO-DATA and Waldkundeinstitut Eberswalde) and soil organisms (Gießen University).

Work carried out at Institute of Animal Ecology (Justus Liebig University Gießen) focused on a Meta-Analysis about the impact of N-deposition on the diversity of soil organisms. Based on 1457 relevant publications soil organisms are threatened most in semi-natural ecosystems and experimental increases of nitrogen reduced soil organism diversity in forest ecosystems. Fungi communities were affected most seriously, with a strong decline of diversity in Mycorrhiza communities in response to experimental nitrogen addition. If N-deposition generally affects soil fauna and bacterial communities remains unclear, as the database is either too small or as results are not unequivocal. Those limitations are also present summarizing the impact of N-deposition on functions and services provided by soil organisms, the current literature database does not provide enough results to predict the impact of N-deposition on decomposition processes and nutrient cycling in soils.

17. Keywords
N-deposition
Biodiversity
Soil organisms

18. Price

		20.

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Einleitung

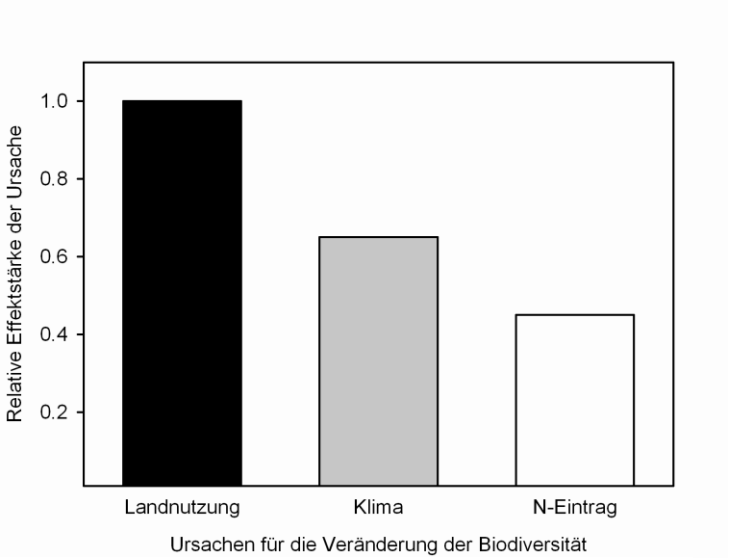

Abb. 1 Relative Effektstärke der globalen Ursachen für eine Veränderung der Biodiversität (verändert nach Sala et al. 2000).

Sala et al. (2000) benennen den Eintrag von Stickstoff als eine der drei wichtigsten globalen Ursachen für die Veränderung der Biodiversität (Abbildung 1). Die Intensivierung der landwirtschaftlichen Produktion (Tierhaltung und Ackerbau), sowie eine Zunahme der industriellen Aktivität haben in den letzten Jahrzehnten zu einer deutlichen Steigerung der Stickstoffeinträge durch Düngung und atmosphärische Deposition beigetragen (Matson et al. 2002). Während die Auswirkung dieser anthropogenen Stickstoffeinträge auf die Diversität von Pflanzen verhältnismäßig gut untersucht ist (Stevens et al. 2004), liegen für die Bodenorganismen nur vereinzelt Ergebnisse vor. Die Bodenfauna ist von außergewöhnlicher Bedeutung für viele mikrobiologische und physikochemische Prozesse und ist eng verknüpft mit anderen edaphischen Organismengruppen (z.B. Pilzen). Anthropogene Einträge stören die Bodenfauna direkt, ändern aber auch die Interaktionen zwischen den Organismen und beeinflussen verschiedene ökosystemare Funktionen (Wolters 2001). Xiankai et al. (2008) haben in einer qualitativen Synthese die Auswirkung von Stickstoffeinträgen auf Bodenorganismen in Waldökosystemen analysiert. Zur genaueren Differenzierung des Einflusses auf Bodenorganismen in Abhängigkeit von der Form des Stickstoffeintrages, des Ökosystems und der Identität der betroffenen Gruppen wird in der vorliegenden Meta-Analyse die Rolle des anthropogenen Stickstoffeintrages für Veränderungen der Biodiversität der Bodenorganismen erstmals quantifiziert.

Material und Methoden

Eine ausführliche Literaturrecherche wurde in folgenden Datenbanken durchgeführt, die genannten Zeiträume geben den verfügbaren zeitlichen Rahmen der Literatur-Datenbanken an: Biological Abstracts Archive (1926-68), Biological Abstracts (1969-2004), Biosis Previews (1969-2004) und ISI Web of Knowledge (1980-2008).

Als Suchwörter wurden folgende Begriffe verwendet:

- nitrogen oder deposition und soil biodiversity
- nitrogen oder deposition und soil fauna
- nitrogen oder deposition und soil community
- nitrogen oder deposition und fungi
- nitrogen oder deposition und bacteria
- nitrogen oder deposition und mycorrhiza

Die Literaturzitate aller relevanten Veröffentlichungen wurden nach weiteren Studien zum Thema durchsucht (siehe Anhang: Literaturliste 1). Mit dieser ausführlichen Literaturrecherche wurden 1457 relevante Veröffentlichungen gefunden (siehe Anhang: Literaturliste). Für eine semiquantitative Auswertung waren 106 Datensätze geeignet, davon waren 55 Datensätze ausreichend präzise dokumentiert, um damit eine quantitative Auswertung in Form einer Meta-Analyse durchzuführen (siehe Anhang: Literaturliste Meta-Analyse). Die zeitliche Entwicklung der Veröffentlichungszahlen ist in Abbildung 2 dargestellt. Diese Darstellung legt den Schluss nahe, dass das wissenschaftliche Interesse an dem Thema in den letzten 15 Jahren deutlich gestiegen ist.

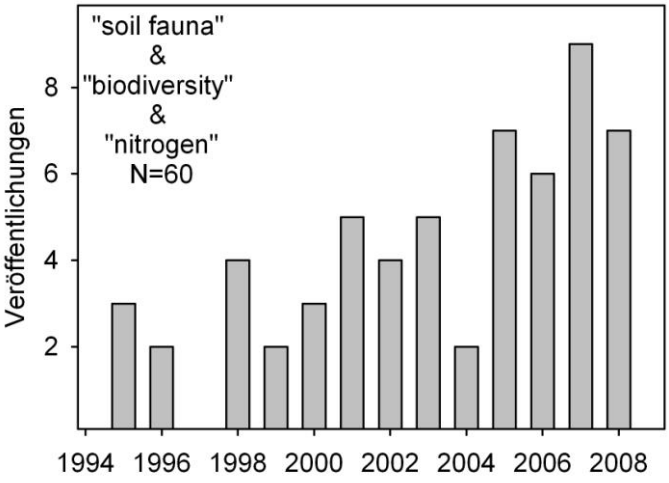

Abb. 2 Anzahl der Veröffentlichungen zu den Suchwörtern soil fauna und biodiversity und nitrogen im ISI Web of Knowledge (Stand: 30.01.2009).

In der Meta-Analyse wurde die standardisierte mittlere Differenz zwischen Biodiversitätsmaßen in einer Kontrolle und einer Stickstoffbehandlung sowie deren 95% Vertrauensintervalle berechnet. Durch dieses Verfahren konnte die Signifikanz einer Abweichung von der Kontrolle unabhängig von der statistischen „Power“ der einzelnen Studien berechnet werden. Außerdem wurde die Effektstärke nach Cohen (1988) in die folgenden Kategorien eingeteilt: kein Effekt, gering, moderat und stark. Um die Datengrundlage zu verbessern wurden entgegen dem üblichen Vorgehen auch Ergebnisse zu unterschiedlichen Taxa, die aus der gleichen Studie stammen, einbezogen. Somit fasst die hier vorgelegte Meta-Analyse das vorhandene Wissen zusammen und versucht außerdem Ansätze und Lücken im Forschungsstand aufzudecken. So verdeutlicht z.B. die geographische Verteilung der im weiteren Verlauf verwendeten Studien klare Unterschiede in der Untersuchungsintensität (Abb. 3).

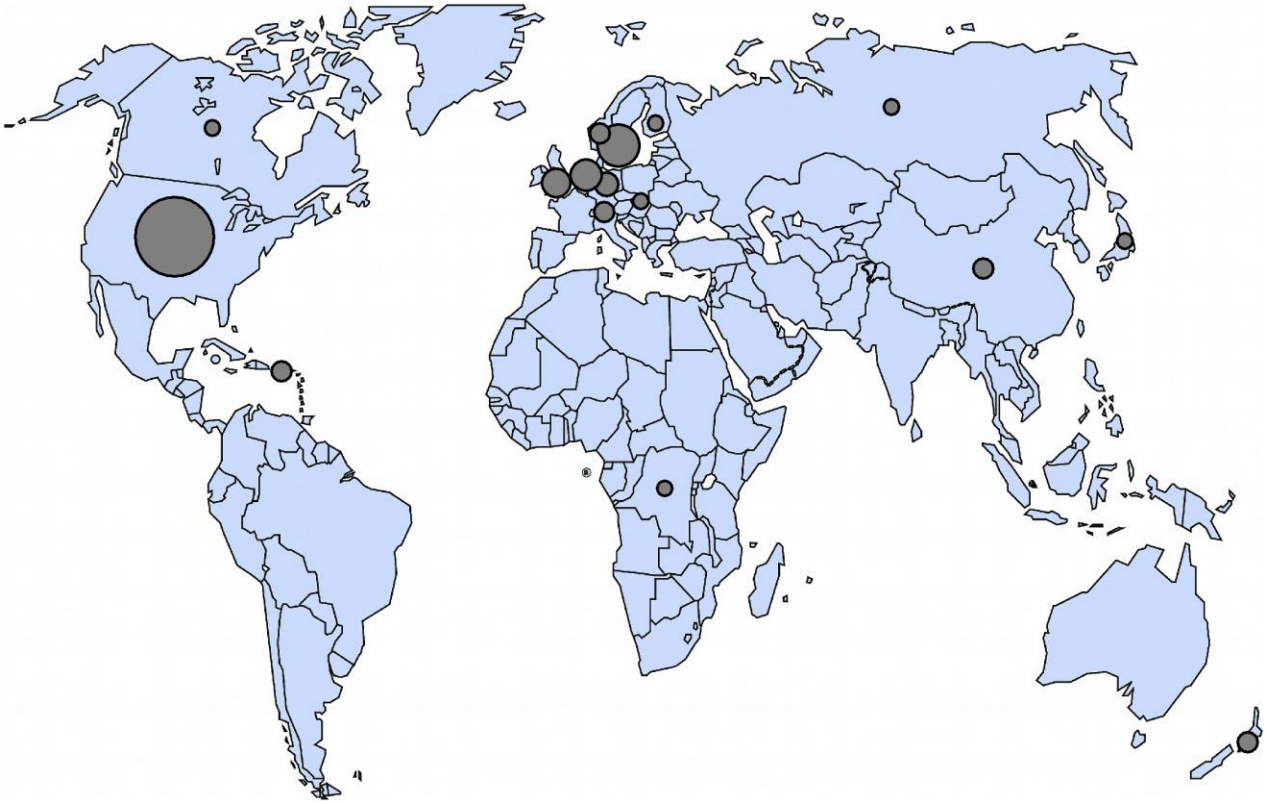

Abb. 3 Geografische Verteilung der 106 Studien, welche in der semi-quantitativen Auswertung verwendet wurden. Die Größe der Kreise reflektiert die Anzahl der Studien aus dem jeweiligen Staat.

Ergebnisse

Unterteilt man die 106 ausgewerteten Studien nach der Art des Stickstoffeintrags in atmosphärisch- oder düngungsbezogen, zeigt sich, dass ein sehr viel höherer Anteil der Veröffentlichungen einen negativen Einfluss auf die Diversität von Bodenorganismen in Folge atmosphärischer Deposition nachweist (75% vs. 38%, Abb. 4).

Analog zur Art des Stickstoffeintrags reagieren auch die Bodenorganismen in den verschiedenen Ökosystemen differenziert auf Stickstoff Depositionen. Die Diversität ist vor allem in semi-natürlichen Systemen negativ betroffen (Abbildung 5). In diesen Untersuchungen wurden vor Allem die edaphischen Organismen der Heiden, Savannen, Küstenvegetation, Steppen und Halbwüsten untersucht. Der Anteil an Veröffentlichungen welche einen vergleichbar negativen Effekt auf die Diversität von Bodenorganismen in Agrar- und Waldökosystemen zeigen, ist nur halb so groß.

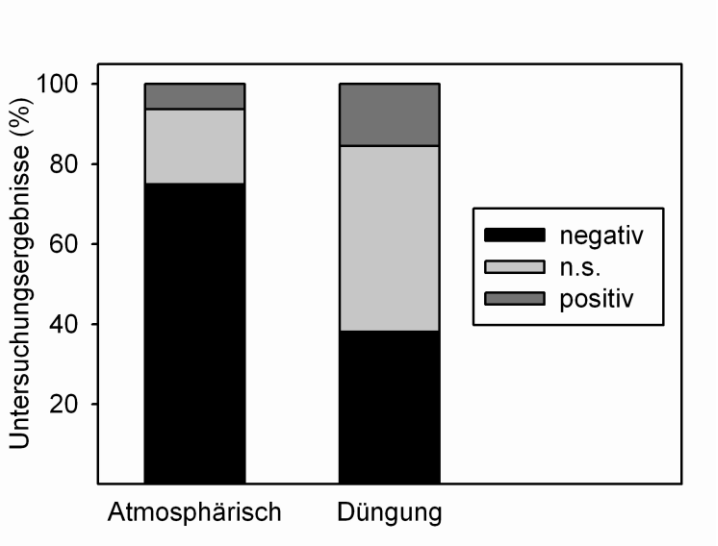

Abb. 4 Proportionaler Anteil der Studien die einen signifikant positiven, negativen oder nicht signifikanten Effekt des Stickstoffeintrages auf die Diversität von Bodenorganismen in Abhängigkeit der Art des Eintrags nachweisen

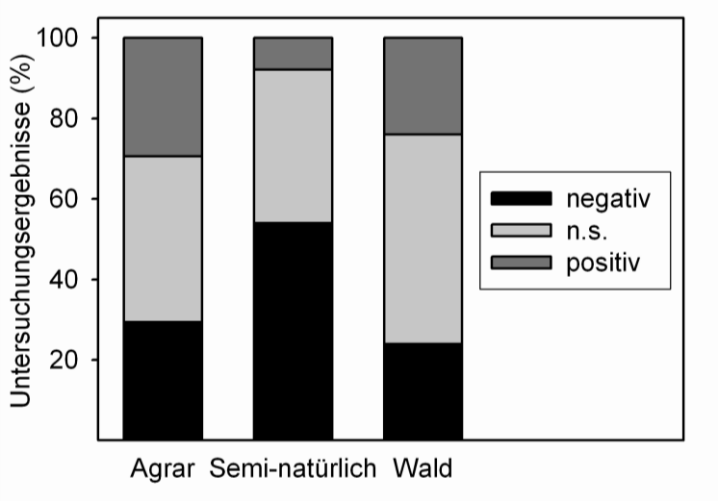

Abb.5 Proportionaler Anteil der Studien die einen signifikant positiven, negativen oder nicht signifikanten Effekt des Stickstoffeintrages auf die Diversität von Bodenorganismen in Abhängigkeit des betroffenen Ökosystems nachweisen.

Bodenbiota sind eine sehr heterogene Gruppe. Die verschiedenen Lebens-formen unterscheiden sich stark in ihren ökologischen Eigenschaften und Bedürfnissen. Daher ist die Frage nach einem Unterschied in der Wirkung von Stickstoffeinträgen auf verschiedene Gruppen von zentraler Bedeutung für die Identifikation von Wirkungs-mechanismen. Die semi-quantitative Auswertung in Abbildung 6 zeigt, dass die Diversität der Mykorrhiza-Pilze im Boden am stärksten negativ durch anthropogene Stickstoffeinträge beeinflusst wird. Hingegen lässt sich besonders für andere Pilze und Bodentiere auch eine große Anzahl Studien nennen, welche keine negativen Auswirkungen nachweisen können.

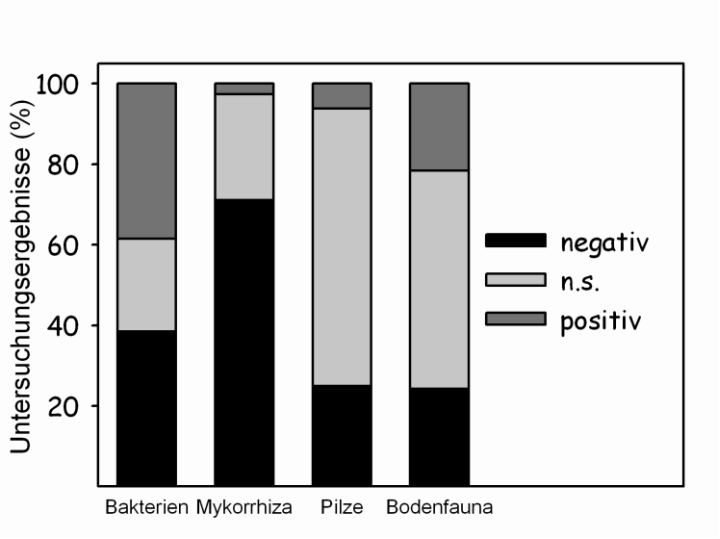

Abb.6 Proportionaler Anteil der Studien die einen signifikant positiven, negativen oder nicht signifikanten Effekt des Stickstoffeintrages auf die Diversität von Bodenorganismen in Abhängigkeit der betroffenen Organismengruppe nachweisen.

Im Gegensatz zu den bisher präsentierten Ergebnissen der Literaturrecherche wird im folgenden Teil mit Hilfe von Meta-Analyse Techniken die statistische Qualität der Studien in die Auswertung einbezogen. Da dafür bestimmte statistische Angaben verfügbar sein müssen, beziehen sich diese Ergebnisse nur auf 55 Datensätze aus Untersuchungen, in denen Stickstoff experimentell zugeführt wurde. Der Gesamteffekt eines experimentellen Stickstoffeintrags auf die Diversität von Bodenorganismen ist mit einer standardisierten mittleren Differenz von -0.47 zwischen Behandlung und Kontrolle signifikant negativ und nach Cohen (1988) von moderater Intensität (Abbildung 7).

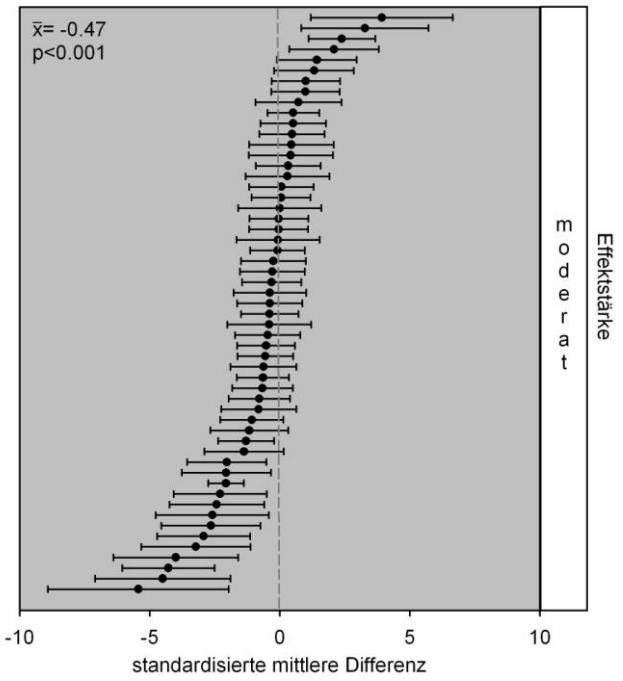

Abb. 7 Ergebnis der Meta-Analyse zum Einfluss experimenteller Stickstoffeinträge auf die Diversität der Bodenorganismen (N=55).

Teilt man die vorhandenen Studien in Habitat-Klassen (Offenland- und Wald-Habitate), ergibt sich ein differenziertes Bild. Während in Offenland-Systemen kein einheitlicher Effekt der Stickstoffeinträge auf die Diversität zu finden ist, sind Bodenorganismen in Waldsystemen stark negativ durch Stickstoffeintrag beeinflusst (Abbildung 8). Zu diesem Ergebnis trägt jedoch auch die vergleichsweise hohe Anzahl an Studien zur Diversität der Pilze in Wäldern bei (siehe auch folgender Abschnitt).

Die Diversität der verschiedenen Großgruppen der Bodenbiota wird unterschiedlich stark durch Stickstoffeinträge beeinflusst. Während die Diversität der Pilze, inklusive Mykorrhiza, in Folge von Stickstoffzufuhr abnimmt, ist dieser Effekt für Bakterien und Bodentiere jeweils nur schwach negativ, jedoch noch als gering zu bezeichnen (Abbildung 9).

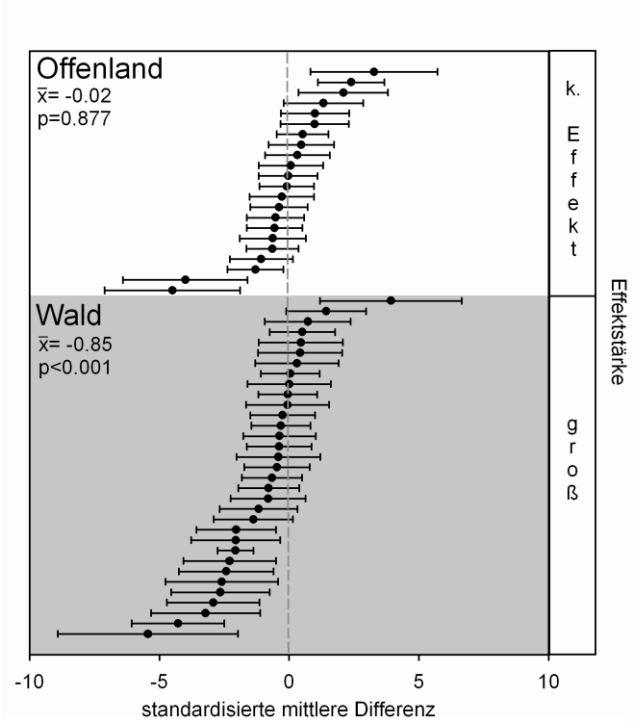

Abb. 8 Ergebnis der Meta-Analyse zum Einfluss experimenteller Stickstoffeinträge auf die Diversität der Bodenorganismen in Offenland und Waldhabitaten (N=55).

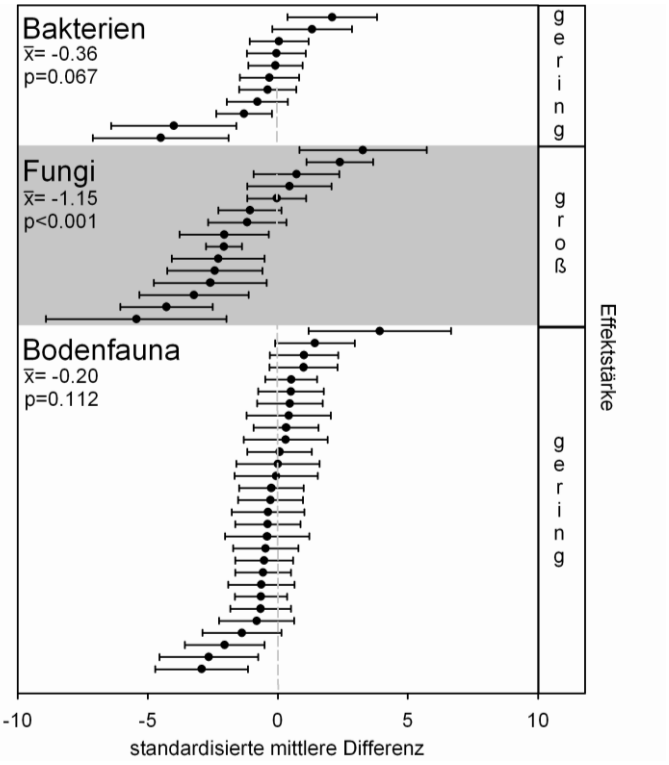

Abb. 9 Ergebnis der Meta-Analyse zum Einfluss experimenteller Stickstoffeinträge auf die Diversität der Bakterien, Pilze und Bodenfauna (N=55).

Diskussion

Die vorliegende Studie zeigt, dass die anthropogene Stickstoffzufuhr meist negativ auf die Diversität von Bodenorganismen wirkt. Dabei gibt es Hinweise auf stärker negative Wirkung atmosphärischer Einträge im Vergleich zur Düngung. Vor allem in semi-natürlichen und Wald Habitaten ist von einer Störung auszugehen. Diese Systeme unterliegen im Gegensatz zu Agrarsystemen einer geringeren Bewirtschaftung durch den Menschen und gelten in Hinsicht auf anthropogene Störungen als besonders empfindlich. Bodenorganismen in Agrarökosystemen sollten aufgrund der kontinuierlichen Zufuhr von Stickstoff (organische und mineralische Düngung) stärker an diese Einträge angepasst sein. Die Literaturlage zum Einfluss von Stickstoffeinträgen auf die Diversität von Bodenorganismen in semi-natürlichen Systemen, als auch in Offenlandhabitaten im Allgemeinen, ist aber im Vergleich zu Studien in Wäldern noch als unzureichend zu bewerten.

Es bestätigt sich, dass die stärksten Effekte für Mykorrhiza Pilze gefunden wurden, denn diese Gruppe ist über eine Pilz-Pflanzen Symbiose stark in den Stickstoffkreislauf der Böden eingebunden. Der hohe Anteil nicht signifikanter Ergebnisse zum Einfluss der Stickstoffzufuhr auf die Bodenfauna (Abbildung 6) relativiert sich im Vergleich der semi-quantitativen und quantitativen Auswertung. Die Darstellung der statistischen Metaanalyse (Abbildung 9) lässt darauf schließen, dass in vielen Studien eine sehr hohe Varianz der Diversitätsmaße zu einem nicht signifikanten Ergebnis führte. Diese Annahme deckt sich mit Ergebnissen zur kleinräumigen Heterogenität in der Verteilung von Bodentieren (Eckschmitt et al. 2003) und unterstützt die Forderung nach sorgfältig und aufwendig angelegten, räumlich expliziten Bodenfauna-Probenahmen in zukünftigen Untersuchungen. Insbesondere ist es sehr unwahrscheinlich, dass eine stark negative Beeinflussung der Diversität von Pilzen nicht auf die Artenzahlen der Bodenfauna rückwirkt, da viele der im Boden lebenden Tiere mykophag sind (Schneider et al. 2004). Der in Abbildung 9 vorhandene Trend zur negativen Auswirkung von Stickstoffdeposition auf die Diversität der Bodenfauna, lässt sich voraussichtlich durch einer Erhöhung der Probestellen (Replikate) und einer Verwendung von Mischproben für viele Arten in zukünftigen Studien statistisch sichern.

Die globale Verteilung der Studien zeigt einen starken Schwerpunkt in der nördlichen Hemisphäre. Dies ist in Hinblick auf klimatische Unterschiede zwischen beiden Teilen der Welt von großer Bedeutung. So sind Aussagen über den Einfluss anthropogener Stickstoffeinträge in den Tropen oder in der klimatisch stärker gepufferten südlichen Hemisphäre derzeit nicht möglich. Unter Berücksichtigung des Klimawandels ist diese einseitige Literaturlage als sehr nachteilig zu bewerten. Die größte Ungewissheit liegt aber in der mangelnden Kenntnis der Auswirkungen von Stickstoffeinträgen auf biotische Interaktionen und den von Bodenor-

ganismen geleisteten ökosystemaren Funktionen und Dienstleistungen. So bleibt es für zentrale Funktionen der Bodenorganismen, wie bspw. die Zersetzungsleistung oder Mineralisierung, ungewiss, ob sich Stickstoffeinträge und die daraus resultierende Beeinflussung der Diversität verschiedener Gruppen negativ auswirken. Die in unserer Analyse aufgezeigten Lücken sollten durch weitere Datenbankrecherchen und Feldstudien geschlossen werden. Parallel sollten Labor- und Freilanduntersuchungen erste Hypothesen zum Zusammenhang zwischen anthropogenen Stickstoffeinträgen und Biodiversitäts-Ökosystem-Funktionen etabliert werden.

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