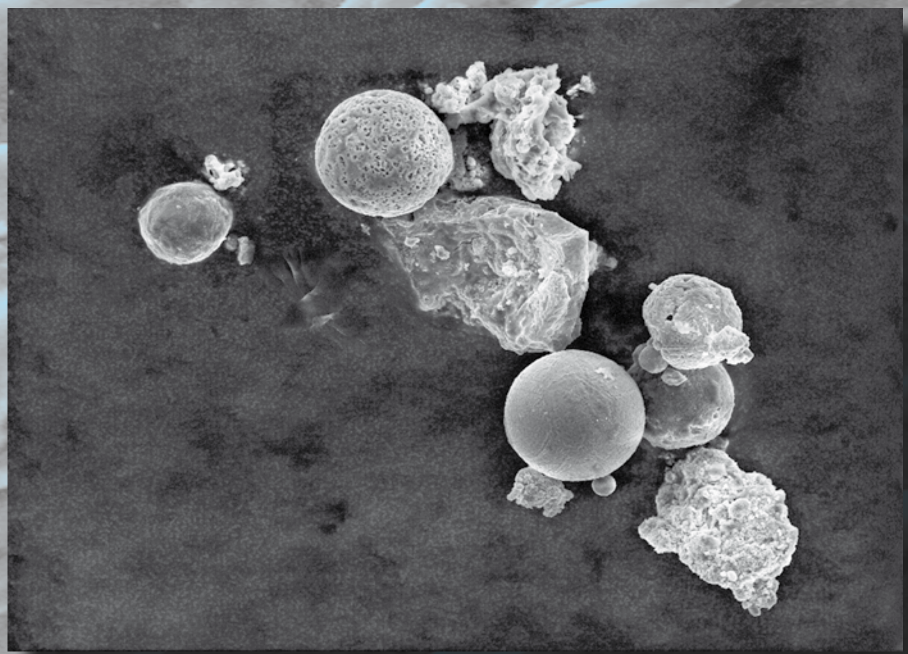
Lignite combustion was the major driver for health and growth of the forests in Dübener Heide.

Nowadays, forests in Dübener Heide are characterized by an ample regeneration of broad-leaved tree species. Negative effects of fly ash deposition are not anymore detectable.



Micro-structures of fly ash. Its detectablity is based on the content in ferrimagnetic iron oxides, such as magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3).

Cover photo: Fly ash is a multi-facted material composed by residuals of organic matter, slags and amorphous vitreous particles.

Fly ash impact in forest ecosystems in Northeastern Germany – an assessment and regionalization approach

Fly ash impact in forest ecosystems in Northeastern Germany – an assessment and regionalization approach

Dissertation

Christine Fürst

Prepared in the frame of the joint research project „ENFORCHANGE“ (FKZ 0330634 K, German Federal Ministry of Education and Research).

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The studies, which form the basis for the publications of this thesis, would never have been carried out without the help of some appreciated colleagues to whom I want to say a warm thank you for all the help, the willingness to discuss open questions and to support the design and realization of the studies. First of all, I want to thank Carsten Lorz for the time he has spent for our common publications and for the never ending patience to give input into the assessment approaches. Without Dietmar Zirlewagen the statistical analysis and especially the regionalization approach could not have been realized. I want to thank him a lot for many additional lessons in statistics and modelling. To sum up all the long-term input which was given by Mengistu Abiy to ENFORCHANGE and to the thesis with few words is impossible. I want to thank him for all his suggestions and contributions, which were a most valuable basis for my work. The field assessment and other contributions by Heiko Fritz, Lars Koschke, Kay Hagemann and Stefan Just were indispensable to complete the data basis of the project facing the challenge to coordinate the ENFORCHANGE project at the same time. I want to thank them explicitly for their outstanding team work during the past years.

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A prerequisite to realize a cumulative thesis is an advisor, who is not only a specialist in his field, but also open and competent enough to give freedom in developing the approach and to trust in the results of several years of intensive work. Thus, it was a great experience to have Franz Makeschin as supervisor. I want to thank him personally for the all the support, his confidence in my work and the valuable time at the Institute for Soil Science and Site Ecology, which was certainly the best period so far in my academic life.

Zusammenfassung

Die vorgelegte Doktorarbeit "**Fly ash impact in forest ecosystems in Northeastern Germany – an assessment and regionalization approach**" (Flugascheeinträge in Waldökosysteme in Nordostdeutschland – ein Erfassungs- und Regionalisierungsansatz) verfolgte die **Ziele**

(a) zu **testen**, ob sich die **Erfassung der ferrimagnetischen Suszeptibilität** eignet, um kosteneffizient **quantitative und / oder qualitative Informationen** zu den eingetragenen **Flugaschemengen** und den in der Folge **veränderten bodenchemischen Potenzialen** zu erheben

(b) zu **testen**, ob der **Indikator „ferrimagnetische Suszeptibilität“** genutzt werden kann, um **Informationen** über Flugascheeinträge von der punktbezogenen Erfassung auf einen **regionalen Maßstab hoch zu skalieren**.

Grundlage dieser Zielstellungen sind **Forschungsarbeiten** zu der Frage der **langfristigen Wirksamkeit und ökologischen Bedeutung von Industrieexhalationen auf Waldökosysteme**, die am Institut bereits in den 1960ziger Jahren begonnen wurden und verstärkt seit Mitte der 1990ziger Jahre fortgeführt wurden. Auf ihrer Basis wurde die **Herausforderung** eines **kostengünstigen und flächenbezogenen Erhebungsansatzes** identifiziert und formuliert. Die vorgelegte Arbeit ordnete sich in diese Forschungsarbeiten ein und führte sie im Rahmen des Verbundforschungsvorhabens ENFORCHANGE ((FKZ: 0330634 K, Bundesministerium für Bildung und Forschung) von 2005 - 2009 fort.

Die Doktorarbeit ist als **kumulative Arbeit** angelegt, im Rahmen derer insgesamt 10 Publikationen zusammengefasst wurden. Davon sind 5 in internationalen Journalen bereits publiziert, akzeptiert oder in einem Fall in Begutachtung; 5 weitere Publikationen wurden ergänzend und auf speziellere Themen bezogen in Proceedings oder Buchbeiträgen publiziert.

Die Arbeit gliedert sich in 5 Abschnitte:

- **Kapitel 1** (Einleitung) gibt einen kurzen Überblick zur Motivation und Struktur der Doktorarbeit.
- In **Kapitel 2** (Ziele und Rahmen der Arbeit) wird der **Arbeitsansatz im Rahmen** des Verbundforschungsvorhabens **ENFORCHANGE** vorstellt.
- **Kapitel 3** umfasst eine **Auswertung von Veröffentlichungen** zur Geschichte und den ökologischen Auswirkungen der Flugascheeinträge am Beispiel der Modellregion Dübener Heide.

- In **Kapitel 4** wird der **methodische Ansatz der Arbeit** vorgestellt, der von einem Vortest zur Eignung der Erfassung der magnetischen Suszeptibilität über die Ableitung eines flächigen Erhebungsansatzes bis hin zur Frage der Modellbildung und Korrelation mit chemischen Kenngrößen reicht.
- **Kapitel 5** beinhaltet die **Ergebnisse** der **räumlichen Modellbildung** und der **Korrelation** der magnetischen Suszeptibilität mit ausgewählten Basen-, Säure- und Schwermetallkationen sowie mit Schwarzem Kohlenstoff.
- **Kapitel 6 diskutiert, vergleicht und bewertet die Ergebnisse** der den Veröffentlichungen zugrunde liegenden Studien und zieht ein **abschließendes Resumé**.

Ein **Schlüsselergebnis** der vorgelegten Arbeit belegt, dass entgegen der ursprünglichen Arbeitshypothese des Projektverbundes ENFORCHANGE **nicht** das mehr als 100 Jahre alte Kraftwerk **Zschornewitz** die **wesentliche Quelle für die Flugascheeinträge** in der Modellregion Dübener Heide war, **sondern** der räumlich entfernter gelegene, aber deutlich größere **Industriekomplex Bitterfeld**.

Bezogen auf die **Zielsetzung** der vorgelegten Arbeit, konnte **mithilfe multipler Regressionsverfahren** und auf Basis von Feldaufnahmen der ferrimagnetischen Suszeptibilität in einem regelmäßigen Stichprobenraster ein **hoch auflösendes räumliches Modell** gebildet werden. Unter Berücksichtigung weiterer Modellparameter, die schrittweise hinsichtlich ihres Erklärungswertes ausgewählt wurden, konnten mikrotopographische und vegetationsbedingte Informationen genutzt werden, um die **räumliche Variabilität des magnetischen Signals differenziert darzustellen**. Damit ergibt sich eine Planungsgrundlage, die die bisher genutzte, auf Waldschadensansprachen basierende Stratifizierung in Zonen unterschiedlicher Eintragsintensität mit Bezug zur Planungseinheit deutlich detaillierter untersetzt.
Der **Versuch**, auf **Flugascheeintragsmengen**, respektive **-vorräte** zu schließen ließ sich hingegen auf Basis der verfügbaren Daten **nicht umsetzen**. Die Korrelationsbeziehungen der von Volumen- in den Massenbezug umgerechneten Suszeptibilität mit Basen-, Säure und Schwermetallkationen sowie Schwarzem Kohlenstoff fielen heterogen aus. Eine **gute Vorhersage auf Basis eines linearen Regressionsmodells** konnte für **Ca, Mg und Mn** getroffen werden, wohingegen die Modellqualität für Fe, Al sowie Cd und Schwarzen Kohlenstoff deutlich schlechter zu beurteilen war.
Dies ergab sich zum einen aus der **verfügbaren Datenbasis**, die **keine durchgängige Harmonisierung für die Erhebungen der Suszeptibilität und der chemischen Kennwerte** erlaubte. Zum anderen geht diese Erkenntnis mit Ergebnissen aus der **Regionalisierung** einher, die einen **Einbezug weiterer Modellparameter und die Nutzung multipler anstelle linearer Regressionsmodelle** nahe legt.

Summary

The presented doctoral thesis „Fly ash impact in forest ecosystems in Northeastern Germany – an assessment and regionalization approach“ intends to

(a) test if the field assessment of ferrimagnetic susceptibility can be used as **cost efficient method** to get **information on fly ash deposition impacted chemical site properties**.
(b) develop a **regionalization approach** to bridge the gap from plot-wise assessed data to spatial management information.

The **thesis** is a **follow-up** of extensive **research activities by the Institute for Soil Science and Site Ecology** on **industrial deposition in Dübener Heide and Upper Lusatian region** which started in the early 1960ies and were intensified from the middle of the 1990ies on. A **central topic** of these research activities was the **assessment of the impact of fly ash deposition on chemical soil properties.**
A major **challenge** was to **transfer the assessed chemical characteristics from plot to region** and to aggregate the measured values to provide an information basis, which can be used for a site potential and risk oriented forest management. This challenge was picked up by the joint research project "ENFORCHANGE" (FKZ 0330634 K, German Federal Ministry of Education and Research). The presented thesis was carried out in the frame of this project during the period 2005 - 2009.

The thesis was conceived as **cumulative work**, which includes ten papers in total. Five articles are published in peer-reviewed journals (ISI listed, 1 paper still in revision), and five are part of books or conference proceedings.

- **Chapter 1 "Introduction"** gives an overview on the motivation, idea and structure of the thesis.
- In **chapter 2 "Aims and Scope of the presented work"** information on the background and frame of the study within the project ENFORCHANGE is given.
- **Chapter 3 "Background and State of the Art"** deals with the history of fly ash deposition in the model region Dübener Heide.
- **Chapter 4 "Material and Methods"** gives information on fly ash and presents the spatial assessment design and the hereon based approaches for up-scaling and correlation of magnetic susceptibility with selected chemical characteristics.
- **Chapter 5 "Results"** presents results of the spatial modeling and linear regression based approach to use ferrimagnetic susceptibility for predicting the contents of selected base cations, selected acid and heavy metal cations and Black Carbon.

- **Chapter 6 "Discussion and Conclusions"** compares the assumptions and findings in the different articles, discusses contradictory findings and open questions and provides a comprehensive evaluation of the outcomes. Final conclusions are drawn and an outlook is given.

A **key finding** of the thesis is that the **industrial complex Bitterfeld** was the **most important source of fly ash** deposited in the model region Dübener Heide. The **power plant Zschornewitz** plays only a minor role contrary to the research hypothesis formulated in ENFORCHANGE.

Related to the targets of the thesis, **spatial variation of magnetic susceptibility** was **predicted with high precision by a multiple linear regression model**. A slightly differing set of model parameters – according to their explanatory value for three selected depth levels – improved the prediction quality.
The selection of the parameters supported understanding the major drivers for magnetic particle deposition, storage, and vertical displacement in the forest soils. **Humus layer** (**depth level 6-10 cm**), **horizontal distance to Bitterfeld** and **soil type** (Podzol, semi-terrestrial sites) were the **most important variables**. These variables point to a slowed-down humus dynamic, which causes the accumulation of fly ash in the humus layer. In **depth level 11 – 15 cm**, variables such as "aspect" gain in importance, which describe the **exposure against the major wind direction** and thus indicate the probability and of deposition.
For the **mineral horizon** (**depth level 21-25 cm**), **exposition** and especially **stand properties** are **most important**. The latter gives evidence for the intensity of deposition caused by surface roughness. Therefore, the variables "coniferous" and "mixed" stands were highly relevant for the model.

Variable correlations between **mass susceptibility** and **selected base cations, acid cations and heavy metals** have been found. When using a **linear regression model**, a **prediction of Ca** and **Mg** and of **Mn** was **possible**. The **model performance** was **lower** for **Fe, Al, Cd and Black Carbon**. A possible reason was the use of different plot types: the assessment of magnetic susceptibility and chemical soil properties was well harmonized at the ENFORCHANGE plots considering the sampling material and sampling location. A comparable harmonization could not be achieved at a number of monitoring plots, which were included into the analysis to broaden the data base.

Comparing the results from the linear regression model based prediction with the results achieved by multiple regression based spatial modeling lead to the conclusion that the **multiple regression approach** is more **promising**: by using other model parameters such as orographic, climatic or stand parameters together with magnetic susceptibility, the **prediction quality of the deposed agents could be improved** and **small scale variations** in nutrient potentials and risks driven by fly ash deposition could be better recognized and made available for forest management decisions.

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1. Introduction

1.1 Motivation

The presented thesis is a follow-up of extensive research of the Institute for Soil Science and Site Ecology on industrial deposition in Dübener Heide and Upper Lusatian region. A focus of these research activities has been the assessment of the impact of fly ash deposition on chemical site potentials and risks. A challenge resulting from the related findings was to transfer the assessed chemical characteristics from plot to region and to aggregate the measured values to provide an information basis, which can be used for a site potential and risk oriented forest management.

The **objective** of the presented research was to **provide** two missing **puzzle-stones** in the **research on fly ash deposition**:

(a) to test if the field assessment of ferrimagnetic susceptibility can be used as **cost efficient method** to get **information on fly ash deposition impacted chemical site properties**.
(b) to develop a **regionalization approach** to bridge the gap from plot-wise assessed data to spatial management information.

The **Dübener Heide** near to the Central German industrial triangle Leipzig-Halle-Bitterfeld was chosen as **model region** because of its long history of industrial deposition, high number of research projects on fly ash effects from the early 1960ies on and the resulting enormous database on deposition influenced vegetation and soil development.
The research was carried out in frame of the joint research project "ENFORCHANGE" (Environment and Forests under Changing Conditions), supported by the Federal Ministry of Education and Research (BMBF, FKZ: 0330634K), which is presented in detail in chapter 2.

1.2 Idea and Structure

The thesis was conceived as **cumulative work**, which includes ten papers in total. Five articles are published in peer-reviewed journals (ISI listed, 1 paper still in revision), and five are part of books or conference proceedings.

In **chapter 2 "Aims and Scope"**, three contributions are integrated, which give information on the background and frame of the study within the project ENFORCHANGE. This includes an overview on the project ENFORCHANGE and its different modules, but also on some results from this interdisciplinary study.

Chapter 3 "Background and State of the Art" includes three contributions dealing with history of fly ash deposition in the model region Dübener Heide and its consequences for forest management. The model region is described and the impact of fly ash deposition on the forest ecosystem is discussed. Hereon based, some conclusions are drawn on how to integrate the past fly ash deposition into process-oriented forest management approaches.

In **chapter 4 "Materials and Methods"**, the properties of fly ash including potentials and risks for affected forest ecosystems are described in the first paper (4.1.1). The second contribution introduces a pre-test of a field assessment method for ferrimagnetic susceptibility. In addition conclusions are drawn how to conceive the field assessment as suitable basis for up-scaling procedures (4.2.1).

Two contributions in **chapter 5 "Results"** introduce the potentials and restrictions of up-scaled ferrimagnetic susceptibility data as basis for forest management decisions. A regionalization model and its parameters are presented and discussed (5.1.1). In addition, ferrimagnetic susceptibility is tested as indicator for key base cations, acid and heavy metal cations and Black Carbon (5.2.1).

Chapter 6 "Discussion and Conclusions" assumptions and findings of the papers are compared. Contradictory findings and open questions are discussed and a comprehensive evaluation of the outcomes is provided. Final conclusions are drawn and an outlook is given.

2. Aims and Scope

2.1 The ENFORCHANGE study – overview, integration and contribution of the presented research approach

"ENFORCHANGE" (Environment and Forests under Changing Conditions, www.enforchange.de) was a research project supported by the Federal Ministry of Education and Research (BMBF, Germany), which pursued the following global targets:

(a) characterization of changes of environmental factors (climate, site, and human beings) relevant for land use with special regard to their interactions,
(b) evaluation of effects of changes on the prioritization of (forest) goods and services,
(c) development of instruments and guidelines for a process-oriented (dynamic) forestry and spatial planning, and
(d) aggregation and transfer of results into the (forest) practice and other relevant target groups ("children", "regional citizen", "scientist", "planner", "policy maker").

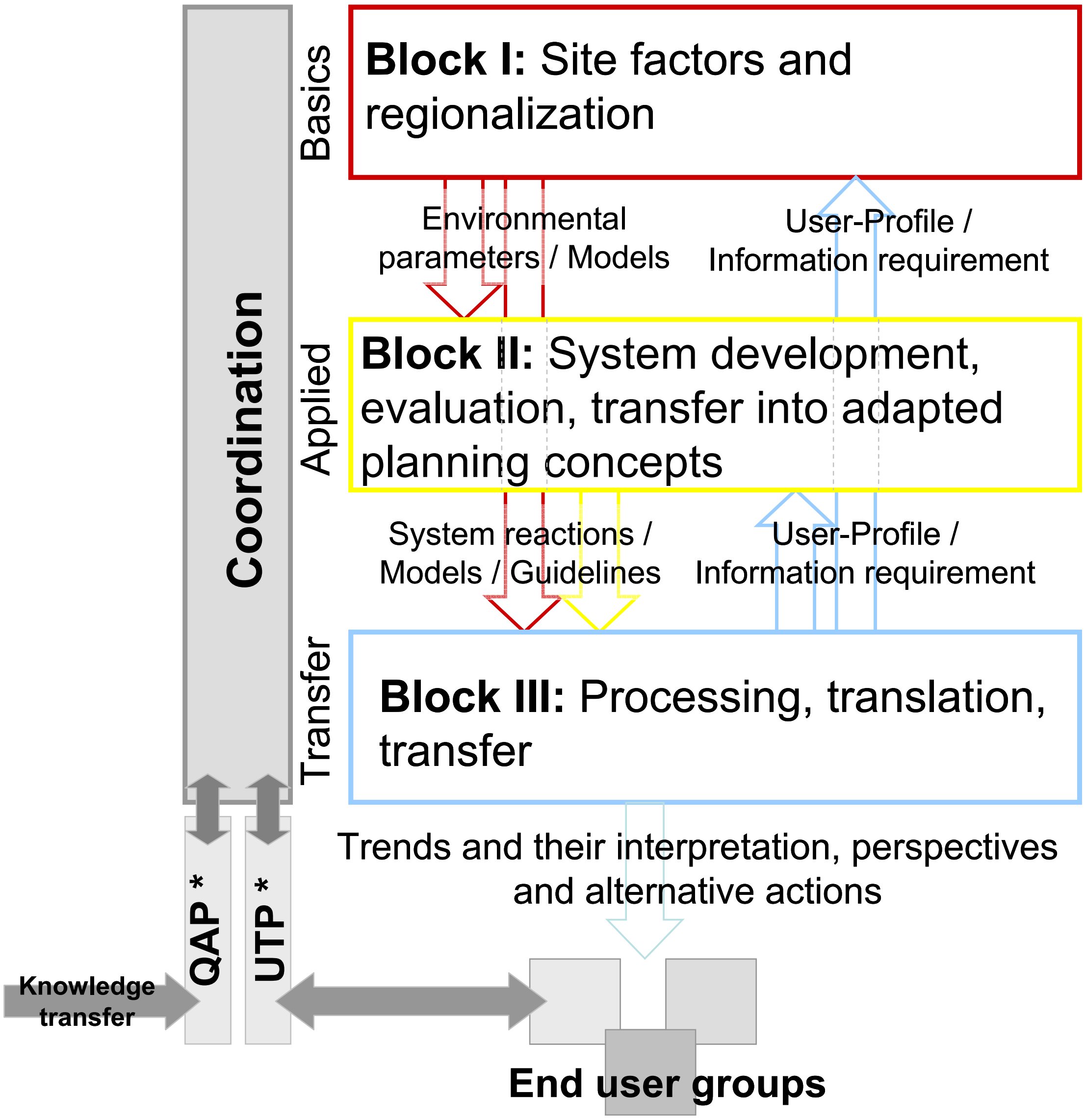
An **outspoken aim of the project** was to **assess and evaluate the long-term effects of former deposition** for two model regions in the New Lander, the Dübener Heide and the Upper Lusatian region, where the latter was mainly considered as validation region for the outcomes in Dübener Heide. Among others, focus was laid on the **impact assessment of fly ash deposition**, as fly ash was considered in the past to be a major driver for forest ecosystem development in both regions (e.g. Klose et al. 2001 and 2002, Koch et al. 2002, Lux 1965 and 1974, Neumeister et al. 1997). Based on the ENFORCHANGE results, approaches could be derived for integrating the current impact of past deposition into forest management (Eisenhauer and Sonnemann 2009).

Figure 1 gives an overview on the research structure of ENFORCHANGE. The project intended to realize the chain from assessment of the environmental situation to the integration into forest management and the transfer into practice and public. ENFORCHANGE was structured into three thematic working groups, which were called "blocks" in the project terminology.

Block I "Site Factors and Regionalization" dealt with an assessment of environmental changes with focus on forest sites and climate frame conditions. The assessment data formed the basis for evaluation and modeling of changing abiotic frame conditions and effects of past and ongoing processes. The research on fly ash deposition assessment and regionalization, which is the main topic of this thesis, was carried out in this group. A crucial part of the research work was the development of regionalization models. This included an up-scaling of chemical soil properties (Zirlewagen 2009, Zirlewagen and von Wilpert 2009) and of ferrimagnetic susceptibility (Fürst et al. 2009 b) and also downscaling of climate change scenarios to regional scale (Bernhofer et al. 2008).

The results from block I formed the basis for **block II "System Development, Evaluation, transfer into adapted planning concepts"**, which linked regionalized data with process models for tree growth and nutrient balances for Climate Change scenarios. As a major result, forest ecosystem responses on ongoing environmental changes might be described. Effects for the provision of forest goods, services and related monetary consequences were appraised. The results were transformed into renewed silvicultural and operational management recommendations (Eisenhauer and Sonnemann 2009, Stang and Knoke 2009).

Block III "Processing, translation, transfer" dealt with the analysis of transfer options to different target groups and for the realization of transfer into practice and publicity.



* QAP: Quality Assuarance Panel, UTP: User and Tranfer Panel

Fig. 1: Structure of the joint research project ENFORCHANGE (Makeschin and Fürst 2007).

In Dübener Heide, ENFORCHANGE started with **two research hypotheses**:

(1) the **regional power plant Zschornewitz**, which is situated in close vicinity to the Northeastern border of Dübener Heide forest was considered as **most important source of fly ash** and other air pollution components. Zschornewitz is the oldest regional power plant with more than 100 years of activity. Furthermore, its technological standard (filtering techniques) was very ancient until its closing in the 1990ies. A **regional deposition gradient** was described first by Lux (1965), later on by Lux and Stein (1977) and by Klose and Makeschin (2005). The highest deposition along the gradient was found at the Eastern border of Dübener Heide in Saxony-Anhalt with strongly affected sites near to Zschornewitz. The gradient stretches with decreasing intensity to the Southwestern corner of Dübener Heide in Saxony (see Fig. 2).

(2) the **sites in four** historically well documented **deposition zones along** the above described **deposition gradient can still be differentiated (a)** according to their **nutrient potentials** and **(b)** according to **specific risks** such as heavy metal release (Fürst et al. 2006, Fritz and Makeschin 2007, Fritz et al. 2009). It was assumed that the vegetation development and the growth potential of forest stands are still impacted by this spatial differentiation as described by numerous authors, such as Amarell (1997), Enderlein and Stein (1962), Erhard and Flechsig (1998), Heinsdorf et al. (1994), Herpel et al. (1995), Hüttl and Bellmann (1999), Konopatzky and Kopp (2001), Kunze et al. (1995), and Lux (1964 a and b, 1974).

Hereon based, twelve key plots and some complementary satellite plots were identified in the Dübener Heide along the deposition gradient from Northeast near the former power plant Zschornewitz to Southwest (Fig. 2). These plots were used to analyse current site and stand properties.

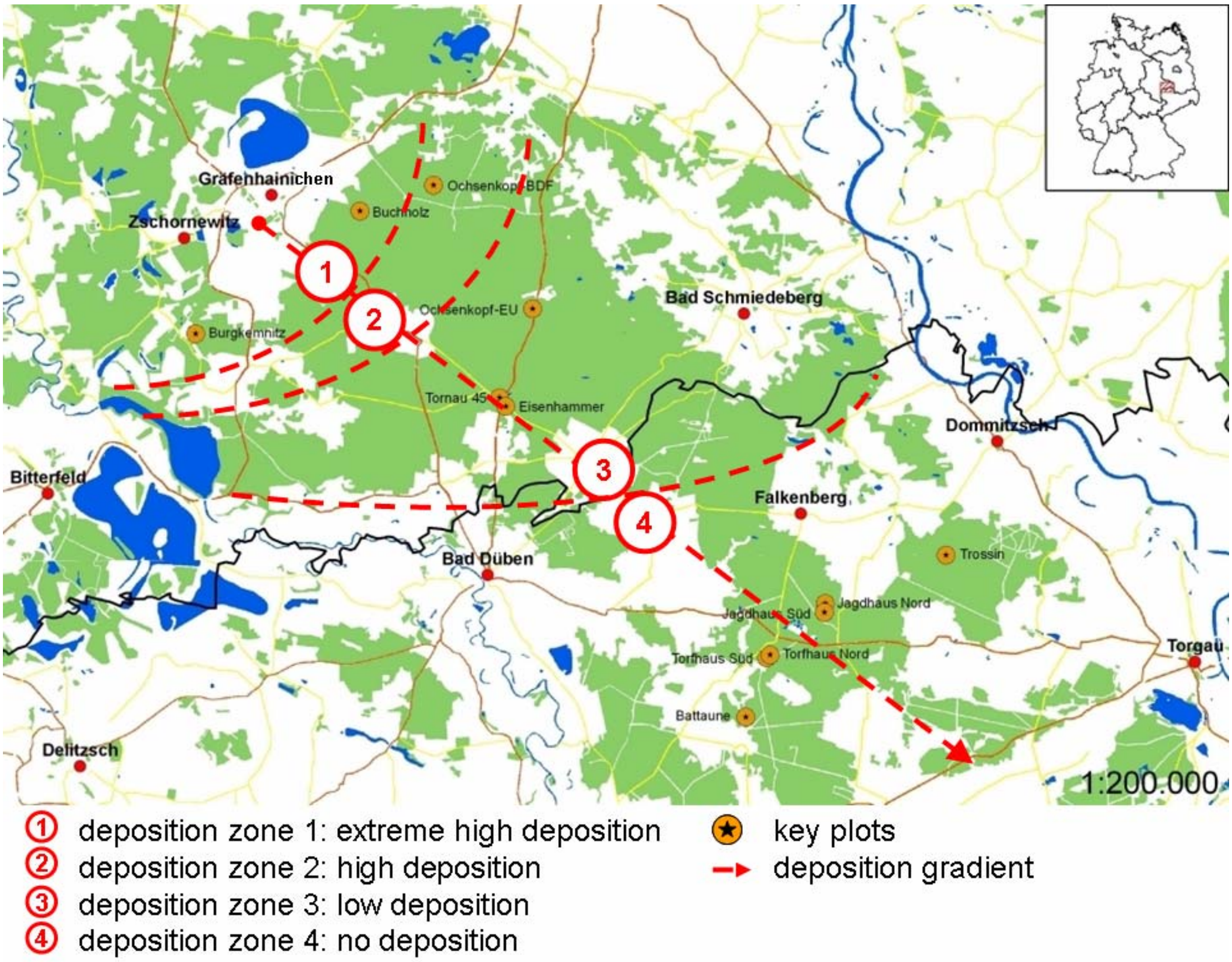


Fig. 2: Model region Dübener Heide with deposition gradient (schematic) and deposition zone related key plots.

The **key plots** represented **major (terrestrial) soil type-stand type-combinations** of the region. They were preferably chosen at sites, where information from former deposition monitoring, forest health monitoring or growth and yield field trials could be involved. At the key plots, chemical and physical site properties were measured depth level-wise with focus on the humus layers and the upper mineral horizons. In addition, forest growth and yield characteristics were assessed.

The key plots were **installed** for the total project duration, i.e. their geographic coordinates were documented, and linked to available GIS-information (site quality maps / geology, topography, etc.).

Missing information, e.g. considering stand type development in a distinct deposition zone and on a distinct site type but in different age classes was collected at **satellite plots**, which were **not permanently installed**.

Ferrimagnetic susceptibility field assessment was carried out at all **key plots** and in a **regular sample grid** with two grid densities (1x1 km² and 4x4 km², nested approach, see also chapter 5.1.1) as basis for the regionalization.

Finally, information from **earlier regional monitoring and survey plots** (Level-I, Level-II monitoring, permanent soil monitoring sites, forest growth and yield field trials, climate stations), **data from literature analysis** and available **GIS-data** were integrated into the **ENFORCHANGE information pool**.

Figure 3 shows the **upscaling approach** in ENFORCHANGE: the key and satellite plots and the grid-wise ferrimagnetic susceptibility measurements were installed to complement the regionally available data and information pool. The assessed environmental information from all measurements in ENFORCHANGE and from the regional data pool was aggregated and provided spatially explicit time series as basis for modeling and regionalization of ongoing ecosystem processes (Fürst et al. 2006, Fürst and Makeschin 2009). This was used as basis for process-oriented forest management (Eisenhauer and Sonnemann 2009).

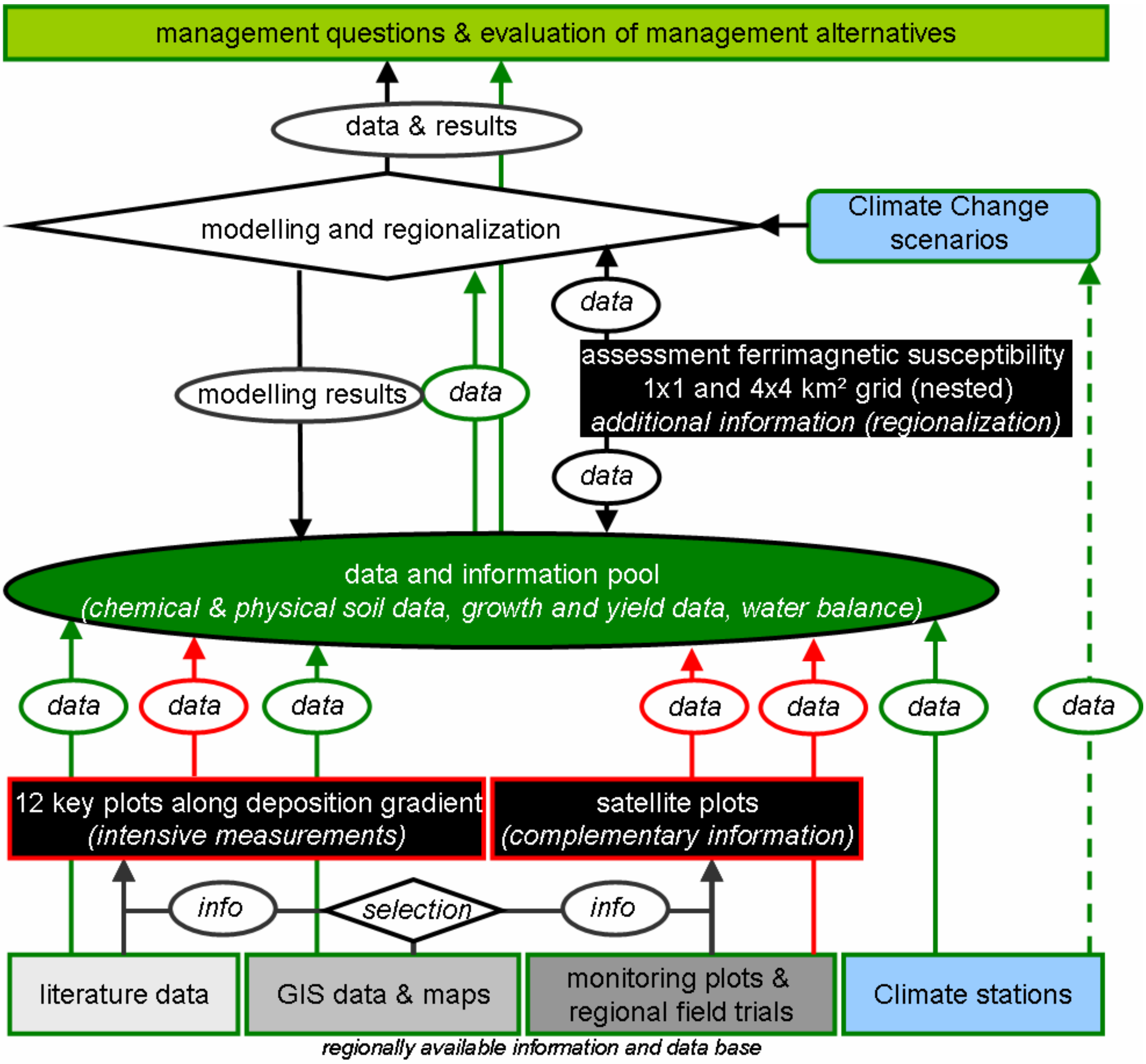


Fig. 3: System of information bundling in ENFORCHANGE consisting of regionally available data, complementary information from own measurements and results from monitoring and regionalization (Fürst et al. 2006, Fürst and Makeschin 2009).

The two articles included in this chapter present the ENFORCHANGE study in the light of its structure, approach and outcomes.

2.1.1 Fürst, C., Abiy, M., Makeschin, F. (2008): Forest ecosystem development after heavy deposition loads – case study Dübener Heide, WIT Transactions on Ecology and the Environment (ISSN 1743-3541), Air Pollution XVI: p. 571-584

Extended summary

The article introduces the ENFORCHANGE study and gives an overview on the history and development of the forest ecosystem Dübener Heide in the light of the influence of air pollution from lignite combustion. The presented and at this point of time not finished investigations along the deposition gradient in Dübener Heide revealed that the deposition impact is still detectable, though the deposition zones defined first by Lux (1965) could not be validated in the course of the ENFORCHANGE study. Chemical site potential differences described by Fritz and Makeschin (2007) and Fritz et al. (2009) allow for a stratification of Dübener Heide in two different zones: a “high influence zone” in up to 8-15 km distance to the power plant Zschornewitz, which is situated near to the western border of Dübener Heide, and a “low influence zone” in more than 8-15 km distance. The “high influence zone” is characterized by high pH-values, and high base cation availability and base saturation in the humus layers, indicating a considerable nutrient pool far beyond from the natural level. The described spatial differentiation was also supported by a cluster analysis of the results of ferrimagnetic susceptibility field assessment in the humus layers, which was done parallel to the chemical analyses at the 12 ENFORCHANGE plots. The plots in a distance up to 8-15 and more than 8-15 km were clearly differentiated from the rest.

The spatial stratification according to the site potential is decisive for silvicultural questions. In the past, forest health and growth were extremely affected by depositions. The four deposition zones described by Lux (1965) were originally defined on the basis of an assessment of forest growth and health. An analysis of forest growth data from different studies (Hüttl and Bellmann 1999, Lux 1964 a, b and 1966) revealed that a clear spatial differentiation of radial increment as forest growth indicator along the deposition gradient seemed to be only valid at the early beginning of fly ash deposition and deposition research. Later on, when fly ash filters were introduced from the 1980ies on and when the SO_2 deposition was still increasing, differences in radial increment could not be found anymore. From this time on, negative impact of deposition on forest growth was equal in the whole Dübener Heide. Nowadays the sites in the “high influence zone” up to 8 – 15 km distance benefit from the former fly ash deposition. In contrast to the sites at the “low influence zone”, they are characterized by an ample soil vegetation and natural regeneration of noble hardwood species and European beech. The vegetation types at the not measurably fly ash influenced sites reflect much more the original regional site potential with domination of Scots Pine and Oak.

2.1.2 Fürst, C., Makeschin, F. (2009): Forest ecosystem development under a changing environment and conclusions for forest management, Forestry in Achieving Millenium Goals, Proceedings, p. 47-55

Extended summary

The article introduces more results from the ENFORCHANGE study regarding the reactions of the forest ecosystem Dübener Heide on the change in the deposition regime and future changes in climate frame conditions. Based on these results, conclusions how to better integrate ongoing environmental processes in forest management concepts are drawn.

The assessment of chemical and physical parameters at the 12 ENFORCHANGE key plots and a field assessment of ferrimagnetic magnetic susceptibility in a regular grid confirmed the spatial differentiation along the deposition gradient, which was concluded in the before presented article. The here presented (extended) results supported finally a stratification of three spatially distinct areas instead of four as proposed by Lux (1965): in up to 8 km distance to the former emitters, pH (KCl) values and base saturation are clearly elevated far beyond the original potential of the sites. In a zone up to 15 km, only pH-values were found to be elevated and in a distance of more than 15 km, no measurable effects could be found.

While the plot-wise chemical analyses were arranged along the deposition gradient, which assumed a strong influence of the power plant Zschornewitz, the magnetic susceptibility screening was based on regular grid measurements. These grid-wise measurements revealed that the impact of the industry site Bitterfeld, which is situated farther from Dübener Heide was clearly stronger than originally believed (see also chapter 5.1.1). It could also be shown that fly ash was deposited much farther than proved by the assessment of chemical and physical properties at the project plots.

Considering site potentials and forest growth, the double-edged effects of fly ash deposition on site potentials and risks under climate change were discussed. Driven by the improved site potential due to fly ash “fertilization”, tree species such as noble hardwoods and European beech regenerate naturally in Dübener Heide. Facing a possible reduction of 20 % of the actual precipitation and an increase of the mean annual temperature of 3.5 °C in the next 100 years, the stability and resilience of such stands could pose future problems. The necessity of a stronger integration of ongoing ecosystem processes into silvicultural management was concluded. Silvicultural management in both parts of Dübener Heide, in Saxony and Saxony-Anhalt, started to consider the idea of a process-oriented forest management by leaving the stand type as decision basis and replacing stand type by “development type” with close reference to indicators for actual ecosystem and site development trends.

3. Background and State of the Art

3.1 Fly ash deposition and consequences for forest management – overview

Forest ecosystems in Eastern Germany are still affected by long-term effects from former deposition caused by unfiltered lignite combustion in Czech, Polish, and German power plants until the early 1990s. Fly ash is defined as particle residue that enters the flue gas stream after lignite (brown coal) or hard coal (black coal) combustion. Observed deposition rates of the most affected regions in Eastern Germany and Eastern Europe range from 140 t / km^2 * a (industrial triangle Leipzig-Halle-Bitterfeld, Northeastern Germany) up to 457 t / km^2 * a (Upper Silesia, Poland) (Lux 1965 and 1976, Lux and Stein 1977, Strzyszcz et al. 1996, Strzyszcz and Magiera 2001, Klose and Makeschin 2003).

In the early 1960s, two trans-regional deposition hot spots were described for Eastern Germany:
Region (1) the lowland transect between Chemnitz-Leipzig-Magdeburg, and
Region (2) the Lusatian / Spree region along the Polish border between Frankfurt / Oder-Lübben-Cottbus-Hoyerswerda-Görlitz (Lux 1965 and 1976).

The deposited fly ash in **region (1)** originated from **lignite with high S content**. The major impact factors on forest ecosystems were sulphur and heavy metal deposition followed by nitrogen and potassium. Additionally, fluorides, chlorides, as well as complex herbicides from chemical industry complexes such as Bitterfeld were important pollutants for some places. **Region (2)** was impacted by fly ash from **lignite with a lower S-content**. The resulting environmental damages (e.g. forest decline) were less serious compared to region **(1)** (Lux 1976, Kunze et al. 1996).

In the **industrial triangle Leipzig-Halle-Bitterfeld**, which forms a part of region (1), an intensive industrialization took place since almost 100 years and substantial deposition amounts resulted especially from lignite combustion for energy production.
The estimated **deposition in Dübener Heide** amounts **from 1910 – 2000 to 18 Mio. t fly ash and 12 Mio t SO_2**. During the decade **1961 – 1970 up to 3 t / ha * a** fly ash were deposited in regional forests (Klose and Makeschin 2004, Lux 1965 and 1976, Neumeister et al. 1991, Nebe et al. 2001).

However, **fly ash deposition** was **not** the **only regionally relevant impact factor**: N-deposition from the regionally most important N-factory Piesteritz, forest management including N-fertilization against deposition effects and nowadays increasing drought and decreasing rainfall influence the ecosystem processes and lead to a **unique situation considering the site potentials and risks** and also the species composition in soil vegetation and stand types.

Fig. 4 resumes for Dübener Heide the history of anthropogenic influence, quantifiable effects on forest vegetation and visible system reactions and processes according to Amarell (1997), Bendix (2001), Lux (1964 a and b, 1965), Lux and Stein (1977) and Konopatzky (1995, 2001).

The intention of **Fig. 4** is to **visualize the interdependencies between deposition of fly ash, forest management and other impact factors** such as climate change and the effects for forest ecosystem development. The impact factors are split up into direct and indirect impacts by human activities. The ecosystem processes are separated into site processes and processes on stand level. Reactions are shown for the soil vegetation and the stand level.

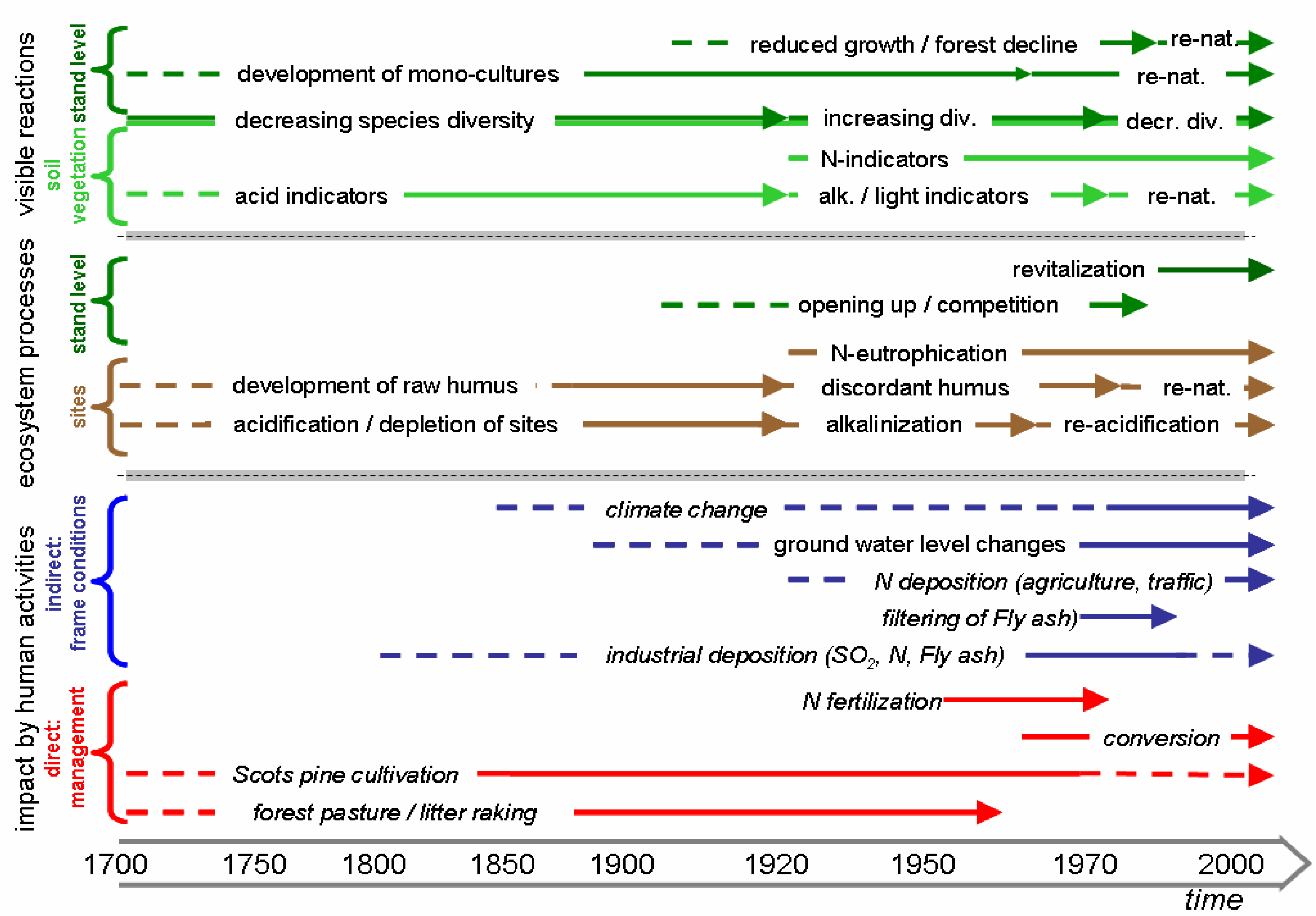


Fig. 4: History of human impact on the Lowland forest ecosystem Dübener Heide (acc. to Fürst et al. 2007, Fürst and Makeschin 2009). The arrows show the duration of impact factors, processes and ecosystem reactions. Dashed lines are used when the exact start or end of impacts, ecosystem processes or visible reactions cannot be specified. (*alk. = alkaline, decr. = decreasing, div. = diversity re-nat. = re-naturalization*).

In the Dübener Heide, **cultivation of Scots pine** (*Pinus sylvestris*, L.) started in the middle of the **18th century**. In **combination with local forest pasture and litter utilization,** Scots pine cultivation resulted in **poor and monotonous Scots pine forests**, which were characterized by acidophilic soil vegetation groups (dwarf shrubs, mosses, lichens) and raw humus forms (Bendix 2001).

Due to easily available near-surface lignite resources, industrialization started already at the end of the 19th century in the immediate vicinity of Dübener Heide, but was limited at the beginning to small power plants with only local deposition effects. From the **1920s** on, an **intensification of industrial energy production** for the capital Berlin led to the yet mentioned high deposition loads.
N deposition from industry (N-factory Piesteritz) and agriculture amounted up to 300 kg N / ha * a, and was even surpassed in the 1960ies for some places by N fertilization of up to 990 kg N / ha. Fly ash was deposited along a characteristic distance and wind direction dependent gradient, whereas SO_2 and N deposition were more evenly distributed within the whole Dübener Heide (Lux 1965, Klose and Makeschin 2004).

Deposition and fertilization dependent vegetation types were observed in the Dübener Heide from the **1920 / 1950ies** on. Basophilic and light preferring species started to grow in the immediate vicinity of the former power plants. They indicated alkaline dust deposition and an artificial opening-up and die back of the Scots pine stands. Raising regional vegetation diversity and especially high species diversity near to the power plants went along with a decreasing vitality of the Scots pine stands. This process was accompanied by artificially elevated pH (KCl) values of up to 7 and a base saturation of up to 100 % in the humus layer and upper mineral horizons. Based on a visual assessment of forest decline the yet mentioned **deposition zones** were defined. They formed the basis for a **spatially differentiated ecosystem management intensity**. Due to intense forest decline, efforts to **convert the Scots pine stands** started from the **1970ies** on in the most affected deposition zones near to the power plants. These efforts were **extended** to the total area from the **1980ies** until now (Lux 1964 a and b, Kopp 2003).

From the **1980ies** on, **fly ash filters** were introduced. As unintended side effect, the still increasing acidic deposition components **NO_x, SO_2 / SO_x were no longer buffered by alkaline dusts**. Herpel et al. (1995) found for some sample plots in Dübener Heide an average decrease of pH(KCl) of 0.4 units and a base saturation decrease of 17 % for 1988 compared to the situation in the 1970s. For the period 1988 to 2000, a further reduction of 0.7 pH-units was reported by Kurbel (2002). **After 1989**, **SO_2 emission and fly ash deposition** were more or less **stopped**, whereas N deposition rates of 28 - 45 kg / ha * a from animal husbandry and traffic amplified the long-term effects of the former N-deposition and N-fertilization in terms of dense grass layers and nitrophile soil vegetation. However, N-eutrophication was balanced to a certain degree by ample ground vegetation development, improved tree growth, and vital natural regeneration of mainly noble hardwoods (Lux 1964 b). Kopp (2003) expected also a re-development of humus forms, which represent the original site potential.

Recently, **re-immigration of acid indicators and disappearance of the dense grass layers** are observed due to vanished base deposition and ongoing acidic deposition (Augustin et al. 2005). The health of the forests in Dübener Heide has improved as a result of lower industrial deposition and extensive conversion activities, but it is still threatened by increasing N deposition (Materna and Fiedler 1994).

Based on the recognition of **differing range and effects of alkaline fly ash and dissolved acidic deposition components**, Lux (1965) discussed first the **necessity to define deposition zones** (planning units with homogeneous deposition impact) around the industrial hot spots in Dübener Heide, but also in the Upper Lusatian region for an adapted forest management. Enderlein and Stein (1962), Lux and Pelz (1968) and Lux (1976) developed a sample plot based approach, where a classification of health state and growth potential in medium-aged Scots pine stands (50 – 90 a, sample plots, n ≈ 150) was used for a regionalization of deposition impact.
The **degree of single tree growth reduction and needle losses** were **aggregated plot-wise** to a **factor**, which indicated the **intensity of damage**. Based on the sample plot results (post-stratification), deposition zone-specific silvicultural management measures were derived and delivered spatial information on additional costs and economic losses caused by fly ash deposition (see e.g. Reiche 2001).

However, the **former** forest growth and decline based **definition of deposition zones cannot be used anymore** due to considerable **changes in regional forests health and species composition** since the 1960ies. However, **impacts on chemical humus and soil properties** are **still evident** (Fritz et al. 2009, Fritz and Makeschin 2007, Klose et al. 2002, Klose and Makeschin 2004, Koch et al. 2002, Koch and Makeschin 2004).

Environmental frame condition changes as described for the Dübener Heide **trigger complex ecosystem processes**. For the Dübener Heide, e.g., fly ash deposition caused a homogenization of site quality differences, and a differentiation of formerly comparable sites and vegetation types along the regional deposition gradient. These modifications are superposed by N deposition and climate change.

Consequently, forest management planning must adapt continuously to such ongoing processes. Site classification and forest inventory deliver a first basis, which however reflects only partly the ongoing processes (Schoenholtz et al. 2000; de Vries et al. 2003). **Process-oriented forest management planning** respects natural dynamics in (forest) ecosystem management on landscape level.

The development of a process-oriented forest management planning requires **three steps**:

(1) Identification of the **major forest ecosystem processes** (see Fig. 4) and the related process indicators. A suitable process indicator must be apt to describe course, direction and progress of processes (“vectored dynamics”) in forest ecosystems. Process indicators for forest soils processes are e.g.

- **(a)** C(hot water extractable (hwe) / cold water extractable (cwe)) ratio as indicator for soil organic matter (SOM) dynamics,
- **(b)** pH(H_2O / KCl) ratio as indicator for the re-acidification potential,
- **(c)** difference between current and expected humus forms as indicator for the influence of management measures on natural humus dynamics,
- **(d)** temporal and spatial changes in ferrimagnetic susceptibility in the Oe / Oa as indicator for fly ash deposition influenced humus dynamics.

(2) Process indicator based regionalization in order to derive process-oriented management units as spatial information base.

(3) Orientation of forest management planning to **process-oriented management planning units**. The economic and ecological targets of forest management are pre-defined by the forest owner (e.g., timber production, sustaining environmental quality). Process-oriented management planning units allow for a more sensitive adjustment of the type and intensity of management planning measures.

Although the delineation of process units is a general aim in landscape ecology (Haber 2005), no generalizeable approach has been developed so far, neither in environmental nor forest management. For the latter, dynamics within a planning unit and the spatial relation between different planning units under changing management concepts or the impact of local variations of environmental changes (e.g. Climate Change impact in dependence from topographical parameters) are of special interest. A better consideration of these factors would not only support a process-oriented forest management but could help to integrate forest management approaches into ecological landscape management approaches on different scale levels (Volk and Steinhard 1999).

Articles 3.1.1 – 3.1.4 focus on the deposition history in Dübener Heide and process-oriented forest management as possible management concept. Some aspects are also part of the publications in chapter 2.

Publication 3.1.1 gives the most detailed overview on the development of the forest ecosystem Dübener Heide und draws conclusions on how to integrate ongoing ecosystem processes in forest management.

Publication 3.1.2 introduces a framework of tools and methods for a process-oriented forest management.

Publication 3.1.3 includes first ideas of a possible concept for a regionalization of information on ecosystem processes as management decision basis.

Publication 3.1.4 was written at the very beginning of the research project ENFORCHANGE and focuses on the historical and actual deposition situation in Dübener Heide.

3.1.1 Fürst, C., Lorz, C., Makeschin, F. (2007): Development of forest ecosystems after heavy deposition loads considering Dübener Heide as example – challenges for a process-oriented forest management planning, SI "Meeting the challenges for process-oriented forest management" Forest Ecology and Management, 248(1-2), p. 6-16

Extended summary

This article gives an overview on the state of art, prevailing studies and existing knowledge on deposition research in Dübener Heide and draws hereon based conclusions for an improved forest management concept.

In its first part, the article reviews literature on the development of the forest ecosystem in Dübener Heide. Dübener Heide was considered as an example for comparable forest ecosystems and ecosystem processes in Central and Eastern Europe, which were driven by a dramatic change in the deposition regime, from heavily to moderately impacted by air pollution.

Main on- and off-site factors and their influence on the forest vegetation and the ecosystem processes are described for different time periods. In the following, approaches for dealing with the influence of deposition on forest management planning are introduced. Finally, a concept for integrating ongoing ecosystem processes into a process-oriented forest management is described.

Therefore, some process-sensitive indicators are identified, among them ratios of chemical site properties, humus form differences and spatial and temporal dynamic of ferrimagnetic susceptibility as physical indicator. These indicators are assumed to support a process-oriented regionalization of management relevant information and especially the formation of process-homogeneous management planning units.

The benefit of the presented approach against classic forest management planning is discussed. It is concluded that a process-oriented management approach allows for a better appraisal and consideration of future on- and off-site potentials and risks in strategic development targets and short-term management measures.

Finally, requirements for the application of the presented approach in practice and resulting research needs are derived.

3.1.2 Fürst, C., Vacik, H., Lorz, C., Makeschin, F., Podraszky, V., Janecek, V. (2007): Meeting the challenges of process-oriented forest management, SI "Meeting the challenges for process-oriented forest management" Forest Ecology and Management 248(1-2), p. 1-5

Extended summary

This article was written as editorial of the special issue “Meeting the challenges for process-oriented forest management” and discusses the question of a better integration of processes into forest management in the light of the actual development and research.

The article gives an overview on the drivers of the development of forest management approaches and summarizes and discusses the contributions of the special issue considering four thematic blocks – (1) background and consequences for a dynamic development of natural systems, (2) regional frame conditions and development of adapted assessment and evaluation approaches, (3) integration of natural processes in modeling and forest management concepts, and (4) tools for supporting cognitive processes and decision making and for transferring information to heterogeneous end-user groups.

The article concludes that a process-oriented management demands a sound and mature knowledge base on ecosystem functioning with regard to reactions on multiple changing conditions from climate change and changing off-site impact from industrial land use towards changing forest management measures and their interrelations.

A network of tools, methods and models is proposed, which facilitates cognitive processes for the change from a static view of forest ecosystems to a process-determined perception and decision making. The specific role of indicators such as ferrimagnetic susceptibility in this network is to form the base for indicator based (process) models, simulators and up-scaling approaches. These are used to describe the joint temporal and spatial development of forest ecosystems.

3.1.3 Fürst, C., Lorz, C., Abiy, M., Makeschin, F. (2006): Fly ash deposition in Northeastern Germany and consequences for forest management, Contributions to Forest Sciences, Ulmer, p. 50-63

Extended summary

The article is part of the book “Future-oriented Concepts, Tools and Methods for Forest Management and Forest Research Crossing European Borders”.

The presented analysis of the state of the art and the hereon based conclusions for forest management and regionalization of management relevant information stood at the very beginning of the project ENFORCHANGE. The paper introduces some aspects of the history of fly ash deposition in Dübener Heide based on prevailing research, where e.g. Zschornewitz was still considered to be the major regional fly ash emitter and the existence of the deposition zones was assumed to be valid.

Some effects of fly ash deposition on the forest ecosystem Dübener Heide are presented under special consideration of forest growth and soil vegetation. Regarding the consequences for forest management, some silvicultural findings from earlier research are discussed and a first stepwise approach for upscaling the investigations in ENFORCHANGE is derived. Finally, possible potentials of a regionalization of ongoing ecosystem processes are discussed.

3.1.4 Fürst, C., Abiy, M., Makeschin, F. (2005): Reaction of forest systems in the industrial triangle Leipzig-Halle-Bitterfeld on a changing immission regime – state of the art, in: Neuhöferovà, P. (ed.) Restoration of Forest Ecosystems of the Jizerske Hory Mountains, Czech University of Agriculture Prague, p. 67-72

Extended summary

The publication was written on the basis of a presentation of the ENFORCHANGE study at the conference "Restoration of Forest Ecosystems of the Jizerske Hory Mountains".

The historical and actual deposition situations in Dübener Heide are compared. The article assumes the deposition gradient described by e.g. by Lux (1965) to be valid and describes the spatial differentiation of different deposition components: in previous studies, a decreasing influence of fly ash and S along the distance dependent gradient was observed, starting at the former power plants at the Southwestern border of Dübener Heide. Considering N-deposition, overlapping gradients with irregular peaks for N were observed.

As a result, also the impact of deposition on the site potentials and risks experienced a spatial stratification, which is relevant for the silvicultural responses. Based on former findings of Lux and Stein (1977) and Nebe et al. (2001) the necessity of a conversion with deciduous tree species is concluded, despite the stated spatial stratification of site potentials and risks was not yet considered in the here presented conclusions.

As a consequence, the regionalization of ecosystem processes is identified as challenge for a better support of silvicultural management decisions.

4. Material and Methods

4.1 Fly ash properties and fly ash impact on forest ecosystems

The **average geo-chemical composition of fly ash** varies depending on **basic material properties** (lignite or coal) and its **origin**. Lignite-derived fly ash from the industrial triangle Leipzig-Halle-Bitterfeld e.g., consisted in av. 26% SO_3, 20% CaO, 18% SiO_2, AlO_3, FeO_3, MgO, TiO_2, Na_2O, K_2O, heavy metals, and „black“ (tertiary) carbon (Neumeister et al. 1991, Peklo and Niehus 1993, Magiera and Strzyszcz 2000, Klose and Makeschin 2003, Fürst and Makeschin 2006; for details see Tab. 1).

Tab. 1: Composition of lignite derived fly ash in the model region (acc. to Neumeister et al. 1991, Peklo and Niehus 1993, Thomasius et al. 1998, Fürst and Makeschin 2006).

molecular deposition components (w- %)								**heavy metals (mg/kg)**			
SO_3	CaO	MgO	K_2O	Fe_2O_3	Al_2O_3	SiO_2	$C_{org.}$	Cd	Cu	Pb	Zn
13-26	15-20	1.5-3	0.1-1	4-10	3-8	10-18	5-20	3-8	140-230	50-100	130-250

means of the total deposition for the example Dübener Heide (kg/ha*a)															
Na	K	Ca	Mg	Fe	Mn	Cu	Pb	Cd	Zn	F	Cl	N	S	P	Ca /S
15.7	8.3	320	36.5	125	1.1	1.4	1.0	0.1	2.3	9.8	54	38	190	0.3	1.7

Typical impacts of **fly ash deposition on forest sites** are wider C : N and C : P ratios as well as an additional input of S and base cations. In the long run, fly ash accumulation leads to an improvement of site quality, particularly for nutrition capacity of naturally poor sites (sandy soils). An **increase of the site index up to two levels** and an **enhancement of the eligible tree species spectrum** are reported by Kopp and Schwanecke (2003) and Thomasius et al. (1998). Amarell (1997), Heinsdorf et al. (1994) and Thomasius et al. (1998) describe a drift of ground vegetation composition towards nitrophile and eutrophic species. An ample tree growth and an exuberant development of ground vegetation were and still observed in the Western parts of Dübener Heide (Lux 1964 b, Amarell 1997, Thomasius et al. 1998).

Another effect, which is still observed, is the **modification of humus form and an abnormal thickness of humus layers**, which influences the water retention capacity and nutrient supply (Thomasius et al. 1998, Hartmann et al. 2008 and 2009). This modification is going along with an augmentation of mineral particle content that exceeds the threshold of 30 %, which distinguishes the humus layer from the mineral top soil (Klose et al. 2001, 2002 and 2003, Klose and Makeschin 2004, Koch et al. 2002). In previous studies, fly ash impacted humus forms were assumed to be characterized by an elevated hydrophobicity, which can hinder the water percolation into mineral soil (Katzur et al. 1998, Thomasius et al. 1998). However, most recent results show that **fly ash** can **decrease** at least **partially the hydrophobicity of humus layers** and leads to **higher air capacities** in the humus layers and **lower available water capacities** (Hartmann et al. 2008 and 2009). Fly ash, which is shifted in the upper mineral soil, can induce **faster percolation of rainfall** due to its specific physical properties (Taubner and Horn 1998). This process can accelerate humus layer dehydration and amplify disturbance of water balance in humus layer (Dekker and Ritsema 2003, Zikeli et al. 2002).

Fly ash deposition **increases the Al, Fe, and heavy metal content** in forest ecosystems (Strzyszcz 1999, Strzyszcz and Magiera 1998 and 2001). Trüby (2003) reported a considerable uptake of heavy metals up to 120 µg Pb / g (dw (dry weight)) for 120 years old conifers, which seemed not to affect tree growth and vitality.
However, heavy metal deposition might also cause a **disturbance of litter decomposition** and can provoke the before described development of **adverse humus forms** (Klose et al. 2003, Magiera et al. 2002 a, Strzyszcz 1999, Strzyszcz and Magiera 1998). Results from wood ash research suggest that heavy metals might remain in the humus layers and the humous upper mineral soil (Bramryd and Fransman 1995, Fritze et al. 1994). The accumulated heavy metals might be mobilized by re-acidification, which is accelerated by N-deposition and the lack of (former) base deposition (Klose et al. 2003, Koch et al. 2002).

The development of the adverse humus forms might also have other reasons: Klose et al. (2003) and Klose and Makeschin (2004) e.g., described **impeding effects** of lignite derived fly ash **on microbial activity**. Also "**Black Carbon**", another component of the fly ash deposition, seems to play a key role in **hindering organic matter decomposition** (Goldberg 1985). The possible role of macromolecular organic pollutants (PCB, PAH), which play e.g. an important role for evaluating wood ash effects, is not yet clear for fly ash deposition.

From **silvicultural point of view**, the influence of fly ash deposition on humus provokes **antithetic effects.** The observed intensification of fine root growth in ash-dominated humus layers together with better availability of base cations improves tree nutrition. On the other hand, the resulting tendency of shallow root systems leads to higher wind throw probability and drought susceptibility (Klose et al. 2003, Koch et al. 2002, Thomasius et al. 1998). Lux (1976) highlightens a particular endangering of functional stability of Scots pine dominated forest systems by the elevated pH-values and base saturation, since fly ash deposition cannot be managed in a site-adapted dosage and thus provokes **additional costs** and

economic losses. Stracke (1996) concludes the necessity of a conversion with hardwood, which increases the expenses for stand establishment and regeneration and decreases economic profit due unfavorable assortments. Economic losses might also result from shortening of the rotation period, which results from fly ash induced stability risks.

Fly ash deposition demands for an **adapted site classification system** in dependence from original site quality and possible on- and off-site effects (Kallweit 1990, Klose et al. 2003, Thomasius et al. 1998, Koch and Makeschin 2004, Makeschin et al. 2004, Zhong and Makeschin 2003 a, b and 2004). A **conversion with broadleaves** (European beech or noble hardwoods) was proposed by Lux and Stein (1977), Thomasius et al. (1998) and Nebe et al. (2001). Broadleaves make better use of the high nutrient potential and can contribute to a stabilization of nutrient balance. Nowadays, the demanded conversion is realized by natural processes, but an **ample natural regeneration with noble hardwoods and European beech** raises the question how to continue with these new stand types.

The following article introduces in detail the properties and risks of fly ash compared to wood ash and rock powder as fertilizers.

4.1.1 Fürst, C., Makeschin, F. (2006): Comparison of Wood Ash, Rock Powder, and Fly Ash – a review, Contributions to Forest Sciences, Ulmer, p. 63-81

Extended summary

The literature review was part of the proceedings “Future-oriented Concepts, Tools and Methods for Forest Management and Forest Research Crossing European Borders and compares the properties of wood ash, rock powder and fly ash regarding their fertilizing effects and risks for forest soils.

Considering fly ash, the average chemical composition in Dübener Heide based on findings from Neumeister et al. (1991), Peklo and Niehus (1993), Thomasius et al. (1998) is presented and the resulting impact on the site potential and possible trade-offs for drinking water quality are discussed.

Recommendations for the application and right use of wood ash and rock powder, and the possible reactions of forest ecosystems on fly ash deposition are given. The application fields of wood ash and rock powder were considered as complementary. Wood ash was recommended to be used on sites with naturally higher organic matter. Rock powder was highlightened to be able to improve the properties of poor (sandy) soils with low organic matter content. Fly ash deposition was considered as a kind of long-term fertilizing experiment for forest soils with some parallels to wood ash fertilization. It was shown that wood ash fertilized and fly ash affected soils experienced the most obvious effects in the Oe and Oa horizon induced by a long-lasting decomposition with litter fall on ash residuals and a slow move of the only partly-decomposed matter to the Oa. The article concludes that fly ash impacted forest soils demand for a careful monitoring considering the turnover rate of the organic matter and the possible eluviation of toxic elements.

Finally, a decision tree is proposed how to handle wood ash and rock powder fertilization and how to integrate “fly ash fertilization” in forest management practice.

4.2 Assessment of fly ash deposition with ferrimagnetic susceptibility

The **magnetic susceptibility** χ is defined as difference between the relative magnetic permeability μ and 1 (μ - 1). It can be used to **express** approximately the **concentration of magnetic particles in** the **soils** (Thomson and Oldfield 1986).

According to their magnetic properties, materials can be divided into **diamagnetic, paramagnetic, ferrimagnetic, and ferromagnetic substances** (Glaser 2001). The **detection of lignite derived fly ash** by magnetic susceptibility is based on its content of **ferrimagnetic iron oxides**, such as magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3), which are natural components of lignite (magnetite) or can be the result of pyrite (FeS_2) oxidation (magnetite and maghemite) and a successive enrichment of the ferrimagnetic oxides during the combustion process (Katzur et al. 1998, Magiera and Strzyszcz 2000, Strzyszcz et al. 1996, Strzyszcz 1999).

In a number of studies, the **indicator magnetic susceptibility** was tested and found suitable as **proxy for fly ash deposition** (Boyko et al. 2004, Grimley et al. 2004, Magiera et al. 2007, Magiera and Zawadzki 2007, Magiera and Strzyszcz 2000, Schibler et al. 2002, Strzyszcz and Magiera 1998).
As proved by previous studies, the **detection method is most suitable for areas with a strong impact of industrial emissions**, since a natural enrichment of magnetic substances as result of geochemical processes and activity of micro organism in humus layers is also reported from non-industrial areas and might blur the effect of minor fly ash deposition (Faßbinder 1994, de Jong et al. 2005, Le Borgne 1955, Magiera and Strzyszcz 2000, Scollar 1965, Thompson and Oldfield 1986).

The **magnetic signal** might be **correlated with Fe, Al, Mn and heavy metals** (Lu and Bai 2006, Goluchowska 2001, Magiera and Zawadzki 2007, Wang and Qin 2005, Zawadzki et al. 2009) and to some extent also with **base cations** and **Black Carbon** (see chapter 5.2.1). A restriction is that these **correlations cannot easily be transferred from one region to another** as they depend from geographical origin and type of the combustion material. Also the **land use type** and even the **forest type** itself can **impact the correlation** (Fialova et al. 2006, Magiera and Zawadzki 2007, Strzyszcz and Magiera 1998). In consequence, the impact of different environmental parameters on the magnetic signal should be considered in the regionalization approach (see chapter 5.1.1).

For the assessment of the ferrimagnetic susceptibility, two basically different designs were used in the studies 4.2.1, 5.1.1 and 5.2.1 (Fig. 5, Tab. 2).

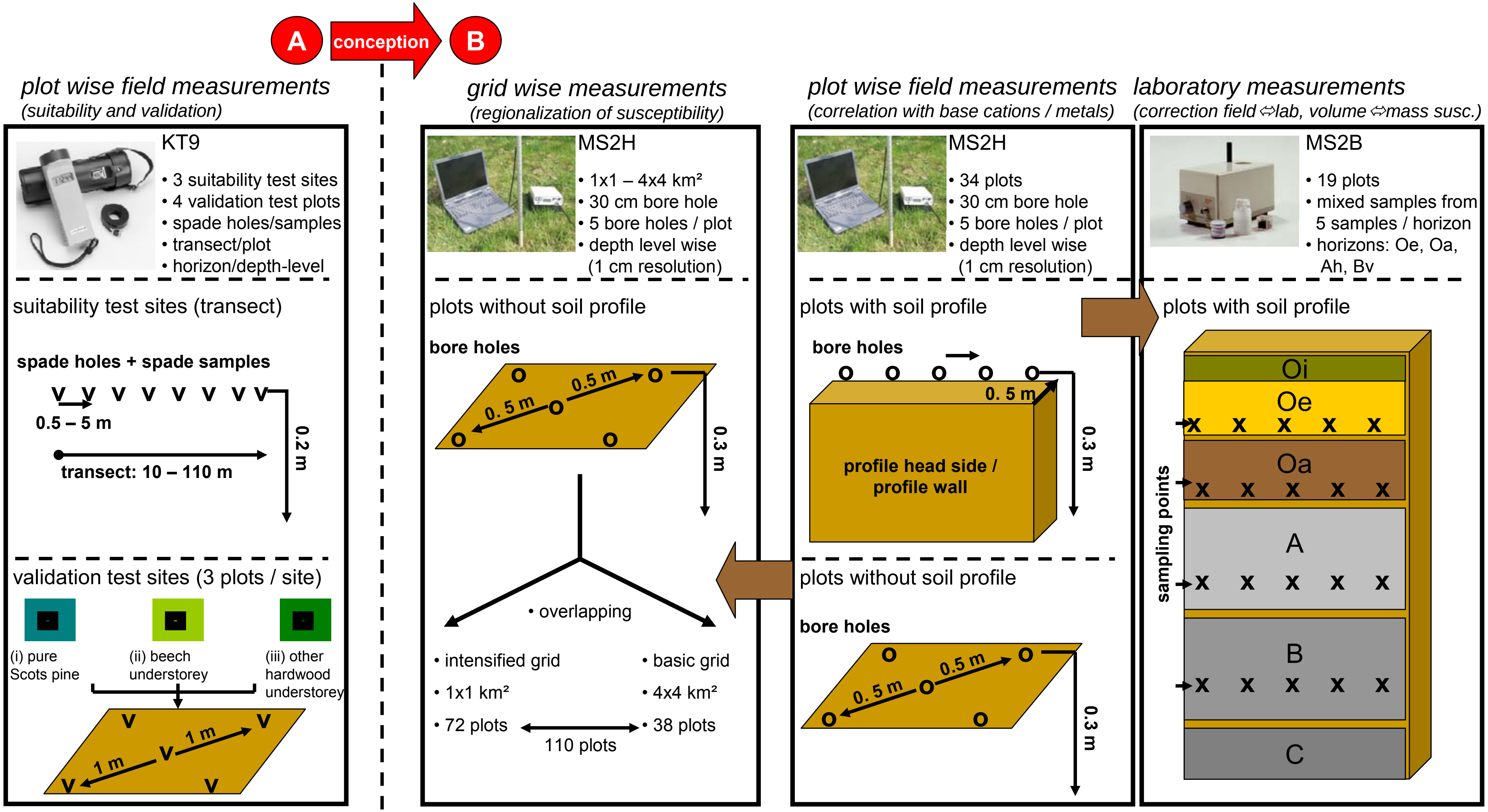


Fig. 5: Overview on the different test designs. The results from the pre-study **(A)** formed the basis for the large-scale assessment **(B)**.

Tab. 2: Overview on the sampling design at the different test plots of the pre-study and the hereon up-building regionalization study.

A / B	A. pre-study		B. regionalization	
	suitability	*validation*	*4x4 km²*	*1x1 km²*
number of plots	3 plots	4 plots	38 plots	72 plots
plot design	a) Burgkemnitz and Tornau: 10 m long transect, 1 spade sample each 0.5 m b) Pretzsch: 110 m long transect, 1 spade sample each 5 m	3 test sites per test plot five bore holes / test site (1 central bore hole, 4 satellite bore holes)	5 bore holes / test plot (a) along the head side of existing profiles or (b) 1 central bore hole, 4 satellite bore holes if no profile was opened up	
measurement design	20 cm deep spade samples, measurements in the spade holes and at the spade samples, each measurement with three repetitions		30 cm deep bore holes, 1 measurement per cm depth directly in the bore holes	
localization measurements	a) depth level wise (1, 2, 5, 10, 20 cm) b) horizon wise (Oe, Oa, A(a), B(w))	horizon wise (Oe, Oa, A(a), B(w))	depth level-wise (1 cm = 1 depth level)	
number of measurements / test plot *	a) 660 b) 528	360	150	150

* For more details see publications 4.2.1, 5.1.1 and 5.2.1.

A. In the frame of a **pre-study on the suitability of the method** including a **validation of the results**, a **portable magnetic susceptibility meter** (KT-9, © Terraplus) was used. The KT-9 is conceived for detecting very low quantities of magnetic Fe-Oxides in compact (rocks) or loose substrates (mineral soil, humus layer). The instrument measures spot wise the volume magnetic susceptibility as sum value up to a depth of 0.5 – 2.0 cm starting from the surface of the measured substrate. The susceptibility meter has a sensitivity of 1×10^{-5} S.I. units and can be used either in a single readout mode or in a continuous (scanning) readout mode.

For testing the **suitability of the field magnetic susceptibility measurements**, three test plots were selected (Fig. 5, Tab. 2), where different deposition levels have been found previously (Klose and Makeschin 2005). The magnetic susceptibility signal was measured **depth-level and horizon wise** at spade samples and in remaining spade holes. In Dübener Heide, extensive disturbances by wild boar were observed during the studies and complicated the differentiation between Oe and Oa and also between humus layer and the upper mineral horizon. Therefore, the measurements of the suitability test were established along transect with a length of 10 m or 110 m and with a distance between each single sampling point of 0.5 m (10 m transects) or 5 m (110 m transect) to achieve information on the relevance and dimension of the influence of variable micro site conditions, including bioturbation and natural variability of humus layer thickness.

For **testing if the historically documented deposition gradient and the deposition zones can be detected by magnetic field measurements**, four test plots were selected. Each test plot represents a specific deposition zone according to Lux (1965) and Lux and Stein (1977), respectively (Fig. 6). Magnetic susceptibility was measured **horizon wise** with the KT-9 and again at spade samples and in remaining spade hole. At each of the validation test plots, three test sites were established, which represented different situations of stand composition. At each test site, five spade samples were collected, where four spade samples were satellites in a distance of 1 m around one central spade hole.

The results of this pre-study were used as basis for the grid- and plot-wise measurements for the regionalization and the correlation with base cations and heavy metals.

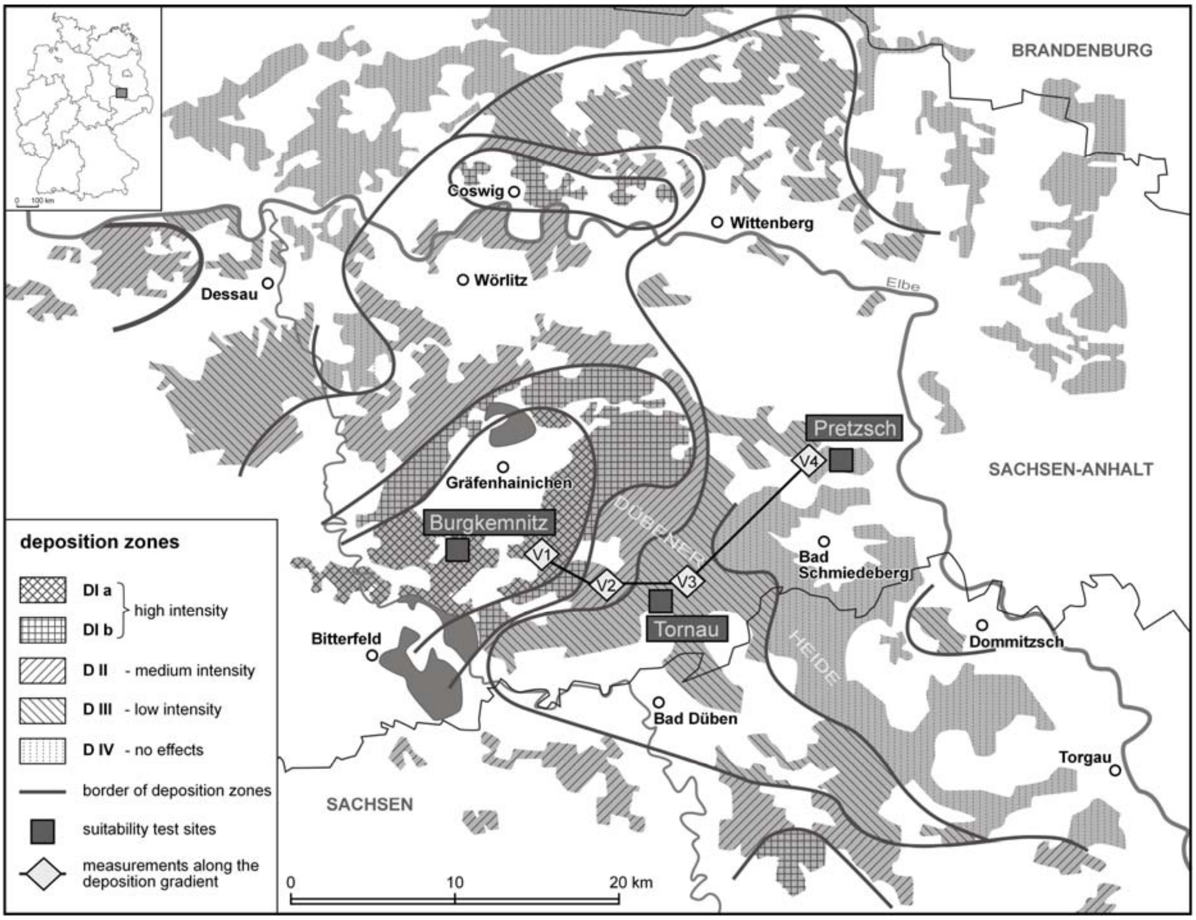


Fig. 6: Localization of the plots in the pre-study in relation to the deposition zones according to Lux 1965, and Lux and Stein 1977. The plots Burgkemnitz, Tornau and Pretzsch were established to test in detail the suitability of field magnetic susceptibility measurements. The plots V1 - V2 were used in a second step to validate the method (Fürst et al. 2009 a).

B. For **spatial transfer** and **correlation of the magnetic signal (mass susceptibility) with contents of base cations, acid and heavy metal cations and Black Carbon**, magnetic susceptibility field assessment was carried out in a 4x4 km² grid (38 plots) and a 1x1 km² grid (72 plots) (Fig. 7). Both grids were overlapping (nested approach). The grid-wise measurements were done to map with sufficiently high resolution the spatial variation of magnetic susceptibility and to test if the formerly observed distant dependent fly ash deposition gradient can be validated. The 4x4 km² basic grid allowed for linking the magnetic susceptibility measurements to chemical soil data from Level-I monitoring. The 1x1 km² grid intensified the information depth for the regionalization of magnetic susceptibility.

Magnetic susceptibility was measured with the **MS2 meter susceptibility system of Bartington Instruments**. The system is developed for detecting very low quantities of magnetic Fe-Oxides in compact (rocks) or loose substrates (mineral soil, humus layer). The susceptibility meter has a sensitivity of 0.1 - 1 × 10^{-5} SI units and can be used in a single readout mode or transfers the measured values to a PC, where the data can be processed with the software Multisus (© Bartington).
The Multisus program is using the Windows 3.1 or Windows 95/NT interface to record the magnetic susceptibility measurements of different field assessment sensors. The program allows for saving as file the results from a batch of individual samples or from a core. For single samples the results can be volume or mass specific and provision is made for automatic increments of depth for core measurements (source: Operation Manual of Multisus 2.0, Bartington Instruments Ltd.).
The MS2 meter susceptibility system comprises a portable measuring instrument, the MS2 meter, and a variety of sensors. The meter displays the magnetic susceptibility value of the tested substrates when these are brought within the influence of one of the sensors, which are each designed for a specific application and sample type (source: Operation Manual of the MS2 system, Bartington Instruments Ltd.).

At the **field assessment**, **volume magnetic susceptibility** was measured centimeter wise in 30 cm deep boreholes with the MS2H down-hole-probe sensor. The MS2H is a subsurface probe for profiling the magnetic susceptibility of zones in 25 mm nominal diameter auger holes. Zones with a thickness down to 15 mm can be discriminated. The starting point 1 of the measurements was defined as first measurement after removing the litter (Oi). The Oi was removed, as the pre-study has shown that fly ash particles could never be detected in this layer.

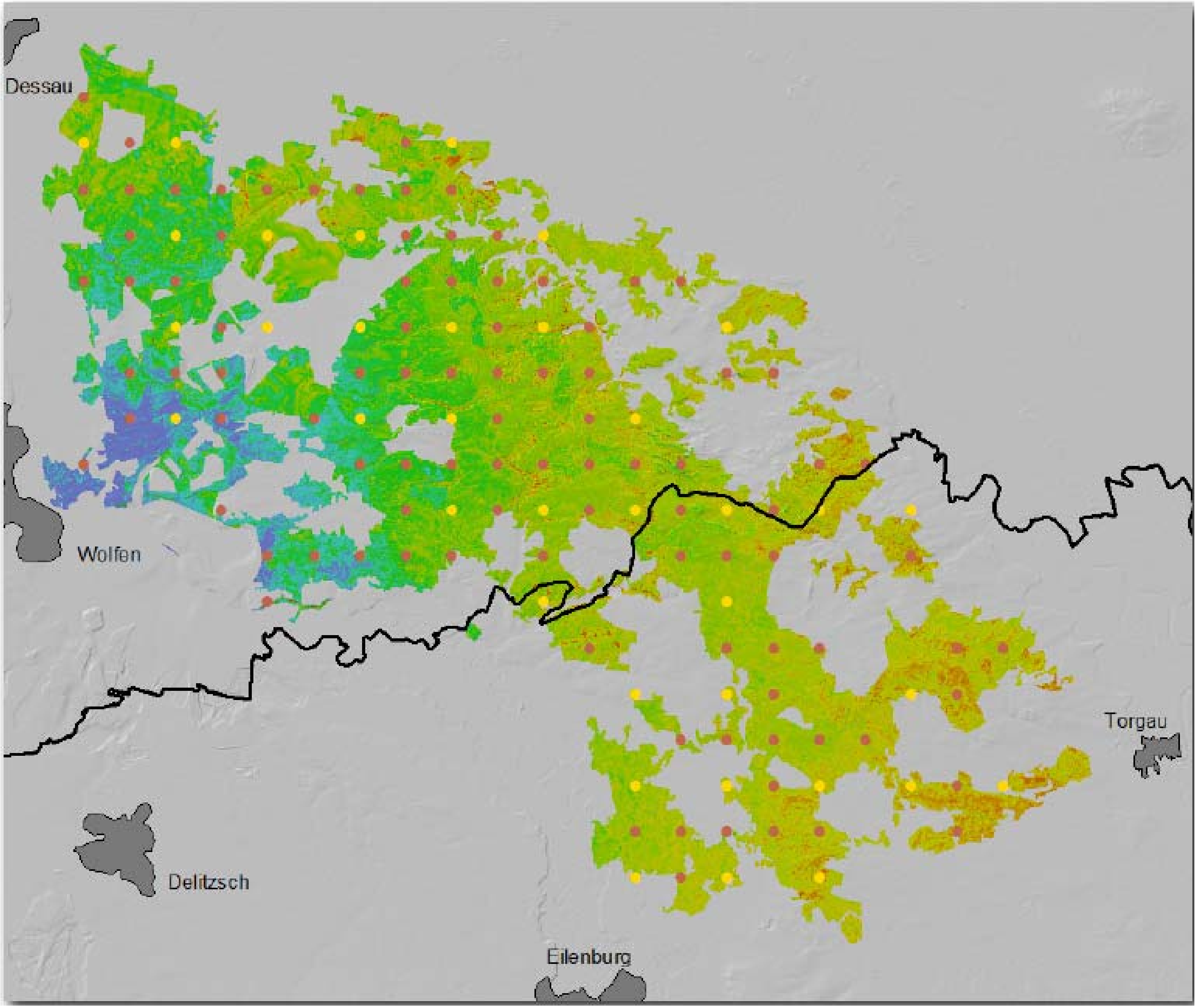


Fig. 7: Grid-wise magnetic susceptibility mapping. The yellow dots belong to the basic 4x4 km² grid, which was identical with the plots of the EU-Level I grid. The orange dots belong to the high-resolution 1x1 km² grid.

For the **regionalization of magnetic susceptibility**, **mean values** of measurements at **three depth levels** were used:

Depth level 6–10 cm represents the zone in the **humus layer**, where in average, the highest magnetic susceptibility values were observed (see also Fig. 8). For this zone, biased measurements can be excluded which can occur at the interface between airspace and humus layer (depth level 0 - 5 cm) due to technical particularities of the sensor. Also, the likelihood of an impact of admixed particles from the mineral soil is low.

Depth level 11–15 cm is situated in the **transition zone between humus layer and upper mineral horizon**, which is characterized by great local variability of humus content in mineral soil and vice versa due to bioturbation caused by wild boars. In most cases, a distinct and sharp border between humus layer and upper mineral soil does not exist. In this zone, an increased magnetic susceptibility is observed.

Depth level 21–25 cm represents the local background value spectrum for the **mineral horizon** as reference for the height of the magnetic susceptibility signal. At the same time, a possible falsification of the measurements due to organic material, which can drop down into the bore hole when taking out the auger, can more or less be excluded in this zone.

To allow for a **correlation between magnetic susceptibility and contents of key base cations, acid and heavy metal cations and Black Carbon**, additional **laboratory magnetic susceptibility measurements** were carried out. The aim was to adjust and correct the field assessments and to calculate a **correction factor** for **field and laboratory assessed volume magnetic susceptibility** and to **calculate** on this basis **mass susceptibility**.

The **corrected values of the magnetic signal** were **correlated with results of chemical analysis** at several plot types.

A. **ENFORCHANGE plots**: a subset of 12 plots origins from the research project ENFORCHANGE. The plots were situated on the most important regional soil type (Eutric Cambisols) to minimize the influence of variable soil properties on the assessed chemical characteristics and the magnetic susceptibility. The influence of different stand types (pure Scots pine stands and mixed stands with English oak and European beech), which are situated at the plots could not totally be excluded (Zawadzki et al. 2007).

Only at the ENFORCHANGE plots it was possible to assess chemical parameters and magnetic susceptibility at identical sampling spots and soil samples. Magnetic susceptibility was first assessed in situ (volume magnetic susceptibility) at the soil profiles exactly at the location where the soil samples were taken. For deriving a correction factor for the in situ measurements, the soil samples, which were also used for the chemical analyses, were measured in the laboratory (volume and mass susceptibility).

In consequence, the plot collective delivered the most proper basis for correlating the content of Ca, Mg, Fe, Al, Mn, Cd and Black Carbon with the magnetic susceptibility. A restriction for statistical analysis was the limited number of plots, which was predefined by the project frame. Furthermore, no reference plots in a non fly ash impacted region such as Dahlener Heide were included in the ENFORCHANGE study.

To widen the data basis for spatial trend analysis, plot collective B was included in the study.

B. **Monitoring plots:** 20 plots from Level-I monitoring and two other plots from a prevailing study were included. The precondition for their selection was the availability of soil chemical data, which were assessed according to the same standard as at the ENFORCHANGE plots. The Level-I plots belong to a European wide network of 6,000 soil monitoring plots for the assessment of long range transboundary air pollution with regular assessment of soil chemical values each five years. The two other monitoring plots were part of a habilitation thesis (Lorz 2008) and were chosen to have a broader data base in Dahlener Heide.

The chemical parameters and the field assessment of the magnetic susceptibility (volume magnetic susceptibility) were done at the same plot, but the sampling spots and soil samples were not identical. The chemical analyses were done up to five years earlier than the presented magnetic susceptibility assessment and the soil samples were not anymore available.

Furthermore, magnetic susceptibility was correlated with regionalized values of the base saturation from the ENFORCHANGE and Level-I plots. This was done to get further information on the spatial variance of magnetic susceptibility in dependence from the distance to the fly ash emitters.

Publication 4.2.1 introduces the pre-study in Dübener Heide as first approach to develop and test magnetic susceptibility field measurements as method for the following mapping of fly ash deposition. The hereon based grid-wise assessment and correlation with base cations and heavy metals is integrated into the results section (chapter 5), because there, major results were derived.
The methodology for the regionalization study however was yet presented in short in this section to give a better overview on the differences in the applied test designs.

4.2.1 Fürst, C., Lorz, C., Makeschin, F. (2009): Testing a soil magnetometry technique in a highly polluted industrial region in Northeastern Germany, Water, Air, and Soil Pollution, 202, p. 33-43, DOI: 10.1007/s11270-008-9956-9

Extended summary

The article focuses on a test of the suitability of ferrimagnetic susceptibility field assessment for assessing historical fly ash deposition in Dübener Heide and for verifying the deposition zones, which were originally defined by Lux (1965).

In this pre-study a hand-held, the KT-9, was used, which implies some restrictions for the methodological approach and the hereon based conclusions: the penetration depth of the magnetic signal is limited to maximally 2 cm and the flashlight-like design of the hand-held with a central sensor makes it difficult to assess the magnetic signal at a specific depth (point) at a profile. Therefore, a depth level-wise assessment and a horizon wise assessment of the magnetic signal were compared and in this case using this specific technology, the horizon wise assessment showed better results.

Despite these problems, the measurements supported the verification of the four historically documented deposition zones. Apart from the measured susceptibility values (mean values), also some statistical characteristics, such as standard deviation and coefficient of variation were proved to be applicable to distinguish the former deposition zones.

The article concluded some weaknesses of the pre-study, which were picked-up later on in the grid-wise assessment of ferrimagnetic susceptibility for the regionalization of fly ash deposition: the KT-9 is designed for assessing volume magnetic susceptibility, which does not allow directly for a calculation of the deposited fly ash amounts. Therefore, parallel assessment of mass susceptibility under laboratory conditions is demanded to derive a correction factor.

Furthermore, it was not possible to get information on the natural level of magnetic susceptibility in the humus layers, when restricting the assessment to Dübener Heide. As a consequence, the measurements were extended later on to Dahlener Heide, where no fly ash deposition was recorded in the past (see chapter 5.2.1).

5. Results

5.1 Regionalization of fly ash deposition based on ferrimagnetic susceptibility measurements

The **pre-study proved the suitability of ferrimagnetic susceptibility field measurements** to detect different levels of fly ash deposition. The deposition zones described first by Lux (1965) could be verified with this method. Although, the approach had still some weaknesses, such as the use of volume magnetic susceptibility and the related problems to correlate the magnetic signal with contents of base cations or heavy metals. This was considered later on (chapter 5.2) be deducing a correction factor from field assessed volume magnetic susceptibility to mass susceptibility.

The aim of the **regionalization** was among others to **explain the spatial variation of the response variable magnetic susceptibility by auxiliary variables**, which are characterized by a pertinent correlation with the response variable (Zirlewagen and von Wilpert 2004) and which are available in digital form. Examples for auxiliary variables are the horizontal distance to former emitters, relief attributes, pedo-geological attributes (substrate / soil type), and stand attributes. For instance, the horizontal distance to emitters explains gradual differences in the magnetic signal along the deposition gradient. Topographical height and exposure give information on deposition intensity. Digital relief parameters, which describe convex or concave orography, can explain hydrological soil and site properties and support also the prediction of the response variable magnetic susceptibility (Zirlewagen and von Wilpert 2004). The soil type gives information on the water regime and matter dynamics and thus indicates for how long fly ash is stored in humus layers. Stand properties such as tree species composition, height, density etc., contain information on the efficiency of combing out of dust particles and – in coherence with the soil type – which humus dynamics can be expected. A pre-selection of auxiliary variables was based on experiences with the regionalization of soil chemical values in the federal state of Saxony (Zirlewagen et al. 2006, 2007).

The observed **magnetic susceptibility values from the field assessment** (volume susceptibility) ranged in the **humus layers** from **0 up to 565 SI units×10^{-5}**. Calculated as **mass susceptibility**, **single outliers** reached values of **up to 800 χ * 10^{-8} m³ kg^{-1}**.
In comparison, the regional background values, which were observed at the **C(w) horizons** at the ENFORCHANGE plots (profiles) vary between **0** (Podzol) and **10 – 20 SI units×10^{-5}** (Eutric Cambisols). Calculated as mass susceptibility, values of **3 - 30 χ * 10^{-8} m³ kg^{-1}** were found.

Considering the **spatial variability of magnetic susceptibility**, the **highest single values** were observed at the **Western part of Dübener Heide**, which was situated nearest and in the major regional wind direction to the former power plants. Here however, also the broadest variability of the measured values was observed, which is supported by results of the pre-study (Fürst et al. 2009 a). The **lowest values and the lowest variability** were observed in the **Northeastern part of Dübener Heide**, which is situated farthest from the power plants.

Within the **bore holes** (Fig. 8), the **highest mean values** were achieved **in the humus layers**, in a **depth of 8 and 9 cm**. The **highest variability of the measured values** was observed in a **depth from 10 to 12 cm**. The **lowest mean values** and the **lowest variability** were found in the **upper humus layer from 1 to 4 cm depth** and in the **mineral horizon from 22 cm depth on**.

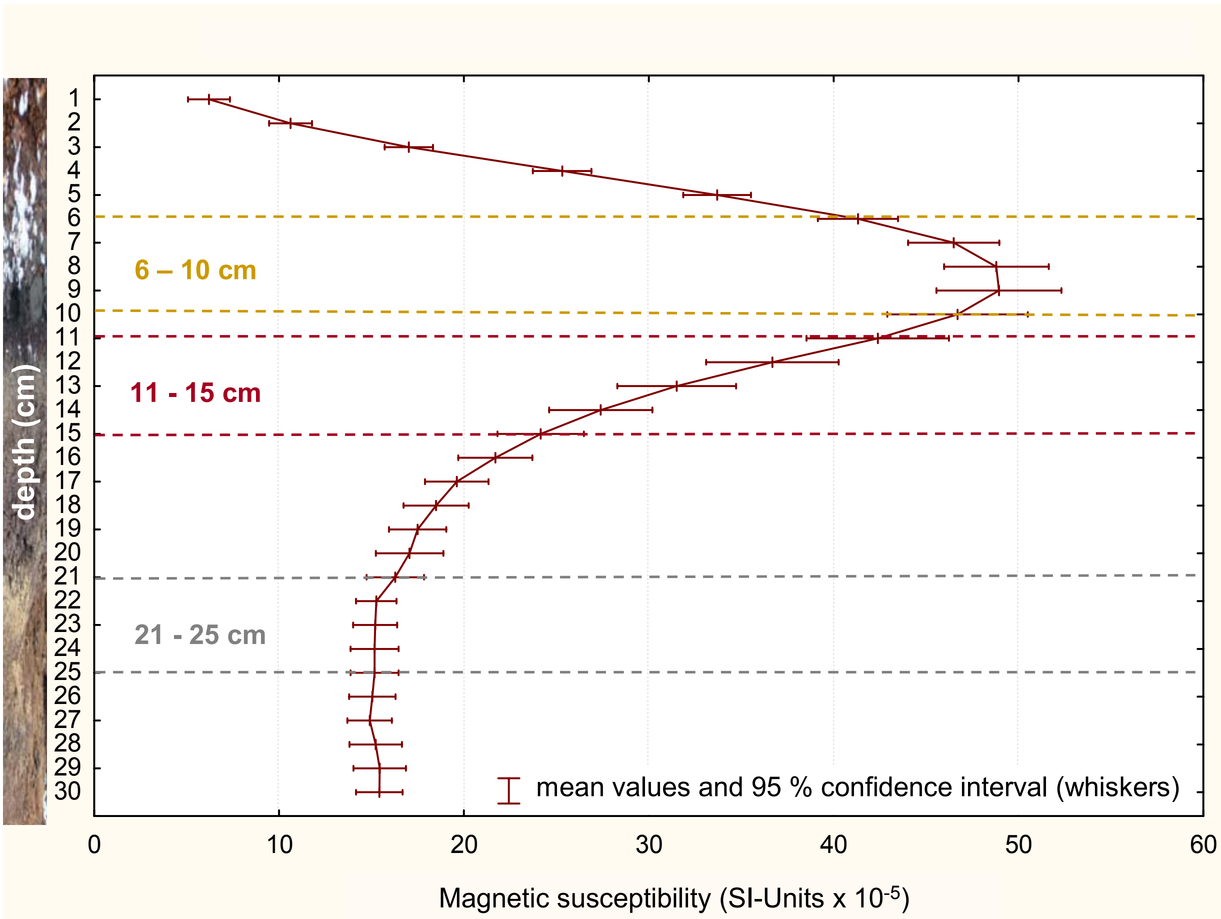


Fig. 8: Magnetic susceptibility (volume susceptibility) mean values (SI-Units x 10 $^{-5}$) and variability expressed by the 95 % confidence interval from 0 – 30 cm depth. Number of test plots: 110 (Fürst et al 2009 b).

These findings and the necessity to correlate the magnetic signal with depth level-wise assessed chemical characteristics according to the EU Level-I monitoring standard, were the reason to **focus** in the following on the results on the three different depth levels described in chapter 4.2:
depth level 6-10 cm where standard deviation and coefficient of variation were lower compared to **depth level 11-15 cm**. At depth level 11-15 cm, the value range was highest and high standard deviation and coefficient of variation express the heterogeneity of this depth level. **Depth level 21-25 cm** was characterized by low standard deviation, which expresses a lower variability of the measured values, despite some outliers, which lead to a higher coefficient of variation than in depth level 6–10 cm.

As basis for the **spatial model**, a **total of 21 auxiliary variables** was identified in a **stepwise selection process** (see 5.1.1), which includes a global modeling approach for the whole area of Dübener Heide and a stratified modeling approach for the near distance zone up to 25 km.
The **application and explanatory value of each variable varied for the different depth levels**, going along with specific characteristics of each depth level, and varies also between global model and stratified model. The validation of the model parameters helped to exclude depth level-wise variables, which do not contribute to a higher model quality or to include additional variables. Some variables, such as the logarithmic distance to Bitterfeld and the stream power index, showed for almost all depth levels and for global and stratified model a high explanatory value. In contrast, the logarithmic distance to Zschornewitz was not significant and has to be rejected as major parameter for fly ash deposition. Neither for the global nor for the stratified model a stable correlation was found.
Contradictory to research hypothesis (1) of the ENFORCHANGE study, the statistical analysis of the grid-wise assessed ferrimagnetic susceptibility revealed that **deposition from the power plants in Bitterfeld reached much farther compared to the deposition from Zschornewitz**, which had only a very restricted local impact. The impact of the Bitterfeld power plants was most evident for depth levels 6-10 cm and 11-15 cm. The maximum distance for detectable fly ash deposition is 40 km. Up to a distance of 10 km, the impact was even detectable in the depth layer 21-25 cm. For the Zschornewitz power plant, only minor impacts were detected up to a maximum distance of 10 km for the depth levels 6-10 and 11-15 cm, while the impact on the depth level 21-15 cm was almost not quantifiable.

The **spatial variation of magnetic susceptibility** was **predicted with high precision by a multiple linear regression model**. The use of a slightly differing set of model parameters for the different depth levels according to their explanatory value improved the prediction quality considerably and supported also the understanding of major drivers for magnetic particle deposition, storage, and vertical displacement in the forest soils.

For **the humus layer** (**depth level 6-11 cm**), the **horizontal distance to Bitterfeld** and **soil type** (Podzol, semi-terrestrial sites) were the **most important variables**. They indicate slowed-down humus dynamics, which supports the accumulation of fly ash in the humus layer.

For the **depth level 11-15 cm**, variables gain in importance, which describe the **exposure (aspect) to major wind direction** and thus indicate the probability of deposition.

For the **mineral horizon** (**depth level 21-25 cm**), **aspect** and especially **stand properties** are **most important**. The latter give indication of the intensity of deposition driven by the variable combing-out effects. Consequently, the variables “coniferous” and “mixed” stands were highly relevant for the model.

The following article presents the regionalization study in detail. Some key findings of the study are highlighted separately and are presented in detail in the article itself (chapter 8.2).

5.1.1 Fürst, C., Zirlewagen, D., Lorz, C. (in print): Regionalization of magnetic susceptibility measurements based on a multiple regression approach, Water, Air, and Soil Pollution DOI: 10.1007/s11270-009-0154-1

Extended summary

The article presents the results of the field assessment of ferrimagnetic magnetic susceptibility in Dübener Heide in a regular grid. The intention of this assessment was to get information on the spatial variation of ferrimagnetic susceptibility and to test the research hypotheses of the ENFORCHANGE project (1) Zschornewitz as major regional emitter and (2) existence of the deposition zones.

The assessment was down with centimeterwise with the down hole probe sensor MS2B of Bartington up to a depth of 30 cm. The measurements were in the following clustered into three different depth levels. These represent the humus layer, the transition zone between humus layer and mineral horizon, and the mineral horizon and allow (see article 5.2.1) linking the results of this assessment with depth level-wise assessed chemical soil characteristics.

Based on the compiled results for the three depth levels, a multiple regression-based regionalization approach was applied, testing and using additional environmental parameters derived from geology, topography, and stand type. The aim was to develop a comprehensive model for the spatial variability of ferrimagnetic susceptibility as indicator for the fly ash deposition.

Spatial variation of magnetic susceptibility was predicted with a high precision by the multiple linear regression models. A slightly differing set of model parameters was selected for the single depth levels. In tendency, magnetic susceptibility values in depth level 6–10 cm were best explained by the distance to Bitterfeld and by soil properties. In depth level 11–15 cm, variables which describe the orographic conditions and stand properties gain in importance. In depth level 21– 25 cm, variables indicating soil and site properties disappear completely. Here, aspect and land surface characteristics play a major role together with stand properties.

A spatial stratification of the model for a distance of up to 25 km to the former emitters provided a further improvement of the model quality considering the prediction of small-scale variations of ferrimagnetic susceptibility.

The study provides key findings of the ENFORCHANGE project and of this thesis:

1. The industrial area Bitterfeld is the most relevant source of fly ash for Dübener Heide. In contrast, the Zschornewitz power plant is only of minor importance.

Figs. 9a and 9b show exemplarily for the depth level 6-10 cm results from the stepwise model parameter test. A good correlation between the height of the magnetic signal and the horizontal distance to Bitterfeld was found (Fig. 9a). A comparable correlation did not exist for the distance to Zschornewitz (Fig. 9b). The missing R^2 and RMSE in Fig. 9b express the impossibility to fit a nonlinear regression for magnetic susceptibility and horizontal distance to Zschornewitz. The nonlinear least-squares estimations did not converge for the tested prediction equations.

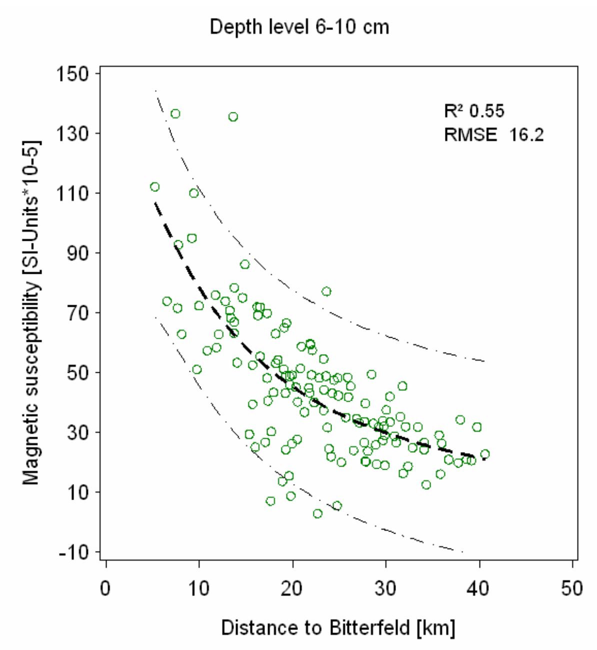


Fig. 9a: Dependence of magnetic susceptibility from the horizontal distance to Bitterfeld for depth level 6-10 cm. The dashed lines show the 95% confidence interval for individual prediction.

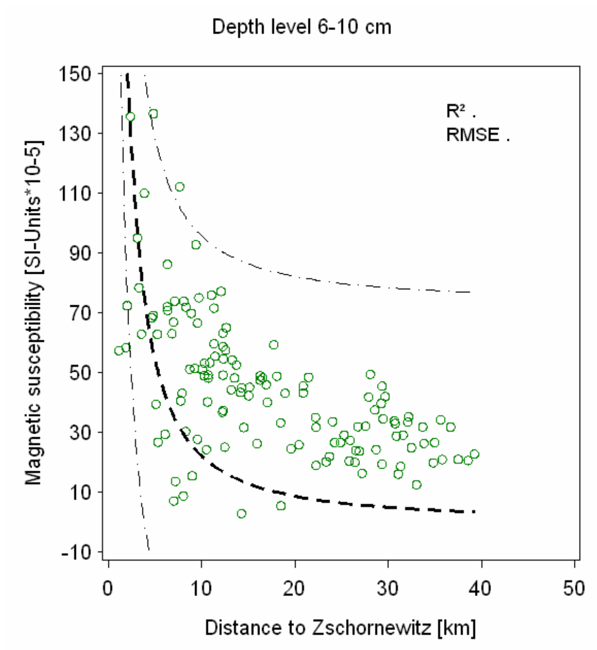


Fig. 9b: Dependence of magnetic susceptibility from the horizontal distance to Zschornewitz for depth level 6-10 cm. The dashed lines show the 95% confidence interval for individual prediction.

2. As result of the regionalization, it was possible to identify strata with more or less comparable height of the magnetic signal. This is especially evident for depth level 6-10 cm (Fig. 9c) and becomes less pronounced with increasing depth (Figs. 9d and 9e). By using parameters for topography, soil type and forest stand type parameters, also the spatial variability within the strata can be modeled. This provides more detailed information for forest management planning than a simple zoning as proposed by Lux (1965). A further improvement in the representation of small scale variations of the magnetic signal was possible by using a stratified modeling approach (Fig. 9f). Figs. 9c – 9e show the regionalization results for the three depth levels. Fig. 9f compares the information depth of the global and a stratified modeling approach.

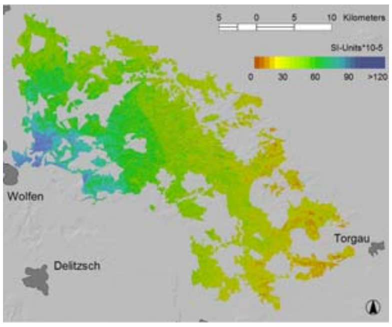


Fig. 9c: Spatial variability of magnetic susceptibility in the global model for depth level 6-10 cm.

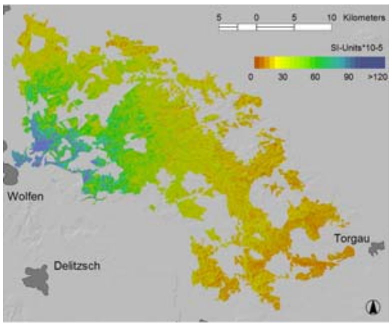


Fig. 9d: Spatial variability of magnetic susceptibility in the global model for depth level 11-15 cm.

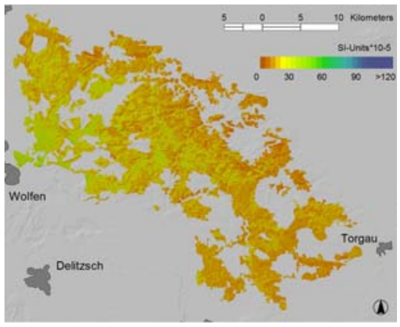


Fig. 9e: Spatial variability of magnetic susceptibility in the global model for depth level 21-25 cm.

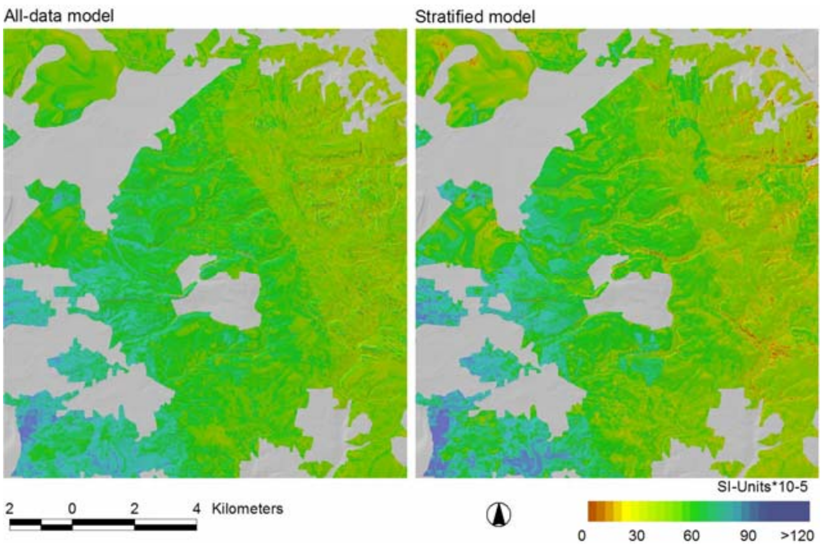


Fig. 9f: Zoom-in into differences between global ("all data") and a stratified model considering high resolution information on small scale differences in magnetic susceptibility for the depth level 6 – 10 cm.

5.2 Indicative value of ferrimagnetic susceptibility assessment for site potentials and risks

When assessing **ferrimagnetic susceptibility**, a major question was, if the magnetic signal allows for **concluding on the content of base cations, acid and heavy metal cations and Black Carbon** as ecologically relevant components of fly ash deposition.
Therefore, an **extended test series** was carried out at the 12 ENFORCHANGE plots and 20 Level-I plots and 2 previously assessed plots (Lorz 2008) in Dübener and Dahlener Heide. Dahlener Heide served as reference region with absence of fly ash deposition to conclude on natural background values of ferrimagnetic susceptibility and chemical properties under comparable geological conditions and in a comparable forest ecosystem type.

Volume magnetic susceptibility, which was assessed in the field, was **converted into mass magnetic susceptibility** by **specific correction factors** for **humus layer** and **upper mineral horizon** respectively, derived from laboratory measurements of ferrimagnetic susceptibility. Hereby, it became possible to **correlate the mass susceptibility** ($\chi \times 10^{-8}$ m^3 kg^{-1}) **with contents of Ca, Mg, Fe, Mn, Al and Cd**, which were assessed according to the Level-I standard procedure (BMELV 2006, Fritz and Makeschin 2007) and with Black Carbon, which was assessed in the frame of a diploma thesis (Koschke et al. subm.). The correlation with Cd and Black Carbon was restricted to the humus horizons Oe and Oa.

The **correlation** expressed by Pearson's correlation coefficient (r) between **mass susceptibility** and the **Ca and Mg content** was **in trend higher at the ENFORCHANGE** plots except for the Mg content at the Oe horizon. Taking the **Fe, Al, Mn and Cd content**, the **results were vice versa**. Also some trends were vice versa: the correlation with Fe and Al (with exception of Oa in case of Fe) was negative for all horizons at the ENFORCHANGE plots. At plot collective B this came only true for Fe at the mineral soil horizon 3 (21 - 30 cm) and for Al at all three mineral horizons.

The **correlation with Black Carbon** was **negative for all plot types**. Taking the absolute values, correlation with Black Carbon at the ENFORCHANGE plots was higher compared to the plot collective B. When **correlating the mass susceptibility over all horizons**, **r** was **higher at the ENFORCHANGE plots for Ca, Mg, Cd and (absolute value) Black Carbon**. The results are **vice versa for Fe, Mn and Al**.

When analyzing the distance dependence of the correlation, no **spatial trend** could be found for all elements, neither **for Pearson's correlation coefficient**, nor for the variability of the measurements expressed by the **standard error**.

The **accuracy** of predicting soil chemical characteristics was tested by using **linear regression equations**. This step was restricted to humus horizons Oe and Oa as they were more intensively and directly impacted by fly ash deposition than the (upper) mineral horizon. Using a **linear regression**, **Ca and Mg** as key nutrients **can be predicted by fly ash deposition**. The prediction quality for these base cations was even better (higher R^2, smaller 95% confidence interval, better distribution of the residuals), than for the metal cations Fe and Al. The **prediction quality** for **Cd** and for **Black Carbon** as possible risk factors was **less satisfying** compared with Ca, Mg and Mn.
In sum, the results of the study have shown that magnetic susceptibility can be used for predicting key element concentrations. Under the specific conditions of this study, the prediction quality for the nutrients Ca and Mg was very high. **Magnetic susceptibility** showed also a comparably **good correspondence with regionalized base saturation**.

The following article presents the results in detail. Some key findings of the study are highlighted separately and are presented in detail in the article itself (chapter 8.2).

5.2.1 Fürst, C., Lorz, C., Makeschin, H. (in review): Testing the indicative value of magnetic susceptibility measurements for concluding on site potentials and risks provoked by fly ash deposition, Environmental management

Extended summary

The article was thought as synthesis of the results so far. In this article, Dübener Heide as fly ash influenced forest ecosystem and Dahlener Heide as reference area are compared.

A major motivation of the ferrimagnetic susceptibility field assessment was to conclude with an easy and cost-efficient method on the fly ash deposition amounts or at least on the contents of deposited base cations, heavy metals and Black Carbon. To test the predictive value of the indicator "ferrimagnetic susceptibility", its correlation with base saturation, the base cations Ca and Mg, the acid cations Fe, Al and Mn, the heavy metal cation Cd (humus layer) and with Black Carbon (humus layer) was tested. Base saturation and base cations were chosen to represent nutrient potentials resulting from fly ash deposition. The acid and heavy metal cations and Black Carbon are selected to represent possible risks.

In a first step, the correlation of magnetic susceptibility with the contents of nutrient, acid and heavy metal cations and with base saturation and Black Carbon was calculated. In the following, the suitability of using magnetic susceptibility as model parameter in a linear regression based model to predict the content of Ca, Mg, Fe, Al, Mn, Cd and Black Carbon was tested.

The Pearson correlation coefficients proved the connectivity between magnetic susceptibility and the selected indicators. Going a step further than prevailing studies, the test proved also the suitability of magnetic susceptibility to predict fly ash deposition influenced nutrient contents. This applied mainly for the humus layers and especially for the Oa. Magnetic susceptibility showed also a comparably good coherence with regionalized base saturation.

However, provoked by the data base and not considered additional impact factors on the measurement and modeling results, some weaknesses in using a linear regression based model were revealed. They led to the conclusion that magnetic susceptibility could be a valuable model parameter in a multiple regression based approach, but should not be used alone for predicting fly ash deposition effects.

The presented findings raise the question of the indicative value and transferability of the results, which forms also part of the discussion (see chapter 6).

Also this study delivered some key findings for the ENFORCHANGE project and within the frame of the thesis, which are resumed in the following.

1. Correlations between mass susceptibility and selected base cations, acid and heavy metal cations and Black Carbon were found. A correlation with base saturation was calculated at the ENFORCHANGE plots and served as reference basis to a spatial regression of magnetic susceptibility and base saturation, which resulted in a comparable good connectivity between the integrative soil chemical parameter base saturation and magnetic susceptibility.

The study revealed some problems using different plot types, where the assessment of magnetic susceptibility and the chemical characteristics were not in any case harmonized. In trend, the correlation between mass susceptibility and the selected cations and Black Carbon was higher in the humus layer compared to the mineral horizon. Within the humus layer, correlation for Oa was higher than for Oe. The correlation between mass susceptibility and all horizons ("total") is mostly higher than the mean value of the correlation coefficients for the single horizons (Tab. 3).

Tab. 3: Pearsons correlation coefficient r for mass susceptibility (χ * 10-8 m³ kg-1) and the content of Ca, Mg, Fe, Mn, Al, Cd and Black Carbon at the ENFORCHANGE plots, the monitoring plots and for both plot types together.

Depth (horizon)	**Correlation magnetic susceptibility ($\chi * 10^{-8}$ m³ kg^{-1})**							
all plots	*base saturation*	*Ca*	*Mg*	*Fe*	*Mn*	*Al*	*Cd*	*Black Carbon*
Oe (0-5)		0,12	0,33	0,73	-0,10	0,72	0,58	-0,09
Oa (5-10)		0,42	0,64	0,72	0,55	0,70	0,53	-0,38
Min 1 (10 - 15)		0,50	0,55	-0,18	0,19	-0,15	-0,44	
Min 2 (15 - 20)		0,50	0,42	-0,08	0,33	0,06	-0,45	
Min 3 (20 - 30)		0,26	0,21	-0,29	0,36	-0,03	-0,26	
Total		*0,76*	*0,76*	*0,86*	*0,49*	*0,72*	*0,13*	-0,26
ENORCHANGE plots								
Oe (0-5)	0,43	0,49	0,21	0,38	0,03	-0,26	-0,48	-0,18
Oa (5-10)	0,58	0,90	0,84	-0,28	0,10	-0,43	-0,03	-0,45
Min 1 (10 - 15)	0,56	0,38	0,51	-0,29	0,19	-0,42	-0,18	
Min 2 (15 - 20)	0,53	0,71	0,78	-0,07	0,09	-0,34	-0,13	
Min 3 (20 - 30)	0,51	0,63	0,84	-0,25	0,12	-0,44	-0,13	
Total	*0,61*	*0,65*	*0,58*	*0,85*	*0,46*	*0,75*	*0,80*	-0,39
Monitoring plots								
Oa (0-5)		0,39	0,66	0,66	0,70	0,68	0,55	-0,04
Oe (5-10)		0,45	0,57	0,62	0,70	0,65	0,46	-0,34
Min 1 (10 - 15)		0,08	0,43	0,27	0,15	-0,41		
Min 2 (15 - 20)		0,00	0,06	0,10	0,37	-0,52		
Min 3 (20 - 30)		0,31	0,28	-0,19	0,43	-0,56		
Total		*0,52*	*0,52*	*0,75*	*0,75*	*0,74*	*0,51*	*-0,20*

2. The prediction of element contents by using volume magnetic susceptibility as model parameter in a linear regression based model showed heterogeneous results.

A clear linear regression model with comparably high coefficients of determination (R^2) could be derived for Ca (displayed exemplarily in Fig. 10a), Mg and Mn. The R^2 for Ca amounted to 0.51, for Mg to 0.52 and for Mn to 0.37. In all three cases, also small 95 % confidence intervals were observed. This indicates a sufficient precision of the linear regression model.

In contrast, the linear regression was not so clear for Cd and Black Carbon. In consequence, the R^2 values were lower and amounted in both cases to 0.09 and also the 95 % confidence intervals were broader.

Absolutely no linear regression could be calculated for Fe and Al. In both cases the R^2 values were approximately 0 and the 95 % confidence intervals became very broad.

The model quality test by using the relation between measured and predicted values and the residuals revealed a visible coherence between measured and predicted values for Ca (displayed exemplarily in Fig. 10b), Mg and Mn with small 95 % intervals. The model quality test for Cd and Black Carbon showed a slight coherence with broader 95 % intervals. In contrast, and supporting the previous findings, no such coherence could be found for Fe and Al and the 95 % intervals became very broad.

Considering the residual histograms, these were slightly right skewed for Ca (displayed exemplarily in Fig. 10c), Mg and Mn and a good coherence with the expected distribution of the observations was given. Also for Cd, the distribution corresponded very well to a standardized normal distribution. For Fe and Al the distribution of the residuals was left skewed and did not fit very well together with the expected distribution. Same applied for Black Carbon.

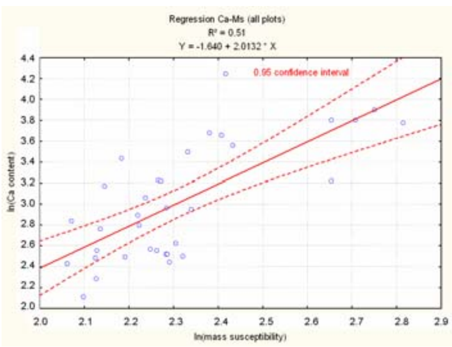


Fig. 10a: Ca content as linear regression function of magnetic susceptibility.

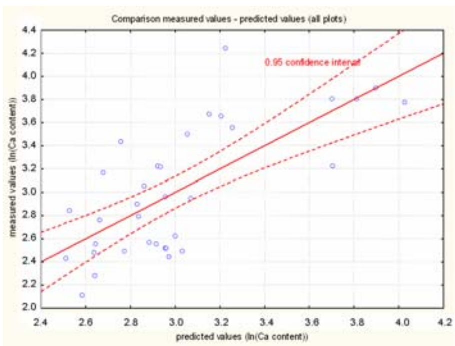


Fig. 10 b: Comparison measured and predicted values for Ca.

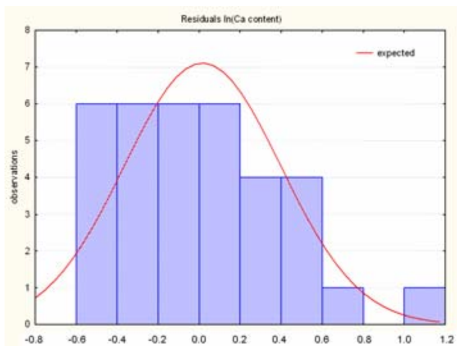


Fig. 10c: Histogram of residuals for Ca.

3. A stratification of the regression models into distance clusters (without illustration) resulted in an improvement of the R^2 of Fe and Al to 0.05 and 0.06, respectively. Also the coherence between measured and predicted values and the distribution of the residuals were improved. However, the sample sizes within each of the distance clusters are very small and in the consequence the 95 %confidence intervals became very broad and let doubt about the quality of respective models. Contradictory results were obtained by a stratification of the regression models in the two plot collectives A and B. Taking Fe as an example, a clear linear regression model could be calculated for the subset of the ENFORCHANGE plots (plot collective A) with $R^2 = 0.43$. However, the 95 % confidence interval became very broad due to the low number of plots. In contrast, the linear regression for the subset of the monitoring plots (plot collective B) was much less clear and the R^2 amounted to 0.12. In this case, the 95 % interval was smaller due to the higher number of plots. However, in both cases, the distribution of the residuals corresponded even less to a standardized normal distribution. The trends for Al were similar.

6. Discussion and Conclusions

6.1 Contradictory findings and open questions

In the frame of the ENFORCHANGE study, the assessment of ferrimagnetic susceptibility aimed at providing a cost-efficient and easy method (i) to estimate the deposited fly ash amount and (ii) to conclude on the extent of change of site potentials (base cations) and site risks (heavy metals, Black Carbon).

Within the ENFORCHANGE study it was firstly assumed that (a) the Zschornewitz power plant has been the major regional emitter and (b) the deposition zones described by Lux (1965) along a deposition gradient starting from Zschornewitz are still existent.
The **pre-study(ies)** in chapter 3 and 4 with a plot-wise assessment of ferrimagnetic susceptibility along the deposition gradient **seemed to support** at least partially these hypotheses. Using **cluster analysis for the plot-wise assessed ferrimagnetic susceptibility**, the **results went very well along with previous results of the assessment of chemical characteristics** (Fritz and Makeschin 2007, Fritz et al. 2009). Three zones with different deposition impact in Dübener Heide were distinguished, (i) a high impact zone in max. 8 km distance to Zschornewitz, (ii) an intermediate impact zone in max. 15 km distance and a low to no impact zone in distances > 15 km.
Using statistical characteristics, e.g., standard deviation or coefficient of variation, the results of presented in 4.2.1 support even a less differentiated stratification into a zone with detectable fly ash (former deposition zone I) and a zone with lesser likelihood of fly ash deposition (former deposition zones II, III and IV). The spatial relation to Zschornewitz with a deposition gradient starting at this power plant seemed to be supported by these results.

A **problem** to be considered with regard to up-scaling is the **non random selection of measurement plots**, which might lead to biased results (Saborowski and Jansen 2002). The 12 ENFORCHANGE plots were selected with the aim to represent as best as possible the most important forest stands – (terrestrial) site combinations along the formerly defined deposition gradient and were selected from an existing set of measurement plots established by Lux (1965). This selection was done to provide a reference base between the actual measurements and data sets. Furthermore, only plots were selected, where the geographical coordinates were known, and which could be retrieved.
The **grid-wise assessment of ferrimagnetic susceptibility** and the spatial model **revealed** that the power plants in **Bitterfeld** – **but not Zschornewitz** – had a much **higher impact on Dübener Heide** with a much larger spatial extent. Furthermore, it was shown that a **spatially distinct stratification** of four deposition zones by different levels of the magnetic signal is

not anymore possible. It should be skipped in favor of a **stronger consideration of micro-scale variability** of fly ash deposition depending on other environmental factors, such as topography site and stand type.

The **deposition zones** defined by Lux (1965) were **based on visual assessment of forest health and growth** at a number of test trees per stand. The identification of deposition zones is based on a step-wise aggregation of the stand-wise assessed results to zones with homogeneous health and growth impact symptoms. The hereby derived deposition zones formed an important basis for financial compensation of pollution effects (Albrecht 2007, Bendix 2007). From the late 1980ies on, **no spatially significant differences in tree growth** could be detected anymore (Hüttl and Bellmann 1999). A probable reason was the regional establishment of fly ash filtering techniques in the 1980ies, thus SO_2 became the most important pollutant. Compared to fly ash, the spatial influence of sulfur (as wet deposition component) bridged greater distances compared to fly ash and therefore no spatial stratification for its influence in the Dübener Heide could be found.

In the pre-study on the suitability of ferrimagnetic susceptibility field assessment (chapter 4.2.1) it was also tested, if depth level-wise or horizon wise measurement deliver better results. Results for **horizon wise measurements** with the KT-9 showed a **more distinct differentiation of fly ash deposition levels** with a wider range of values, a lower standard deviation and a lower coefficient of variation compared to depth level-wise measurements. However, **depth level-wise assessment** delivers a **better basis for comparing and correlating** the results with **depth level-wise measured chemical characteristics** of the ENFORCHANGE plots and other plots. Furthermore, the depth level-wise approach allows for a higher objectivity of the measurements despite the problem to link them later on to soil horizons.

6.2 Comprehensive evaluation of the results

A demand formulated in the pre-study (chapter 4.2.1) was to **assess and compare ferrimagnetic susceptibility in a reference region** as it was done e.g. in the frame of the SANA study (Hüttl and Bellmann 1999), where three plots were analyzed along a deposition gradient from Rösa (located about 10 km east of the industrial complex of Bitterfeld and influenced by high deposition loads) via Taura (located about 50 km north east to Bitterfeld) to the background site Neuglobsow (located in northern Brandenburg) (Weisdorfer 1999, Schaaf 2004). Hereby, it was possible to conclude on the natural range of the chemical characteristics of the humus layers and the mineral horizons.
In frame of the presented thesis, **Dahlener Heide** was chosen **as reference region**, where no fly ash deposition nor air pollution driven forest decline was reported in the past (see chapter 5.2.1).

The **maximum ferrimagnetic susceptibility values** observed in Dübener Heide in the pre-study (chapter 4.2.1) occurred in the **Oe and Oa horizons**, which corresponds to the findings of Klose et al. (2002) and Koch et al. (2002). In contrast to their observations, the peak was found mainly in the Oa horizon (see also chapter 4.2.1) and no longer in the Oe horizon.
This finding can be explained by the **temporal dynamic of the humus layers in Dübener Heide** with a **vertical movement of the fly ash containing humus horizons** due to litter fall and decomposition processes.

In Dübener Heide, **maximum values of ferrimagnetic mass susceptibility** (outliers near to Zschornewitz) reached values of up to 800 $\chi * 10^{-8}$ m³ kg^{-1} (see chapter 5.2.1). This is in **agreement with findings by Klose and Makeschin** (2003), who found almost equal maximum values near to Zschornewitz. In comparison, Magiera et al. (2002 b) found maximum values of up to 2,741.3 $\chi * 10^{-8}$ m³ kg^{-1} in the most polluted soils of Poland in the district Katowice (Upper Silesia), where the observed fly ash deposition is roughly three times higher (457 t / km²) than in Dübener Heide (140 t / km²) (Klose and Makeschin 2003, Lux 1965 and 1976, Lux and Stein 1977, Strzyszcz et al. 1996, Strzyszcz and Magiera 2001). Comparing the relations between the deposition amounts and the magnetic susceptibility values in Poland and Germany, the dimensions (“3-times higher”) fit also very well.

The **mean values of mass susceptibility** in the **humus layers** at the **Eastern border of Dübener Heide** (i.e. the less or almost not deposition impacted part with a distance of around 50 km to the former emitters) reached values of up to **180 $\chi * 10^{-8}$ m³ kg^{-1}**, which corresponds to the values observed in Dahlener Heide.

At both areas, Dübener and Dahlener Heide, the values observed in the **mineral horizon** are much lower than in the humus layer. The maximum values were observed at the Western part of Dübener Heide in the **vicinity of Zschornewitz** and amounted to **30 $\chi * 10^{-8}$ m³ kg^{-1}**. In the **other parts of Dübener and Dahlener Heide**, the values in the mineral horizon ranged between **3 - 20 $\chi * 10^{-8}$ m³ kg^{-1}**.

Even if it is not possible to exclude minor sources of fly ash (domestic fuel) in Dahlener Heide, the spatial trends of the magnetic signal observed in chapter 5.2.1 indicate, that **values of more than 200 $\chi * 10^{-8}$ m³ kg^{-1} in the humus layers** can be considered as regional **threshold for verifiable fly ash deposition**. Klose and Makeschin (2003) found minimum values of up to 350 $\chi * 10^{-8}$ m³ kg^{-1} for the most Western point of their deposition gradient, which reached up to 25 km distance to the former emitters. As shown in the presented studies, it must be considered that the impact of the Bitterfeld power plants on the humus layers is detectable at least for a distance of 40 km (chapter 5.1.1, 5.2.1) with an asymptotical trend. This allows for the conclusion that the proposed threshold value for the magnetic signal, which is stable for distances of more than 50 km, might be valid in general.

Fig. 11 gives an overview on the value range of different materials (rocks, minerals, organic material, water and air) from other studies (Glaser 2001, Hasso-Agopsowicz et al. 2004, Hunt et al. 1995, Klose and Makeschin 2003). This comparison supports the proposed threshold value: maximum values for not fly ash influenced humus layers amount in these studies to ~ 100 $\chi * 10^{-8}$ m³ kg^{-1}. The proposed threshold is two times higher and thus includes the possibility of exceptionally higher values due to natural enrichment of magnetic particles (Faßbinder 1994, de Jong et al. 2005, Le Borgne 1955, Magiera and Strzyszcz 2000, Scollar 1965, Thompson and Oldfield 1986).

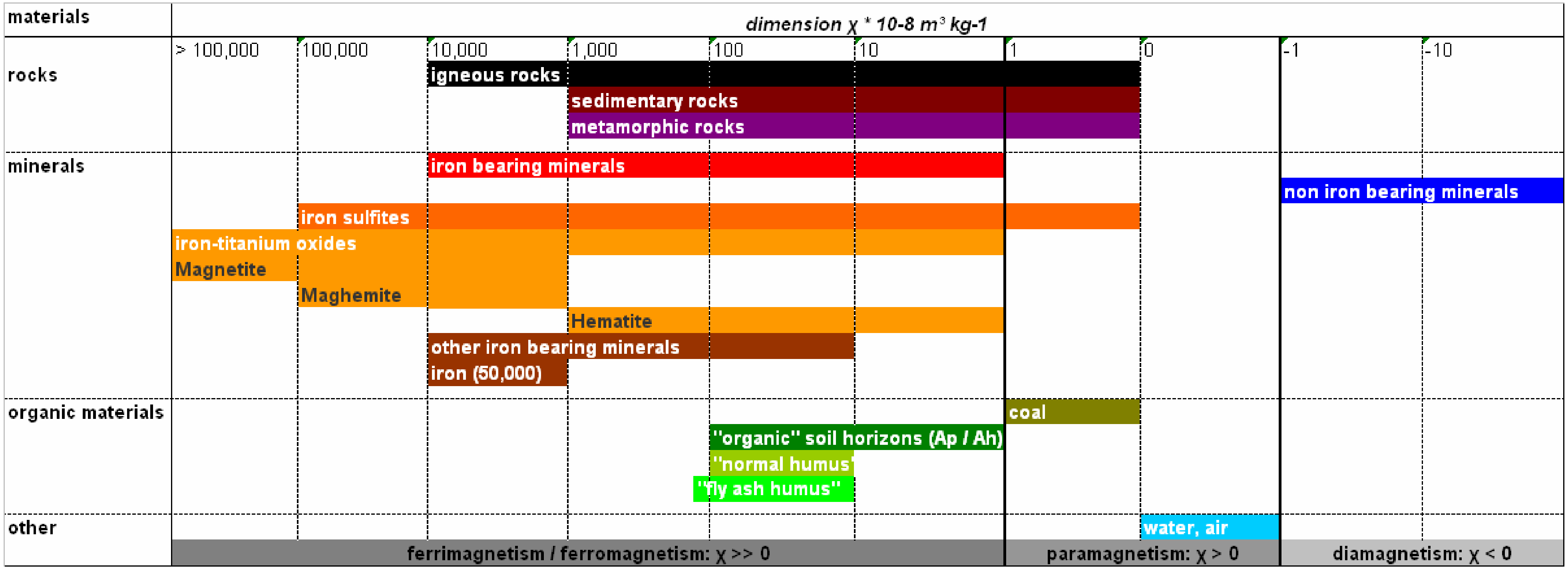


Fig. 11: Overview on the mass susceptibility value ranges of different material classes observed in previous studies (Glaser 2001, Hasso-Agopsowicz et al. 2004, Hunt et al. 1995, Klose and Makeschin 2003).

The use of ferrimagnetic field assessment to detect fly ash deposition was successfully tested and approved by numerous studies (e.g. Boyko et al. 2004, Grimley et al. 2004, Magiera et al. 2006, Magiera and Strzyszcz 2000, Magiera and Zawadzki 2007, Schibler et al. 2002, Strzyszcz and Magiera 1998). The major motivation of these studies was to get information on the spatial distribution of deposited fly ash. Magnetic susceptibility can also be easily correlated with a number metals, especially Fe, Al, Mn and heavy metals (Goluchowska 2001, Lu and Bai 2006, Magiera and Zawadzki 2007, Wang and Qin 2005, Zawadzki et al. 2009). The correlation however varies in dependence from geographical origin, type of combustion material (lignite or hard coal) and land use type and can not easily be transferred from one test region to another (Fialova et al. 2006, Magiera and Zawadzki 2007, Strzyszcz and Magiera 1998).

Within the **frame of the study presented in chapter 5.2.1**, the correlation with Fe, Al, Mn and Cd were tested. The **results were in parts contradictory to the findings** of other studies, especially considering the relation between magnetic susceptibility and the Fe content. A major **impact factor on the correlation** was the **use of several plot types** (project plots, monitoring plots), where the **assessment of ferrimagnetic susceptibility and the chemical characteristics were not always well synchronized**.
Furthermore, **mass susceptibility** was not directly measured at all plots, but **calculated by correction factors for humus layer and mineral horizon** in a two-step procedure, from field assessed volume susceptibility to volume susceptibility as assessed under laboratory conditions and from “laboratory” volume susceptibility to mass susceptibility. These correction factors can only describe an average correlation between field assessed volume and laboratory assessed mass susceptibility. As an example, the distance between the magnetic susceptibility sensor and the material to be measured cannot be totally standardized in bore holes and can underlay manifold variations by truncated roots, structural disturbances, when removing the borer, etc.
In the consequence, it was **not possible to develop a linear regression based model to predict the Fe and Al content**, while such a linear relation was found for Mn. This might be a **weakness of the linear regression based modeling approach**, which does not allow for including further model parameters to improve the model quality.

The **approach presented in chapter 5.2.1** went a step further than prevailing studies and **tested**, if the **content** of other agents, such as **base cations and Black Carbon can** also **be predicted by ferrimagnetic susceptibility**. Under the specific conditions of the presented study, it was **possible to develop a linear regression based model for predicting the**

content of Ca and Mg as important nutrients with ferrimagnetic susceptibility as model parameter. However, this did **not** apply **for Black Carbon**.

In contrast to the results presented in chapter 5.2.1, Wang (2009) found a very high and positive correlation between Black Carbon and mass susceptibility. The **applied analysis method** and the hereby isolated part of the **Black Carbon combustion continuum** (Masiello 2004) might be the major impact factor on the correlation with magnetic susceptibility and the possibility to predict Black Carbon with magnetic susceptibility as model parameter.

When calculating **Pearson's correlation coefficient in dependence from the distance** to the Western border of Dübener Heide with its closeness to the former emitters, at least **no spatial trends** could be found for **Ca, Mg, Fe and Al**, while slight trends were observed fro Cd and Black Carbon. Missing spatial trends support the use of magnetic susceptibility as model parameter.
However, a **missing trend** could only be **expected for the correlation with Fe** as main source of magnetism but e.g. not for Ca or Mg.
The observation leads to several possible hypotheses. Possibly, the **indicative value of magnetic susceptibility** for fly ash and the related deposits is **superposed** to a higher extend by **natural humus properties**, than assumed at the beginning of the studies (Faßbinder 1994, Zawadzki et al. 2007). The humus layer in forests is an important nutrient reservoir and magnetizable Fe or Mn compounds occur also in "normal" humus layers (Faßbinder 1994, Scollar 1965, LeBorgne 1955).

In the case of **Ca and Mg**, **liming** might be a most important factor. Liming effects are **likely** in Dübener Heide in the zone **10 - 20 km** distance, where alkaline particles of the fly ash were almost not anymore deposited (Fritz and Makeschin 2007). In this zone, acid deposition components have provoked even higher forest health damages than near to the former emitters and in the consequence extensive compensation measures were carried out (Fürst et al. 2007, Fritz and Makeschin 2007). This would explain the observation that the correlation between magnetic susceptibility and Ca and Mg in this zone was slightly lower and the standard error was slightly higher than in the other distance clusters (see article 5.2.1, without illustration).

With **increasing distance** to emitters, **additional factors** might have an **influence** on the **indicative value of magnetic susceptibility** for fly ash and decrease the prediction quality of magnetic susceptibility for all tested elements and Black Carbon. Previous studies showed that especially stand or soil type have a considerable influence on natural magnetic susceptibility values blurring possibly its increase by fly ash deposition (e.g. Blundell et al. 2009, Hanesch and Scholger 2005, Kapicka et al. 2001, Zawadzki et al. 2007, 2009).
In chapter 5.1.1 it was **proved** that different **sets of model parameters** must be chosen to **predict magnetic susceptibility at different depth levels**, which could be related to the humus layer, the zone between humus layer and mineral soil and the mineral soil. In tendency, magnetic susceptibility values in the humus layer (depth level 6–10 cm) were best explained by the distance to Bitterfeld, soil type characteristics and characteristics for the land surface. The stand type e.g. plays an important role as model parameter in the depth level 21-25 cm.

The **different model parameters support the understanding of the deposition and accumulation process** for different depth levels. **Soil type related parameters** “Podzol” and “Semi-terrestrial sites”, which were very relevant for the humus layer (depth level 6-10 cm, chapter 5.1.1), **indicate a slowed down humus dynamics**, which supports a long-term accumulation of fly ash (Magiera and Zawadzki 2007). **Topographical parameters** such as “Streampower index” or “Slope length factor” were also relevant for the depth level 6-10 cm and can be explained with regard to their **indication of humus accumulation or erosion**.
However, **stand properties** play a minor role in the model for the humus layer (depth level 6-10 cm), but became **more relevant for the transition zone** (depth level 11-15 cm) and especially for the **mineral soil** (depth level 21-25 cm). Probably, stand type impacts on the findings for the humus layer are widely superposed by soil type and orographic parameters, which decide upon humus dynamics.

For the **transition zone between humus layer and mineral soil** (depth level 11-15 cm), variables describing **orographic conditions gain in importance**. New variables have a high explanatory value, such as the **divergence from western aspect**, which **indicates** the exposure against the major wind direction and thus the **probability of deposition**. Also, stand properties (mixed forest) contribute to the model for this depth layer, though their explanatory value is lower compared to their importance for the model in the mineral horizon (depth level 21-25 cm).

For the **mineral horizon** (depth level 21-25 cm), the importance of variables indicating soil and site properties is not existent anymore. Here, **aspect and land surface characteristics**,

which indicate the **deposition probability**, play a **major role together with stand properties**. Here, the classes mixed forests and coniferous forests from Corine Landcover 1990 and 2000 were selected as model parameters. They can be considered as **indicators for the probability that deposition was combed out by the crown layer**. Coniferous and mixed stands have a higher surface roughness of the crown layer compared to deciduous stands and furthermore, the combing out effect of conifers in mixed or pure stands is extended to the whole year and not limited to the vegetation period compared to pure deciduous stands.
This raises the question why stand type is not relevant for the model for the humus layer. For depth level 21-25 cm, the stand type might indicate a vertical displacement of magnetic iron complexes together with sesquioxides and humus complexes by initial podzolization processes. This is supported by the findings that (a) only coniferous or mixed types show an explanatory value and not deciduous types and that (b) the older Corine Landcover classification from 1990 contribute to the modeling in this depth layer and not the classification of 2000. Finally, also the **precipitation amount from 1971 to 2000** contributed to the model in the mineral horizon. This might be in agreement with the hypothesis formulated before: Locally, **higher precipitation** amounts can **support podzolization processes**.

The analysis of model parameters and their indicative value leads to a more differentiated view on findings listed in chapter 5.2.1, where the correlation between the indicator magnetic susceptibility and key element contents was also different at different depth levels. A **possibility to improve the prediction quality of the element and Black Carbon contents** is the **use of a multiple-regression based model with a step-wise selection of highly indicative model parameters** as shown in chapter 5.1.1.

6.3 Conclusions and Outlook

The two aims of the presented work, which were formulated in chapter 1.1, were realized in major parts.

(a) The **field assessment of ferrimagnetic susceptibility was approved as cost efficient method** to detect historical fly ash deposition and to distinguish different levels of deposition intensity and accumulation in dependence from the distance to the fly ash emitters and further environmental parameters, such as exposition, soil and stand properties.

(b) Very early(Lux 1976), research started to develop complex models for the air transport of particles for a better differentiation of impacts of the variable deposition components and to react with adapted forest management measures, such as liming or conversion (Fürst 2007). So far, forest health and growth as well as soil vegetation characteristics were used as most indicative parameters to come to the requested spatial stratification into different deposition zones, while the air transport based modeling approaches failed due to their high level of complexity and the numerous parameters to be considered.

The **grid-wise assessment and multiple-regression based modeling of magnetic susceptibility allows for a complex spatial model for fly ash deposition under consideration of further environmental influence factors**, which were in the past decisive for fly ash deposition. A high resolution spatial model was developed, which gives also information on micro-site differences of magnetic susceptibility as indicator for fly ash deposition. This might **correspond better to the management need to develop strategies for a stand wise differentiated silvicultural treatment** in dependence from growth relevant differences in site potentials. Beyond this background, the study in chapter 5.2.1 has tested (with success) the suitability of ferrimagnetic susceptibility also as indicator for the Ca and Mg content.

However, some expectations could not be fulfilled. The **results of predicting some key element and Black Carbon contents based on a linear regression were not fully satisfactory** and revealed that **ferrimagnetic susceptibility as single model parameter in a linear regression based model is not sufficient**. Same applies, when correlating Ca, Mg, Fe, Al, Mn, Cd and Black Carbon contents with ferrimagnetic susceptibility in different depth levels. However, the results were rather heterogeneous. This leads to the conclusion that a **precise prediction of the deposited fly ash amount by the model parameter ferrimagnetic susceptibility** as intended at the very beginning of the different studies **is only possible with restrictions**, especially since fly ash itself is characterized by a very heterogeneous composition (see chapter 4.1.1).

The question must be posed, if information on the absolute fly ash deposition amount is a management relevant factor and not – to a much higher priority – the ecological impact of fly ash deposition. Using **ferrimagnetic susceptibility together with further model parameters in a multiple-regression based approach** could be **sufficient** to **obtain spatially highly differentiated information on still relevant site potentials and risks**. A pre-condition to be considered, is the better synchronization of magnetic susceptibility field assessment and chemical analysis as concluded in chapter 5.2.1.

Here, the **choice of the further model parameters** decides upon the possibility to get **additional information on processes** such as humus accumulation or vertical displacement of base or acidic cations. **Further experiments on the stability of the correlations between element contents and ferrimagnetic susceptibility over time** would be necessary to get information on possible temporal dynamics to be considered.

Furthermore, the **question** must be raised, **if the content in ferrimagnetic substances** in the humus layers **underlies also other impact factors**: Faßbinder (1994), de Jong et al. (2005), Le Borgne (1955), Magiera and Strzyszcz (1999), Scollar (1965), and Thompson and Oldfield (1986) described the natural enrichment of ferrimagnetic substances as a result of microbial activity. Vice versa, it **cannot be excluded that ferrimagnetic iron oxides are removed from the humus layers into the mineral horizon,** e.g. by leaching or bioturbation. Elevated values of ferrimagnetic susceptibility in the A(h) and even in the B(wh) horizon (see chapters 4.2.1 and 5.1.1) indicate that vertical displacement together with humus particles must be considered as relevant process with impact on the height of the magnetic signal in the humus layers.

Even the **minerals** magnetite and maghemite**, which** are related to the phenomenon "ferri-magnetic susceptibility", may underlie a **transformation from magnetite to maghemite and finally to hematite** driven by low pH values of rainwater (Correa et al. 2006) or microbial activity (Brown et al. 1997).
When **comparing the value ranges of ferrimagnetic susceptibility** of these three minerals shown in Fig. 11, it becomes clear that this **transformation process leads also to a considerable reduction of the detectable ferrimagnetic values**. On the other hand, the mentioned **in situ formation of ferrimagnetic substances by microbial processes might counteract the loss of ferrimagnetic susceptibility** (Faßbinder 1994, Le Borgne 1955, Scollar 1965, Thompson and Oldfield 1986). In sum, both interfering processes will super-pose in the long run the magnetic signal induced by fly ash deposition.

A possible solution and future challenge to **include** such **temporal processes into a spatial model of ferrimagnetic susceptibility** would be to **assess the magnetic signal in a "chronosequential" approach**: i.e. in regions with comparable geological and vegetation characteristics, but with different duration of fly ash deposition. Respective sequences are already realized for analyzing the impact of pedogenic processes in mineral and magnetic properties of soils (e.g. Lu et al. 2008) and are still outstanding for humus dynamics.

Finally, to conclude on the suitability of the indicator **ferrimagnetic susceptibility** for a process-oriented forest management approach, the presented work has shown that this indicator gives

(a) **good indication of the spatial variation of former deposition** and is

(b) **highly sensible against a dynamic development of sites** and especially of the humus layers.

The only **remaining problem** and possibly topic of future research is to come to a **comprehensive formulation of thresholds** not only for the spatial trends as described in chapter 6.2, but also **for the temporal trends** and the manifold and sometimes interfering impact factors on the height of the magnetic signal.

7. References

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8. Annexes

8.1 Overview on the papers included in the thesis

The following Tab. 4 gives an overview on the papers, which form part of this cumulative thesis and their scientific impact.

Tab. 4: Papers included in the thesis

Chapter	Paper	Impact factor
2.1.1	Fürst, C., Abiy, M., Makeschin, F. (2008): Forest ecosystem development after heavy deposition loads – case study Dübener Heide, WIT Transactions on Ecology and the Environment (ISSN 1743-3541), Air Pollution XVI, p. 571-584	-- (peer-reviewed proceedings)
2.1.2	Fürst, C., Makeschin, F. (2009): Forest ecosystem development under a changing environment and conclusions for forest management, Forestry in Achieving Millenium Goals, Proceedings, p.47-55	-- (peer-reviewed proceedings)
3.1.1	Fürst, C., Lorz, C., Makeschin, F. (2007): Development of forest ecosystems after heavy deposition loads considering Dübener Heide as example – challenges for a process-oriented forest management planning, SI "Meeting the challenges for process-oriented forest management" Forest Ecology and Management, 248(1-2), p. 6-16	2.11
3.1.2	Fürst, C., Vacik, H., Lorz, C., Makeschin, F., Podraszky, V., Janecek, V. (2007): Meeting the challenges of process-oriented forest management, SI "Meeting the challenges for process-oriented forest management" Forest Ecology and Management 248(1-2), p. 1-5	2.11
3.1.3	Fürst, C., Lorz, C., Abiy, M., Makeschin, F. (2006): Fly ash deposition in Northeastern Germany and consequences for forest management, Contributions to Forest Sciences, Ulmer, p. 50-63	-- (peer-reviewed proceedings)
3.1.4	Fürst, C., Abiy, M., Makeschin, F. (2005): Reaction of forest systems in the industrial triangle Leipzig-Halle-Bitterfeld on a changing immission regime – state of the art, in: Neuhöferovà, P. (ed.) Restoration of Forest Ecosystems of the Jizerske Hory Mountains, Czech University of Agriculture Prague, p. 67-72	-- (peer-reviewed proceedings)

4.1.1	Fürst, C., Makeschin, F. (2006): Comparison of Wood Ash, Rock Powder, and Fly Ash – a review, Contributions to Forest Sciences, Ulmer, p. 63-81	-- (peer-reviewed proceedings)
4.2.1	Fürst, C., Lorz, C., Makeschin, F. (2009): Testing a soil magnetometry technique in a highly polluted industrial region in Northeastern Germany, Water, Air, and Soil Pollution, 202, p. 33-43, DOI: 10.1007/s11270-008-9956-9	1.398
5.1.1	Fürst, C., Zirlewagen, D., Lorz, C. (accepted): Regionalization of magnetic susceptibility measurements based on a multiple regression approach, Water, Air, and Soil Pollution, DOI: 10.1007/s11270-009-0154-1	1.398
5.2.1	Fürst, C., Lorz, C., Makeschin, H. (subm.): Testing the indicative value of magnetic susceptibility measurements for concluding on site potentials and risks provoked by fly ash deposition, Environmental management	1.109

The actually discussed guidelines for cumulative dissertations propose a modular composition with an evaluation of the articles according to their publication status and the authorship with a minimum amount of 7 evaluation points. The following Tab. 5 resumes the status of the contributions included in the presented theses and resulting total evaluation points.

Tab. 5: Evaluation of the included articles.

authorship		**status**		**evaluation**
first author	co-author	accepted / in press (x 6)	submitted (x 2)	
peer-reviewed with impact factor				
5	0	4	1	26
peer-reviewed without impact factor				
5	0	5		0
SUM				26

8.2 Papers (attached)

Forest ecosystem development after heavy deposition loads – case study Dübener Heide

C. Fürst, M. Abiy & F. Makeschin
Institute for Soil Science and Site Ecology,
Dresden University of Technology, Germany

Abstract

Forest ecosystems in the New Lander (Germany) were impacted for more than one century by industrial emissions. The deposition amount has decreased since the middle of the 1980s due to technological progress and closing of main emitters. In the research project ENFORCHANGE (www.enforchange.de), the impact of past industrial depositions on forest ecosystems is assessed in two model regions, and approaches how to integrate deposition residuals into forest management are developed. The here presented model region Dübener Heide is a ca. 300 km² large forest area in the industrial triangle Leipzig-Halle-Bitterfeld, which is one of the most polluted regions in the New Lander. A total deposition amount of 18 Mio t fly ash and of 12 Mio t SO_2 led to considerable changes of site properties, forest growth and health. The actual investigations in Dübener Heide revealed that the historical deposition impact still results in a spatial differentiation of forest growth conditions: nowadays, Dübener Heide can be divided into two parts with different impact level and intensity. Verifiable fly ash influence with high pH values and nutrient potential is limited to a zone of maximally 8–15 km distance to the former emitters, whereas SO_2 impacted the total 300 km² area, but its effects are no longer detectable. This spatial differentiation is relevant for tree species choice in the future: the heavily fly ash impacted sites are characterized by ample regeneration and growth of noble hardwood species and European beech, whereas the not measurably fly ash influenced sites are more or less suitable for Scots Pine and Oak. The prediction of the long-term development of the site potential and tree species suitability on heavily fly ash affected sites under different climate change scenarios are part of ongoing studies.

Keywords: forest ecosystem development, fly ash deposition, SO_2 deposition, forest growth and health, site potential, forest management planning.

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1 Introduction – case study Dübener Heide and assessment of former deposition loads (ENFORCHANGE)

1.1 Deposition history in the model region Dübener Heide

For more than one century, forest ecosystems in the New Lander were heavily impacted by industrial depositions. In the industrial triangle Leipzig-Halle-Bitterfeld, one of the most polluted regions of the New Lander, this deposition originated from unfiltered brown-coal combustion and exhalations from chemical industry (Fürst et al. [5]). The extreme alteration of the natural conditions, which lasted until the early 1990s, is still impacting the site properties and vegetation dynamics and must be considered in actual forest management. Zooming into the region Leipzig-Halle-Bitterfeld and taking the Dübener Heide – the most important regional forest area – as an example, the historically documented deposition amounted from 1910 – 2000 to 18 Mio t fly ash and 12 Mio t SO_2. In the decade from 1961 – 1970, a fly ash deposition of up to 3–8 t / ha * a is reported by Lux [21, 24], Neumeister et al. [30], Nebe et al. [31] and Klose and Makeschin [13]. To demonstrate the extend of deposition impact on the forest soils: pH (KCl) values in the humus layer and upper mineral horizon of the regional forest soils (mainly poor sandy brown soils and podzols) increased in that period from originally 3–4 up to 7–9 and a base saturation of up to 100% is still detectable (Fritz and Makeschin [3]). From the 1980s on, the introduction of fly ash filters lead to a more or less acidic deposition regime (NO_x, SO_2 / SO_x). After 1989, a strong reduction of fly ash emission went along with raising atmospheric N deposition in a magnitude of 28 – 45 kg/ha*a and changed completely the regional deposition characteristics (Hüttl and Bellmann [11], Marquardt et al. [29], Gauger et al. [8]).

Lux [21, 24] and Lux and Stein [26] have shown that the Dübener Heide deposition situation is characterized by a wind direction and distance dependent gradient (Fig 1), starting in the eastern part of the forest mainly at the power plants and chemical industries clustered in Bitterfeld and its surroundings (Gräfenhainichen, Zschornewitz). The different deposition fractions SO_2 and fly ash, which contains "black" (tertiary) carbon, alkali / earth alkali metal salts, heavy metals and silicium compounds, were distributed along this gradient according to their aggregate state and particle size (Lux [22, 24], Niehus and Brüggemann [32], Magiera and Stryszcz [27], Stryszcz [35]).

Stein [34] and Lux [24] used a visual classification of forest decline for distinguishing up to five deposition zones along this gradient, where the differentiation between zone 1 a and 1 b (zones of highest intensity) was given up later on. Lux [21] and Lux and Pelz [25] proposed to take these deposition zones as basis for forest management planning. The deposition zones were defined on the basis of a sample plot supported evaluation system: visible crown damages (forest decline classes) in 150 plots in medium aged Scots pine stands were assessed on single tree level, then compiled for stand level and "regionalized" by subsequent spatial aggregation of comparable stands to the deposition zones. Each deposition zone was assumed to be homogenous

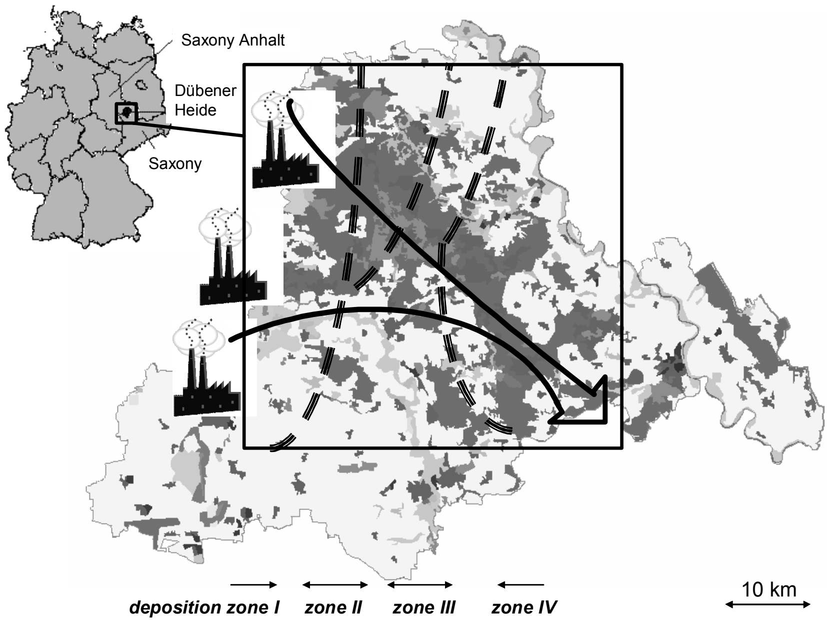

Figure 1: Schematic overview on the localization of Dübener Heide (black square) and the regional deposition gradient (black arrow), starting at the industrial sites in the East and following the dominant wind direction (map basis: CORINE LANDCOVER (CLC) 2000). The deposition zones are marked with scattered lines.

considering the deposition impact on forest growth and health, on specific risks and on possible silvicultural strategies and economic output. In deposition zone 1 e.g., Scots pine, the regionally dominating tree species, was heavily threatened by the alkaline fly ash deposition or dropped even totally out. In consequence, conversion efforts were concentrated to this zone and management intensity was reduced to deposition damage driven harvesting.

At the late 1980s, Herpel et al. [10] documented at heavily fly ash influenced sites a decrease of pH(KCl) of 0.4 units and base saturation decrease of 17% compared to the 1970s. This went along with incipient installations of fly ash filters at the main regional emitters. From 1988 to 2000, a further reduction of 0.7 pH-units was reported by Kurbel [18]. In the long run, a rapprochement of the site properties to the original regional characteristics is expected (Kopp [16], Kopp and Jochheim [17]).

As a result of deposition reduction, the health state of the forest and especially of Scots pine stands improved considerably since the 1990s. Actually, ample regeneration of noble hardwoods and European beech can be observed especially in the extremely fly ash influenced parts of the Dübener Heide. This however, might be a temporary phenomenon, whose sustainable development and ability to be integrated into regional silviculture must be evaluated beyond the background of the described re-acidification tendency.

1.2 ENFORCHANGE – assessment and evaluation of former deposition loads

"ENFORCHANGE" (Environment and Forests under Changing Conditions, www.enforchange.de) is a research project supported by the Federal Ministry of Education and Research (BMBF, Germany), which intends to assess the long-term effects of former depositions in two model regions in the New Lander, among them Dübener Heide. Based on this assessment, approaches are derived for better respecting this special situation and its expected impact on a number of forest services in forest management.

ENFORCHANGE started with the NULL-hypothesis, that the forest sites in the historically documented deposition zones in Dübener Heide are still different considering (a) their potentials such as nigh nutrient availability and (b) specific risks such as heavy metal release, which are relevant for forest management decisions (Makeschin and Fürst [28]). Furthermore, it was assumed that at least forest growth is still impacted by the spatial differentiation of the site properties along the former deposition gradient. Finally, ENFORCHANGE intended to model and regionalize ongoing ecosystem processes as basis for process-oriented forest management decisions.

Figure 2 resumes the ENFORCHANGE approach, how to come to an information pool providing spatially explicit time series data as basis for modelling and regionalization of ongoing ecosystem processes (Fürst et al. [5, 6]).

A number of 12 *key plots* was installed in the Dübener Heide along the historically documented deposition gradient. The key plots represent the major (terrestrial) soil type and stand type combinations in the region. They were preferably chosen at sites, where information from former deposition monitoring, forest health monitoring or growth and yield field trials could be involved. At the key plots, chemical and physical site properties are measured depth level-wise with focus on the humus layers and the upper mineral horizons and forest growth and yield characteristics are assessed.

The key plots were installed permanently for the total project duration, i.e. their geographical coordinates are documented, and geo-referenced to available GIS-information (site maps / geology, topography, etc.). Missing information, e.g. considering stand type development in a distinct deposition zone and on a distinct site type but in different age classes was collected at *satellite plots*, which are not permanently installed. Last but not least, field assessment of former fly ash deposition was carried out at the key plots and in a *regular sample grid* with two different grid densities (1*1 km^2 and 4*4 km^2) as interface to the regionalization of the actually detectable deposition load. Here, ferrimagnetic susceptibility was used, which describes the amount of magnetizable iron-oxides, a distinctive component of fly ash from coal combustion (Fürst et al. [4]). Ferrimagnetic susceptibility was also measured depth-level wise with focus on the humus layers and the upper mineral horizons.

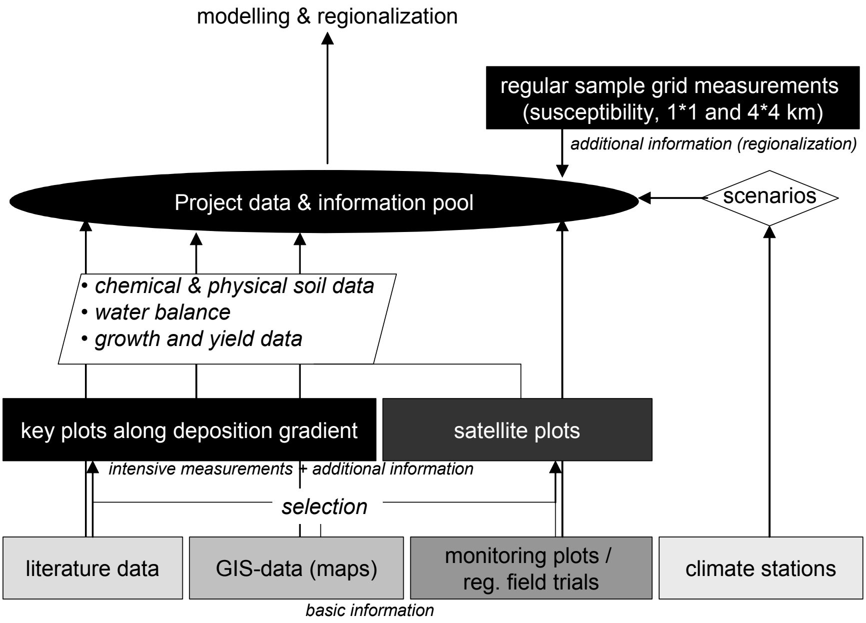

Figure 2: System of information bundling in ENFORCHANGE consisting of regionally available data, complementary information from own measurements and results from monitoring and regionalization.

Finally, information from *further regional monitoring and survey plots* (Level-I, Level-II monitoring, permanent soil monitoring sites, forest growth and yield field trials, climate stations), data from *literature analysis* and available *GIS-data* were integrated into the ENFORCHANGE information pool.

2 Long-term deposition impact on forest ecosystems – some first results

2.1 Deposition impact on the site potential

The analysis of chemical and hydrological site properties at the 12 key plots and the ferrimagnetic susceptibility based screening revealed that the differences along the historical deposition gradient still exist. They are mainly induced by former fly ash deposition. SO_2 deposition impact could not be detected anymore. The former deposition zones are still traceable by differences in the equipment with nutrients, especially base cations (Fig. 3a), by differences in physical humus properties, such as content of mineral matter in the humus layer (Klose et al. [14], Koch et al. [15]) and by different levels of ferrimagnetic susceptibility (Fig. 3b). Though, the borderlines of the former forest decline classification based spatial stratification and the actual spatial stratification according to chemical and physical characteristics are not completely identical.

Fig. 3a shows results from the multiple-regression based regionalization of the actual base saturation in the humus layer, Fig. 3b provides results from the kriging based regionalization of ferrimagnetic susceptibility (volume susceptibility) as indicator for the verifiability of fly ash deposition in the Dübener Heide.

Figure 3: a (left): Regionalization of base saturation in the humus layer. b (right): Regionalization of magnetic susceptibility in the humus layer.

Fig. 3a and b reveal major differences between the immediate vicinity to the former emitters in the eastern part of Dübener Heide and the western part, which is farthest from the emission sources. A differentiation of the part in between is possible, but the absolute values of the measured chemical and physical properties and their high variability do not support a clear separation into several deposition zones.

Actually, site potential differences, which are indeed relevant for differentiated forest management strategies, can only be ascertained for two zones: a "high influence zone" in up to 8–15 km distance to the former emitters and a "low influence zone" in more than 8–15 km distance. Fig. 4 (next page) introduces the results of a cluster analysis of the magnetic susceptibility values in the humus layers of the 12 key plots. The plots in a distance up to 8 and up to 15 km differentiate clearly from the rest. This finding is supported by similar cluster analysis results of further chemical and physical humus properties. The "high influence zone" is characterised by high base cation availability and base saturation in the humus layers, indicating a considerable nutrient pool far beyond from the natural level. The stock of extractable Ca in the humus layer and upper mineral soil until a depth of 30 cm e.g., reaches up to 4,000 kg / ha in the zone up to 8 km distance to the former emitters (Fritz et al. [3]). This is 10 to 20 times higher compared to the plots in a distance of 30 km, which are farthest to the former emitters and whose chemical properties represent more or less the original regional potential. Based on first tentative extrapolations, pH values might approximate to the original regional values in a time period of around 30–

50 yrs. Until now, it is however not foreseeable until when the high base cation potential can still be considered as silviculturally relevant factor. Considering the physical humus properties, a smaller fine pore volume going along with higher air capacity can be stated (Hartmann et al. [9]). In the "low influence zone", humus properties are much more dependent from the original site characteristics and the stand type.

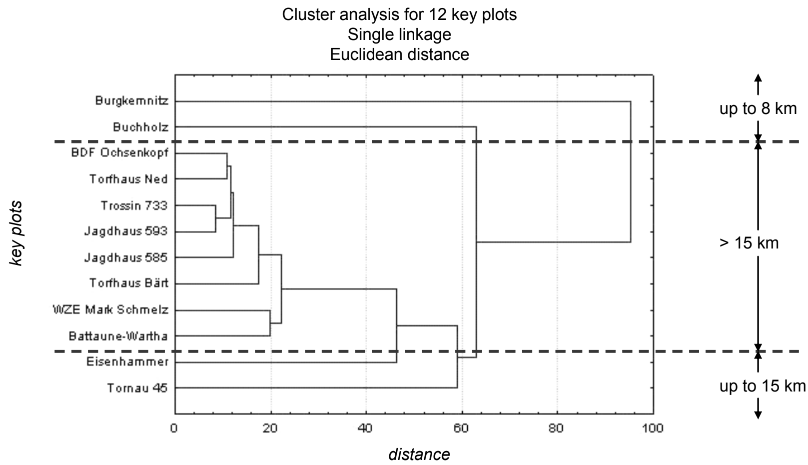

Figure 4: Results from a cluster analysis of magnetic susceptibility (laboratory measurement, humus layer) at the 12 key plots.

One of the major challenges for future management of the forests in Dübener Heide is the change of the regional climate. The down-scaling of global climate change scenarios for Dübener Heide proved that a reduction of the mean annual precipitation of up to 100 mm and an increase of the mean annual temperature of up to 3.5 °C can be expected. Even worse, the water deficiency during the summer period is estimated to become aggravated, which affects especially the regionally dominating poor sandy soils (Bernhofer et al. [1], Franke and Köstner [2]). Beyond that background, results from effects of fly ash deposition on hydrological properties of the humus layers become important. Fly ash can not only be considered as multi-nutrient fertilizer (Fürst et al. [7]), but can also impact the properties of the regionally dominating moder–raw humus forms with their high hydrophobicity. In contrast to former findings (Thomasius et al. [36], Katzur et al. [12]), Hartmann et al. [9] revealed that fly ash reduces the water repellency and hydrophobicity of the humus layers in the "highly influenced zone" and increases the water conductivity. At the same time, the available water for plant growth, expressed by the field moisture capacity becomes smaller due to the fly ash caused decrease of the fine pore volume. Additionally, a tendencially decreased depth of the root zone due to high nutrient availability at the humus layer and upper mineral horizon at fly ash influenced sites might amplify the future risk of drought stress (Thomasius et al. [36], Koch et al. [15], Klose et al. [14]).

2.2 Deposition impact on forest growth

Forest health and consequently growth were extremely affected by the former depositions. Comparing different time strata, (a) the late 1960s until 1980, (b) the 1980s, (c) the time from 1940 until 1991 and (d) the mid of the 1970s until 1991, Lux [23] and Hüttl and Bellmann [11] proved the enormous impact of the industrial emissions on the forest development in Dübener Heide. Fig. 5 compares the reaction in radial increment of Scots pine for the four time strata at the historically documented four deposition zones.

Figure 5: Reduction of the radial increment of Scots pine in four different time strata. In the 1980s, first fly ash filters were installed, whereas SO_2 emission was not yet stopped. Consequently, emission impact on forest health and growth became even worse (Lux [23], Hüttl and Bellmann [11]).

In tendency, radial increment was negatively impacted by the depositions at Dübener Heide. This resulted mainly from the extremely high SO_2 deposition: from 1965 to 1981, deposition showed the expected spatially differentiated impact on the mean radial increment, with decreasing intensity from deposition zone I (DI) to deposition zone IV (DIV). But afterwards, in the period 1982–1988, the spatial differentiation seemed to disappear. This period was characterized by beginning fly ash filtering, where at the same time, SO_2 deposition even increased. From the 1990s on, the last power plants were closed or were equipped with modern fly ash and SO_2 filtering techniques.

Comparing the radial increment tendencies between 1940–1991 and 1975–1991, where data were only available for zone I (DI) and zone IV (DIV), it can else be demonstrated that the influence of the deposition on differences in mean radial increment does not show the extreme spatial differentiation, which was assumed in the 1960s, the time, were the deposition zones were defined. The height growth tendencies followed comparable trends. This supports the impression that SO_2 deposition, which affected the forest over a wide area and not fly ash deposition with its more or less local importance, was the relevant agent. Of course, forests in the immediate vicinity of the former emitters reacted first and thus supported the stratification into four deposition zones at least in the first period of heavy deposition (Lux [22]).

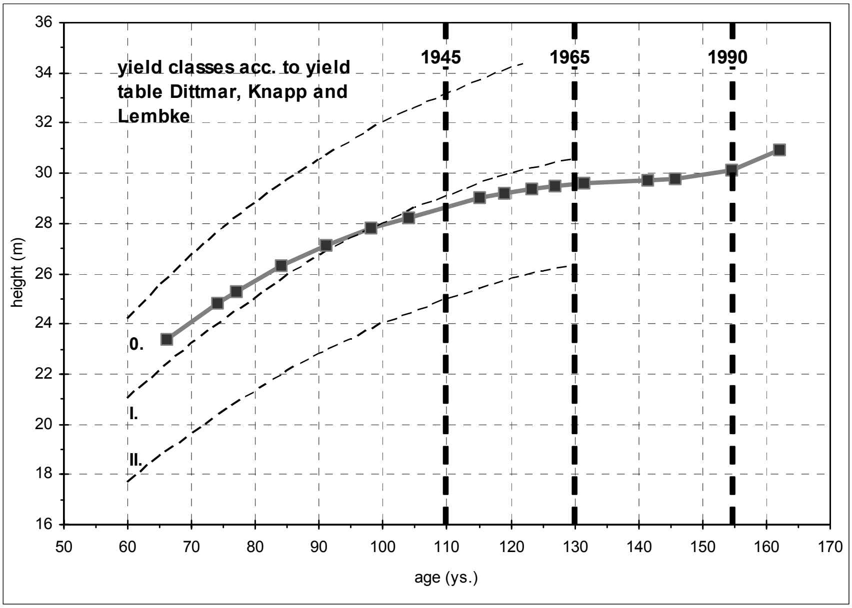

Figure 6: Trends of height growth development of a Scots pine stand (plot Tornau 45, 15 km distance to the emitters) before, during and after the deposition period. In the period from 1965–1990, a stagnation in height growth can be shown. After 1990, Scots pine restarted to grow in an age of even 155 yrs [data source: investigations of the former State Forest Research Centre Flechtingen, Saxony-Anhalt, 2005).

Investigations from intensive forest growth monitoring plots have proved that height growth of Scots pine recovered after the 1990s (Fig. 6).

Ongoing measurements at the ENFORCHANGE key plots show that nowadays, height and diameter growth of forests in Dübener Heide follow the general trend to be superior to the benchmark data in the regionally valid growth and yield tables (Pretzsch et al. [33]). This applies to all relevant stand types and especially for the regionally dominating Scots pine stands.

3 Conclusions and preview

After stopping the heavy depositions, the situation has been improved considerably for the regional forest ecosystem Dübener Heide. On the other hand, it should be highlightened that at least fly ash deposition effects can not only be considered as damaging factor. Fly ash deposition increased the available nutrient potential in the humus layers and the upper mineral horizons in the dominating poor sandy soils of Dübener Heide (Fürst et al. [5]). Furthermore, fly ash deposition tends to result in improved hydrological properties of the humus layers, a fact which gains in importance facing the problem of reduced water availability in the future. A visible consequence of the fly ash deposition caused improvement of the site potential is the ample noble hardwood and European beech regeneration, which can be observed in the zone of 8–maximally 15 km distance to the former emitters. Its potential to be integrated into silvicultural concepts must be discussed quite critically: considering the ongoing re-acidification of the fly ash influenced sites and the uncertainty how long the artificially increased nutrient potential is available for plant growth, the future regional suitability especially of noble hardwoods on sandy soils is doubtful. Furthermore, results of climate change modelling and regionalization suggest a severe decrease of regional precipitation, which amounts to almost 20–25% of the actual rainfall. This supports a turn back to drought resistant tree species such as Scots pine and Oak, which however are not able to benefit from the actually increased nutrient potential.

Some first results on the analysis of heavy metal loads in the regional forest sites as a result of fly ash deposition revealed total net values which exceed by far (up to 5-times) the thresholds given by national regulations for heavy metal values such as LABO [19]. Critical values however are more or less restricted to the immediate vicinity of the former emitters, where still high pH-values confine the mobility of endangering heavy metals and limit their possible discharge into the ground water. Prolonging the actual re-acidification tendency of the regional sites of 0.7 pH units within around 12–15 years after the closure of the former emitters and the additional acidification impact of regional N-deposition, a supposable potential of ground water quality impact can be expected in the next 50 ys. Conversion of the Scots pine and Oak dominated forests with European beech could be a countermeasure. Facing the problem of reduced water availability, this demands however for adapted conversion and transformation concepts with respect to the potential of different stand structures and tree species mixture types to reduce the evapotranspiration.

Therefore, model coupling approaches in ENFORCHANGE, linking forest growth (SILVA) with nutrient and water balance (BALANCE) and impact of forest structure and tree species composition on stand climate (HIRVAC) help to test and consider the above outlined multiple aspects in regional silvicultural planning. The future challenge will consist in using the still existing deposition driven site potentials under new climate conditions and to find strategies for responding on possible environmental risks.

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FOREST ECOSYSTEM DEVELOPMENT UNDER A CHANGING ENVIRONMENT & CONCLUSIONS FOR FOREST MANAGEMENT

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Summary: *Lowland forest ecosystems in Saxony and Saxony-Anhalt were impacted for more than a century by heavy industrial pollution. Especially the so called "Dübener Heide", the largest forest area at the border between Saxony and Saxony-Anhalt was affected by depositions from the most important industrial triangle of the former GDR Leipzig-Halle-Bitterfeld. At the same time, management of Dübener Heide underwent high pressure for ensuring the timber supply and the recreation of citizens in this congested urban and industrial region.*
Regional silvicultural management decisions, which were confronted to both, increasing industrial deposition and increasing demand in biomass production, led to large-scale establishment of pure Scots pine stands. These were confronted to extremely high amounts of alkaline deposition (18 Mio. t fly ash) and acidic depositions (12 Mio. t. SO_2*) from regional power plants and chemical industry. This disastrous combination led finally to the break-down of large parts of the regional forest ecosystems and entailed high efforts for conversion and restoration of the forests. Nowadays, a recovery of the forest ecosystems can be observed, which is indicated by large scale re-establishment of original site properties and the original ground vegetation types and which is accompanied by tree growth, which exceeds by far the original regional level. However, climate change poses new challenges to these forest ecosystems. A reduction of 20 % of the actual precipitation and an increase of the mean annual temperature of 3.5 °C are expected for the next 100 years. Beyond this background, the stability and resilience of the actual forest ecosystems must be questioned critically. First studies however show, that the capability of the actual forest ecosystems in buffering such changes allows concluding that changing climate conditions can be responded by respective silvicultural management measures.*
The article introduces (a) the reactions of the exemplary forest ecosystem Dübener Heide on changing environmental frame conditions, where a complex study was conducted in the frame of the research project ENFORCHANGE (www.enforchange.de), supported by the German Federal Ministry of Education and Research. (b)Conclusions on possible management consequences and future challenges are drawn.
Keywords: *Forest ecosystem development, industrial deposition, ecosystem processes, process-oriented forest management.*

INTRODUCTION

Forest ecosystems all around Europe were faced since the very first settlements to an intensive impact of human activities, which led early to changes in the forested area itself and influenced among others the tree species distribution by selective use, furthering or fighting of tree species. Furthermore, human activities influenced the environmental frame conditions under which forests grow. Most actual examples are large-scale deposition of industrial exhalations, especially SO_2, which led to severe forest decline effects up to the 1990ies, ongoing N deposition from agriculture and traffic, which provoke nutrient imbalances and last but not least climate change as the main driver for the actual development of European forest ecosystems. Lowland forest ecosystems are particularly sensible to such impact, as they grow mainly under dry conditions and as their growing area is mostly restricted to sites with unfavourable conditions for other land-use forms. Furthermore, they are often - as a result of favourable topographic conditions - situated near to densely settled and used areas and thus are confronted today to widely spread demands from regional society. Fig. 1 records as an example 200 years history of human impact on the so called Dübener Heide, a well investigated Lowland forest ecosystem in North-Eastern Germany.

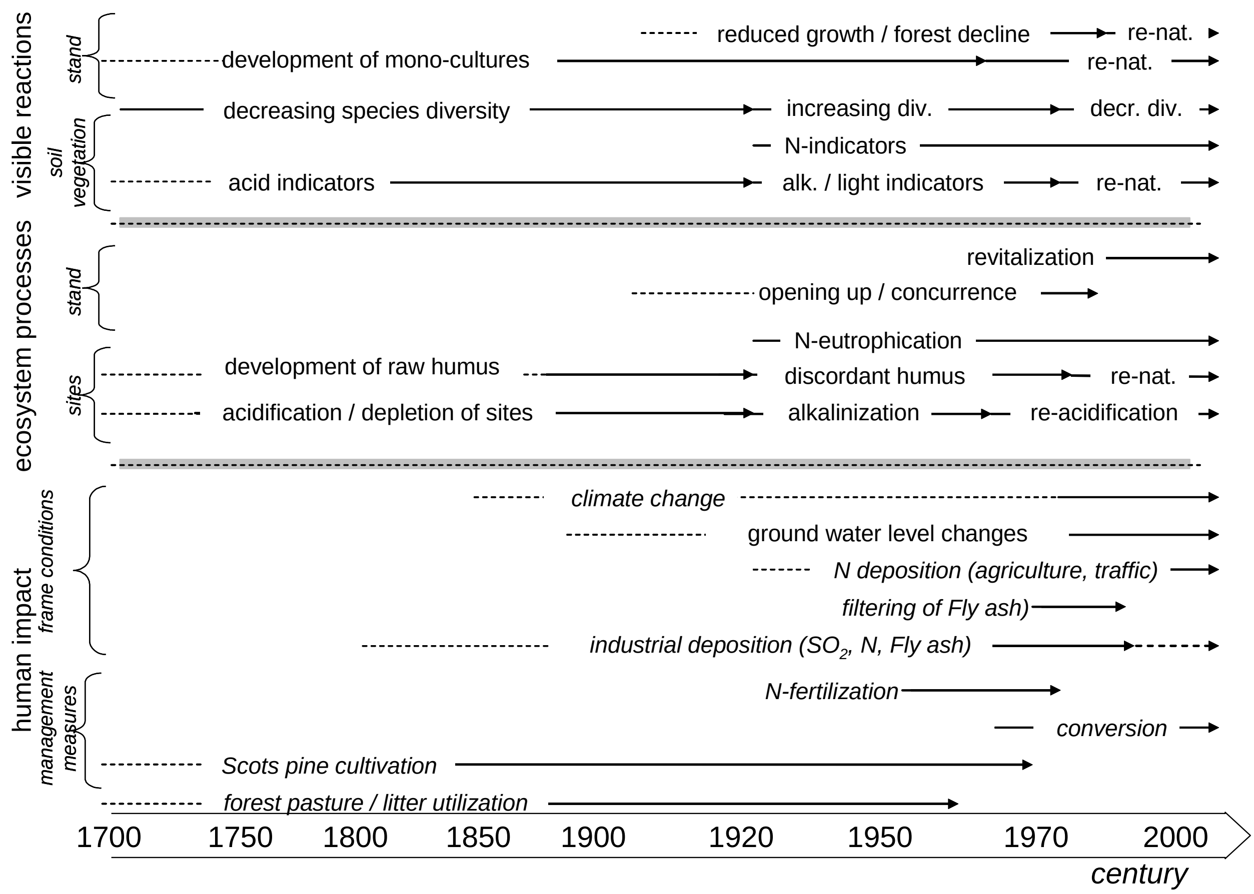

Figure 1. History of human impact on the Lowland forest ecosystem Dübener Heide (acc. to Fürst et al., 2007). Main processes and visible reactions are resumed. Arrows show the duration of the impact factors, processes and ecosystem reactions. Dashed lines are used when the exact start of an impact, an ecosystem process or a visible reaction is not known. The impact factors shown in Fig. 1 are separated into impact by management measures and impact by change of the frame conditions for the ecosystem development. Ecosystem processes are separated into site processes and processes on stand level. Visible reactions are shown for the soil vegetation and the stand level. (alk. = alkaline, div. = diversity re-nat. = re-naturalization).

In Dübener Heide, systematic cultivation of Scots pine (Pinus sylvestris, L.) started from the middle of the 18th century on. This led in combination with local forest pasture and litter utilization to poor Scots pine forests, which were characterized by acidophilic soil vegetation groups (dwarf shrubs, mosses, lichens) and raw humus forms (Bendix, 2001).

Due to the regional lignite occurrence, industrialization started early in the immediate vicinity of Dübener Heide, but was limited at the beginning to small power plants with local deposition effects. From the 1920s on, an intensification of industrial energy production led finally to incredibly high deposition loads, which amounted from 1910 – 2000 to 18 Mio. t fly ash and 12 Mio t SO_2. N deposition from industry and agriculture amounted up to 300 kg / ha * a, and was even surpassed in the 1960ies by local N fertilization of up to 990 kg / ha. Fly ash was deposited along a characteristic distance and wind direction in dependent gradient, whereas SO_2 and N deposition were more evenly distributed (Lux, 1965; Klose and Makeschin, 2004).

Deposition and fertilization dependent vegetation types appeared in the Dübener Heide from the 1920/1950ies on. Basophilic and light preferring species started to settle in the immediate vicinity of the former power plants. They indicated alkaline dust deposition and the hereby provoked opening-up and die back of the Scots pine stands. Raising regional vegetation diversity and high species diversity near to the power plants went along with a decreasing vitality of the Scots pine stands. This process was accompanied by artificially elevated pH (KCl) values (up to 7) and base saturation (up to 100 %) in the humus layer and upper mineral horizons. Based on a visual assessment of forest decline, up to four deposition zones were distinguished, which formed the basis for a spatially differentiated ecosystem management intensity. Efforts to convert the Scots pine stands started from the 1970ies on in the zones with heavy forest decline phenomena and they were widened to the total area from the 1980ies until now (Lux, 1964 a, b; Kopp, 2003).

From the 1980s on, fly-ash filters were introduced and the still increasing acidic deposition components NO_x, SO_2 / SO_x were no longer buffered by alkaline dusts. Herpel et al. (1995) documents for some sample plots in Dübener Heide a decrease of pH(KCl) of 0.4 units and base saturation decrease of 17 % until 1988 compared to the situation in the 1970s. From 1988 to 2000, a further reduction of 0.7 pH-units was reported by Kurbel (2002).After 1989, SO_2 and fly ash deposition were more or less stopped, whereas N deposition in a magnitude of 28 – 45 kg/ha*a from animal husbandry and traffic amplifies the long-term effects of the former N-deposition and N-fertilization in terms of dense grass layers and nitrophile soil vegetation. However, N-eutrophication was balanced to a certain degree by ample ground vegetation development, improved tree growth, and vital natural regeneration of mainly noble hardwoods (Lux, 1964 b). Kopp (2003) expects also a re-development of humus forms, which represent the original site potential.

Nowadays, re-immigration of acid indicators and disappearance of the dense grass layers are observed due to vanished base deposition and ongoing acidic deposition (Augustin et al., 2005). The health of regional forests has improved as a result of lower industrial deposition and conversion, but they are still threatened by increasing N deposition (Materna & Fiedler, 1994).

One of the major challenges for future management of the forests in Dübener Heide is the change of the regional climate. Here, considerable decrease of precipitation and increase of temperature are expected. This raises the question, if the actual tree species composition and noble hardwood regeneration are well adapted for the future.

MATERIALS AND METHODS - FOREST ECOSYSTEM STUDY ENFORCHANGE

"ENFORCHANGE" (Environment and Forests under Changing Conditions, www.enforchange.de) is a research project supported by the Federal Ministry of Education and Research (BMBF, Germany).Within the project, long-term forest ecosystem reactions and processes as a result of changing frame conditions and the consequences for a sustainable forest ecosystem management are studied.

ENFORCHANGE tested the hypothesis that forest sites in Dübener Heide are still impacted considering potentials such as nutrient availability and water balance as well as specific risks such as heavy metal release. Furthermore, it was assumed that forest growth is still superposed by the spatially differentiated effects of former depositions along a historically documented regional deposition gradient. To support forest ecosystem management, ongoing ecosystem processes under special consideration of climate change effects are modelled and finally up-scaled from a number of sample plots by statistic regionalization approaches. Figure 2 resumes the monitoring - modelling - management information and support chain, which is realized in the project.

A combination of available GIS-data, data from climate and environmental monitoring, field trials and own measurements is used to feed the process model BALANCE, which is coupled with the stand climate model HIRVAC and the tree growth model SILVA. The model output delivers information on the effects of changing environmental frame conditions and different management alternatives on ecological and economic parameters, which are given as feed-back to the user. Two reference regions serve for the validation of the modelling results and the development of process-regionalization approaches.

12 project plots were installed in Dübener Heide along the regional deposition gradient. These plots represent major (terrestrial) soil type and stand type combinations in the region and are chosen from a pool of 150 study plots, which was established in the 1960ies. At the key plots, chemical and physical site properties including magnetic susceptibility are measured depth level-wise with focus on the humus layers and the upper mineral horizons, and forest growth and yield characteristics are assessed. The project plots deliver the data base for the multiple-regression based regionalization of environmental data. The plot-wise data set is complemented by grid-based screening of spatial differentiation in magnetic susceptibility with two different grid densities (1*1 km^2 and 4*4 km^2). Magnetic susceptibility describes the amount of magnetizable iron-oxides, a component of fly ash from lignite combustion. By correlation with heavy metal or base

cation content, this indicator supports the spatial transfer of respective plot-wise measurements in regions with high deposition amounts. In the project context, magnetic susceptibility is used, to identify spatial strata, which are differentiated (a) by the intensity of former deposition load and (b) by the speed of ongoing processes, such as re-acidification and base cation leaching. These strata are proposed to be used for differentiated handling in regional forest management.

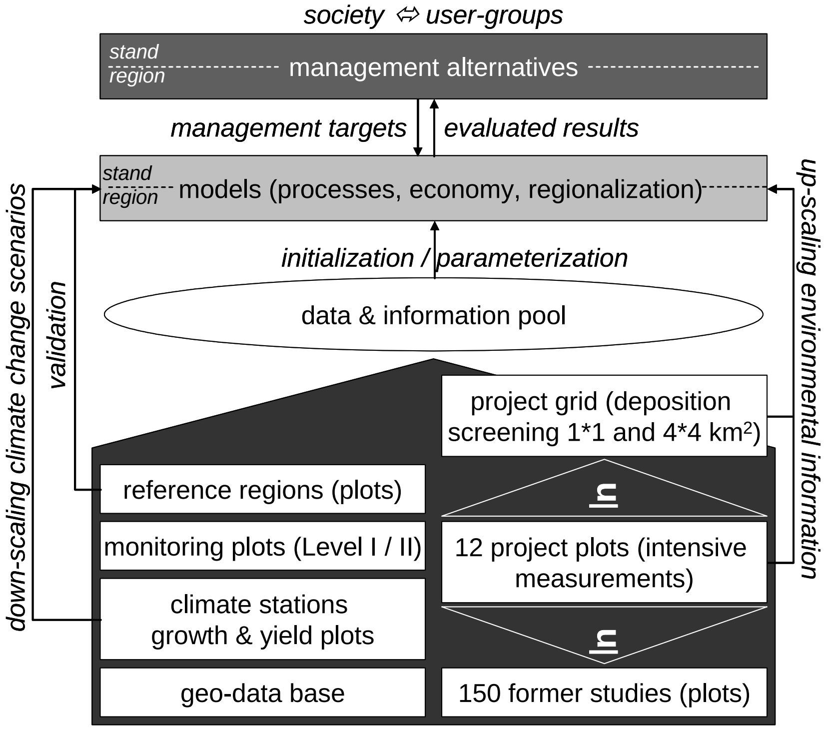

Figure 2. Monitoring - modelling - management information and support chain in the project ENFORCHANGE.

RESULTS

Deposition impact on the site potential

The assessment of chemical and physical parameters at the project plots and the screening of magnetic susceptibility revealed that the spatial differentiation along the historically documented deposition gradient still exists. This gradient is mainly driven by former fly ash deposition. SO_2 deposition impact could not be detected anymore and N deposition affects all parts of Dübener Heide. Differences in the nutrient equipment and the pH values as well as differences in physical humus properties, such as content of mineral matter in the humus layer (Klose et al., 2002; Koch et al. 2002) and last but not least different levels of magnetic susceptibility support a stratification of maximally three spatially distinct areas instead of four as proposed by Lux (965): in up to 8 km distance to the former emitters, pH (KCl) values and base saturation are clearly elevated far beyond the original potential of the sites. Here, fly ash impacts also the physical properties of the regionally dominating raw humus forms with their high hydrophobicity. Hartmann et al. (2007) revealed that fly ash reduces the water repellency and hydrophobicity of the humus layers and increases the water conductivity. At the same time, the available water for plant growth, expressed by the field moisture capacity becomes smaller due to the fly ash caused decrease of the fine pore volume. Additionally, a tendencially decreased depth of the root zone due to high nutrient availability at the humus layer and upper mineral horizon at fly ash influenced sites might amplify the future risk of drought stress (Koch et al., 2002; Klose et al., 2002). In a zone up to 15 km, only pH-values are elevated and in a distance of more than 15 km, no measurable effects could be found.

Based on first tentative extrapolations, pH values tend to approximate the original regional values in a time period of around 30 - 50 ys, where the re-acidification rate in the zone up to 8 km distance is 5 - 10 times higher compared to the zone in more than 15 km distance. In the zone up to 8 km distance, the stock of extractable Ca in the humus layer and upper mineral soil until a depth of 30 cm reaches up to 4,000 kg / ha (Fritz & Makeschin 2007). This is 10 to 20 times higher compared to the plots in a distance of 30 km, which are farthest to the former emitters and whose chemical properties represent more or less the original regional potential. Until now, it is not foreseeable, until when base cation leaching scales down the extremely high base cation potential and especially the Calcium stock in the zone up to 8 km distance to the regionally characteristic level.

While the plot-wise measurements were arranged along the formerly documented deposition gradient, which assumed a strong influence of the power plant "Zschornewitz" in the immediate vicinity of Dübener Heide, the magnetic susceptibility screening was based on regular grid measurements. These measurements revealed (1) that the spatial effect of the deposition went especially at the humus layers much farther than proved by the assessment of chemical and physical properties at the project plots (Fig. 3 a). Furthermore, the measurements highlightened that (2) the impact of the industry site Bitterfeld, which is situated farther from Dübener Heide was clearly stronger than originally believed (Fig. 3 b).

Deposition impact on forest growth

Forest health and growth were extremely affected by the former depositions. Table 1 shows exemplarily the volume increment ($m^3/ha*a$) and volume increment reduction (% of reference value in zone IV) along the regional deposition gradient (Lux 1964 b modified, 1965).

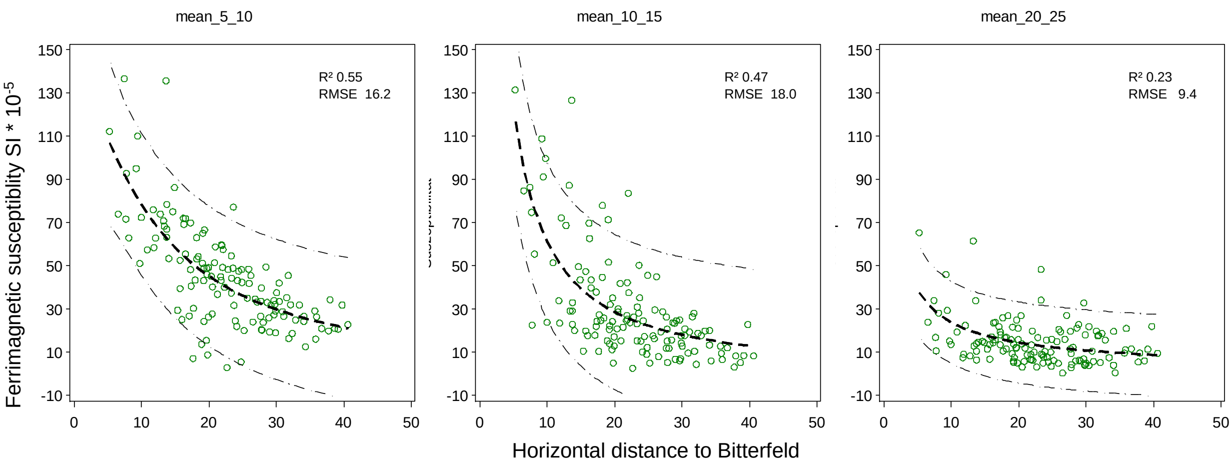

Figure 3a. Spatial range of detectable fly-ash deposition in the depth levels 5 - 10 cm, 10 - 15 cm and 20 - 25 cm, mean values. The correlation between distance and magnetism decreases from 5 - 10 cm to 20 - 25 cm. Fly ash deposition affected mostly the upper 0 - 15 cm.

Comparing the late 1960ies until 1980 with the 1980ies, deposition showed only at the first time period the expected spatially differentiated negative impact on tree growth, with decreasing intensity with increasing distance to the power plants. In the period 1982 - 1988, the former spatial differentiation disappeared. This period was characterized by beginning fly ash filtering, where at the same time, SO_2 deposition even increased. Comparing tree growth parameters between 1940 - 1991 and 1975 - 1991 nearest and farthest to the power plants underpins that the influence of the deposition does not show the extreme spatial differentiation, which was assumed in the 1960ies, the time, were the deposition zones were defined. Of course, forests in the immediate vicinity of the former emitters reacted first on the emissions and thus supported the stratification into four deposition zones at least at the beginning of heavy deposition (Lux, 1966). Later on, the extremely high and spatially widely distributed SO_2 deposition might have been the driving factor for the observed large scale impact on tree growth (Hüttl & Bellmann, 1999) From the 1990ies on, the last power plants were closed or were equipped with modern fly ash and SO_2 filtering techniques. Investigations from intensive forest growth monitoring plots have proved that height growth of Scots pine recovered after the 1990ies. Ongoing measurements at the ENFORCHANGE key plots show that nowadays, height and diameter growth of forests in Dübener Heide follow the general trend to be superior to the benchmark data in the regionally valid growth and yield tables. This applies to all relevant stand types and especially for the regionally dominating Scots pine stands.

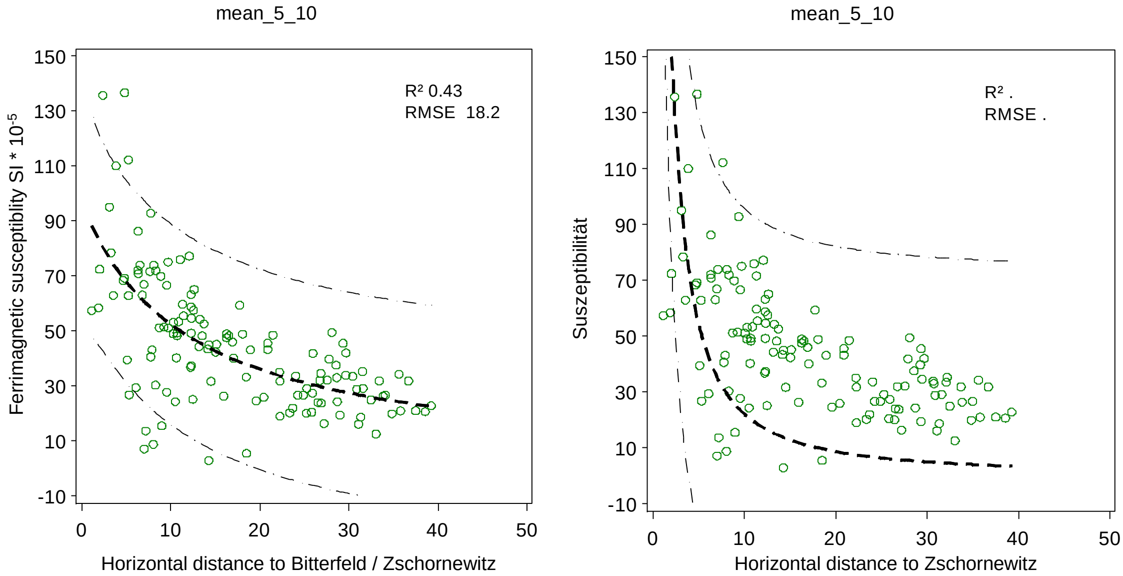

Figure 3 b. Spatial influence of fly ash at the depth level 5 - 10 cm in dependence from the distance to Bitterfeld and Zschornewitz. The spatial correlation between magnetic susceptibility values and horizontal distance is lower for Zschornewitz and the spatial range of detectable fly ash deposition is smaller compared to the impact of Bitterfeld.

Table 1. Volume increment (m^3/ha*a) and volume increment reduction (% of reference value in zone IV) in the deposition zones. DI highest, DII high, DIII medium, DIV low deposition.

Deposition zone		**DI**	**DII**	**DIII**	**D IV - regional reference value**
growth parameters	height (m/a)	0,09	0,15	0,16	*0,23*
	basal area (m^2/ha*a)	0,38	0,53	0,53	*0,64*
	volume (m^3/ha*a)	4,6	5,9	6,2	*8*
growth reduction (referred to zone D0)	height growth reduction (%)	-61	-35	-30	*0*
	basal area increment (%)	-41	-17	-17	*0*
	volume increment (%)	-43	-26	-23	*0*

At a glance, fly ash deposition effects on Dübener Heide can not only be considered as damaging factor, but resulted in double-edged effects on regional forests: positive aspects are a higher nutrient availability (base saturation) and cation exchange capacity and an improvement of physical humus properties like texture and sorption capacity. On the other hand, a disturbance of ground vegetation composition and organic matter decomposition can be observed (Kopp, 2003). A visible consequence of fly ash deposition is the ample noble hardwood and European beech regeneration, which can be observed in the zone of 8 - maximally 15 km distance to the former emitters. Its potential to be integrated into silvicultural concepts must be discussed critically beyond the background of ongoing re-acidification and worsening of climate conditions. Especially re-acidification has a negative impact on the stability and development of the fly ash-adapted stand types and the quality of by-products like water, biodiversity and socio-economic functions.

Climate change impact and forest growth

The down-scaling of global climate change scenarios for Dübener Heide proved that a reduction of the mean annual precipitation of up to 100 mm and an increase of the mean annual temperature of up to 3.5 °C can be expected. Even worse, the water deficiency during the summer period is estimated to become aggravated, which affects especially the regionally dominating poor sandy soils (Goldberg et al., 2007; Franke & Köstner, 2006). The temperature increase and precipitation decrease will not follow a regular trend. Until 2010 an increase of precipitation and small temperature decrease is expected, while from 2010 on a clear worsening of climate frame conditions for forest ecosystem development is predicted.

Modelling of the impact of climate change impact on growth parameters revealed that growth under the recent regional climate conditions is highest. Taking the IPCC scenario A2 and European beech stands as an example, height growth reduction can reach up to 4 m during the stand life, which means a decrease of one yield class in the regional yield tables with respective consequences for future timber production. This applies especially for the young stands, while the consequences in elder stands are considerably lower.

On the other hand, forest ecosystems are able to buffer the predicted decrease of precipitation and increase of temperature almost completely considering inner stand climate. This depends from the stand type: Scots pine stands aggravate the predicted development by their high evapotranspiration rate and low Albedo. Mixed stands or pure broadleaved stands reduce the admission of solar radiation to the soil surface and thus are characterized by clearly lower evapotranspiration rates and temperature compared to open land climate. The ability to regulate the stand climate of mixed and well structured stands is the highest and countervails against the predicted shortening of precipitation and temperature increase (Fischer et al., 2008).

DISCUSSION - CONSEQUENCES FOR MANAGEMENT

Environmental frame condition changes as described for Dübener Heide trigger complex ecosystem processes. Forest management planning should adapt to these ongoing processes instead of basing decisions to descriptions of the actual status, which are delivered by forest inventory and site classification (Schoenholtz et al., 2000; de Vries et al., 2003). Process-oriented forest management planning respects natural dynamics in (forest) ecosystem management on landscape level. In Dübener Heide e.g., fly-ash deposition provoked a homogenisation of site quality differences, and a differentiation of formerly comparable sites and vegetation types along the regional deposition gradient. These modifications are superposed by N deposition and climate change.

The realization of process-oriented forest management planning demands to identify main forest ecosystem processes (see Fig. 1). Development targets and management measures should be based on area-related process-indicators (vegetation types, change ratios in chemical and physical parameters) as discussed by Scheuner and Makeschin (2005), Kopp (2003), and Schoenholtz et al. (2000). This allows for a better appraisal and consideration of future on- and off-site potentials and risks in strategic development targets and short-term management measures.

In a second step, a regionalization of process-information (speed / intensity, direction) based on the process-indicators and results from process modelling should be realized. Respective regionalization techniques for up-scaling of processes from monitoring and inventory plots are still under development. The regionalization of process parameters is a major topic in most landscape related sciences (Diekrüger et al., 1999; Volk & Steinhardt, 1999). Some promising approaches were yet presented by Zirlewagen & v. Wilpert (2004) and Saborowski & Jansen (2002).

Finally, process-homogeneous planning units must be identified, which allow for drawing process-sensitive and spatially differentiated decisions on type and intensity of management measures. Although the delineation of process units is a general aim in landscape ecology (Haber, 2005), no generalizeable approach has been developed so far. The dynamics within a planning unit and the spatial relation between different planning units under regionally changing management concepts or local variations of environmental changes are of special interest. They should be pursued and tested considering their practical suitability for spacious application. This would support a statistically valid process-oriented forest management, which could easily be integrated into ecological landscape management approaches on different scale levels (Volk & Steinhard 1999).

Integrating processes into management concepts could help to avoid unreasonable investments, e.g. furthering of tree species and stand structures, where the future development provokes ecological risks or financial losses. In Dübener Heide, spatial differentiation of re-acidification rate and base cation leaching demands for respective silvicultural responses. In the nearest distance to the former emitters, natural (noble) hardwood regeneration can be used as cost-efficient countermeasure, as the elevated base cation stock is expected to be available for more than one forest generation. In medium distance, it is expected that the actually still improved site potential will soon be lost. At the same time, natural hardwood regeneration occurs less frequently in this zone, while Scots pine regeneration struggles still with grass dominated soil vegetation and thick moder - raw humus layers. Conversion efforts could help to slow down the re-acidification, but are faced to the problem of future water scarcity, which in this case cannot be compensated by the positive effects of fly ash on hydrological humus properties and high nutrient availability. Fly ash deposition brought also a higher heavy metal input into the sites, where the mobility is expected to increase with ongoing re-acidification. Consequently conversion with tree species, which do not support re-acidification is recommended, where magnetic susceptibility values let expect a locally higher fly ash input. In the far distance zone, fly ash deposition and re-acidification ratio are low. With regard to climate change, the actual Scots pine dominated stands can be considered as well adapted and no additional efforts are demanded.

Silvicultural management in both parts of Dübener Heide, in Saxony and Saxony-Anhalt starts to consider the idea of a process-oriented forest management by leaving the stand type as decision basis and replacing stand type by "development type" with s close reference to indicators for actual ecosystem and site development trends.

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Development of forest ecosystems after heavy deposition loads considering Dübener Heide as example—challenges for a process-oriented forest management planning

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Abstract

The article reviews in its first part literature on the development of forests in the lowland region Dübener Heide (Saxony, Central Germany). The Dübener Heide acts as example for regions in Central and Eastern Europe, which are undergoing a dramatic transformation from heavily to moderately affected by air pollution. Main on- and off-site factors and their influence on forest vegetation and processes are described. In the following, regional approaches for dealing with spatial influence of deposition in forest management planning are introduced and a concept for integrating ongoing processes into a process-oriented forest management is described. Additionally, the special suitability of the presented approach compared to classic forest management planning is discussed. Requirements and research needs for an application of the presented approach are noted. The article is based on an approach, which is pursued in the regional research project ‘‘Environment and Forests under Changing Conditions’’ (ENFORCHANGE). ENFORCHANGE is running in two regions in former Eastern Germany: ‘‘Dübener Heide’’ (Saxony/Saxony-Anhalt) and Upper Lusatian region (Saxony). Major aim of the project is the development of improved forest management planning concepts including landscape management and land-use optimization in former industrial hotspots.

Keywords: Deposition; Environmental changes; Process-oriented forest management planning; Process indicators; Regionalization

1. Introduction

Forests are major air pollutant receptors due to high surface roughness and long rotation period (Ulrich, 1983; Strzyszcz and Magiera, 1998, 2001; Strzyszcz, 1999). Changing deposition regime and environmental changes like climate shift are forcing forest ecosystems to adapt to new frame conditions. They trigger complex ecosystem processes, which should be considered in forest management planning. Especially regions, which are subjected to a dramatic transformation from heavy to moderate air pollution like the former industrial hotspots in Eastern Germany, demand for a process-oriented forest management concept (see Section 2, Lux, 1965; Jensen et al., 1996; Schoenholtz et al., 2000; de Vries et al., 2003).

Process-oriented forest management planning can be based on the ecosystem management framework concepts discussed by Rauscher (1999) and Rauscher et al. (2000) as well as Bormann et al. (1994). Additionally, it should meet with the intention of respecting natural dynamics in (forest) ecosystem assessment and management on landscape level as described by Jensen et al. (1996). When using the term (forest) ecosystem management in the following, the definition of Wagner (1995) is preferred, who suggests that ‘‘ecosystem management is the skilful manipulation of ecosystems to satisfy specified societal values’’. Jensen et al. (1996) highlighted that this definition is especially comfortable, ‘‘because it does not imply that optimization of biodiversity, ecosystem health and integrity, and commodity production must be included in every ecosystem management effort’’. For forest (eco)systems in intensively settled and managed regions as presented in Section 2, this understanding of ecosystem management seems to be particularly suitable: it turns away from the approach to protect native ecosystem integrity as proposed by Grumbine (1994) and picks up a more anthropocentric resource management idea, which of course respects the basic principles of a sustainable forest management (SFM) (Anonymous, 1995). The aspect of

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''planning'' in the presented process-oriented forest management planning was chosen in order to emphasize the claim of placing management strategies into a proper, i.e. spatially explicit context based on the concept of ''coordinated planning unit maps''. Coordinated planning unit maps are used in multi-scale ecological assessment to delineate ecosystems for specific planning or reporting needs on the scale levels of national resource planning, area planning and project planning to facilitate multi-agency, multi-ownership and multi-government collaboration in monitoring and land-use planning (see Jensen and Everett, 1994; Jensen et al., 1996).

The presented approach is pursued in the regional research project ''Environment and Forests under Changing Conditions'' (ENFORCHANGE), which is realized in two regions in former Eastern Germany: ''Dübener Heide'' (Saxony/Saxony-Anhalt) and Upper Lusatian region (Saxony). The aim of the project is the development of improved, i.e. process-oriented forest management planning concepts including landscape management and land-use optimization in former industrial hotspots.

The presented article intends (i) to identify the main historical on- and off-site factors for forest ecosystem development in the region Dübener Heide, their impact on forest ecosystem processes and the existing regionalization and management concepts for the disturbed ecosystem. (ii) Based on this background information, a process-oriented forest management planning concept is introduced and discussed.

2. Forest ecosystem development in Dübener Heide

Forest ecosystems in Eastern Germany are still influenced by long-term effects from former deposition produced by unfiltered lignite combustion in Czech, Polish, and German power plants until the early 1990s. In the early 1960s, two trans-regional deposition hot spots were identified in Eastern Germany: (1) a lowland transect between Chemnitz/Leipzig/Magdeburg, and (2) the Lusatian/Spree region along the Polish border between Frankfurt/Oder-Lübben-Cottbus-Hoyerswerda-Görlitz (Lux, 1965, 1976) (see Fig. 1).

The deposition regime in region (1) was characterized by lignite with high S content. The main impact factors were sulphur and heavy metal deposition followed by nitrogen and potassium. Additionally, fluorides, chlorides, as well as complex herbicides from chemical industry were locally important pollutants. Region (2) was mainly influenced by the combustion of lignite with lower S content. The resulting environmental damages (e.g. forest decline) were appraised as slightly less serious compared to region (1) (Lux, 1976; Kunze et al., 1996).

Fig. 2 resumes for the comparably well investigated lowlands (Dübener Heide), the history of anthropogenic influence on regional forests, main effects on forest vegetation and (visible) system reactions and processes according to Lux (1964a,b, 1965), Lux and Stein (1977), Konopatzky (1995), Amarell (1997) and Bendix (2001). The intention of Fig. 2 is to highlight the interrelations between the two impact factors forest management and deposition changes and the resulting forest ecosystem development.

The impact factors shown in Fig. 2 are (a) on-site factors and their effects (light grey), i.e. forest management measures, (b) off-site factors and their effects (dark grey), i.e. mainly industrial emission and climate change and (c) combined effects of on- and off-site factors (hatched grey).

2.1. History and development in the period 18th century until 1920s

From the middle of the 18th century, raising cultivation of conifers, especially Scots pine (*Pinus sylvestris*, L.) locally combined with forest pasture and forest litter utilization resulted in the development of heathland Scots pine forests. These forests had been dominated more or less by broadleaved species like oak, European beech, lime, and hornbeam before. However, a large scale change of ground water level as a result from active and now abandoned open cast mines superposed the original site and vegetation characteristics. Real start, end and intensity of the impact of this change are not well described (Reiche, 2001). The artificial Scots pine forests (''Kiefernforstgesellschaften'') in the region were characterized by acidophilic soil vegetation groups (dwarf shrubs, mosses and lichens) with comparably low species diversity and occurrence of poor humus forms like raw humus (Amarell, 1997; Bendix, 2001).

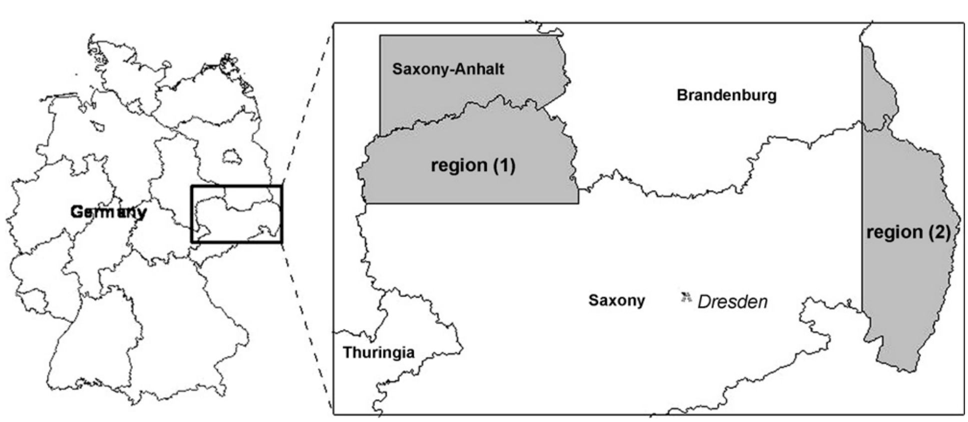

Fig. 1. Localization of region (1) and (2).

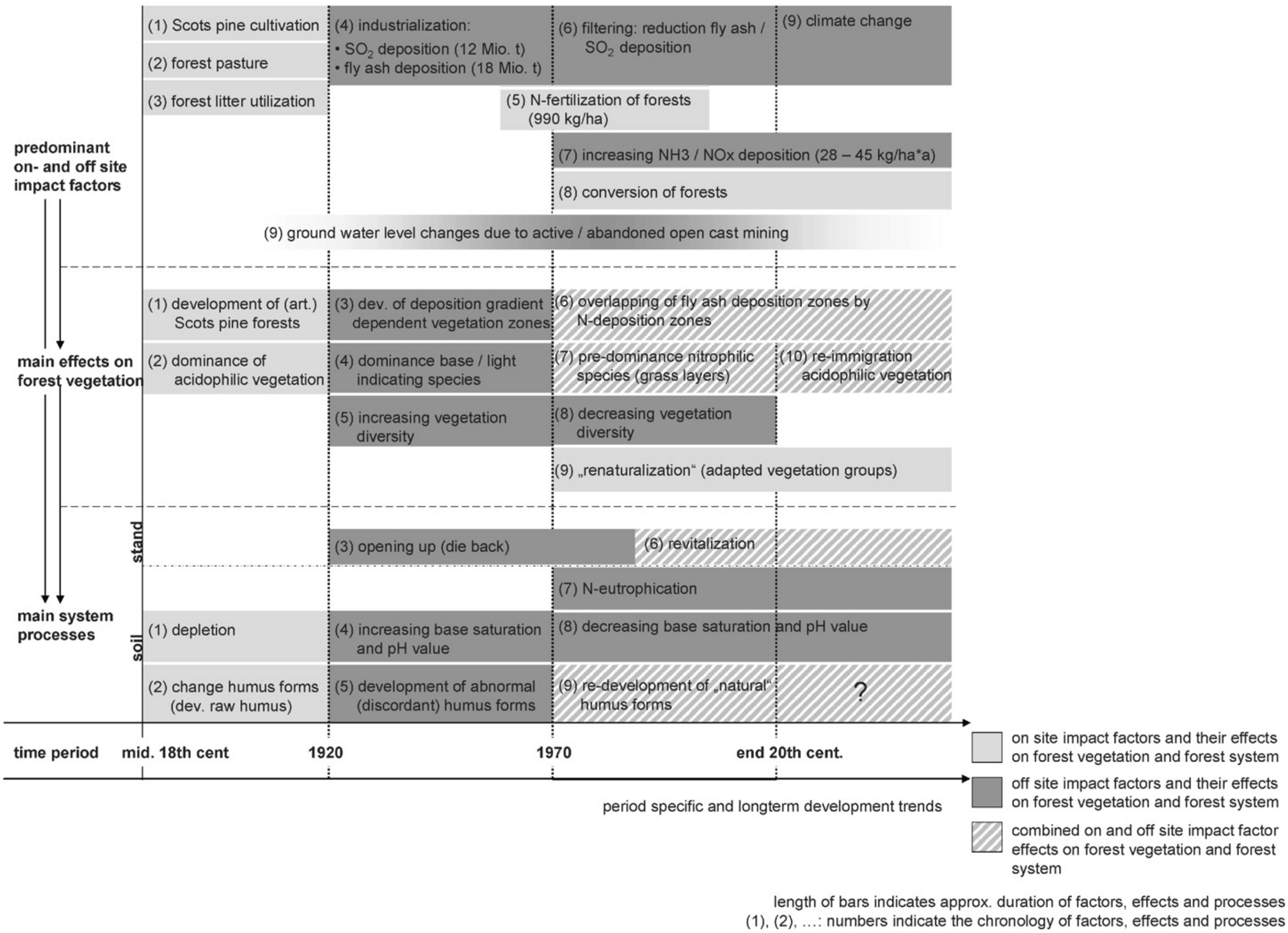

Fig. 2. History of human influence on forest systems in the lowlands (Dübener Heide), their effects on forest vegetation and resulting system reactions.

2.2. History and development in the period 1920s–1970s

Starting in the 1920s, off-site impact factors became more important and an intensification of industrial energy production led to high deposition loads in the regional forests. The total deposition in the most important regional woodland, the so-called ‘‘Dübener Heide’’, amounted from 1910–2000 to 18 Mio t fly ash and 12 Mio t SO_2[1], and in the decade from 1961–1970 up to 3–8 t/(ha a) of fly ash were deposited in the regional forests (Lux, 1965, 1976; Neumeister et al., 1991; Nebe et al., 2001; Klose and Makeschin, 2004). The different deposition fractions SO_2 and fly ash, which contains ‘‘black’’ (tertiary) carbon, alkali/earth alkali metal salts, heavy metals and silicium compounds were distributed according to (a) their aggregate state, (b) their particle size and form and (c) landscape shape and land-use form along a regional gradient. This gradient was dependent on distance and wind direction in case of clustered emitters (power plants and industry in the Bitterfeld district) or characterized by overlapping areas of several emitters with irregular peaks of local deposition (mainly N from agriculture and industrial N production) (Lux, 1966, 1976; Niehus and Brüggemann, 1995; Magiera and Strzyszcz, 1999; Strzyszcz, 1999). Additionally, the impact of industrial deposition on regional forests was overlapped by locally clustered N fertilization of forests, which amounted up to 990 kg/ha (Konopatzky, 1995). In consequence, deposition (and fertilization) dependent vegetation zones appeared, with typical indicators of alkaline or acidic deposition components and N fertilization (Lux, 1964a; Konopatzky, 1995; Amarell, 1997; Konopatzky and Kopp, 2001). Basophilic and light preferring species started to settle in the immediate vicinity of the former power plants. They indicated alkaline dust deposition and an irregular opening ups of (nonadapted) Scots pine stands by advanced felling as a consequence of ongoing needle losses, forest die back and calamities. Increasing regional vegetation diversity and especially high species diversity near to the power plants were reported as

[1] In the consulted literature, the term ‘‘SO_2-deposition’’ is used and comprises the total deposition in the forest ecosystem including all compartments. The quantification of SO_2-deposition was based on time-related concentration measurements. Information on the S_{tot} or SO_3/SO_4^{2-}deposition equivalent in forest soils was not available. Consequently, the term ‘‘SO_2-deposition’’ is also used in the presented paper.

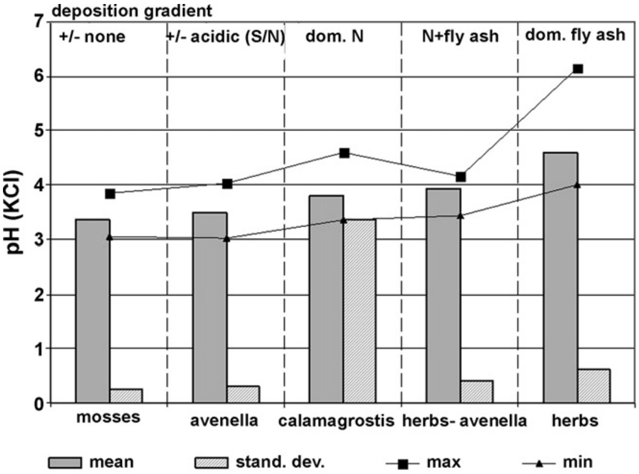

Fig. 3. pH (KCl) value in humus layers (Oe/Oa) of characteristic soil vegetation types of Dübener Heide along the deposition gradient (Heinsdorf et al., 1994, modified).

contradictory development to a decreasing vitality of the Scots pine stands (Lux, 1964a,b). This process went along with artificially elevated pH (KCl) values (up to 7) and base saturation (up to 100%) in the humus layer and upper mineral horizon of the regional forest soils. Fig. 3 shows exemplarily pH (KCl) values in humus layers of typical soil vegetation types under Scots pine stands along the deposition gradient (N_{total} = 122 sample plots).

The vegetation types in Fig. 3 comprise (a) vegetation groups representing the different deposition (and fertilization) types, e.g. mosses (+/− no deposition), *Calamagrostis* (mainly local N deposition/fertilization) and herbs (mainly fly ash deposition), and (b) types with complex dynamic, e.g. *Avenella* (acidic deposition, but also opening up of the stands), and herbs-*Avenella* type (beginning pre-dominance of acidic depositions/re-acidification). These vegetation types can be used as indicator for artificially changed chemical top soil properties (Konopatzky and Kopp, 2001). Their indicative value for site quality (changes) seems to describe better the regional site quality (changes) compared to the vegetation indicated site quality grid proposed by Ellenberg (1988).

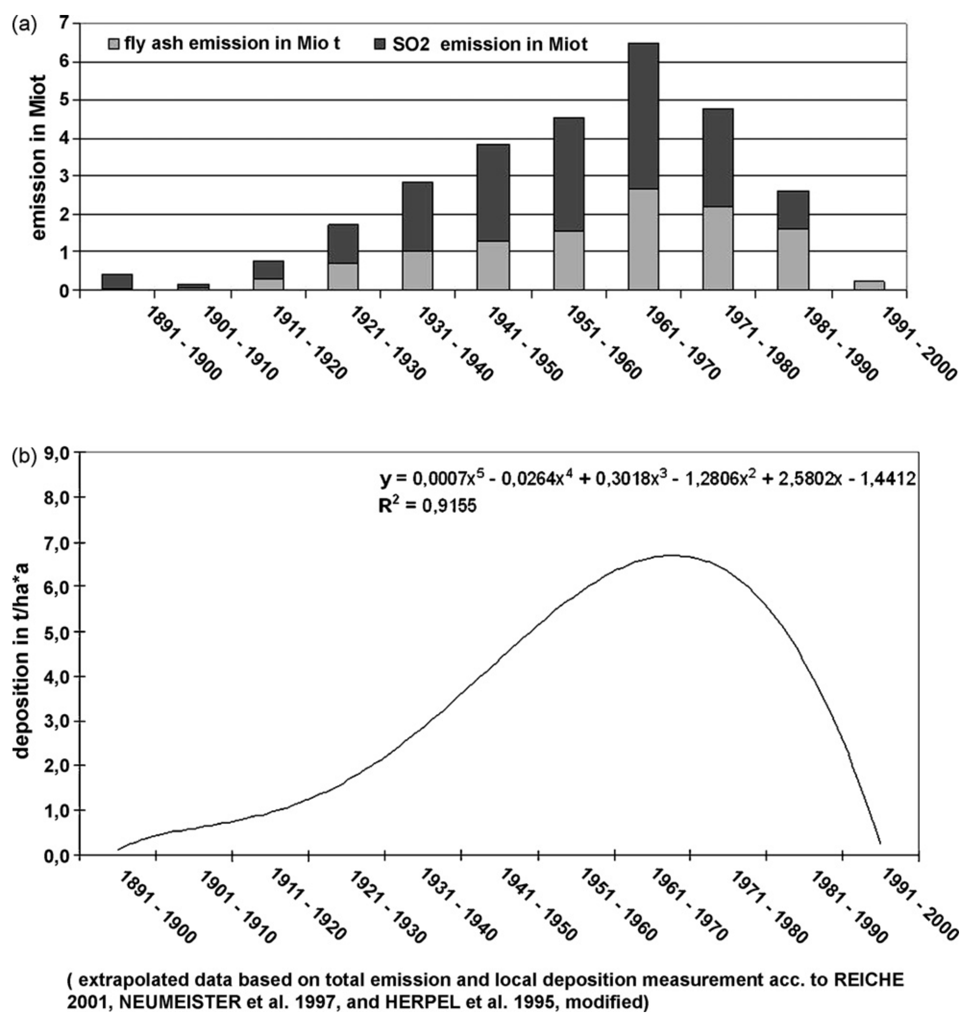

Fig. 4. (a) Development of the emission situation in Dübener Heide (acc. to Herpel et al., 1995; Neumeister et al., 1997; Reiche, 2001, modified). (b) Fly ash deposition in t/(ha a) in the Dübener Heide.

However, Kopp (2003) mentions also that the time-delayed response of soil vegetation composition restricts its indicative value. Considering the humus layer, discordant humus forms occurred, which are recognizable by (a) abnormal thickness of Oe/Oa-horizon, (b) increased microbial respiration and (c) reduced organic matter decomposition. They indicate the dramatic disturbance of natural soil processes in forest ecosystems affected by deposition (Lux, 1974; Klose et al., 2003; Koch and Makeschin, 2004).

2.3. History and development in the period 1970s – end of 20th century

The period of 1970s until the end of 20th century was characterized by an intensification of silvicultural counter-measures such as conversion, but also ongoing N-fertilization (Lux, 1976; Konopatzky and Kopp, 2001; Nebe et al., 2001; Kopp, 2003). From the 1980s on, an introduction of fly ash filters lead to a more or less acidic deposition regime (NO_x, SO_2/SO_x). After 1989, a strong reduction of fly ash emission along with an even increasing levels of N emissions (NO_x, NH_4) changed the deposition characteristics in formerly fly ash influenced areas (e.g. Hüttl and Bellmann, 1999; Marquardt et al., 2001; Gauger et al., 2002; Wellbrock et al., 2005). Fig. 4a provides information on the special development of the emission situation in Dübener Heide from 1891 to 2000 (Herpel et al., 1995, Neumeister et al., 1997; Reiche, 2001), Fig. 4b shows the extrapolated development of regional fly ash deposition in Dübener Heide in the same period based on regional deposition measurements and emission data.

Raising atmospheric N deposition in a magnitude of 28–45 kg/(ha a) caused by intensive animal husbandry and acceding traffic intensity superposed the former regional deposition gradient. This additional N input amplified the long-term effects of N-fertilization in terms of dense grass layers (*Calamagrostis epigejos*) and other nitrophile soil vegetation. For long time this posed a severe obstacle for natural forest regeneration and required high technical input for stabilizing forest ecosystems. Decreasing vegetation diversity was observed in this period, which can be considered as an indicator for ongoing N-eutrophication. However, N-eutrophication in the soils was to some extent balanced by an ample of ground vegetation growth, revitalization and improved tree growth, and vital development of immigrating tree species (noble hardwoods) (Lux, 1964b; Amarell, 1997). This indicated the development towards another system balance (''renaturalization''). Herpel et al. (1995) documented a decrease of pH (KCl) of 0.4 units and base saturation decrease of 17% until 1988 compared to the situation in the 1970s. From 1988 to 2000, a further reduction of 0.7 pH-units in the most stands affected by fly ash was reported by Kurbel (2002). In the long run, a re-development of humus forms is expected, which are more similar to the original site potential (Kopp and Jochheim, 2002; Kopp, 2003).

2.4. History and development in the 21st century

In the scope of climate change, a decrease in precipitation and increasing temperature represent considerable off-site impulses for forest system development in Dübener Heide.

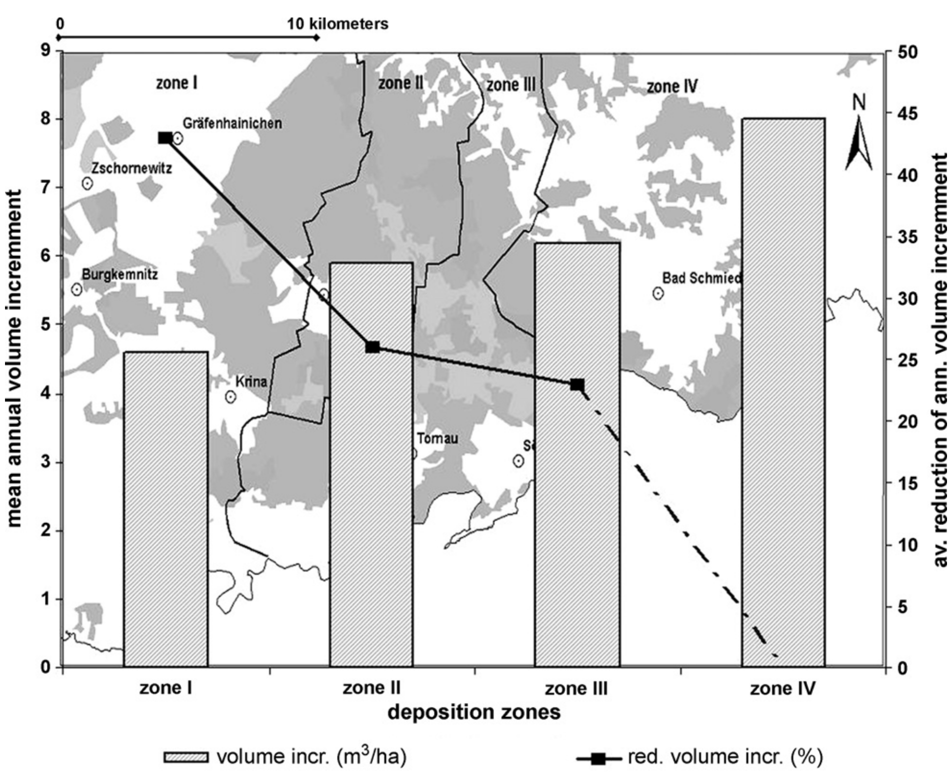

Fig. 5. Volume increment (m^3/(ha a)) and volume increment reduction (% of reference value in zone IV) in the deposition zones (acc. to Lux, 1965, 1964b, modified).

Küchler and Sommer (2005) expect an average reduction of annual precipitation of 31 mm compared to 1977–1997 for the next 50 years and an average increase in temperature of over 3 K in Saxony. Re-immigration of acidity indicators and disappearance of the dense grass layers in formerly fertilized areas are observed due to vanished base deposition and ongoing acidic deposition (Augustin et al., 2005; Wellbrock et al., 2005). The health of regional forests has improved partially as a result from conversion effects and lower S deposition, but is threatened by increasing N deposition on the other hand (Materna and Fiedler, 1994). Climate change and long-term re-acidification lead to the question if the actual tree species composition and especially the noble hardwood regeneration can be integrated into future silvicultural concepts.

2.5. Regional planning approaches

Based on the prevailing recognition of differing range and effects of alkaline fly ash and dissolved acidic deposition components, Lux (1965) defined first of all the necessity to identify deposition strata (planning areas) around the industrial hot spots for an adapted forest management. Enderlein and Stein (1962), Stein (1965), Lux and Pelz (1968) and Lux (1976) developed a sample plot based approach, where a classification of health state and growth potential in medium-aged Scots pine stands (50–90 a, $N_{\text{sample plots}}$: approximately 150) was used for a regionalization of the deposition impact. Fig. 5 shows exemplarily the volume increment (m^3/(ha a)) and volume increment reduction (% of reference value in zone IV) along the regional deposition gradient (Lux, 1964b modified, 1965).

The degree of single tree growth reduction and needle losses were aggregated sample plot-wise to a factor, which indicated the intensity of damage. Post-stratification based on the sample plot results was used for an application of stratum-specific silvicultural management measures and for obtaining area-related information on additional costs and economic loss. This formed the basis for financial compensation by regional industry. Stock volume, recreation potential and water management aspects were integrated into a multidimensional approach for evaluating the effects of complex depositions on forest management (see, e.g. Reiche, 2001).

Nowadays, the former damage classification cannot be used anymore due to changes in regional forests health and species composition, whilst on the other hand impact on chemical humus and soil properties is still evident (Klose et al., 2002; Koch et al., 2002; Klose and Makeschin, 2004; Koch and Makeschin, 2004). For a process-oriented forest management the establishment of planning units, which are more or less homogeneous considering (a) basic (site) properties, (b) site processes, and (c) vegetation type development with special respect to back-coupling effects between site and vegetation seems to be promising (Kopp and Schwanecke, 1994; Kopp, 2003). For instance, Schoenholtz et al. (2000) recommend a stronger integration of (site) process indicators into planning concepts.

3. Concept of process-oriented forest management

The reaction of forests on a changing deposition regime depends on tree species composition and site properties (Kunze et al., 1995, 1996) and their interrelations. In Dübener Heide, fly ash deposition provoked (a) a homogenisation of site quality differences, and (b) a differentiation of formerly comparable sites and vegetation types along the regional deposition gradient. These artificial modifications now are disappearing or are overlapped again by current N deposition (Neumeister et al., 1991; Thomasius et al., 1999; Schaaf, 2004). Forest management planning is forced to adapt to these ongoing processes (including stand and site) instead of using exclusively the actual (vegetation and stand) status as decision basis (Schoenholtz et al., 2000; de Vries et al., 2003). Integrating processes into management concepts helps to avoid unreasonable investments, e.g. furthering tree species and stand structures, where the future development provokes ecological risks or financial losses.

The development of a process-oriented forest management planning requires three steps:

(1) Identification of the main forest ecosystem processes (see Fig. 2) and the related process indicators. A suitable process indicator must be apt to describe course, direction and progress of processes (‘‘vectored dynamics’’) in forest ecosystems. Process indicators for forest soils processes may be, e.g.
   a. $C_{(hwe/cwe)}$ ratio as indicator for soil organic matter (SOM) dynamics,
   b. pH (H_2O/KCl) ratio as indicator for the re-acidification potential,
   c. difference between actual and expected humus form as indicator for the influence of management measures on natural humus dynamics,
   d. temporal and spatial changes in ferrimagnetic susceptibility in the Oe/Oa as indicator for fly ash deposition influenced humus dynamics.
(2) Process indicator based regionalization in order to derive process-oriented management units as spatial information base.
(3) Orientation of forest management planning to process-oriented planning units. The economic and ecological targets of forest management are pre-defined by the forest owner (e.g. timber production, sustaining environmental quality). Process-oriented management planning units allow for drawing a more sensitive derivation of type and possible intensity of concrete management measures.

Fig. 6 gives an overview on a concept for process-oriented management planning units based on the propositions of Kopp and Schwanecke (1994), Konopatzky (1995) and Konopatzky and Kopp (2001). The following explanations refer to Fig. 6.

Natural frame conditions, anthropogenic impact and the factor ‘‘time’’ are determining basic and variable site properties. Basic site properties result from geological and climatic frame conditions. Without man made changes, a balance

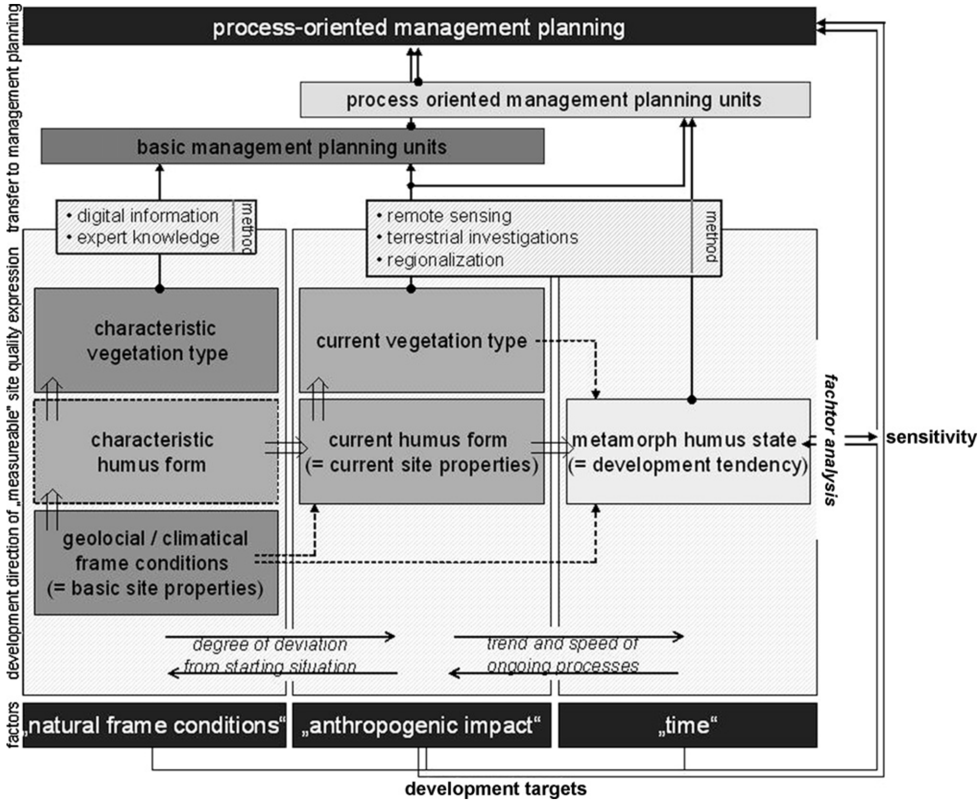

Fig. 6. Schematic conception of process-oriented management planning.

between characteristic soil type(s) and corresponding humus form(s) and vegetation type(s) would reflect the natural frame conditions. "Characteristic" humus form and vegetation type as reference for the current situation can be defined by means of expert knowledge ("dashed line"), whereas the frame conditions are verifiable ("solid line"). Anthropogenic impact leads to the current "measurable" situation as described in Section 1: this impact influences humus and vegetation type and to certain extent also soil properties (chemical and magnetic characteristics in the uppermost mineral layer, but without changing the soil type itself). The differences between the current situation and the reference situation can be seen as a measure for the deviation from a development under undisturbed conditions. Course, direction and progress of ongoing processes are expressed by a change of humus and soil properties (e.g. SOM, C:N ratio, pH-value, base saturation and ferrimagnetic susceptibility) and the state of vegetation development. This change over time can only be detected by re-investigation of humus and soil properties and vegetation composition. Both, deviation from undisturbed development as well as the trend and progress of ongoing processes are a valuable base for evaluating necessity, type and intensity of silvicultural management measures.

Information on geological and climatic properties, resulting site properties and "characteristic" vegetation types can be used for defining basic management planning units, which represent more or less the natural frame for regionally possible development scenarios. In case of Dübener Heide, it is difficult to identify the original vegetation type: apart from many different impact factors on regional forests and forest soils (as described in Section 1), the change of the ground water level superposed the original situation from the beginning of opencast mining (see, e.g. Reiche, 2001). Consequently, expert knowledge is demanded for a spatial classification of the most probable reference situation. Information on current vegetation and humus types can be obtained by (a) remote sensing (forest vegetation types and macro structure) and (b) complementary terrestrial investigations (soil vegetation types, humus forms, and chemical soil properties). This helps to refine the basic management planning units and to integrate the current development state. In case of Dübener Heide, a detection and regionalization of the actual deposition load and its effects is indispensable for two reasons:

(1) the formerly defined deposition strata reflected more or less forest health as sum parameter of fly ash, S, and N deposition and also climatic influence (Lux, 1965, 1966; Erhard and Flechsig, 1998).
(2) The deposition type underlies manifold changes as mentioned in Section 1. The regionalization of the actual (fly ash) deposition load in humus layers and top soils should be based on easily measurable indicators like ferrimagnetic susceptibility in a first step in order to achieve an optimal spatial field assessment (Tölle and Raasch, 1983; Strzyszcz and Magiera, 1998; Magiera and Strzyszcz, 1999; Hanesch and Scholger, 2002; Maier and Scholger, 2004). Trend and speed of ongoing processes can be expressed by the change of chemical humus and soil properties (SOM,

C:N, pH-value, base saturation, see, e.g. Scheuner and Makeschin, 2005; Landgraf et al., 2006) and stand development (age class, mixture, stand density, etc.) after re-investigation. Especially for a regionalization of the changes in humus properties, a combination of floristic indicators – soil vegetation species with high indicative value – and chemical indicators like base saturation and C:N ratio is recommended (Kallweit, 1990; Amarell, 1997; Konopatzky and Kopp, 2001; Wilson et al., 2001; Klose and Makeschin, 2004).

Basic management planning units as described in Fig. 6 comprise information on basic and current site quality and vegetation reflecting the historical development in the naturally given frame up to date. Basic management planning units can be used as reference for the formulation of silvicultural targets, which are geared to the actual regional development potential. On the sandy soils of Dübener Heide, the choice of tree species is mainly driven by the poor availability of water and nutrients. Fly ash deposition superposed the spectrum of natural tree species due to an artificially increased nutrient availability. High fly ash deposition in the immediate vicinity of power plants enabled an immigration of noble hardwood in formerly pure Scots pine stands even on poorer sites, whilst stability and increment of the Scots pine stands as economically most important stand type in the lowland was considerably reduced (Kunze et al., 1995, 1996).

Process-oriented management planning units comprise information on the current site quality and the ongoing processes to indicate possible spatial development scenarios. In Dübener Heide, information on (a) intensity and speed of (re-)acidification and (b) subsequent depletion of (deposited) nutrients and heavy metals under different stand types and stand development states is most important with regard to process-related management information. Spatial information on such processes would help to improve cost efficiency of regional silvicultural management strategies.

Process-oriented management planning should be based on three pillars – (1) basic management planning units (natural frame conditions), (2) process-oriented management planning units (potentials and processes over time) and (3) targets for economic and ecological development by the land owners. For a better understanding of processes and prediction of realistic development scenarios, an integrative application of process-based models is indispensable (e.g. Mäkelä et al., 2000; Peng, 2000; Wallman et al., 2005). This should be accompanied by a sensitivity analysis in order to assess the influence of the factors (and factor combinations) ''natural frame conditions'' and ''anthropogenic impact'' on the predicted processes and for integrating the most significant predictors (Battaglia and Sands, 1998).

Finally, two examples should explain typical questions in Dübener Heide, where improved spatial information on long-term availability of nutrients and sensitivity to re-acidification would support an economically efficient and ecologically satisfactory silvicultural management.

(1) Where along the deposition gradient and to which extent can natural noble hardwood regeneration in Scots pine stands be integrated into the future stand composition: in case of noble hardwood dominated stands, climate change and re-acidification might endanger the future economic success or even the maintenance of the stands. On sites with high base saturation, these risks are expected to be less relevant. The other extreme is to continue the work with pure Scots pine stands. This however, could further unfavourable processes like re-acidification and nutrient depletion. Furthermore the stability of Scots pine stands and the wood quality are poor on sites with high fly ash influence.
(2) Considering the deposition gradient – at which distance to the formal emitters and how to continue with old Scots pine stands with low stand density index (SDI) and dense ground vegetation (grass layers). Natural regeneration of Scots pine is actually retrogressive on these sites and the increasing N deposition is expected to tighten this situation. Conversion with broad leaved tree species (oak, European beech) might slow down re-acidification, but is quite expensive and its success is limited by the ample development of soil and vegetation. Douglas fir could be an economically interesting alternative on such sites, but its regional growth potential is not well known so far.

4. Conclusions and preview

Deposition impact in Dübener Heide leads to double-edged effects on regional forests: (i) a higher nutrient availability (base saturation) and cation exchange capacity, (ii) an improvement of physical properties like texture and sorption capacity. On the other hand, (iii) a disturbance of ground vegetation composition and organic matter decomposition can be observed and (iv) an imbalance of the nutrition state of (coniferous) forests (Kallweit, 1990; Kopp and Schwanecke, 1994; Herpel et al., 1995; Amarell, 1997; Konopatzky and Kopp, 2001; Kopp, 2003). Regional forest management has to take into consideration that the tendency of re-acidification is mainly driven by S mineralization, sulphate leaching accompanied by cation losses (Schaaf et al., 2004) and to regionally varying extent by increasing N-immissions: re-acidification has a negative impact on the stability and development of the fly ash-adapted stand types and the quality of by-products like water, biodiversity and socio-economic functions.

Fig. 7 compares against this background a ''process-oriented'' forest management planning approach with a management approach as applied in German forest practice (in the following: ''classic'' forest management approach, see Speidel, 1972) considering mainly the necessary information input.

The ''classic'' forest management approach reflects the vegetation dynamics (natural vegetation versus current vegetation and stand development state) in development targets and concrete management measures, but assumes at the same time that site quality is more or less static. This approach ignores an essential part of ongoing system processes (Martell et al., 1998;

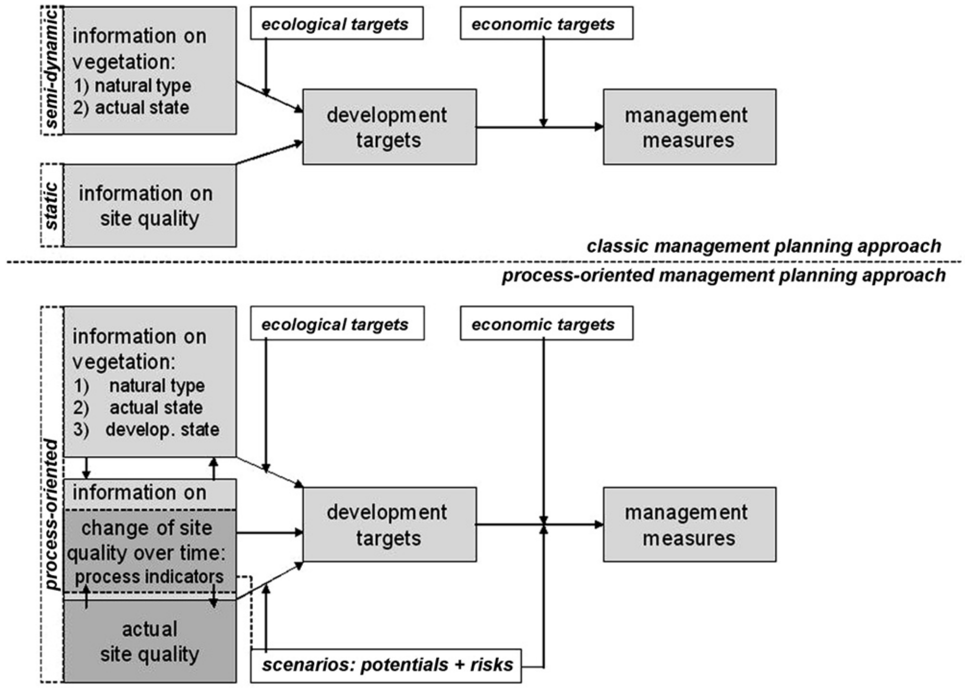

Fig. 7. "Classic" and "process-oriented" forest management approach.

Peng, 2000; Schoenholtz et al., 2000). In areas with major changes of environmental frame conditions like Dübener Heide, an orientation on management planning units, which are characterized by comparable trends of site development would be better suitable for taking the differences along the spatial deposition gradient into consideration (Erhard and Flechsig, 1998).

In a "process-oriented" management approach as proposed in Section 4, development targets and management measures are based on area-related process indicators (vegetation, site, deposition load and changes) as discussed by Scheuner and Makeschin (2005), Maier and Scholger (2004), Kopp (2003), Hanesch and Scholger (2002), Konopatzky and Kopp (2001), and Schoenholtz et al. (2000). This allows for a better appraisal and consideration of future on- and off-site potentials and risks in strategic development targets and short-term management measures.

For applying a process-oriented management planning approach, regionalization techniques for the up-scaling of processes from monitoring and inventory plots must be developed (de Vries et al., 2003; Augustin et al., 2005). The regionalization of process parameters is a major topic in most landscape related sciences (e.g. Diekrüger et al., 1999; Volk and Steinhardt, 1999). Although the delineation of process units designated as ecotopes, physiotopes, or patches is a general aim in landscape ecology (Mosimann, 1990; Haber, 2005), no general approach has been developed so far. For a process-oriented management planning the delineation of "process-homogeneous" management planning units (compare the concept of hydrologic response units (HRU) by Flügel, 1995) focussing on the reaction of sites on forest measures under changing environmental conditions seems to be a promising approach. The dynamics within a planning unit and the spatial relation between different planning units under regionally changing management concepts or local variations of environmental changes are of special interest. Some promising approaches were presented by Zirlewagen and v. Wilpert (2004), Saborowski and Jansen (2002) and Erhard and Flechsig (1998). They should be pursued and tested considering their practical suitability for spacious application. This would support a statistically valid process-oriented forest management, which could easily be integrated into ecological landscape management approaches on different scale levels (Volk and Steinhardt, 1999; Kopp, 2003).

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Editorial

Meeting the challenges of process-oriented forest management

Abstract

The article gives an overview on the drivers of the development of forest management approaches and summarizes and discusses the contributions of the presented Special Issue considering four thematic blocks: (1) background and consequences for a dynamic development of natural systems, (2) regional frame conditions and development of adapted assessment and evaluation approaches, (3) integration of natural processes in modeling and forest management concepts, and (4) tools for supporting cognitive processes and decision making and for transferring information to heterogeneous end-user groups. Conclusions are drawn on the challenges of a future-capable forest management. A concept of a process-oriented management is introduced that intends to consider better the dependence of forest management from societal and natural processes.

Keywords: Forest ecosystems; Dynamic development; Processes; Indicators; Models; Network for process-oriented forest management

1. Introduction

The first well regulated management approaches introduced by v. Carlowitz (1713) and others intended more or less to assure a sustainable provision with timber. They assumed a rather simple development of forests and provoked in the consequence a considerable ecosystem simplification, loss of integrity and stress (Gale, 2000). Nowadays, worldwide forestry experiences a considerable change of its role and socio-cultural acceptance, which lead to a regionally diversified self-understanding of forest management concepts (Kohm and Franklin, 1997; Kissling-Näf and Bisang, 2001; Farell et al., 2000). Since the mid-1970s forest ecologists started to focus on ecological processes and emphasized the need to understand and to manage forests as ecosystems. An ecosystem-based management taking multifunctionality of forests on landscape level into account became one of the central, but also sometimes misleading ideas (Führer, 2000; Schlaepfer et al., 2002). Multi-purpose forest management concepts have to consider a broad range of ecosystem attributes and bridge conflicting management objectives. Concepts of adaptive management (Holling, 1978), hierarchy theory (Midmore and Whittaker, 2000), and forest ecosystem sustainability (McGinley and Finegan, 2003) have been proposed to develop sustainable forest management (SFM) concepts as well as to fullfill the demands of public participation in forest planning (Bell, 2001). Forest management can be seen as a continuous process of monitoring, evaluation, planning, and action aiming at the sustainable use of forests providing values, goods, and services requested by society under changing environmental and socio-economic conditions (Davis et al., 2001; Reynolds, 2005).

The success of sustainable forest management depends on the ability to adapt management strategies to natural dynamics, or to manipulate the natural processes according to the management objectives. Forest management goals and methods must be based on a sound knowledge of natural processes and their potential external drivers and pressures, which allow forest dynamics to be predictable under different management regimes (Bergeron and Harvey, 1997).

Process-oriented forest management should be able to bring together (i) the ecological view emphasizing environmental and ecosystem processes and (ii) the economic view of optimizing forest management planning and decision making. The DPSIR approach discussed by Mander et al. (2005) might be a suitable framework for dealing with environmental management processes in a feedback loop, which controls the interactions within the cycle of Drivers–Pressures–State–Impact–Responses. The idea of this more or less indicator based approach will be extended in this Special Issue: (i) indicators for environmental changes, (ii) indicator based (spatial) modeling approaches, (iii) tools for supporting (collaborative) decision processes, and (iv) advanced group communication and knowledge management techniques are interlinked to enable the end-user to retain control on multi-scale system and planning processes.

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2. The Special Issue

The Special Issue ''Meeting the challenges of process-oriented forest management'' presents contributions from ForwardFORESTs[1]—a transdisciplinary virtual conference on multiple-purpose forestry held in 2005. One of the major aims of the conference was to find pathways for future-oriented approaches by linking forest and environmental research with socioeconomic (political) approaches and bringing together experiences gained in complementary scientific disciplines. More than 100 participants from 16 countries namely Austria, Canada, Czech Republic, Belgium, Finland, France, Germany, The Netherlands, Poland, Portugal, Slovenia, Slovakia, Sweden, Switzerland, the Russian Federation and Canada presented the current state of knowledge in 56 presentations, including eleven keynotes. Selected contributions from the conference were compiled and organized around four major topics in this Special Issue of *Forest Ecology and Management*.

The background and consequences for a dynamic development of natural systems is the focal point of the first part of the Special Issue. Sustaining the functionality and productivity of forest ecosystems demands ecosystem management respecting natural dynamics and processes (Kint et al., 2006). Approaches how to integrate processes into forest management planning from stand level to landscape level must be developed (Andersson et al., 2000). Fürst et al. (act. issue) propose an integrated approach. Its advantages are discussed and compared to classic forest management concepts. The authors conclude that development targets and management measures must be based on regionalized process-indicators (vegetation state, site conditions, deposition load). This allows a better appraisal and consideration of future on- and off-site potentials and risks in strategic development targets and short-term management measures. Lorz et al. (act. issue) are extending the stand-centred approach to the role of forests in River Basin Management. The simulation of land use effects on water resources in forested river basins has been carried out in a great number of projects, but mostly without consideration of the spatial distribution of forests. The authors' objectives are (i) to implement the spatial distribution of forests in large scale models and (ii) to simulate its effect on water yield and water quality. Their conceptual approach includes a schematic five-units-model (FUM) representing cross sections with typical land use sequences. In addition the creation of artificial catchments is proposed to test model settings and thus simulating and optimizing different land use systems.

To understand the dynamics of forest ecosystems systems especially in (post)industrialized regions with high anthropogenic impact requires an analysis of regional frame conditions and their impact and the development of adapted assessment and evaluation approaches (Bellmann, 2000). Despite improved technical standards and a reduced emission, heavy deposition load can still be observed in forest ecosystems in the New Member States in Central Europe. This indicates the urgent need to provide easily usable tools to identify and assess potential environmental risks (Hanesch and Scholger, 2002; Maier and Scholger, 2004). The contribution by Jamnicka et al. (act. issue) shows the chances of using the accumulation of nutrients and contaminants in fungi and plants as proxies for soil conditions. A similar idea is behind the methodological approach using ferromagnetic susceptibility to detect heavy metal contamination in soils (Magiera et al., act. issue). Both approaches are aiming to develop cheap and fast assessment methods that support the regionalization of soil pollution. They demonstrate the wide spectrum of laboratory and field methods, which can be used in environmental risk assessment.

Additionally, suitable indicators and advanced regionalization techniques are necessary to model spatially explicit the forest ecosystem status (Ryan et al., 2000). Complex up-scaling approaches based on multiple linear regression analyses coupled with geo-statistics using a two-stage procedure with global and regional transfers allow, e.g. to conclude from plot-wise measurements and indicators on deposition impact on forests at landscape level (Zirlewagen et al., act. issue). The results of the presented approach can be used as base for better adapted silvicultural concepts and forest management measures. Forest management measures must be analysed considering the impact of climate change and their long term impact on soil properties (Horn et al., act. issue). Only few studies are available which analyze the effects of alternative silvicultural strategies on carbon sequestration, timber production, soil functionality and other forest services and functions at the operational level of the forest management unit (FMU). Forest management can contribute actively to reducing atmospheric CO_2 despite some limitations of the achievable quantities due to biological and societal constraints. Sustainable soil functionality and economic success by using high tech in forestry must not be incompatible demands, but emphasize the importance of developing sustainable forest management strategies that serve the multiple demands on forests in the future (Seidl et al., act. issue).

In this context, the question must be raised how to bring data and experiences on existing frame conditions and the resulting natural processes into modelling and forest management concepts? To understand and predict the potential impact of changes in global environment forest simulation models can be used. Recently, it has become fashionable among ecologists to favour mechanistic approaches instead empirical ones (Korzukhin et al., 1996; Battaglia and Sands, 1998). The strength of these process models is the weakness of the growth and yield models, and vice versa. Most traditional growth and yield models, which exclude soil processes and the role of ecosystem disturbance in determining ecosystem function, may be able to predict the continuity of timber harvest and the nature of future forest stands, but tell us little about the effects of timber harvesting on ecosystem structure and function (Peng, 2000). The link between foresters and ecologists coupled with combining empirical and mechanistic approaches into a hybrid approach will certainly advance our understanding of the effects of future changing environment on SFM. Linking furthermore models on different scale levels, from landscape

[1] http://forwardforests.czu.cz/.

related land-use pattern and vegetation dynamics on the level of forest stands to wood quality related questions on the level of the single tree individual is crucial for the development of a knowledge based evaluation of forest management strategies under changing conditions (Lindner et al., 2002).

Especially climate change is one of the most severe environmental problems, and the future impact on forest ecosystems and their potential to fulfil functions in a sustainable way is under debate (Lasch et al., 2002, 2005). For estimating the impact of such dramatically changing conditions, e.g. on biodiversity, ecological-coenotic species groups can be used. They allow for forecasting the dynamics of forest ground vegetation diversity on the base of forest ecosystem modeling outputs. Long term modeling results of forest type and species richness show that silvicultural strategies with cuttings support higher ecosystem diversity in comparison to natural development. However, it seems that only natural development furthers the development of climax forest types (Khanina et al., act. issue). An integrated wood quality modeling, including growth and pathogen driven deterioration processes supports management decisions from single tree to stand level. Without such an integrated approach, misinterpretations and inaccuracies might arise in the interpretation of economic results based on simple tree growth simulators (Seifert, act. issue).

To come to a common understanding and acceptance of process-based management approaches, tools for supporting cognitive processes and decision making and for transferring information to heterogeneous end-user groups are an indispensable contribution. In the past, institutions dealing with natural resource management sector have been relatively slow to adopt Knowledge Management Technologies (Reynolds et al., 2005). Although decision making and processes for knowledge creation, storage and transfer are interdependent, research has not adequately considered their integration (Bolloju et al., 2002). Knowledge management practices might be categorized according to their contribution to problem solving and problem recognition in the management process. The fact that many problems require the generation of new knowledge and the application of existing ideas leads to the classification of practices that support the identification and resolution of new or unique problems and those that deal with previously solved problems (Gray, 2001).

ICT (Information and Communication Technology) advances and innovations have enabled significant changes in the practice of forest management. Contributions at the conference covered recent advances in decision support systems, e-learning, information transfer and knowledge management activities. Upcoming methods for supporting sustainable forest management are especially of high interest when dealing with small scale forestry, where collaborative planning processes and group decision making tools must be taken into consideration. Stimulated by developments in business administration and industry, computer-based decision support systems (DSS) are currently drawing much attention as a means of improving the quality and transparency of decision making in natural resource management (Rauscher, 1999). The increasing number of stakeholders involved in natural resource management and the corresponding need to consider multiple interests and preferences in the decision-making process led to the use of Multi-Criteria Decision Making (MCDM) techniques in DSS development. Collaborative technologies such as Group Decision Support Systems (GDSS) might help to avoid the consequences of knowledge fragmentation and will extend that support to decision-making processes involving several individuals. In this context Martins and Borges (act. issue) are addressing collaborative planning methods and tools in forest management of multiple small non-industrial forest owners. The key issues of the planning process and a review of methods and tools used to support group decision-making in forest management planning are presented. They conclude that the development of technological platforms promote the effective integration of methods and tools which enhances the ability of stakeholders to analyse more information and more facets of the forest management problem and support group decision-making.

Distance education in natural resource management has historically generated a great deal of interest in areas where student population was widely distributed. Self-motivated individuals worked on their own, with supplied course materials, print-based media and postal communication, often using some learner support from tutors via telephone or e-mail (Sherry, 1996). Study courses, tutorials and simulation tools provided via Internet have brought a new dimension to virtual education and raised philosophical and practical issues unique to the method of delivery, interaction and administration of online instruction (Vacik et al., 2006).

3. Do we really need something new?—Conclusions

The majority of forests is multifunctional: they fulfil, to varying extend, ecological, economic and social functions simultaneously (Farell et al., 2000). A clear functional specialisation of forests exists only on small scale (e.g. protective forests, short rotation plantations, nature conservation), requiring completely different management strategies (Führer, 2000). The multiple purpose nature of today's forestry requires from forest resource managers to consider a broad range of ecosystem attributes at various spatial and temporal scales in developing management strategies and operational plans, in evaluating the effectiveness of management activities, and in tracking trade-off relationships among conflicting management objectives. One of the most important questions is how we can solve these typical decision problems effectively and how to improve constantly our decision-making processes and our decision support capabilities (Rauscher et al., 2005). Modern forest management approaches can take profit from scientific understanding of forest ecosystems and from tools for modeling, decision support and Information and Communication Technology (ICT). Due to the resulting complexity of the management approach, a system analysis approach including feedback and dependencies between the different system elements seems to be a reasonable path (Vacik et al., 2007). It should be the rationale to combine the strengths of available tools, methods and models to foster the holistic understanding

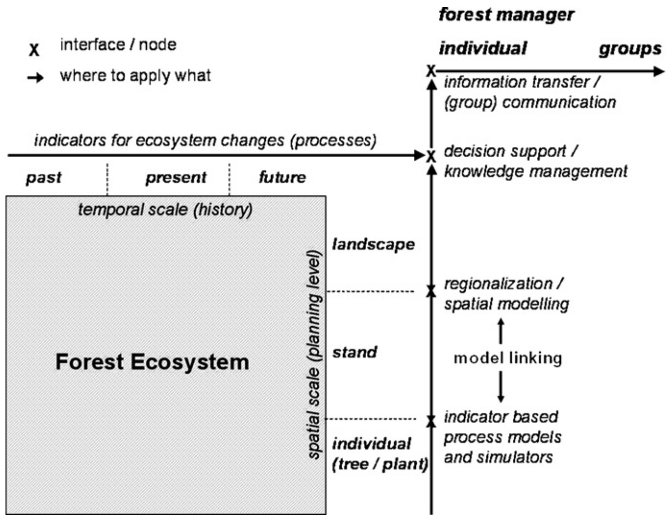

Fig. 1. Overview on a possible network of tools, methods and models for process-oriented forest management.

of forest ecosystem processes and the effects of SFM techniques for supporting forest management at strategic and tactical planning level.

Fig. 1 gives an idea, how a network of tools on different time and scale levels for supporting a process-oriented management can be designed.

Forest ecosystems and their dynamics are characterized by their history (temporal scales), where the past is decisive for the present and the present determines the future. They are also characterized by the scale level, from which they are regarded. To describe the temporal development of forest ecosystems (processes), respective indicators must be used, which form the base for indicator based (process) models and simulators and regionalization approaches. These are used to describe the joint temporal and spatial development of forest ecosystems. The models along the different scale levels must be linked, in order to give an adequate input to decision support tools and knowledge management systems at the interface between forest ecosystem[2] and forest manager. As management and decision making are rarely a matter of only one individual person, but related to communication processes, information transfer and group communication techniques are the last puzzle stone to complete the process-oriented management network. Such a network of tools, methods and models is actually intended to be realized in the frame of the DynamicDATA EU25+[3] activity, a project platform, which is supported by the German Federal Ministry of Education and Research (BMBF) for supporting the development of transregional land-use management approaches in Central and Eastern Europe.

Process-oriented management demands a sound and mature knowledge base on ecosystem functioning with regard to reactions on multiple changing conditions from climate change over changing off-site impact from industrial land-use towards changing forest management measures and their interrelations. The forest manager(s) must be supported by a network of tools, methods and models, which facilitates cognitive processes for the change from a static view of forest ecosystems to a process-determined perception and decision making. Such an approach could also be employed for external applications regarding the promotion of forest services and benefits as well as the coordination of stakeholder interests.

[2] For this discussion, man was not regarded as integral part of the forest ecosystem in order to better clarify the interfaces and links between the different methods, tools and models in the process-oriented management network.

[3] http://www.dynamicdata.fle.czu.cz/.

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Fly-ash deposition in North-Eastern Germany and consequences for forest management

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Abstract

The article gives a short overview on the development of forests in North-Eastern Germany focussing on Dübener Heide as model region. This region was affected for more than 90 years by fly ash deposition from unfiltered lignite combustion in Czech, Polish, and German power plants, which still superposes natural matter cycles and balance. Long term fly-ash deposition resulted in a homogenisation of differing site qualities along a distance dependent regional gradient and in a new mosaic considering formerly comparable sites and stand types. Changing deposition regime and environmental changes like climate change initiate new and complex ecosystem processes. They demand from forest ecosystems a continuous adaptation to new frame conditions, which should be considered in a skilful forest management. In the following the article introduces an approach for the regionalization of ongoing processes based on process-indicators. The intention of the approach is to come to a delineation of process-homogeneous planning units, which form a base for a better integration of future potentials and risks into forest management planning.

Fly-ash deposition history in North-Eastern Germany

Overview

The development of environment and particular of forests in North-Eastern Germany is affected by a special deposition history: fly-ash from unfiltered lignite combustion in Czech, Polish, and German power plants containing high amounts of (average in brackets) SO_3

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(26%), CaO (20%), SiO_2 (18%), AlO_3, FeO_3, MgO, TiO_2, Na_2O, K_2O, heavy metals (Cd, Cu, Pb, Zn), and tertiary carbon (KLOSE and MAKESCHIN, 2004) still superposes the natural matter cycles and matter balance. Two main deposition regions were defined from the early 1960ies on: **(a)** the lowland region Chemnitz via Leipzig till Magdeburg, and **(b)** the hilly Lusatian/Spree region along the Polish border between Frankfurt/Oder-Lübben-Cottbus-Hoyerswerda-Görlitz. Especially region **(a)**, part of the central German lignite mining area is characterized since more than 90 years by an intensive industrialization and especially by lignite combustion for energy production. The article refers in the following to the comparably well investigated region **(a)**.

In the most important forest in region **(a)**, the so called "Dübener Heide", fly ash deposition amounted from 1910 – 2000 to a total of 18 Mio. t, and during the decade 1961 – 1970 up to 3 - 8 t / ha * a fly ash were deposited in the regional forest ecosystems (KLOSE and MAKESCHIN, 2004, NEUMEISTER et al., 1991, LUX, 1976 a, b, 1978). Fig. 1 gives an overview on the total deposition in Dübener Heide in the period 1891 – 2000 (REICHE, 2001), Tab. 1 provides exemplary information on the emission situation (main emitters) in the middle of the 1970ies (LUX, 1965), the period with the highest amount of emission and deposition. The comparison between daily coal combustion and related fly ash and CaO emission reveals the varieties of technical standards of the regional power plants and industries. Especially the power plant "Zschornewitz", which was characterized by a very poor technical standard, was known to be one of the most important regional pollution sources (ENDERS and PEKLO, 1975).

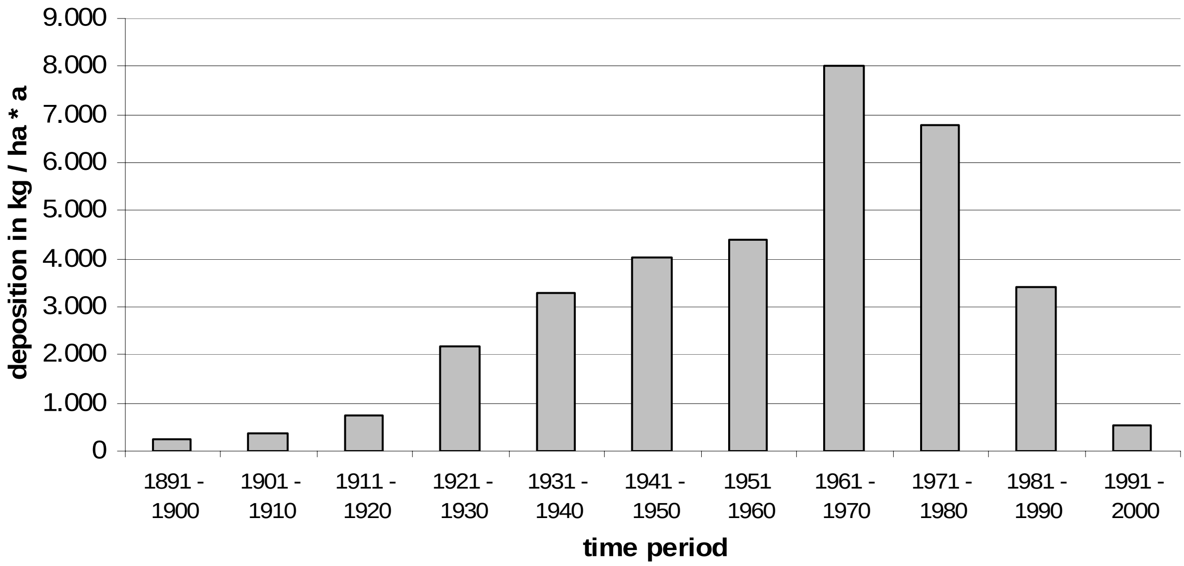

Fig. 1: Fly ash deposition development from 1891 – 2000 (acc. to REICHE, 2001, mod.)

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Tab. 1: Main emitters in the industrial triangle Leipzig-Halle-Bitterfeld (LUX, 1965)

	main emitters (1965)	coal combustion (t/d)	fly ash t/d	CaO t/d
power plants	Zschornewitz	10.500	420	84
	Muldenstein	1.184	47	9
	K. Liebknecht	3.120	69	14
	Vockerode	12.500	125	25
	gov. energy production	13.500	135	27
chem. industry	film industry	3.500	70	14
	dye industry	4.000	80	16
	other chem. industry	2.616	104	21

Nowadays, the reduction of regional power plants and chemical industry as well as improved filter techniques on the one hand and an exponential increase of traffic and intensive agriculture (animal husbandry) on the other, lead over to a change in the deposition quality: fly ash disappeared completely, whereas NO_x, SO_x and NH_3 are still on a high level (FÜRST et al., 2005, WELLBROCK et al., 2005).

Effects of fly-ash deposition

Fly-ash deposition is defined as particle residue from coal combustion, which enters the flue gas stream. The different components of fly-ash – "black" (tertiary) carbon, alkali / earth alkali metal salts, heavy metals and silicium compounds were distributed according to **(a)** their aggregate state, **(b)** their particle size and form and **(c)** the landscape relief and **(d)** the dominant land use type along a regional gradient. According to LUX (1978) and HAASE (1995), the differing range and effects of alkaline particles and soluble acidic deposition components requires a stratification of the affected areas around the industrial hot spots as base for an adapted forest management. LUX (1965, 1976 a, b), STEIN (1965) and ENDERLEIN and STEIN (1964) developed respective stratification standards (Fig. 2). This approach intended to regionalize economic losses caused by depositions. The deposition zones were defined according to a sample plot based evaluation system, which comprises a

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single tree and stand wise characterization of visible damages in medium aged Scots pine stands combined with a spatial regression of the results.

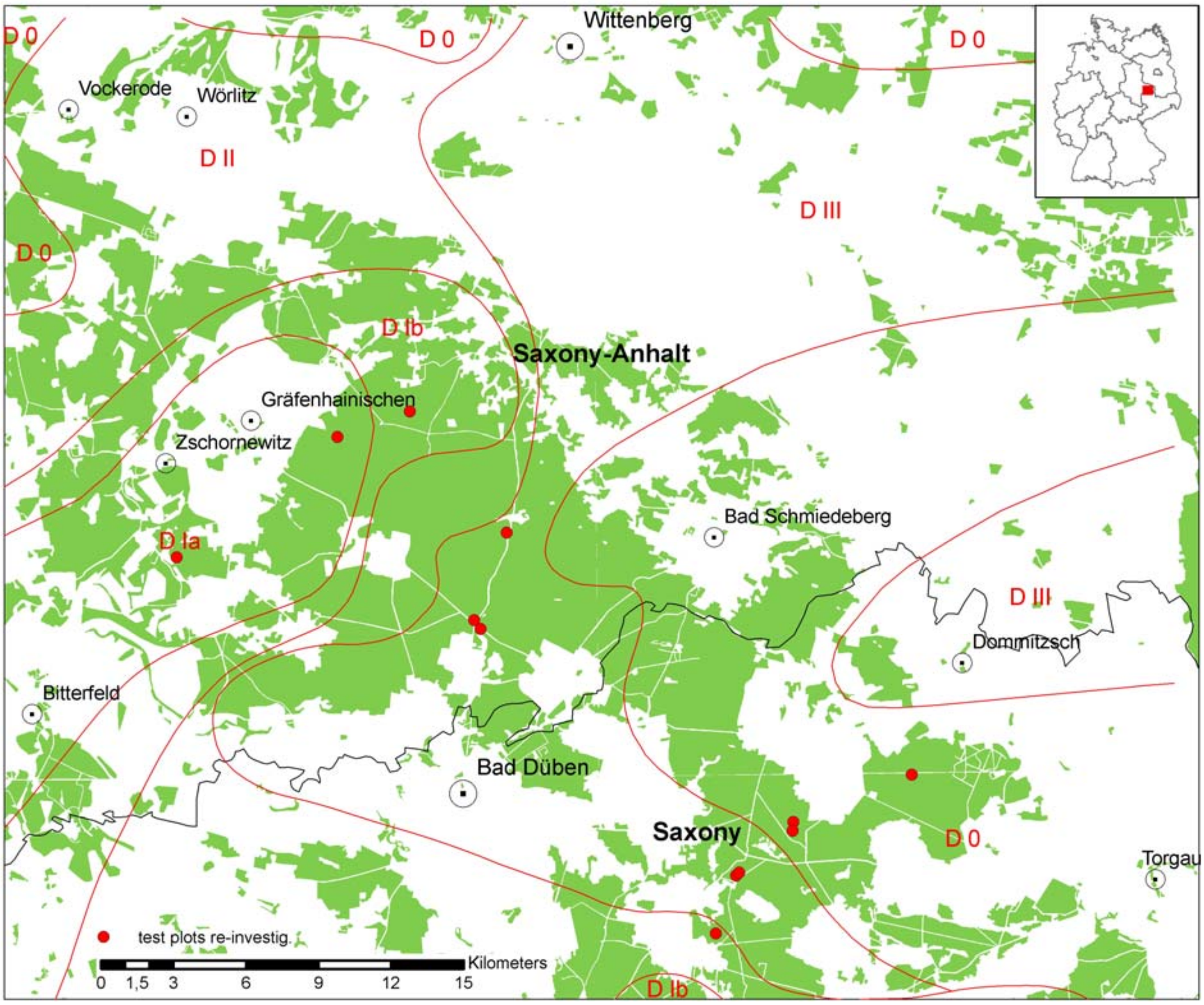

Fig. 2: Deposition zones in the Leipzig-Halle-Bitterfeld region according to LUX (1965)

Zone DI a and DI b were the most affected zones. DII and D III are characterized by a spatially continuous decrease of fly ash deposition. D0 was almost not affected by fly ash deposition, but suffered from the generally high S and N deposition level in GDR. The regional fly-ash gradient in Dübener Heide is mainly distance-dependent due to the locally concentrated emitters (power plants) and is reflected by **(i)** an impact on growth parameters (Tab. 2), and **(ii)** the development of “typical” ground floor vegetation groups (Fig. 3) (KOPP, 2003, KONOPATZKY and KOPP, 2001, HEINSDORF et al., 1994, LUX, 1964 a, LUX and STEIN, 1977).

The fly ash impact on regional forests is nowadays overlapped by additional local emission sources (mainly N emission from farming). In consequence, an irregular spatial pattern of acidic or alkaline deposition effects can be observed (STRZYSZCZ, 1999, MAGIERA and STRZYSZCZ, 1999, THOMASIUS et al., 1998, NIEHUS and BRÜGGEMANN, 1995, LUX, 1976 a).

Tab. 2 gives an overview on height, basal area and volume growth and growth reduction from the most affected zone DI (= DI a + DI b) to the "reference" zone D0. Compared to D0, a major impact on growth was observed in DI, whereas the impact on stand growth in DII and DIII was more or less comparable. LUX (1965) concluded that the influence on height growth (for Scots pine) seemed to be the best indicator for fly ash impact.

Tab. 2: Deposition impact on the growth of 50 – 90 yrs. old Scots pine stands (150 sample plots) in Dübener Heide according to LUX and STEIN (1977)

deposition zone		DI	DII	DIII	D0
growth parameters	height (m/a)	0,09	0,15	0,16	0,23
	basal area (m^2/ha*a)	0,38	0,53	0,53	0,64
	volume (m^3/ha*a)	4,6	5,9	6,2	8
growth reduction (referred to zone D0)	height growth reduction (%)	-61	-35	-30	0
	basal area incr. (%)	-41	-17	-17	0
	volume incr. (%)	-43	-26	-23	0

Fig. 3 gives an overview on the regionally typical ground floor vegetation groups along the deposition gradient in Dübener Heide and the corresponding nutrient stock in the humus layers according to HEINSDORF et al. (1994, N=122 sample plots). The vegetation groups in Fig. 3 reflect the different deposition load and deposition type along the gradient. In the immediate vicinity of the former power plants basophile and light preferring species (*herbs*) related with high nutrient and S stock in the humus layers are still the predominating ground floor vegetation group. In a greater distance (> 30 km, corresponding to zone D0) from the power plants, *mosses* are dominating. They coincide with a comparably poorer nutrient stock in the humus layers. The groups "*Calamagrostis epigejos*" (mainly local N deposition / fertilization), "*Deschampsia* (*Avenella) flexuosa*" (acidic deposition, but also opening up of the stands), and "*herbs-Deschampsia flexuosa*" type (beginning pre-dominance of acidic depositions / re-acidification) reflect the local pre-dominance of N and acidic deposition. These vegetation types can be used as indicator for the artificially changed chemical top soil properties (KONOPATZKY and KOPP 2001, WILSON et al., 2001). Especially the "*herbs-Deschampsia flexuosa*" type seems to have a high indicative value for the ongoing re-acidification process. However, KOPP (2003) mentions the time-delayed response of ground floor vegetation composition, which restricts its indicative value.

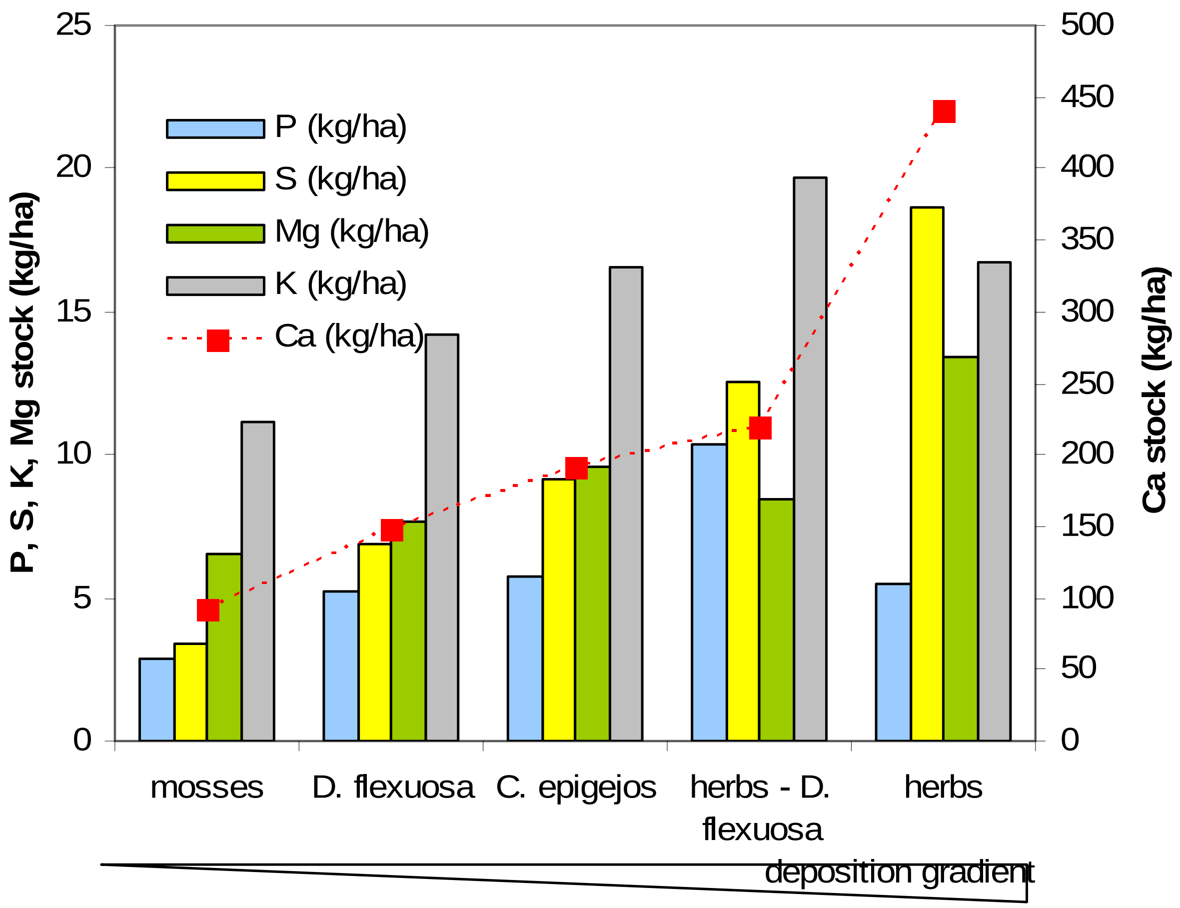

Fig. 3: Differentiation of "typical" vegetation groups along the fly ash deposition gradient in Dübener Heide and nutrient stocks in the humus layers acc. to HEINSDORF et al., 1994

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Consequences and challenges for Forest Management

Consequences in forest management practice

Forests are predisposed receptors for fly-ash due to their high surface roughness and the long production periods (STRZYSZCZ and MAGIERA, 1998, 2001, STRZYSZCZ, 1999, ULRICH et al., 1979). The reaction of forests on fly-ash deposition depends on tree species composition and site properties (KUNZE et al., 1995, 1996). Fly-ash deposition can cause a homogenisation of existing site quality differences and a differentiation of formerly comparable sites and stand types (THOMASIUS et al., 1998, FIEDLER, 1986). Fly ash deposition leads **(i)** to a higher nutrient availability (base saturation) and cation exchange capacity, to a change of physical properties like texture and sorption capacity, **(ii)** to a disturbance of ground floor vegetation composition and organic matter decomposition and **(iii)** to an imbalance of the nutrition state of (coniferous) forests (KOCH and MAKESCHIN, 2004, KLOSE et al., 2002, KOCH et al., 2002, KONOPATZKY and KOPP, 2001, AMARELL, 1997, HERPEL et al., 1995, KALLWEIT, 1990, LUX, 1964 b). From a silvicultural point of view, fly-ash deposition widens in the immediate vicinity of power plants the eligible tree species spectrum: high fly-ash deposition allows even on poorer sites a change from Scots pine stands to mixed stands with beech and noble hardwoods like lime, elm, and maple. On the other hand, stability and increment of Scots pine stands as economically important stand type in the lowland were considerably reduced (KUNZE et al., 1995, 1996). Consequently, a conversion of pure Scots pine stands with less fly-ash sensitive tree species was demanded (NEBE et al., 2001, THOMASIUS et al., 1998, LUX, 1976 b). Considering respective economic consequences, e.g. VILLA (1989) and STRACKE (1996) developed multidimensional approaches for evaluating the effects of deposition on forest management including development of stocking volume, change of rotation period and of costs for regeneration as well as development of recreation potential and water management aspects. Recapitulating the economic consequences, deposition increased considerably the costs for (sustainable) forest management and reduced the revenue due to a negative impact on production period and assortment structure. In the former GDR, this was approved by chemical industry in the form of a yearly appointed monetary compensation (see e.g. LUX, 1965, ENDERS and PEKLO, 1975, VILLA, 1989).

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Challenges for forest management

From the 1980ies on, the introduction of fly-ash filters lead to a merely acidic deposition regime (NO_x, SO_2). After 1989, a strong reduction of fly-ash emission going along with still high or even increasing level of N emissions (NO_x, NH_4) changed totally the deposition characteristics in formerly fly-ash influenced areas (NIEHUS, 1996). These trends initiated a process of re-acidification and impacted matter balance and matter cycle in the formerly fly-ash influenced sites (KURBEL, 2002, HERPEL et al., 1995). In consequence, the long term development of broad-leaved tree species regeneration, e.g. noble hardwood species is still unclear. The ongoing re-acidification as well as an expected temperature increase and precipitation decrease (KÜCHLER and SOMMER, 2005) might cause a re-adjustment of the inter-specific competition in regional stands. Furthermore, by-products like water quality / quantity and socio-economic functions are affected by the described trends (WAGNER, 2004). Ongoing research is aimed to reveal respective development potentials and risks (FÜRST et al., in preparation).

The special development of forests in regions like Leipzig-Halle-Bitterfeld demands for an integration of ongoing processes into forest management planning (FÜRST et al., in preparation). A pre-condition is the regionalization of processes as base for process-oriented evaluation and management approaches. Fig. 4 introduces a respective approach, which is applied in the context of the project ENFORCHANGE [1].

[1] The project “Environment and Forests under Changing Conditions” (ENFORCHANGE, www.enforchange.de) is supported by the Federal Ministry of Education and Research and deals among other with the development of process-oriented regionalization and management concepts in the regions Leipzig-Halle-Bitterfeld and Upper Lusatia.

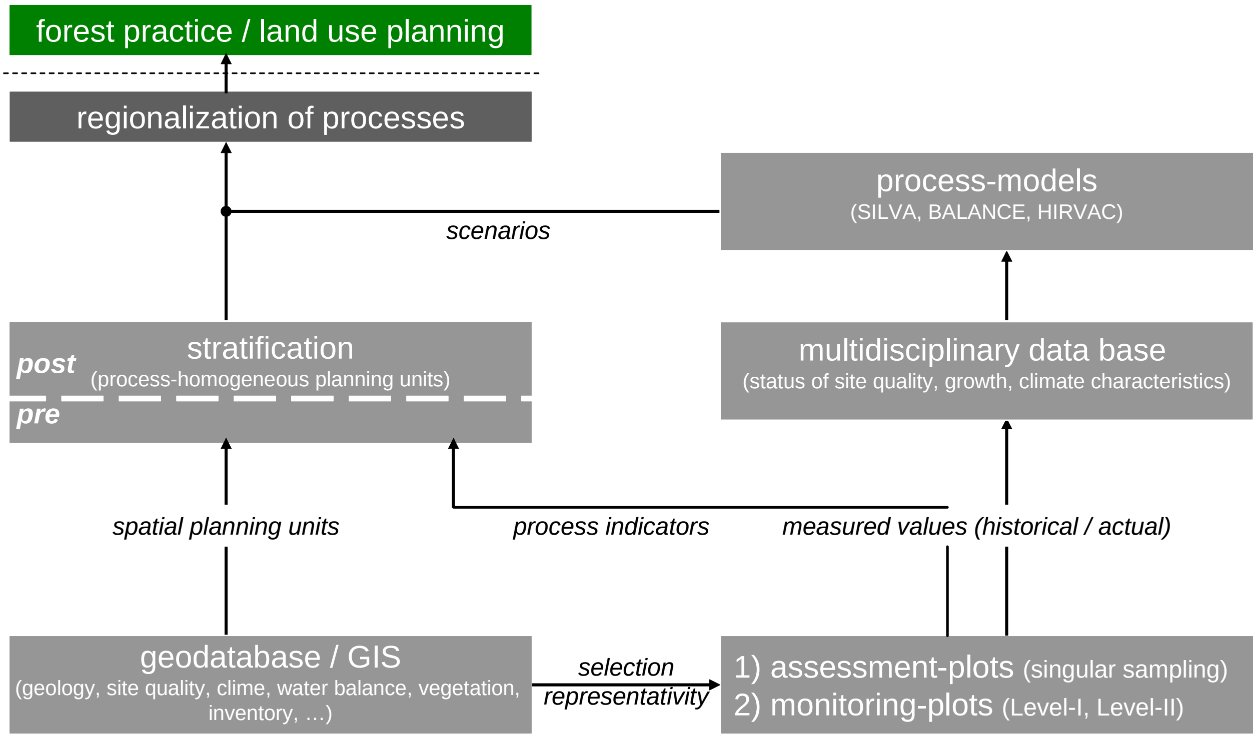

Fig. 4: Stepwise regionalization of process as base for (forest) management planning

Process-regionalization is based on a network of assessment and monitoring plots (v. WILPERT and ZIRLEWAGEN, 2003). These plots represent within the project ENFORCHANGE the regional fly-ash deposition gradient in the model region Dübener Heide, the main site classes and stand types (assessment plots) and are the source for long term time series data (monitoring plots). The recorded site quality, growth and climate characteristics are integrated into a multidisciplinary data base and form the base for a parameterization and validation of process-models. These deliver regionally adapted scenarios of climate and of stand growth development. Selected process indicators, which are recorded on the assessment plots like ferromagnetic susceptibility (see MAIER and SCHOLGER, 2004, HANESCH and SCHOLGER, 2002, MAGIERA and STRZYSZCZ, 1999, STRZYSZCZ and MAGIERA, 1998, PEKLO and NIEHUS, 1992), vegetation indicators (KONOPATZKY and KOPP, 2001, AMARELL, 1997) and chemical and physical humus properties (see e.g. KLOSE and MAKESCHIN, 2004, ZIRLEWAGEN and v. WILPERT, 2004, KALLWEIT, 1990) are combined with basic spatial information (geology, site quality, climate, etc.) in order to realize a process-oriented spatial stratification (process-homogeneous planning units). The combination of these process-oriented planning units with the regional development scenarios forms the base for the regionalization of multi-dimensional processes in the regional forest ecosystems. This process-regionalization intends to support regional forest practice and land use planning by better reflecting the effects of past (and future) environmental changes and forest management measures on regional forests. This is aimed to be a base for a more time and cost efficient forest ecosystem (and land use) management.

Discussion and conclusions

Fly ash deposition in the past and the current change of the deposition regime result in ambivalent consequences for forest management in regions like Leipzig-Halle-Bitterfeld. On the one hand side, an improvement of site quality and an enlargement of silvicultural possibilities can be observed. On the other hand, system stability and long term potential of economically relevant tree species might be affected. Regions with such elementary changes demand for concepts for a better integration of processes in forest (and land-use) management in order to realize a sustainable landscape development.

Beyond this background the delineation of "process-homogeneous" management planning units (compare e.g. the concept of Hydrologic Response Units (HRU) by FLÜGEL, 1995) focussing on the further development of sites as response on forest management under changing environmental conditions seems to be a promising approach. The hereby provided information allows to integrate future on- and off-site potentials and risks into strategic development targets and short-term management measures, whereas the actually available (more static) management planning information base ignores an essential part of the ongoing ecosystem processes (PENG, 2000, SCHOENHOLTZ et al., 2000, MARTELL et al., 1998). AUGUSTIN et al. (2005) and de VRIES et al. (2003) emphasize the demand of regionalization techniques for up-scaling processes from monitoring and inventory plots. Regionalization of process parameters is an overall objective in landscape related research (e.g. DIEKRÜGER et al., 1999, KLEEBERG et al., 1999, VOLK and STEINHARDT, 1999) and the delineation of process units like ecotopes, physiotopes, or patches is a frequently used approach in landscape ecology (HABER, 2005, MOSIMANN, 1990).

Some promising approaches for regionalization were recently presented by ZIRLEWAGEN and v. WILPERT (2004), ZIRLEWAGEN (2003), SABOROWSKI and JANSEN (2002), MUES (2000) and ERHARD and FLECHSIG (1998). They are mainly based on indicators for the current status of forest ecosystems and should be enhanced with regard to process-regionalization by integrating process-indicators. This would be a valuable contribution for a statistically valid process-oriented forest management and would furthermore offer the possibility to form a better interface to ecological landscape management on different scale levels (KOPP, 2003, VOLK and STEINHARD, 1999).

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Reaction Of Forest Systems In The Industrial Triangle Leipzig - Halle - Bitterfeld On A Changing Immission Regime – State Of The Art

Christine Fürst, Mengistu Abiy, Franz Makeschin

Abstract

Forests in the industrial triangle Leipzig-Halle-Bitterfeld underlie since more than 90 years an intensive influence of depositions. The deposition history is characterized by high SO_2, N, and fly ash loads until the late 1980ies / early 1990ies and a later change in the immission quality towards a disappearance of fly-ash and further on high N depositions. The influence of depositions on regional forests shows a spatial differentiation with a decreasing influence of fly ash and S along a distance dependent gradient starting from the former power plants and overlapping gradients with irregular peaks for N. The stability of the region typical Scots pine forests is still endangered by past and ongoing immissions. Consequently, a conversion towards forests, which are adapted to the actual site conditions and their future development, is demanded. This requires a revision of the site classification system by a regionalization of the former and actual depositions and the resulting soil processes and vegetation development.

Immission regime in the industrial triangle Leipzig-Halle-Bitterfeld – some tendencies

The industrial triangle Leipzig-Halle-Bitterfeld, part of the central German lignite mining area was characterized since-more than 90 years by an intensive industrialization and especially by lignite combustion for energy production. The immission regime in the regional forests was dominated by SO_2, heavy metals, followed by N and Potassium salts. In the surroundings of chemical industry hotspot Bitterfeld, additionally Fluorides, Chlorides, as well as complex Herbicides from the local chemical industry were emitted. The deposition in the most important regional woodland, the so called "Dübener Heide" amounted from 1910 – 2000 to 18 Mio. t fly ash and 12 Mio t SO_2, and in the decade from 1961 – 1970 up to 3 t / ha * a fly ash were stored in the regional forests (LUX, 1965, 1976 a, b, 1978, NEBE et al., 2001, NEUMEISTER et al., 1991, PEKLO and NIEHUS, 1992, KLOSE and MAKESCHIN, 2004).

The reduction of regional power plants and chemical enterprises as well as improved filter techniques on the one hand and an exponential increase of traffic and a still high number of agricultural enterprises (mainly chicken farms, pig husbandries) on the other, lead to a change in the immission regime: fly ash immission disappeared completely, whereas NOx-(act: 5.650 t/a), SOx-(act.: 3.660 t/a) and NH_3-(act. 780 t/a) are still on a high level. Fig. 1 provides an overview on the actually most important regional emission components according to EPER, 2005.

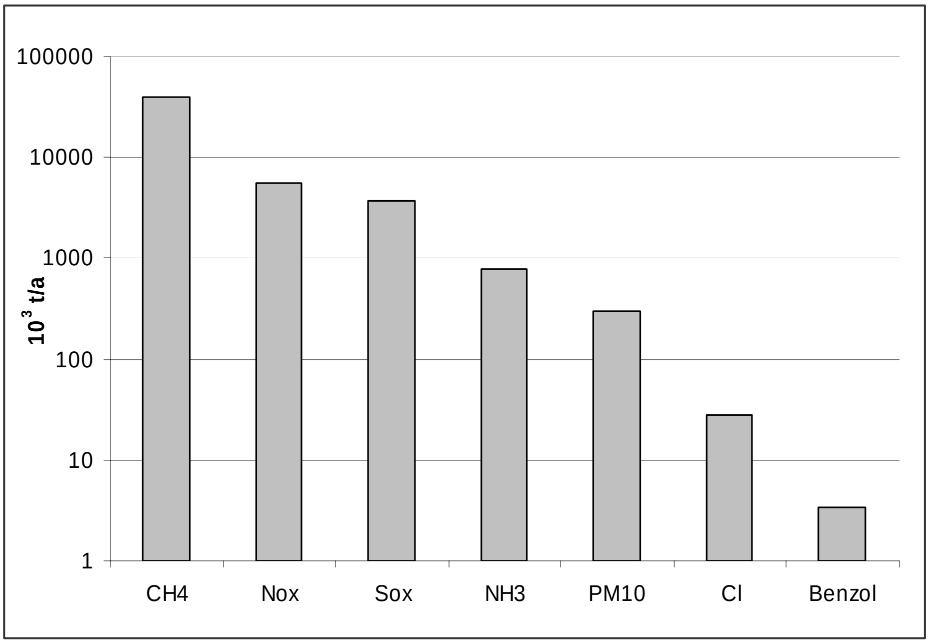


Fig. 1: Actual annual emissions in the industrial triangle Leipzig-Halle-Bitterfeld (EPER, 2005).

In the past, two characteristic classes of emitted matter, (a) fly-ash including black carbon, alkaline dust, heavy metals and silicium compounds and (b) soluble emissions like SO_2, NH_3, and NOx, were distributed along a gradient according to their aggregate state, their particle size, the landscape characteristics, and the local wind rose around the power plants (see THOMASIUS et al., 1998). The fly-ash gradient was characterized by a more or less a continuously decreasing deposition in dependence from the distance to the regional power plants in Bitterfeld, Zschornewitz, Wörlitz, and Wolfen. In the case of N-depositions with a higher spatial distribution of local emitters, the gradient is characterized by overlapping deposition areas with irregular local deposition peaks (LUX, 1976 a, NIEHUS and BRÜGGEMANN, 1995, STRZYSZCZ, 1999, MAGIERA and STRZYSZCZ, 1999). According to LUX (1978) and HAASE (1995), the differing range and effects of alkaline particles and soluble acidic deposition components requires a stratification of the influenced areas as basis for an adapted forest management. ENDERLEIN et al. (1961), STEIN (1965) and LUX (1965, 1976 b) developed a regionalization approach based on the classification of visible damages on sample plots in medium-aged Scots pine stands (see Fig. 2).

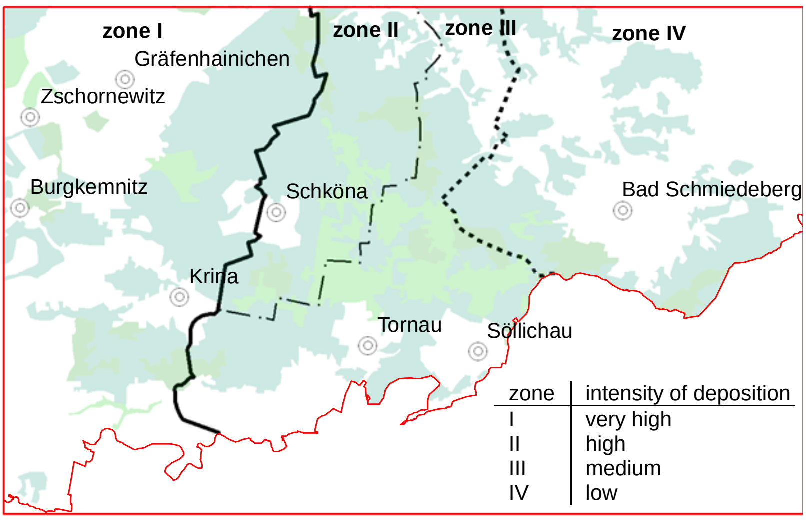


Fig. 2: Deposition zones in the Dübener Heide (acc. to Lux, 1965).

Fig. 2 shows the stratification in the Dübener Heide, which describes zones with a distinct height of financial losses, calculated according to the deposition effects on tree growth, timber marketing, and additional costs (LUX, 1965, see also KURTH, 1985, STRACKE, 1996).

Reactions of forest systems

The regional woodland in the industrial triangle Leipzig-Halle-Bitterfeld is mainly characterized by coniferous stands, where Scots pine is the regional dominant tree species (see Fig. 3). Scots pine was part of the natural vegetation in the Dübener Heide, but became its actual importance due to the transformation process going along with the industrialization of the region and the hereby provoked timber need in the 18^{th} and 19^{th} century (BENDIX, 2001). According to the results from the ecological forest monitoring (see e.g. BIEBERSTEIN, 1988) more than 70 % of the forests in the former district Leipzig were strongly affected by immissions at the end of the 1990ies, and large parts of the pine-dominated stands especially near to the power plant impended to break down.

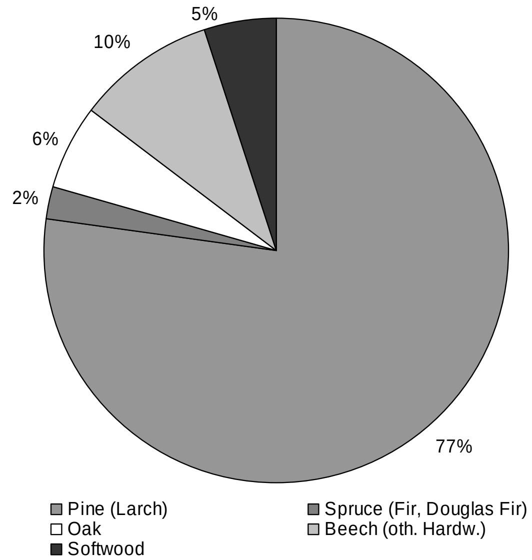
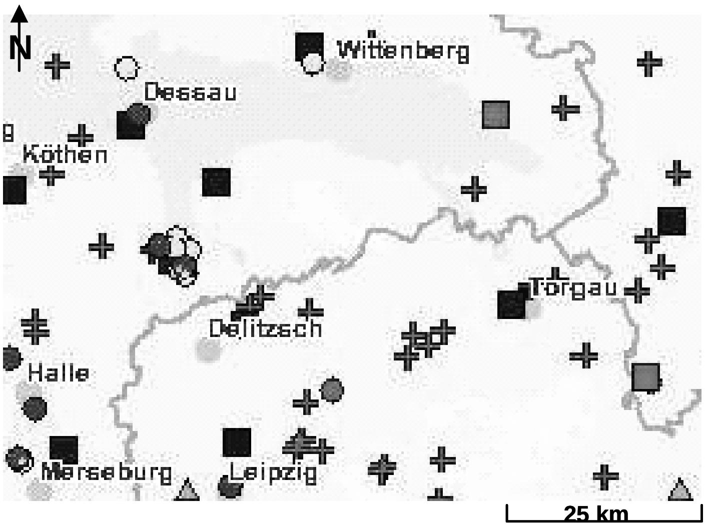


Fig. 3: Tree species composition in the Dübener Heide (MLU, 1999, SMUL, 2005)

The influence of the immissions on forest systems and their reaction is correlated with the regional immission gradient. Regarding former fly-ash immissions, fertilizing-like effects could be observed in a distance up to 25 km (ENDERLEIN and STEIN, 1964), which ensue from the high deposition of base cations, S and N. This provokes (a) an exuberant development of the ground vegetation and supports tree growth, but leads (b) to a lower stability of the Scots pine stands, which are negatively effected by too high base depositions (LUX, 1964 a, b; 1976, KURTH, 1985). AMARELL, 1997, KNOCHE et al., 2001, and THOMASIUS et al., 1998 describe a drift of the ground vegetation towards nitrophile and nutrient indicating species, which accentuates the change of the growth conditions. Fly ash deposition improves the nutrition capacity of the regional sites. KOPP and SCHWANECKE, 1994, THOMASIUS et al., 1998 and KNOCHE et al., 2001, report an eutrophication up to two degrees and an enlargement of the eligible tree species spectrum. Fly ash depositions improves especially the nutrient provision in the humus layer and to some extend also in the uppermost mineral horizon (e.g. STRYSZCZ, 1991, 1993). This provokes the development of flat root systems and thus, endangers the stand stability against wind throw and drought (THOMASIUS et al., 1998, KNOCHE et al., 2001, KOCH et al., 2002, KLOSE and Makeschin, 2004). Going along with fly ash immission, round about 5 kg/ha*a heavy metals (Cu, Cd, Pb, Zn) were deposited in the regional forests in the past century (NEUMEISTER et al., 1991, PEKLO and NIEHUS, 1992). Due to their high storing capacity and the long term accumulation, heavy metals might endanger in the future the stability and resilience of the forest systems and lead also to off-site effects regarding e.g. regional water quality (ULRICH ET AL., 1979, STRZYSZCZ, 1999, STRZYSZCZ AND MAGIERA, 1998, 2001). STRZYSZCZ, 1993, 1999, STRZYSZCZ and

MAGIERA, 1998, MAGIERA et al., 2002, KLOSE et al., 2003 report e.g. a disturbance of the litter decomposition and the development of the adverse humus forms. In the outskirt-forests characterized by a wider distance than 25 km to the power plants, acidic depositions (SOx, N) were not compensated by simultaneous alkaline immissions and consequently a nutrient disharmony in the forest vegetation occurred and led to intensive liming actions in the past.



Enterprises registered by EPER

- energy production
- metallurgy
- mineral processing industry
- chemical industry
- waste treatment
- other:
- food production
- intensive animal husbandry

Source: EPER 2005, modified;

Fig. 4: local emitters in the region Leipzig-Halle-Bitterfeld

Nowadays, the locally high NOx and NH_3 emissions (see Fig. 4, EPER, 2005) sustain a spatially differentiated N deposition, which overlaps the immission strata described by LUX, 1965. In the former fly ash influenced forests, the hereby provoked acidification of the forest sites might be levelled by the still high basic cation storage in the humus layer. However, a considerable loss of NH4+-soluble cations since 1988 was reported by KOCH et al., 2002, which indicates a continuous reduction of the buffer capacity and nutrition state of the artificially up-based sites. In the outskirt-forests, the local N immissions can accentuate the existing nutrition imbalance.

Conclusions and preview

Immission history and actual depositions in the industrial triangle Leipzig result in ambivalent consequences for forest management: the former fly-ash depositions entail actually in an artificially high base nutrition status of the forest sites near to the former power plants. A development of the ground floor vegetation towards base and nitrogen indicators and an intensive natural regeneration of noble hardwoods (maple, ash, lime) on de facto mid-quality sites can be observed. The stability and durability of this situation is still open (THOMASIUS et al., 1998). The continuously high N deposition supports on the artificially up-based sites the ample vegetation growth, but endangers further on the stability of the Scots pine forests. Besides, the spatially differentiated N deposition provokes a faster acidification of the sites and can support the release of the accumulated heavy metals especially in the outskirt-forests. NESAFI (2005) e.g. revealed a decrease of the total stock in heavy metals and a simultaneous augmentation of the mobile pool along a transversal deposition gradient in the Dübener Heide. LUX and STEIN, 1977 and NEBE et al., 2001 propose a conversion with deciduous tree species in order to stabilize the Scots pine stands on the artificially up-based sites. A conversion with site-adapted hardwood species might also help to counteract the effects of the N depositions in the whole region. As a precondition for an adapted silvicultural planning, an adaptation of the site classification system in dependence from the original site quality and the ongoing development is required (KALLWEIT, 1990, KLOSE et al., 2002, KOCH and MAKESCHIN, 2004). For this purpose, a regionalization of the past and actual regional deposition (see e.g. MUES, 2000, ZIRLEWAGEN, 2003) and the ongoing soil and vegetation development is subject of ongoing research activities (FÜRST and MAKESCHIN, 2005).

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Comparison of Wood Ash, Rock Powder, and Fly Ash - a review

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Abstract

The article intends to discuss the effects of the liming alternatives wood ash and rock powder in comparison to the effects of fly-ash deposition on forest soils. As result, recommendations considering the characteristic application field and right use of wood ash and rock powder, and the possible reactions of forest ecosystems on fly ash deposition are given. The application fields of wood ash and rock powder can be considered as complementary. Wood ash should be preferred on sites with naturally higher organic matter, whereas rock powder can particularly improve the properties of poor (sandy) soils with low organic matter content. Fly ash deposition can be considered as a kind of long-term fertilizing experiment for forest soils with some parallels to wood ash fertilization. Both, wood ash fertilized and fly ash affected soils show the most obvious effects in the Oe and Oa horizon induced by a long-lasting decomposition with litter fall on ash residuals and a slow move of the only partly-decomposed matter to the Oa. Past fly ash impact to forest soils demands under a changing deposition regime a careful monitoring considering the turnover rate of the organic matter and the possible eluviation of toxic elements.

The paper is based on a presentation given at the International Conference on Restoration of Forest Soils in Polluted Areas, Prague.

Introduction

Since long time, the necessity of an amelioration of forest soils is discussed controversially. BAULE and FRICKER (1967), LUNNAN et al. (1991), and HOEN and SOLBERG (1994) emphasized the increased production potential and C-sequestration ability as reason for ameliorative measures. REHFUESS (1990), WOLFF et al. (1997) and EISENBEIS et al. (1996) considered the

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consequences of atmogene deposition like the possible imbalance of nutrients and the low microbiological activity as important argument for amelioration. Contrariwise GULDER and KÖLBEL (1993) argue that a special need for an improvement of forest soil fertility is scrutinized by a sufficient nutrient supply of the vegetation. KREUTZER (1995) showed that liming enhances the nitrification and the nitrate eluviation and thus, provokes undesirable off-site effects like a decrease of water quality. SKRINDO and OKLAND (2001) and SCHÄFER (2002) observed a decrease of the diversity of soil flora and fauna provoked by liming. As a consequence, alternatives to liming, like wood ash / lignite ash or rock powder can be taken into consideration. NAROVEC and SACH (1994) and STENICKA and NAROVEC (1994) mentioned the special improvement of physical soil properties by amelioration with rock powder. Furthermore, residues from combustion processes for energy production like wood ash demand sustainable ways for recycling. However, also these alternatives include characteristic risks. BUNDT et al. (2001) warned against the possible input and remobilization of organic contaminants provoked by the use of combustion residuals like wood ash or lignite ash.

In order to estimate such effects of ash deposition, fly-ash affected forest soils, which can be found in the vicinity of industrial barycentres in Eastern Germany and Eastern Europe, can serve as a kind of long term practical test. Fly-ash supplied macro- and micro-nutrients but also heavy metals to a very high extend and entailed ameliorative effects, but lead also to a contamination of the soils (FÜRST et al, in preparation).

The article intends to discuss the effects wood ash and rock powder in comparison to the effects of fly-ash deposition on forest soils and intends to asses their potential positive effects and the ecological risks for forest ecosystems and the environment. The paper is based on a presentation given at the International Conference on Restoration of Forest Soils in Polluted Areas, Prague.

Soil Amelioration - Materials, Potentials and Risks

Wood ash

The (re-)introduction of wood ash as ameliorative material went along with increased use of wood for energy supply at the beginning of the 90ies (CLARHOLM, 1994), in some regions also with the question of woody biomass as substitute for lignite. Basic research on wood ash effects was carried out in Sweden since 1910 and in Finland since 1937 (BÜTTNER, et al., 1998, HOLMBERG and CLAESON, 2002). One challenge of the use of woody biomass for energy production is the proper handling of the combustion residuals. The remaining ashes must be deposited (expensive), can be used as aggregate in cement (small potential), or can be applied as fertilizer in agriculture and forestry (POHLANDT, 1995). Table I provides information on the ash content in the combustion residuals of exemplary bio-materials according to ZOLLNER and REMLER (1998), OBERNBERGER (1997) and SCHULZE and MARUTZKY (2002).

Tab. 1: Ash content of selected materials

material	**ash content** *% of dw*	**coarse ash** *% of fractions*	**cyclone ash**	**fly ash**
sawdust / saw mill rests	0.5 – 3.0			
timber without bark	0.8 – 1.4	20 - 30	55 - 65	10 - 15
timber with bark	1.0 - 2.5	70 - 90	10 - 30	3 - 6
bark	5.0 – 8.0	75 - 85	15 - 25	1 - 4
straw	5.0 – 12.0			
waste timber	6.0 – 12.0			

The average ash content of the above mentioned materials ranges between 0.5 % and 12.0 %. The ash content of timber combustion residuals depends on whether the timber is burnt with bark (up to 2.5 % ash content) or without bark (max. 1.4 % ash content). This is a result of (a) the higher lignification and accumulation of inorganic matter in cortical cells and (b) of the potential soiling of bark during harvesting and transport. The ash content of bark can range between 5.0 – 8.0 % and resembles therein lignite-(and silicate) rich organic matter like straw (5.0 – 12.0 % ash content). The comparison indicates the necessity to separate timber and bark and to avoid the use of waste timber in order to reduce the resultant ash amount.

Timber with or without bark and pure bark can be differentiated according to the content of three ash fractions (i) coarse ash, (ii) cyclone ash and (iii) fly ash, which can be differentiated by their chemical composition (see also Tab. 2). Generally the nutrient content decreases from (i) to (iii), while the content of critical substances (e.g. heavy metals) is increasing. Combustion residuals from bark and timber with bark consist dominantly out of coarse ash, and pure bark combustion produces less fly ash compared to timber with bark combustion.

The combustion residuals of timber without bark show a clearly higher content in cyclone and fly ash than pure bark and timber with bark.

Properties and application

Wood ash application in forest systems is related with the idea to re-establish the nutrient cycle after nutrient removal by whole tree harvesting (HAKKILA and KALAJA, 1983, NAYLER and SCHMIDT, 1986 and 1989, ANDERSSON and LUNDKVIST, 1989, CAMPBELL, 1990, OHNO and ERICH, 1991, HUANG et al. 1992, MUSE and MITCHELL, 1995, OBERNBERGER, 1997, ZOLLNER and REMLER, 1998, V. WILPERT, 2002, V. WILPERT et al., 2002, KHANNA et al., 2002, HOLMBERG and CLAESON, 2002). FROSTEGARD et al. (1993), BAATH and ARNEBRANT (1994) and OBERNBERGER (1997) pointed out that wood ash fertilizing effects are comparable with normal liming, but with a higher vertical depth effect (V. WILPERT, 2002, V. WILPERT et al., 2002). Wood ash can be seen as Ca-dominated multi-nutrient fertilizer, which improves especially the potassium supply of forest vegetation (ZOLLNER and REMLER, 1998, V. WILPERT, 2002, V. WILPERT et al., 2002, SCHÄFER, 2002, NIEDERBERGER et al., 2002). The nutrients are predominately bound in form of metal oxides, hydroxides, carbonates, sulphates, and chlorides. Due to its chemical properties – pH-value 11 – 13, quicklime resembling chemical reaction, and high buffering potential with basicity up to 35-weight-%, wood ash can be seen as appropriate material for a compensation of acidic depositions (ANDERSSON and LUNDKVIST, 1989, BONNEAU et al. 1990, TVEITE et al. 1990, OHNO, 1992, CLARHOLM, 1994, MEIWES, 1995, OBERNBERGER, 1997, BÜTTNER, et al., 1998, NIEDERBERGER, 2002 b, V. WILPERT, 2002, V. WILPERT et al., 2002). MISRA et al. (1993) mention the dependence of the chemical composition of wood ash from the furnace temperature. The combustion process leads to a hundredfold enrichment in minerals (BÜTTNER, et al., 1998). Table II (next page) gives an overview on the chemical composition of the three ash fractions according to BÜTTNER et al. (1998), POHLANDT (1995), OBERNBERGER (1997), NIEDERBERGER et al. (2002) and SCHULZE and MARUTZKY (2002).

Coarse ash contains the mineral residuals of timber and bark combustion and soil particles sticking on the combustion material. Coarse ash consists merely of macro nutrients like Ca, Mg, K, P, with an average composition of 41.7 % CaO, 6.0 % MgO, 6.4 % K_2O, and 2.6 % P_2O_5. Heavy metals like Ni, Cr, and V form only a minor part of the dry mass. Cyclone ash contains a high amount of nutrients but is characterized by a higher percentage of heavy metals like Cd, Cu, Pb, and especially organic pollutants (OBERNBERGER, 1997). Fly (micro) ash shows the highest percentage of heavy metals and contains in particular easily volatile ones like Zn, Pb, and Cd. (OBERNBERGER, 1997, NIEDERBERGER et al., 2002). Due to the high content of macronutrients and the comparably low content of heavy metals, OBERNBERGER (1997) advices the preferable application of coarse and cyclone ash for fertilizing. Only the cadmium and lead content of cyclone ash can limit it's utilization in some cases (FRITZE et al., 1995). The main problem of fly ash consists in its high content in Cr (IV).

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Tab. 2: Chemical composition of the three ash fractions coarse, cyclone, and fly ash.

element content		fraction coarse ash			cyclone ash			fly ash		
		min	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*
g/kg dry matter	P	1.6		27.6	0.6		25.8	2.1		22.4
	S	0.4		12.4	0.7		34.0	3.2		69.4
	K	11.2		135.6	10.9		165.1	5.6		219.6
	Ca	105.4		408.1	16.1		438.9	105.6		268.1
	Mg	9.6		61.4	2.2		56.9	8.0		41.7
	Al	4.2		30.1	1.1		28.5	3.2		46.6
	Mn	0.6		34.7	0.8		39.2	1.2		45.1
	Fe	3.5		31.9	1.8		531.1	3.4		42.3
mg/kg dry matter	Cu	14.0		160.0	43.0		493.0	55.0		1 450.0
	Mo		2.8			3.8			13.2	
	Zn	100.0		200.0	740.0		1 400.0	109.0		6 200.0
	V		43.3			40.5			23.6	
	Co		21.1			19.2			17.5	
	Cl		198.0			1 120.0			5 250.0	
	Ni	12.7		367.2	8.6		88.3	12.8		484.4
	Cr	1.3		473.6	5.0		419.3	17.0		810.0
	Cd	0.2		20.3	2.1		110.3	5.0		113.0
	Pb	0.9		218.0	15.7		3 527.0	24.1		7 300.0
	Hg	--		--	--		--	0.1		--
	As	< 1.0		4.1	2.0		6.7	7.0		37.4
	F		68.0			2 100.0			4 860.0	
	Cr(IV)	1.3	61.5	473.6	5.0	71.8	419.6	18.0	113.3	621.0

Potentials

Wood ash can improve chemical and physical soil properties (BÜTTNER, et al., 1998, RUMPF et al., 2001, SCHÄFER, 2002) and enhances tree growth and particularly fine root development (GENEGER, 2001). Wood ash increases the pH-value and the plant availability of base cations. In some cases less soluble chemical complexes (K) can occur and lead to a restrained K-availability (KHANNA et al., 1994). OBERNBERGER (1997) highlightens that wood ash shows a minor effect on the short term availability of nutrients compared with ashes from other plant materials. BÜTTNER, et al. (1998) and also EBERL and HILLMANN (2002) emphasized the long-lasting duration of wood ash decomposition. BÜTTNER, et al. (1998), SCHÄFER (2002), EBERL and HILLMANN (2002), HALLENBARTER and LANDOLT (2002) and SCHÄFFER et al. (2002) reported a long-term improvement of pH-value and Ca, K, and P availability. The observed improvement of the base cation availability reaches up to 30 cm depth, whereas an influence on the pH-value could be observed up to 50 cm depth. The influence on the pH-value shows a dependency from stand composition: In beech stands, the possible pH-value augmentation amounts up to 2 degrees, in spruce stands up to one degree. BÜTTNER, et al. (1998) and LAMERSDORF (2002) documented a tendencial improvement of plant nutrition, i.e. a higher K, P, and N-contents in needles, EBERL and HILLMANN (2002) mentioned a reduction of heavy metal content in needles. However, the better tree nutrition status entails not necessarily in better tree growth (UNGER and FERNANDEZ, 1990, LWF, 1997). BÜTTNER, et al. (1998), BAATH and ARNEBRANT (1993, 1994), BAATH et al. (1995) revealed ambivalent effects on microbial activity as well as on fungi diversity, which can provoke back coupling effects on tree growth. PERIÖMÄKI and FRITZE (2002) observed an increased microbial activity and a change in microbial community structure in boreal forest systems. ZIMMERMANN and FREY (2002) documented a higher rate of CO_2-deposition and an augmentation of microbial biomass as well as an increase of N-Cycle related enzyme activity. In contradiction, BAATH et al. (1995) reported a decrease in microbial biomass contents, where fungi seemed to be more sensitive than bacteria.

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Restrictions

According to HOLMBERG and CLAESON (2002), wood ash application can lead to pH and salt chocks, burning of plant tissues and excessive nutrient release. Depending from the dominating ash fraction, high amounts of heavy metals can be brought into the soil, which however under normal conditions remain in the upper mineral horizon (BRAMRYD and FRANSMAN, 1995, FRITZE et al., 1995, BÜTTNER, et al. 1998, EBERL and HILLMANN, 2002). Another problem of wood ash application is the Cr (IV) content. This rare oxidation state results under special conditions from organic matter combustion. Cr (IV) is normally reduced due to its high redox-potential to the stable oxidation state Cr (III), except in the particular case of sandy soils with low organic matter content (POHLANDT, 1995, LATSCHA and KLEIN, 1994, V. WILPERT, 2002, V. WILPERT et al., 2002, NIEDERBERGER, 2002 a, BRILL and SCHLOTHMANN, 2001, BRILL, 2002).

Wood ash can provoke a clear-cut like surplus nitrification (BÜTTNER, et al., 1998, V. WILPERT, 2002, V. WILPERT et al., 2002, SCHÄFER, 2002, LAMERSDORF, 2002, OBERNBERGER, 1997). FRITZE et al. (1994, 1995) and HOLMBERG and CLAESON (2002) compared wood ash effects with forest fire impact, which provokes nitrogen leaching but leads to an improvement of nutrient availability. BÜTTNER, et al. (1998) e.g. revealed K^+ and Mg^{2+} leaching from the upper mineral soil. These effects were only temporary and NO_3^--mobilization did not reach the deeper mineral soil. Wood ash application can decrease P-availability due to the formation of stable Ca-P and Al-P complexes and thus reduce the soluble P-fraction (PUNGH et al., 1978, CLARHOLM, 1994, CLARHOLM and ROSENGREN-BRINCK, 1995, LWF, 1997). In some cases, soluble P-fractions were documented (CLARHOLM, 1994), and SCHÄFFER (2002) mentions that the possible P-availability reduction restricts not conclusively the P-nutrition. CLARHOLM (1994) observed an increase of acid phosphatase activity in top soils but found at the same time a negative correlation with P-content of needles. ZIMMERMANN and FREY (2002) documented a decline of the P-cycle related enzyme activity.

Fertilization with wood ash inserts at least organic pollutants like **P**olycyclic **A**romatic **H**ydrocarbons (PAH) and **P**oly**C**hlorinated **B**iphenyls (PCB), where the PAH content seems to be predominant. A mobilization of these complex molecules in the A-Horizon is possible and can affect water quality (POHLANDT and MARUTZKY, 1994, POHLANDT, 1995, BÜTTNER, et al., 1998, BUNDT, 2001, KOHL, 2002, SCHÄFFER, 2002, HOLMBERG and CLAESON, 2002).

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Recommendations

The recommended dosages for wood ash range between 3 t/ha in 50 years and 8 t/ha in 3 years (NOGER et al., 1996, OBERNBERGER, 1997, BÜTTNER et al., 1998, V. WILPERT, 2002, V. WILPERT et al., 2002, SCHÄFFER et al., 2002). Wood ash is recommended to be applied in dosages up to 5 t/ha (LWF, 1997, SCHÄFFER, 2002). CLARHOLM (1994) remarked that an amount of 1 – 5 t/ha wood ash delivers the equivalent in nutrients lost by whole tree harvesting. Low dosages can lead to a higher nitrification ratio than elevated dosages and entail in an insufficient Ca/Al balance (LAMERSDORF, 2002). In order to avoid plant damages and salt chock and to improve long term fertilization, a mixture with dolomite is proposed by V. WILPERT (2002). ERIKSSON (1998), and HOLMBERG and CLAESON (2002) highlightened the importance of a carbonatisation for slowing down nutrient solubility and Ca-eluviation and recommended a hardening of wood ash with water and dolomite or cement. As consequence of the differing chemical composition of the ash fractions, an exclusive use of coarse ash and cyclone ash and renunciation of fly ash are demanded by BÜTTNER, et al. (1998), ZOLLNER and REMLER (1998), V. WILPERT (2002), V. WILPERT et al. (2002), OBERNBERGER (1997), LWF (1997). Regarding coarse ash, the combustion technique dependent Cd and Organic Pollutants content must be considered. Due to the stability of Cr (IV) under aerobe conditions, wood ash should not be applied on poor sandy soils, except those, which are characterized by elevated organic matter content (V. WILPERT, 2002, NIEDERBERGER, 2002 a).

Rock Powder

Rock powder is especially used in regions where other fertilizers are not easily available. The “petrofertilizer” rock powder is considered as adequate material for “remineralization and recapitalization” of degraded soils under tropical conditions (LEONARDOS et al., 1987, 2000, V. FRAGSTEIN et al., 1988, CORONEOS et al. 1996). Under temperate climate, rock powder can be used for an “ecologization” of soils with atmogenic acidification. Rock powder supports tree growth and the establishment hardwood plantations (NAROVEC and SACH, 1994). Basic research on rock powder has been carried out in Germany and Poland since the beginning of the last century (1905) (RZEZNIK and NEBE, 1968). Today, rock powder fertilization is rarely applied due to high transportation costs exceeding those of other fertilization alternatives.

Properties and Application

Rock powder can be applied for the amelioration of forest or agricultural soils with originally poor starting situation, e.g. podzols, podzols with hardpan and gley soils (NAROVEC and SACH, 1994). Rock powder improves physical soil properties and increases the soluble nutrient availability (Ca, Mg, K, and P) (NAROVEC and SACH, 1994, HARTMANN and KEPLING, 2003, HARTMANN et al., 2003 and V. WILPERT and LUKES, 2003). HEINZE (1990) mentions a generally insufficient P supply when using rock powder, whereas other macro-nutrients seem to be released in sufficient quantities. These contradictory effects result from the variable basic material for rock powder production, e.g. crushed Basalt, Diabase, Gabbro Rock, Amphibolite Rock, Phonolite Rock, Volcanic Ash, Quartz-Porphyry, and Granite are used (HEINZE, 1990, NAROVEC and SACH, 1994, STENICKA and NAROVEC, 1994, V. WILPERT and LUKES, 2003). Table III resumes observed pH-values of different basic materials according to V. FRAGSTEIN (1988), HEINZE (1990), and SAYEDAHMED (1993).

Tab. 3: pH-values of different basic materials for rock powder

basic material	pH(H_2O)	pH(KCl)
Phonolite	> 10	no values available
Basalt	8 - 10	
Diabase	~ 8	
Granite	7 - 10	
Diabase, Basalt, Pyroxenphorphyry, Angitporhyrite	no values available	6.1 – 7.6
Quarzporphyry		5.6 – 6.0

SAYEDAHMED (1993) reports for different rock powders an average silicic acid content of 48.3 – 64.7%. The pH (H_2O) value varies between > 10 up to 7 and compared with wood ash, rock powder shows a generally lower buffer potential for the application in acidic conditions (V. FRAGSTEIN et al., 1988, SAYEDAHMED, 1993). HEINZE (1990) mentions a variability of pH (KCl) values from 6.1 to 7.6 for test materials despite Quartz-Porphyry, where the pH (KCl) values range from 5.6 – 6.0. This was considered as reason for the special suitability of this material for fertilizing Scots pine stands. The plant availability of elementary nutrients like potassium is strongly dependent from the basic material. BAKKEN et al. (1997, 2000) ranked Biotite (Feldspar) above Nepheline and Epidote Schist. With regard to the general macro nutrient supply, SAYEDAHMED (1993) laid down the ranking Basalte < Diabase < Volcanic ash < Superbiomin < Igneols Rock meal. Diabase and Basalte show the highest trace element content and Basaltic Rocks followed by Phonolite Rocks are known for the highest nutrient release ratio (V. FRAGSTEIN, 1988).

Potentials

Rock powder decreases soil acidity, increases base saturation and nutrient availability, and improves the adsorption exchange activity (NAROVEC and SACH, 1994, STENICKA and NAROVEC, 1994). The intensity and variability of these effects are material dependent. Smectite rich volcanic ashes e.g. are known for a special improvement of the base cation availability (BLUM et al., 1989 a, b). V. WILPERT and LUKES (2003) highlightened the acid neutralization capacity and pH-level stabilization of Phonolites. SAYEDAHMED (1993) found a generalizeable increase of K-mobility and K-flux into mineral top soil for different basic materials, which lead to a better K-availability and higher K and P uptake. Also Ca-availability was positively affected. HILDEBRAND and SCHACK-KIRCHNER (2000) found that these effects can only be achieved by higher dosages compared with liming. Rock powder supports the C- and N-mineralization (MERSI, 1993), initiates a lower nitrification ratio and slower nutrient release than dolomite and thus is a suitable long-term fertilizer (V. WILPERT and LUKES, 2003). HARTMANN and KEPLING (2003) and SAYEDAHMED (1993) remark in this context the resulting long-term improvement of tree growth on poor soils.NAROVEC and SACH (1994) and STENICKA and NAROVEC (1994) observed a rising biological activity and humification after rock powder application. MERSI (1993) revealed contrasting effects. In some cases Xylanase and Protease activity in the A-Horizon decreased after rock powder application. A decrease of Phosphatase, a partial increase of Protease activity and nitrification ratio were also documented and accompanied by augmenting nitrate content and pH-value in the soil solution.

Restrictions

A possible restriction is an augmenting nitrification ratio compared to a complete renunciation of fertilization (NAROVEC and SACH, 1994, STENICKA and NAROVEC, 1994). The material

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dependent nutrient release ratio and the applied particle size can counteract the fertilizing intention (ROSCHNIK et al., 1967, LEONARDOS et al., 1987, V. FRAGSTEIN, 1988, BLUM et al., 1989, BAKKEN et al., 2000, GILLMANN et al., 2001). An increased death rate of young plants due to salt-chock under dry conditions is another possible risk (HARTMANN and KEPLING, 2003). V. WILPERT and LUKES (2003) revealed probable negative effects of Phonolite rocks due to high sodium content and deduced the necessity of a careful material choice.

Recommendations

Rock powder is an adequate fertilizer for long-term amelioration of physical and chemical properties of poor sandy soils (NAROVEC and SACH, 1994, STENICKA and NAROVEC, 1994). In order to achieve sufficient fertilizing effects, the average dosage should be 3 – 4 times higher than liming doses (HILDEBRAND and SCHACK-KIRCHNER, 2000). V. FRAGSTEIN et al. (1988) discuss critically the necessity of high dosed rock powder application in agricultural systems and their costs. ROSCHNIK et al. (1967) observed for agricultural purposes an exponential growth effect for application rates between 5 – 40 t/ ha and D´HOTMAN DE VILLIERS (1961, 1962) tested successfully dosages up to 180 t / ha. Respective recommendations could not be found for forest purposes.

Rock powder should not be used as start fertilizer , but after establishing the culture in order to improve tree growth conditions (HARTMANN and KEPLING, 2003). The chemical properties – e.g. sodium content in Phonolite Rocks - should be taken into account and risky basic materials should be excluded from application (V. WILPERT and LUKES, 2003). Rock powder can be applied as alternative to liming on sites which are sensitive against a fast nitrification and nitrate mobilization, but should however be renounced in sensible regions like water preservation areas. The particle size should be adapted to the weathering rate and nutrient release rate, which are (1) dependent from the fertilizing purpose and (2) acceptable for the region-specific environmental conditions.

Fly ash

Fly ash deposition is defined as particle residue from coal combustion that enters the flue gas stream as a result from lignite (brown coal) or hard coal combustion. The possible deposition amount per year in the most affected regions in Eastern Germany and Eastern Europe can range from 140 t / km^2 * a (industrial triangle Leipzig-Halle-Bitterfeld, North-Eastern

Germany) and up to 457 t / km^2 * a (Upper Silesia, Poland) (LUX, 1970, 1976, LUX and STEIN, 1977, NEUMEISTER et al., 1991, PEKLO and NIEHUS, 1992, STRZYSZCZ, 1993, 1999 a, b, STRZYSZCZ et al., 1996, STRZYSZCZ and MAGIERA, 1998, 2001, KLOSE and MAKESCHIN, 2003).

In the immediate vicinity of recent and former power plants an ample tree growth and exuberant development of ground vegetation can be observed (LUX, 1964 b, KURTH, 1985, AMARELL, 1997, THOMASIUS et al., 1998). These fertilizing-like effects result from the high deposition of alkaline cations. However, also heavy metals are deposed and accumulated in the long run (ULRICH et al., 1979, STRZYSZCZ, 1999, STRZYSZCZ and MAGIERA, 1998, 2001). TRÜBY (2003) reported a considerable uptake of heavy metals up to 120 µg Pb/g dw for 120 years old conifers, which however seems not to affect tree growth and vitality.

Properties

The average geo-chemical composition of fly ash varies in dependence from basic material (lignite or mineral coal) and its origin. Lignite-derived fly ash from the industrial triangle Leipzig-Halle-Bitterfeld e.g., consisted in av. 26% SO_3, 20% CaO, 18% SiO_2, AlO_3, FeO_3, MgO, TiO_2, Na_2O, K_2O, heavy metals, and „black" (tertiary) carbon (NEUMEISTER et al., 1991, PEKLO and NIEHUS, 1992, MAGIERA and STRZYSZCZ, 1999, and KLOSE and MAKESCHIN, 2003). For more details see Tab IV.

Tab. 4: Characteristic chemical composition of lignite fly ash in North Eastern Germany (acc. to NEUMEISTER et al., 1991, PEKLO and NIEHUS, 1992, THOMASIUS et al., 1998)

molecular deposition components (w- %)								**heavy metals (mg / kg)**			
SO_3	CaO	MgO	K_2O	Fe_2O_3	Al_2O_3	SiO_2	C_{org}.	Cd	Cu	Pb	Zn
13-26	15-20	1.5-3	0.1-1	4-10	3-8	10-18	5-20	2.7-7.6	140-230	50-100	130-250

means of the total deposition for the example Dübener Heide (kg/ha*a)															
Na	K	Ca	Mg	Fe	Mn	Cu	Pb	Cd	Zn	F	Cl	N	S	P	Ca /S
15.7	8.3	320	36.5	125	1.1	1.4	1.0	0.1	2.3	9.8	54	38	190	0.3	1.7

Potentials

Characteristic fly ash deposition effects on forest sites are the widening of the C/N and C/P relation and additional input of S and base cations. In the long run, fly ash accumulation in forest systems leads to an improvement of site quality, particularly regarding the nutrition capacity of naturally poor sites (sandy soils). An increase of the site index up to two degrees and an enhancement of the eligible tree species spectrum were reported by KOPP and SCHWANECKE (1994), THOMASIUS et al. (1998) and KNOCHE et al. (2001). AMARELL (1997), KNOCHE et al. (2001), and THOMASIUS et al. (1998) describe a ground vegetation drift towards nitrophile and nutrient indicating species, which accentuates the growth conditions change. The durability of this situation and long term ecosystem responses are still unknown.

Another effect is the modification of the humus form and thickness of the humus layer, which influences the water retention capacity and nutrient supply (THOMASIUS et al., 1998, KNOCHE et al., 2001). This modification is going along with an augmentation of mineral particle content that exceeds the threshold of 30 %, which is demarcating humus layer from mineral top soil (KLOSE et al., 2001, 2002, 2003, KLOSE and MAKESCHIN, 2004, KOCH et al., 2002).

Risks

Fly ash deposition increases the Al, Fe, and heavy metal content in forest ecosystems. This provokes a disturbance of litter decomposition and leads to the development of adverse humus forms (STRZYSZCZ, 1993, 1999, STRZYSZCZ and MAGIERA, 1998, MAGIERA and STRZYSZCZ, 2002, KLOSE et al., 2003). When considering results from wood ash research, heavy metals will remain in the upper mineral soil (BRAMRYD and FRANSMAN, 1995, FRITZE et al., 1995, BÜTTNER, et al., 1998, EBERL and HILLMANN, 2002). However, the accumulated heavy metals can be mobilized by a re-acidification of the sites, which is speeded up by N-deposition and absent base deposition (KOCH et al., 2002, KLOSE et al., 2003). KLOSE et al. (2003) and KLOSE and MAKESCHIN (2004) described the impeding effects of lignite derived fly ash on microbial activity. “Black” carbon seems to play a key role in hindering the organic matter decomposition (GOLDBERG, 1985). The possible role of macromolecular organic pollutants (PCB, PAH), which play and important role for evaluating wood ash effects, is not yet clear. Fly ash specific humus forms are characterized by an elevated hydrophobicity, which can hinder the water percolation into mineral soil (THOMASIUS et al., 1998, KATZUR et

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al., 1998). In contrast, fly ash, which shifted in the upper mineral soil, can induce faster percolation of rainfall due to their special physical properties (low density) (TAUBNER and HORN, 1998). This process can accelerate humus layer dehydration and amplify the disturbed water balance in humus layer (ZIKELI et al., 2002, DEKKER and RITSEMA, 2003).From silvicultural point of view, the influence of fly ash deposition on the humus provokes antithetic effects: the observed intensification of fine root growth in ash-dominated humus layers improves (a) tree nutrition, but (b) endangers stand stability against wind throw and drought by supporting the development of flat root systems (THOMASIUS et al., 1998, KNOCHE et al., 2001, KOCH et al., 2002, KLOSE et al., 2003). LUX (1976) and KNOCHE et al. (2001) mention a particular endangering of functional stability of Scots pine dominated forest systems by too high base depositions. Fly ash deposition cannot be managed in a site-adapted dosage and thus provokes additional costs and economic losses. STRACKE (1996) mentions e.g. the necessity of a conversion with hardwood, which increases the expenses for stand establishment and regeneration and decreases economic profit due unfavourable assortments. Economic losses can also result from shortening of the rotation period, which results from fly ash induced stands destabilization.

Recommendations

Fly ash deposition demands for an adapted site classification system in dependence from original site quality and possible on- and off-site effects (KALLWEIT, 1990, THOMASIUS et al., 1998, KNOCHE et al., 2001, KLOSE et al., 2003, ZHONG and MAKESCHIN, 2003 a, b, KOCH and MAKESCHIN, 2004, ZHONG and MAKESCHIN, 2004, MAKESCHIN et al., 2004). A conversion with broadleaves (beech or noble hardwoods) is proposed by LUX and STEIN (1977), THOMASIUS et al. (1998) and NEBE et al. (2001). This seems to be promising at artificially alkalinized sites near to the (former) power plants, also with regard to the destabilization of coniferous stands reported by LUX (1976) and KNOCHE et al. (2001). Furthermore, broadleaves can use better the additional nutrients due to a better rooting and better use of the nutrition potential for tree growth.

Comparative Evaluation and Conclusions

Wood ash and rock powder are an alternative to other industrial fertilizers. A long-term increase of pH-value and base cation availability, and an improvement of physical soil properties can be achieved. However, these positive effects on plant nutrition are not significant in any case and in contrast also damages like salt or pH-chock are possible, particularly in forest cultures. The composition of rock powder and wood ash can deviate from real requirements of forest systems. Besides, undesirable matter like organic pollutants, heavy metals, or sodium is deposed into forest ecosystem. Consequently, a careful analysis of (a) site deficiencies, (b) nutrition and stress situation of forest systems and (c) fertilizing material composition are required in order to avoid negative effects. Besides, a cost-benefit analysis considering material specific costs (e.g. transport and production of rock powder or cost-evading for deposing wood ash) is necessary in order to realize the most economic fertilization alternative. Fig. 1 (next page) resumes the application fields for the materials wood ash, rock powder, and fly ash and summarizes recommendations for practical handling.

The application of wood ash and rock powder is primarily dependent from the fertilizing target (1). Rock powder can be used for improving physical and chemical soil properties especially at originally poor sites in a dry climate. Rock powder is an alternative to other fertilizers on soils, which are endangered by intensive nitrification. Under tropical conditions, a recapitalization and remineralization of degraded soils is possible. Under temperate climate, rock powder can be used for an ecologization of heavily disturbed soils. These can be found e.g. in industrialized regions, where soils suffer from long-term deposition influence. However, in case of fly-ash affected soils, a critical check of the necessity of an additional nutrient supply is indispensable.

Wood ash application is suitable for restoring the biochemical cycle after nutrient removal by (whole) tree harvesting.

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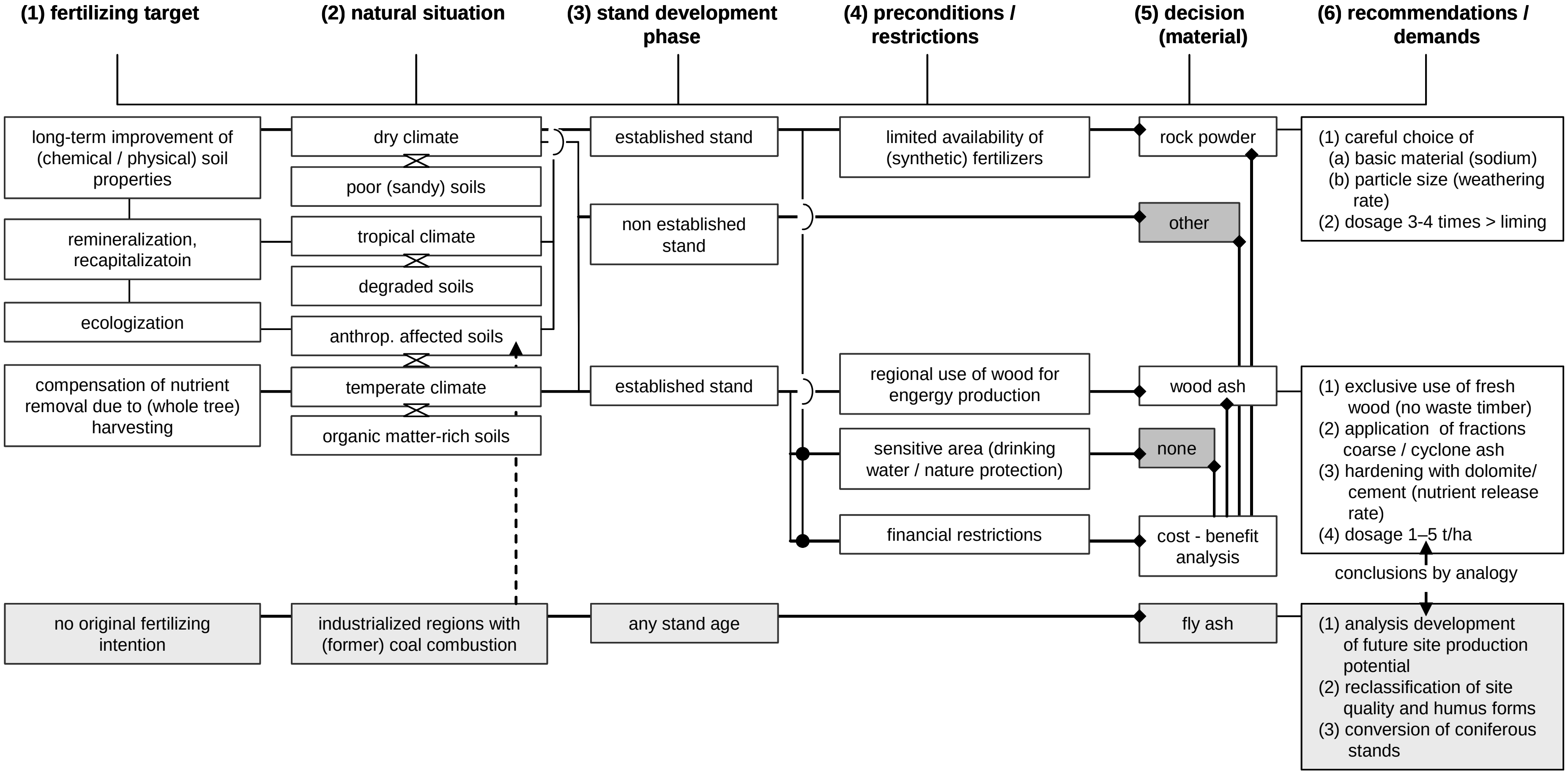

Fig. 1: Application fields of wood ash, rock powder, and fly ash and recommendations for practical handling

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The natural situation (2) confines the use of wood ash and rock powder, which show complementary application fields: wood ash may limit P-availability, leads to an additional Cr-(IV) input and possible pH- and salt chock of the vegetation. Consequently, it should be applied on soils with higher organic matter content in a temperate climate and not be used on poor sandy soils under dry climate. Under dry conditions, rock powder has its complementary application field. Fly ash deposition is a special case of unintended long-term amelioration.

Wood ash and rock powder use should take into consideration the stand age (3): Both can provoke salt chocks and burning of plant tissues and thus endanger recently established stands. As conclusion by analogy with fly ash, wood ash use might also provoke heavy concurrence problems of young trees with an ample soil vegetation development (LUX, 1964 a, PEKLO and NIEHUS, 1992, AMARELL, 1997). Fertilizing alternatives or postponing fertilization in dependence from stand top height development should be considered.

As precondition (4) for wood ash and rock powder use of, regional availability is the decisive factor: rock powder is used in regions, where other ameliorative materials are hardly available. The use of wood ash dependent from the role of wood for energy production, which might increase in the next years (V. WILPERT, 2002). In areas dedicated to water protection or natural protection, the use of both fertilizers should be carefully checked or completely neglected. Financial restrictions demand for a cost-benefit analysis, which reveals the regional potential and application costs.

After the decision (5) for one of the alternatives, the following recommendations (6) should be respected: Rock powder demands high dosages (3 – 4 times > liming) for verifiable fertilizing effects. Low nutrient release and possible ingredients like sodium can counteract the intention of growth condition improvement. Attention should be paid to basic material choice (K, pH, Sodium) and particle size. Wood ash application requires an exclusive use of fresh wood for reducing the amount of combustion residuals and its content in critical substances. A careful separation of the different ash fractions and preferable use of coarse ash and cyclone ash are recommended in order to avoid needless heavy metal and Cr (IV) input. A hardening with dolomite/cement helps to prevent plants against chocks and to improve fertilization effects in the long run. For forest purposes dosages between 1 – 5 t/ha are recommended.

Fly ash deposition can be considered as kind of long-term amelioration experiment. The effects of fly ash deposition can support the understanding of forest ecosystem reactions on

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(ash) fertilization: spatial and temporal variability of the fly ash composition result in a dynamic development of site specific production potentials and ecosystem reactions. On landscape level, fly-ash deposition leads to a homogenisation of differing sites and to a diversification of comparable sites and demands for an adapted classification of site quality as basis for sustainable silvicultural strategies. Fly ash research may help to evaluate the effects of ash fertilization through conclusion by analogy: fly ash affected and wood ash fertilized soils show both most obvious effects in the Oe and Oa horizon. Research on long term effects of fly ash revealed that this leads to an intensification of tree rooting in the Oe and Oa. The better plant nutrition leads to a better tree growth, but also to a higher drop out risk by supporting the development of flat root systems which are sensible against wind throw and water stress. Hardwood stands react less sensible than coniferous stands (especially Scots pine stands) and are able to use the additional nutrition potential more efficient. Consequently, a conversion of (formerly) fly-ash deposition influenced coniferous stands can be recommended.

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Testing a Soil Magnetometry Technique in a Highly Polluted Industrial Region in North-Eastern Germany

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Abstract The paper presents the results of a study in the region *Dübener Heide* (Central Germany) testing the suitability of field measurements of magnetic susceptibility for the detection of historical fly-ash deposition. The measurements supported the verification of historically documented deposition zones along an emission gradient. Mean values, standard deviation, and coefficient of variation can be used to characterize the former deposition zones, although the study revealed several problems, which will be the subject of future work: (1) the volume susceptibility measurements used in the study do not allow the calculation of the actual fly-ash amount stored in the soil and thus must be calibrated with correction factors from laboratory measurements; and (2) measurements in regions with similar conditions but without fly-ash deposition are needed to obtain reference values for the natural range of magnetic susceptibility.

Keywords Ferrimagnetic susceptibility · Industrial air pollution · Fly-ash · Forest soils

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1 Introduction

The industrial triangle Leipzig–Halle–Bitterfeld (see Fig. 1), as part of the Central German lignite mining region, was characterized for almost 100 years as a source region for emissions caused by intense industrial activity and the combustion of lignite for energy production. The adjacent forested landscape Dübener Heide (Fig. 1) at the eastern border of the industrial triangle received an estimated deposition load of up to 18 million tons of fly-ash and of 12 million tons of SO_2 during the period 1910–2000. For the decade 1961–1970, the fly-ash deposition for this region ranged between 3 and 8 t ha^{-1} $year^{-1}$ (Lux 1976, 1978; Neumeister et al. 1991). Klose and Makeschin (2004, 2005) reported even local peak loads up to 128 t ha^{-1} $year^{-1}$. The fly-ash from the region consists of SO_3[1] (26%), CaO (20%), SiO_2 (18%), AlO_3, FeO_3[1], MgO, TiO_2, Na_2O, K_2O, heavy metals (Cd, Cu, Pb, Zn), and black carbon (Fürst and Makeschin 2006; Klose and Makeschin 2004). Start-

[1] The molecular composition (oxides) of fly-ash is given according to Klose and Makeschin (2004).

ing in the early 1990s, the closure of power plants and the reduction of emissions from remaining industries due to improved filter techniques resulted in a considerable improvement of air quality. Fly-ash emission was omitted completely.

However, the fly-ash stored in the forest soils has still a considerable influence on the forest ecosystems of the Dübener Heide and will be a major factor for their further development: (1) the turnover rate of organic matter is reduced, and abnormal thick humus layers can be observed, which alter the water balance of the forest soils (Strzyszcz 1993, 1999; Strzyszcz and Magiera 1998; Katzur et al. 1998; Taubner and Horn 1999; Magiera et al. 2002; Klose et al. 2001). (2) The deposited elements, especially base cations, influence ground vegetation as well as growth and species composition of the forest stands (Lux 1978).

The intensity of these effects is mainly driven by the total amount of deposition, which depends on the distance to former emitters, the dominating wind direction, relief, canopy surface, and the particle size and solubility of the deposition components (Katzur et al. 1998; Strzyszcz et al. 1996). According to Lux (1978), the different ranges and effects of alkaline nonsoluble particles and soluble acidic deposition require the identification of deposition zones as basis for an adapted forest management. The choice of tree species, thinning intensity, and rotation period must be adapted to the amount of deposited fly-ash. Therefore, Stein (1965) and Lux (1976) proposed an approach which uses classes of forest decline for the differentiation of up to five deposition zones (see Fig. 1). The deposition zones were defined on the basis of a sample plot-supported evaluation system. Visible damages in 150 plots in middle-aged Scots pine stands were surveyed on a single tree level, then compiled for stand level and regionalized by a subsequent spatial aggregation of comparable stands of the deposition

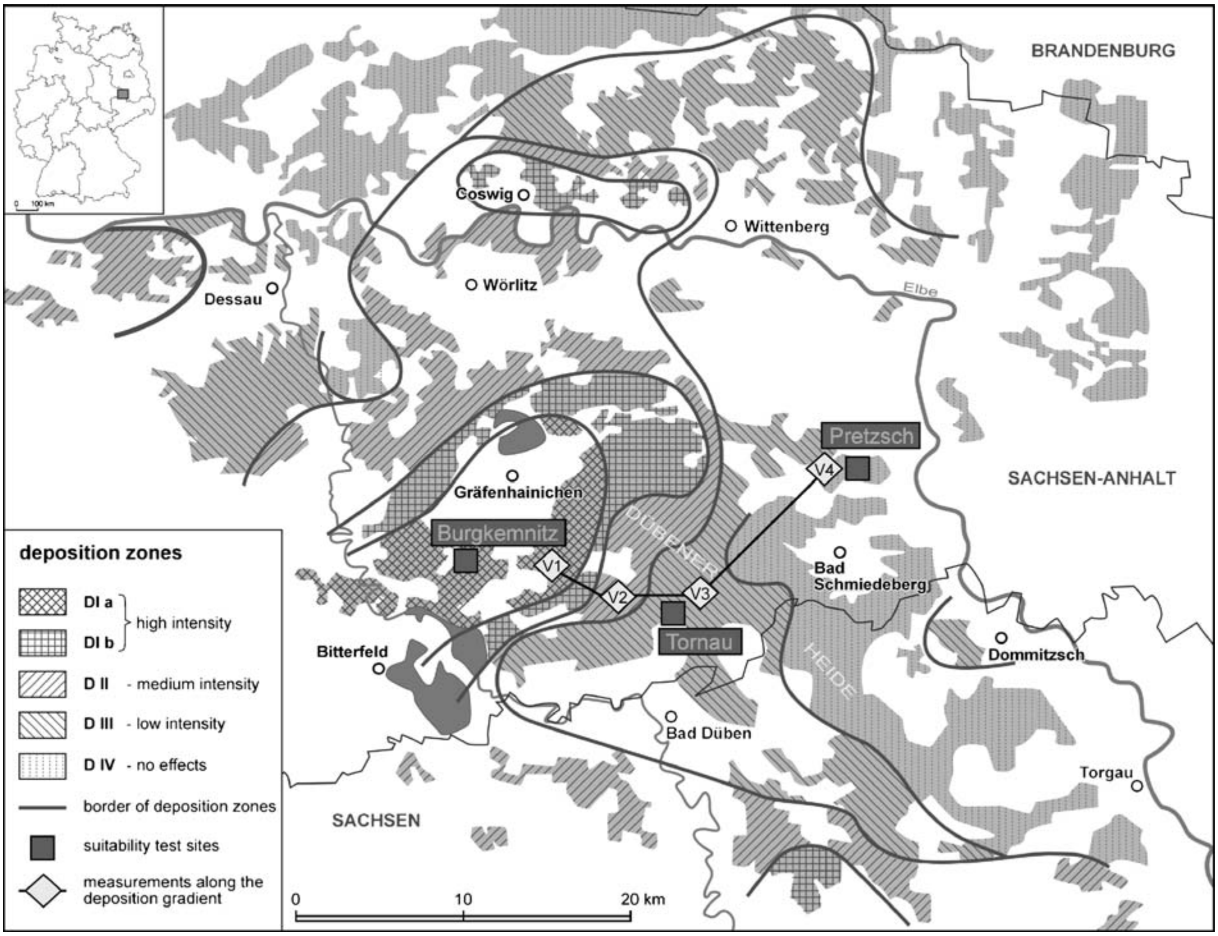

Fig. 1 Deposition zones in the Dübener Heide (Lux and Stein 1977, modified) and location of test sites

zones. The latter were assumed to be more or less homogenous regarding the impact of the deposition on forest production and economic outcome.

However, forest decline classes can only be seen as a rough indicator for the estimation of actual fly-ash deposition and storage in forest soils: (1) Forest damages are a sum parameter, which in this region are not only linked to fly-ash deposition, but also to high air concentrations of SO_2 and NH_3 and climatic extremes. (2) Since the 1990s, a considerable improvement of the health state of the Scots pine can be observed. Past differences in the health state, which could be used for estimating the total deposition of fly-ash along a regional deposition gradient, do not exist anymore. Therefore, other methods are needed for the detection of the actual fly-ash load in the past and the current amount of fly-ash in forest soils. As cost efficiency was an important criteria for the selection of a suitable field detection technique, magnetic susceptibility was chosen as suitable parameter based on the broad experiences in other regional studies (e.g., Katzur et al. 1998; Strzyszcz 1993; Klose et al. 2002; Chianese et al. 2006; D'Emilio et al. 2006; Magiera et al. 2006).

The presented paper intends to evaluate (1) if field measurements of magnetic susceptibility are a suitable technique for an in situ detection of past fly-ash deposition in the Dübener Heide and (2) to which extend the former deposition zones can still be found by field measurements of magnetic susceptibility.

2 Materials and Methods

2.1 Magnetic Susceptibility Measurement

Magnetic susceptibility can be used as a cost-efficient detection method for fly-ash deposition (Strzyszcz and Magiera 1998; Magiera and Strzyszcz 2000; Grimley et al. 2004). The magnetic susceptibility χ is defined as difference between the relative magnetic permeability μ and 1. It can be used, e.g., to express approximately the concentration of magnetic minerals in the soils (Thompson and Oldfield 1986). According to their magnetic properties, materials can be divided into diamagnetic, paramagnetic, ferromagnetic, and ferrimagnetic substances (Strzyszcz 1993; Glaser 2001). The detection of lignite-derived fly-ash by magnetic susceptibility is based on its content of ferrimagnetic Fe-oxides. These are mainly magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3), which are both (1) a natural component of lignite (magnetite) or (2) a result of pyrite (FeS_2) oxidation (magnetite and maghemite; Strzyszcz et al. 1996; Katzur et al. 1998; Strzyszcz 1999; Magiera and Strzyszcz 2000).

The detection method is suitable only for areas with a strong impact of industrial emissions, since a natural enrichment of magnetic substances as result of (1) geochemical processes and (2) activity of micro-organism in humus layers is also reported from non-industrial areas and might blur the effect of minor fly-ash deposition (Le Borgne 1955; Scollar 1965; Thompson and Oldfield 1986; Faßbinder 1994; Jong de et al. 2005; Magiera et al. 2007).

For the measurements in the Dübener Heide, a portable magnetic susceptibility meter (KT-9, © Terraplus) was used. The KT-9 is developed for detecting very low quantities of magnetic Fe-oxides in compact (rocks) or loose substrates (mineral soil, humus layer). The instrument measures spot-wise the volume magnetic susceptibility as sum value up to a depth of 0.5–2.0 cm starting from the surface of the measured substrate. The susceptibility meter has a sensitivity of 1×10^{-5} SI units and can be used either in a single readout mode or in a continuous (scanning) readout mode.

2.2 Selection and Design of the Test Plots

The Dübener Heide (see Fig. 1) is situated in Central Germany south and north of the border between the federal states Saxony and Saxony-Anhalt. The region belongs to the transition zone from oceanic to continental climate with a mean annual temperature of 8–9°C and a mean annual precipitation of 550–650 mm. The geologic underground of the Dübener Heide is dominated by pre-Weichsel glacial and glaciofluvial sands, which are mostly covered by sandy to loamy periglacial deposits of the late Weichsel. The region is characterized by a comparably high homogeneity of the parent material with the exception of a few and small terminal moraines, which were excluded from the study. The predominant soil types are Eutric and Distric Cambisols with small areas of Glossic Podzo-Luvisols, Spodo-Dystric Cambisols and Orthic Podzols (Kopp and Schwanecke 1997).

The results of the forest inventory show that the main stand type is pure Scots pine (*Pinus sylvestris*, [L.]), partially with deciduous tree species understory of European beech (*Fagus sylvatica* [L.]), White birch (*Betula pendula* [Roth), and Sessile oak (*Quercus petrea* [(Matt) Liebl.]) from artificial or natural regeneration.

The site conditions and composition of ground vegetation are impacted by past fly-ash deposition along a regional gradient, reflecting the former deposition zones. The test plots of this study were arranged along this gradient (Fig. 1). To ensure that fly-ash is the main reason for the differences in susceptibility measurements, all plots have the same soil type (Eutric Cambisol, i.e., “Nedlitzer Sand-braunerde”) and the same stand type (80 to 90-year-old Scots pine stands [with deciduous trees in understory]).

2.2.1 Suitability Test of Magnetic Field Measurements

For testing the suitability of the field magnetic susceptibility measurements, three sites were selected (Fig. 1), where different deposition levels have been found in earlier research (Klose and Makeschin 2005).

- Site *Burgkemnitz* is located in the deposition zone I, 8 km east from former emitters, where a high intensity of fly-ash deposition was recorded.
- Site *Tornau* is located in the deposition zone III, 18 km east from former emitters, where a low intensity of fly-ash deposition was recorded.
- Site *Pretzsch* is located in deposition zone IV, 30 km east from former emitters, where no or minimal deposition effects are assumed.

At the sites *Burgkemnitz* and *Tornau*, magnetic susceptibility was measured with the KT-9 in spade samples and in the remaining spade hole. The measurements were carried out (1) for five depth levels (1, 2, 5, 10, and 20 cm) and (2) horizon-wise (Oe, Oa, A(h), B (w), measurements in the center of each horizon). Each measurement was repeated three times. The Oi horizon was excluded from the measurements because several pretests had shown that magnetic susceptibility cannot be detected in this horizon (see e.g., Olson et al. 2004), since the Oi horizon formed after fly-ash deposition. For the B(w) horizon, the maximum depth was 20 cm. The C horizon was not sampled.

At the sites *Burgkemnitz* and *Tornau*, the sampling was arranged along a 10-m-long transect, and the samples were taken in a horizontal distance of ~0.5 m (see Fig. 2a for design of test plots).

At the site *Pretzsch*, focus was laid on a horizon-wise measurement following the above described design. The experiences from the sites *Burgkemnitz*

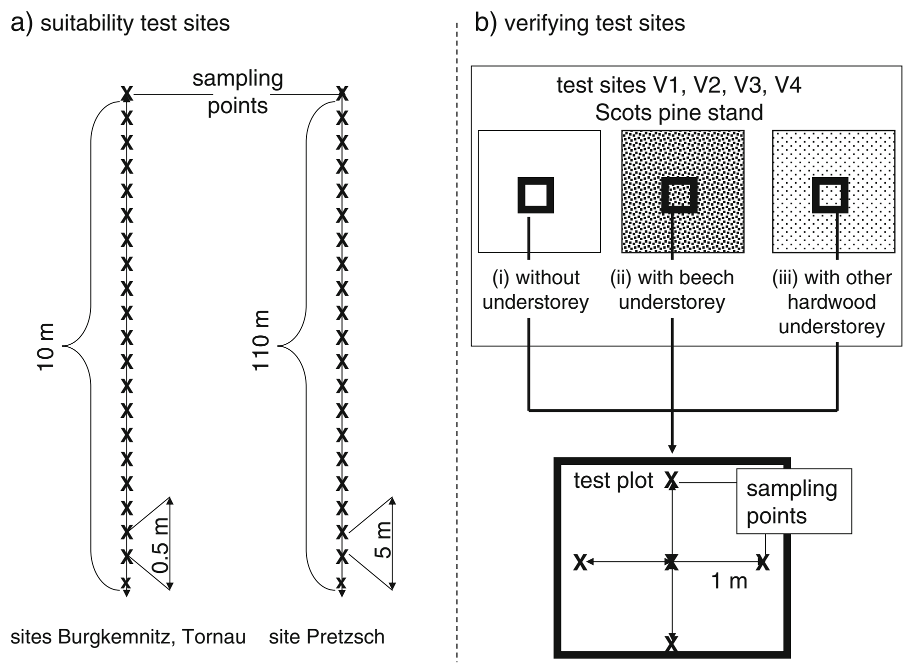

Fig. 2 **a** Sampling design for the suitability test sites. **b** Sampling design for test site for verification of the deposition zones

and *Tornau* indicated a higher accuracy of this approach. At the site *Pretzsch*, the sampling was arranged along a longitudinal transect of 110 m. The samples were taken in a horizontal distance of 5 m (Fig. 2a). Thus, a clearer picture of the natural variation of humus properties (texture, structure) for the selected soil type and the corresponding magnetic signal was expected.

2.2.2 Test of the Verification of the Former Deposition Gradient with Magnetic Susceptibility

For testing if the historically documented deposition gradient and the deposition zones can be detected by magnetic field measurements, four test sites were selected. Each of these sites represents a specific deposition zone according to Lux and Stein (1977) (Fig. 1). At each of the test sites (site V1–4), three test plots were installed representing typical situations within the stand, (1) Scots pine without understory, (2) Scots pine with European beech understory, and (3) Scots pine with other hardwood (oak, birch) understory. The plot characteristics refer to the local variability of the humus properties depending on stand composition and structure. At each of the three test plots per site, samples were taken in the center of the plot and in four satellite positions in 1 m distance around the plot center (see Fig. 2b for details). Magnetic susceptibility was measured horizon-wise with the KT-9 at the spade samples and in the remaining spade hole following the above described design. Each measurement was repeated three times. Table 1 gives an overview on the observed thickness of the horizons Oe, Oa, and A(h) at all test sites.

3 Results

3.1 Suitability Test

It was possible to detect three deposition zones, represented by the sites *Burgkemnitz* (zone I), *Tornau* (zone III), and *Pretzsch* (zone IV), by the field measurement technique for magnetic susceptibility. Table 2 resumes the results for the depth and horizon-wise measurements. For the total sample size (n=132, horizon or depth level) mean value, standard deviation, and coefficient of variation were calculated. Compared to the sites *Tornau* (zone III) and *Pretzsch* (zone IV), the means of site *Burgkemnitz* (zone I) are nearly three times higher for the topsoil (depth <5 cm, Oe and Oa horizons). For the lower solum (depth 10 and 20 cm), the means are still two times higher. A continuous peak of magnetic susceptibility in the Oa horizon occurs despite the higher natural variability of humus properties. A similar peak could not be detected by the depth-wise measurements at the sites *Burgkemnitz* and *Tornau*. All three sites showed a similar level of magnetic susceptibility for the B horizons.

Standard deviation and coefficient of variation were used as indicators for the variability of the magnetic susceptibility for the respective zone (Table 2, Figs. 3 and 4). The mean and standard deviation for the depth levels 1–10 cm and for the humus layers Oe and Oa is about two to four times higher compared to the depth 20 cm and the mineral horizons A(h) and B(w). The coefficient of variation shows that the variability tend to be highest for the upper top soil (depth 1 cm, Oe horizon) and the solum (depth 20 cm, B(w) horizon). However, the coefficient of variation is comparably

Table 1 Overview on the range of thicknesses for the horizons Oe, Oa, and A(h) for all test *sites*

Horizon	Oe + Oa (cm)	Oe (cm)	Oa (cm)	A(h) (cm)	Design	Spade samples (n)
Suitability test Burgkemnitz (zone I), Tornau (zone III), Pretzsch (zone IV)						
Burgkemnitz	5–15	2–6	3–9	5–8	10 m long transect, spade samples each 0.5 m	22
Tornau	4–9	2–4	2–5	4–5		
Pretzsch	4–10	2–4	2–6	3–6	110 m long transect, spade samples each 5 m	
Test along the gradient (V1 = zone I, V2 = zone II, V3 = zone III, V4 = zone IV)						
V1	4–9	2–4	2–5	4.5–6	3 plots/site, 5 spade samples (1 center, 4 satellite)/plot	15
V2	6.5–12	2.5–5	4–7	3–5		
V3	4–12	2–5	2–7	3–4		
V4	4–6	2–2.5	2–3.5	2–3		

Table 2 Mean value (x), standard deviation (σ), and coefficient of variation (vc [%]) for the suitability test sites

Site	Burgkemnitz (zone I)			Tornau (zone III)			Pretzsch (zone IV)		
Sample size n	n=132[a] per horizon and depth level[b]						N=132[c]/horizon[b]		
	$\overline{x}$	σ	vc [%]	$\overline{x}$	σ	vc [%]	$\overline{x}$	σ	vc [%]
Depth (cm)									
1	124.8	57.9	46.4	45.8	22.3	48.7	–	–	–
2	156.0	46.9	30.0	64.6	22.2	34.3	–	–	–
5	154.0	49.3	32.0	63.9	26.8	42.0	–	–	–
10	88.0	42.9	48.7	39.9	18.1	45.3	–	–	–
20	40.2	24.9	61.9	22.1	11.1	50.1	–	–	–
Horizons									
Oe	126.4	42.7	33.8	47.7	16.5	34.6	37.6	12.4	33.1
Oa	182.1	50.6	27.8	78.0	21.1	27.1	69.7	13.6	19.5
A(h)	66.0	32.2	48.8	48.1	15.7	32.6	37.1	13.9	37.6
B(w)	28.5	11.1	38.8	20.8	8.1	39.2	19.1	9.8	51.0

[a] Burgkemnitz/Tornau: 10 m transect, measurements each 0.5 m, measurement in spade sample and at spade probe, three repetitions per measurement = sample size of 132/horizon or depth level

[b] n_{total}/site: depth level-wise measurements, 660, horizon-wise measurement, 528

[c] Pretzsch: 110 m transect, measurements each 5 m, measurement in spade hole and at spade sample, three repetitions per measurement = sample size of 132/horizon

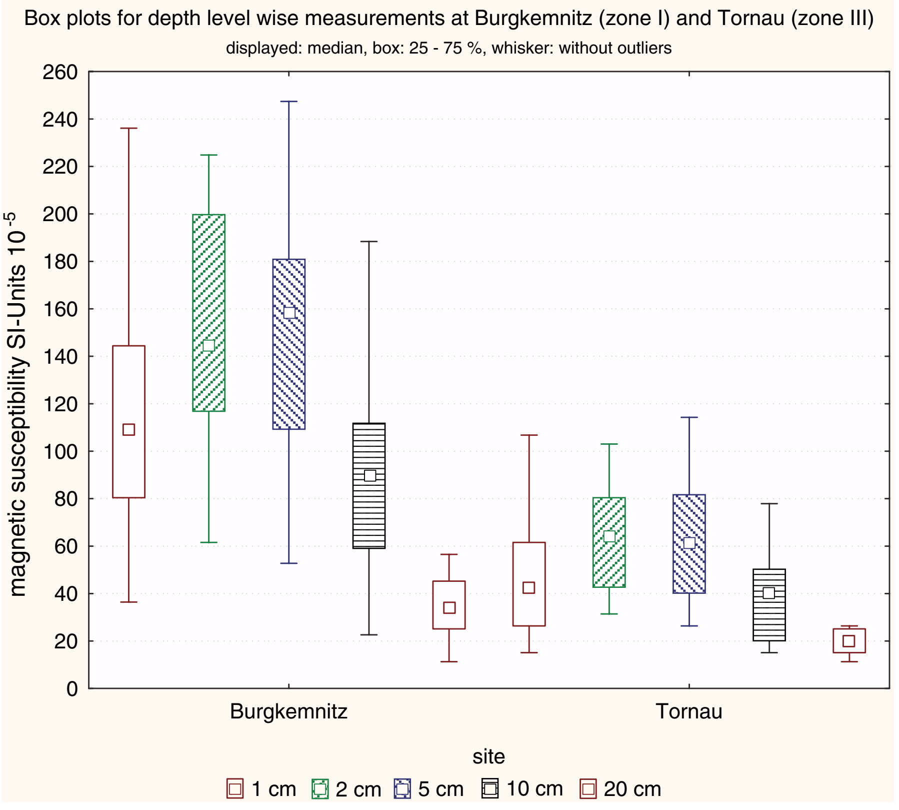

Fig. 3 Box plots for depth level-wise measurements at site Burgkemnitz (zone I) and site Tornau (zone III), displayed is median, box (25–75%), and whisker without outliers

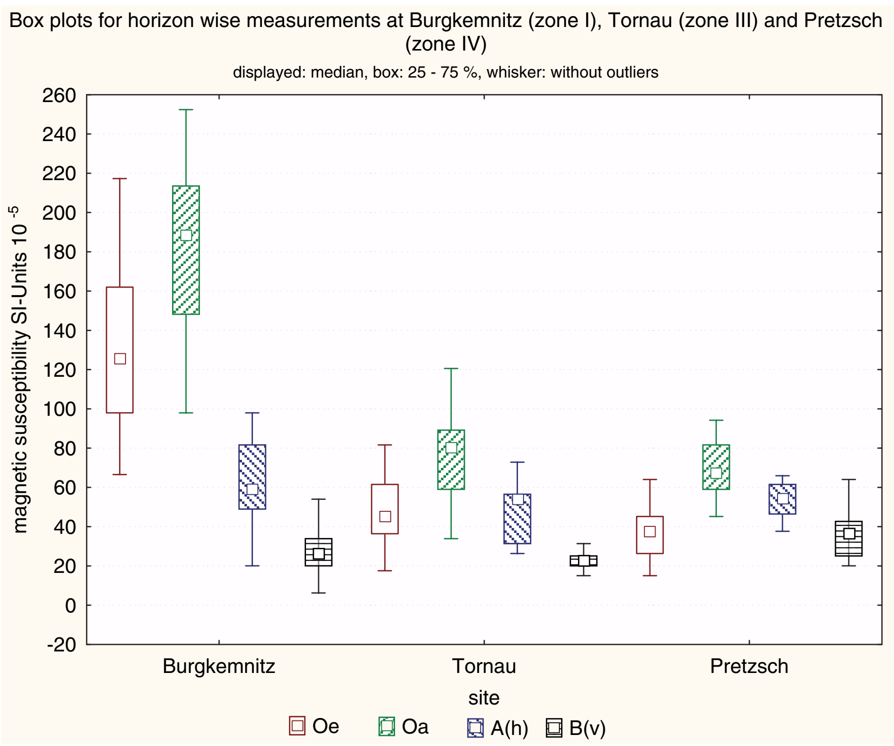

Fig. 4 Box plots for horizon-wise measurements at all three sites (Burgkemnitz, zone I; Tornau, zone III; and Pretzsch, zone IV), displayed is median, box (25–75%), and whisker without outliers

invariable along the gradient from zone I (*Burgkemnitz*) to zone IV (*Pretzsch*), but most times, it is higher for the lower soil. The reasons might be various. For the upper top soil, a high likeliness of disturbance by bioturbation or other turbation processes is assumed, forming a highly variable mixture of younger and older material. For the lower soil, a varying influence of fly-ash deposited at the surface and later vertically transported into the lower soil to a various extent is assumed.

Regarding the sites *Burgkemnitz* and *Tornau*, the coefficient of variation seems to be higher at depth level-wise measurements compared to the horizon-wise measurement, which was the reason for the horizon-wise measurement of the magnetic susceptibility at the site *Pretzsch*. Regarding the coefficient of variation at the horizon-wise measurements for all sites, there is no clear trend along the gradient in contrast to mean and standard deviation. On average, the variance is approximately 30–40% of the mean.

At site *Pretzsch*, the correlation between the thickness of the humus layer[2] and magnetic susceptibility is calculated. The magnetic susceptibilities of the Oe horizon were slightly negatively correlated with humus thickness ($r=-0.19$) with a coefficient of determination of $r^2=0.04$ ($\rho<0.001$). The indicative value of the Oe horizon is rather low. However, the values of the Oa horizon are positively correlated ($r=0.46$) with a coefficient of determination of $r^2=0.21$ ($\rho<0.001$). Consequently, the horizon Oa seems to have a high indicative value for the former fly-ash deposition, which is in accordance with results from Klose et al. (2001) and Koch et al. (2002).

3.2 Test of the Verification of the Former Deposition Gradient with Magnetic Susceptibility

The results from the measurements of magnetic susceptibility were the basis for the test design along the historically documented deposition gradient according to Lux and Stein (1977). Since a lower variation coefficient was obtained from the horizon-wise measurement, the measurements of magnetic susceptibility focussed on the horizons Oe, Oa, A(h), and B(w).

The means (Table 3 and Fig. 5) of sites representing zones I, III, and IV show a comparable level within the suitability test. Standard deviation and

[2] In the test region, a high spatial variability of humus layer thickness was observed in dependence from stand characteristics and local topography. “Thickness” is here used as a proxy indicator for humus compactness and consistency: very thick humus horizons in the test region are often related to a higher bulk density.

Table 3 Mean value x), standard deviation (σ) and coefficient of variation (vc [%]) for the verification test sites

Site	Site V1 (zone I)			Site V2 (zone II)			Site V3 (zone III)			Site V4 (zone IV)		
Sample size n	n=90[a]/horizon[b]											
Horizons	$\overline{x}$	σ	vc [%]	$\overline{x}$	σ	vc [%]	$\overline{x}$	σ	vc [%]	x	σ	vc [%]
Oe	88.8	42.2	47.6	81.2	9.8	12.0	73.7	24.1	32.8	48.2	17.1	35.4
Oa	151.1	24.6	16.3	98.0	18.5	18.9	58.2	8.9	15.3	75.4	6.7	8.8
A(h)	61.5	33.9	55.0	42.3	7.1	16.9	17.6	4.4	24.7	48.2	6.9	14.4
B(w)	37.7	37.0	98.2	18.8	6.5	34.6	18.4	6.3	34.3	31.8	5.9	18.7

[a] Three plots per stand, five measuring points per plot, measuring at spade hole and spade sample, three repetitions/measurement = sample size of 90/horizon

[b] n_{total} per site, 360

coefficient of variation tend to be lower compared to the suitability test. This might be a result of the different test designs between the two test series, although the verification test intended to cover the spatial variability of the humus under different stand situations. The coefficients of variation are highest in zone I (site V1) and indicate again that the spatial variation of magnetic susceptibility values near to the former emitters is higher than in more distant zones.

The mean values of magnetic susceptibility and the related confidence intervals decrease from zone I (site V1) to zone IV (site V4; Fig. 5 and Table 3). The Oa horizon shows—with exception of site V3—again a distinct peak of magnetic susceptibility. At site V3, the peak is located in the Oe horizon. Hydromorphic soil characteristics at this site indicate a slowing down of the humus turnover, which might have led to a longer conservation of the magnetic ash particles in the Oe.

Comparing the means of the three test plots per test site, which were situated under different stand situations with and without understory, slightly higher

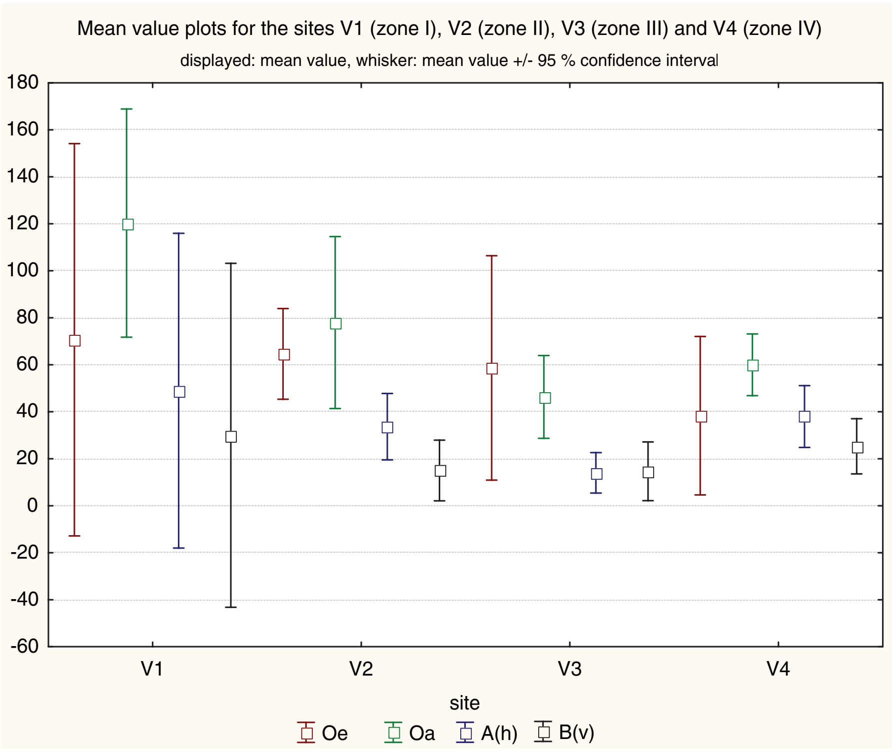

Fig. 5 Mean values and confidence intervals of magnetic susceptibility measurements for the verification sites

susceptibility values could be detected at all four test sites under European beech understory, whereas under pure Scots pine or Scots pine with other hardwood understory, magnetic susceptibility ranges on a comparable level. These differences could not be statistically verified. The influence of stand composition will be one focus of future investigations.

4 Discussion and Conclusions

The high fly-ash deposition for the Dübener Heide ended more than 20 years ago. But it still results in elevated magnetic susceptibilities, which are highest close (up to 8 km) to former emitters and decreased with increasing distance from the emitters. These results are in accordance with studies by Klose et al. (2001, 2002), Klose and Makeschin (2005), and Koch et al. (2002). The variability of the measured values expressed by standard deviation and coefficient of variation tends also to decrease with increasing distance from the former emitters (Table 3). However, the results support rather a differentiation into an area with clearly detectable fly-ash input (former zone I) and an area with lesser likelihood of fly-ash deposition (former zone II, III and IV). The high variability of the measured values at zone I and the trend of decreasing variability along the former deposition indicate that the use of indicators for statistical transfer should be taken into consideration for spatial transfer (regionalization) of the results.

The horizon-wise measurements resulted in lowest standard deviation and coefficient of variation. The Oa horizon showed—with exception of site V3—a peak of magnetic susceptibility. Its indicative value was also reported in preliminary laboratory studies and could be confirmed by our field measurements (Klose et al. 2002; Koch et al. 2002). However, this might change with ongoing humus turnover and site development and will be subject of further investigations (Olson et al. 2004).

The two different test designs of the suitability and the verification test—longitudinal transect and plot-wise investigations—delivered comparable susceptibility values. The variability of the values expressed by standard deviation and coefficient of variation is lower at the plot-wise measurements in the verification test. Both designs supported a differentiation of the test sites into an area with clearly detectable fly-ash input (zone I) and a larger area with constricted detectability of fly-ash deposition (zone II, III and IV). For the development of an optimal test design, which includes (1) the spatial variability of fly-ash deposition in dependence from the distance to the emitters and (2) the additional influence of stand and soil properties on the humus layer and thus on the measured susceptibility values, a broader sampling basis and a statistically sound area-related approach are requested as basis for a spatial transfer (up-scaling) model in order to get better information for a deposition zone-adapted forest management. A regular grid-based sampling with different grid sizes will therefore be tested for the Dübener Heide in the future.

Compared to the laboratory measurements of Klose et al. (2001, 2002) and Koch et al. (2002), which referred to mass susceptibility, a major weakness of the field measurements with the KT 9 is the use of volume susceptibility. Furthermore, the penetration depth of the sensor measurements is dependent from the measured material and ranges from 0.5 to 2 cm. Therefore, an extrapolation of the quantity of magnetic particles in the sampled sites based on the measured susceptibility values is not possible. However, it is sufficient for a differentiation of the test sites along the regional deposition gradient. For referencing the volume susceptibility to mass susceptibility, accompanying laboratory measurements are planned. They will support a qualitative estimation of the actual fly-ash storage and in the consequence also an estimation of the potential heavy metal storage at the test sites as regionalization and planning basis (e.g., Strzyszcz and Magiera et al. 2004; Wang and Qin 2005).

Additionally, comparative measurements in regions with similar geological conditions and forest vegetation but without fly-ash deposition are needed to show the natural level of susceptibility as reference for the test region. These reference values are necessary as correction basis for an intended extrapolation of the fly-ash storage in forest soils on basis of the field measurements of magnetic susceptibility.

In summary, the study supports the conclusion that (1) magnetic susceptibility field measurements are suitable for detecting fly-ash from former industrial deposition in the study area. (2) Noticeable differences to the deposition zones defined by Lux and Stein (1977) were found with the tested approach. In contrast to their findings based on visual forest health assessment, a spatially explicit differentiation could only be concluded for a zone with clearly detectable fly-ash deposition and a larger zone where the likelihood of fly-ash deposition is lower.

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Regionalization of Magnetic Susceptibility Measurements Based on a Multiple Regression Approach

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Abstract The article presents results of a case study in northeastern Germany, where magnetic susceptibility assessment was carried out at grid-wise field measurements. The measurements were clustered into three different depth levels, which represent the humus layer, the transition zone between humus layer and mineral horizon, and the mineral horizon. Taking these three depth levels, a multiple regression-based regionalization approach was applied, testing and using additional environmental parameters derived from geology, topography, and stand type with the aim to develop a comprehensive model for spatial variability of magnetic susceptibility. Spatial variation of magnetic susceptibility was predicted with a high precision by the multiple linear regression models. A slightly differing set of model parameters was selected for the single depth levels. In tendency, magnetic susceptibility values in depth level 6–10 cm were best explained by the distance to Bitterfeld and by soil properties. In depth level 11–15 cm, variables which describe the orographic conditions and stand properties gain in importance. In depth level 21–25 cm, variables indicating soil and site properties disappear completely. Here, aspect and land surface characteristics play a major role together with stand properties. A spatial stratification of the model for a distance of up to 25 km to the former emitters provided a further improvement of the model quality considering the prediction of small-scale variations of magnetic susceptibility.

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Keywords Fly ash · Magnetic susceptibility assessment · Regionalization of magnetic susceptibility · Multiple regression · Stepwise model parameter selection

1 Introduction

For supporting forest ecosystem management decisions, mostly information on stand parameters and on geologically determined site properties is used (Brand 1997; Slocombe 1998; Hickey et al. 2005). In contrast, information on variable impact factors such as deposition, which are also major drivers for site properties and vegetation development, is rarely considered, though information from environmental monitoring (levels I and II) is available (Hansen et al. 2007; Fürst et al. 2007b). A major reason might be that information from permanent monitoring is only available on plot

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level with a high temporal resolution but with missing spatial transfer. This complicates the consideration of deposition loads in regional or management planning unit-oriented decisions (Riley 2001; Zirlewagen et al. 2006, 2007). A further complication arises by the fact that many agents are deposed in combination but with heterogeneous relevance for short-, medium-, and long-term management decisions.

As an example, fly ash from combustion of fossil fuels is known to be stored in forest sites for many decades (Klose and Makeschin 2003, 2005; Fürst et al. 2007a, 2009). Its average geochemical composition comprising mostly sulfur oxides, metal oxides, and black carbon is variable in dependence from the origin of combusted material (Magiera and Strzyszcz 2000; Klose and Makeschin 2003). Fly ash deposition provokes a long-term widening of the C/N and C/P relation in the affected humus layers. Even after total stop of fly ash deposition, it can take more than one century until increased pH values and base saturation reach values, which reflect the original natural potential (Fritz and Makeschin 2007). Fly ash accumulation in the humus layers improves the nutrient supply at poor sites with consequences for tree species composition and productivity of the forest stands (Fürst et al. 2006; Fürst and Makeschin 2006). On the other hand, the Al, Fe, and heavy metal content in forest ecosystems are raised. This provokes a disturbance of litter decomposition and leads to the development of adverse humus forms, which still can be found many years after an active fly ash deposition (Strzyszcz and Magiera 1998; Magiera et al. 2002; Klose et al. 2003). In the long run, the deposed heavy metals can be mobilized by re-acidification of the soils (Koch et al. 2002; Klose et al. 2003). Recently, black carbon is discussed to play a role in hindering the organic matter decomposition (Goldberg 1985; Klose et al. 2003).

To integrate the multiple effects of such a single impact factor “fly ash deposition” in management decisions, a combination of information from monitoring and grid-wise measurement of fast assessable characteristics could be used to transfer the information to the right scale as proposed, e.g., by Morvan et al. (2008).

In a number of studies, the suitability of the indicator magnetic susceptibility for obtaining proxy information on fly ash deposition was proved (Strzyszcz and Magiera 1998; Magiera and Strzyszcz 2000; Schibler et al. 2002; Grimley et al. 2004; Boyko et al. 2004; Magiera et al. 2007; Magiera and Zawadzki 2007). Magnetic susceptibility assessment is based on the detection of magnetic Fe-oxides such as magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3), which are enriched in fly ash (Strzyszcz et al. 1996; Magiera and Strzyszcz 2000). The magnetic signal can be correlated with Fe, Al, Mn, and heavy metals (Strzyszcz 1999; Goluchowska 2001; Wang and Qin 2005; Lu and Bai 2006; Magiera and Zawadzki 2007; Zawadzki et al. 2009) and to some extent also with base cations and black carbon. A restriction is that these correlations cannot easily be transferred between different regions as they depend from geographical origin and type of the combustion material. Also, the land-use type and even the forest type itself can impact the correlation (Strzyszcz and Magiera 1998; Fialova et al. 2006; Magiera and Zawadzki 2007). In consequence, the impact of different environmental parameters on the magnetic signal should be considered in the regionalization approach.

The article presents a case study in northeastern Germany, where magnetic susceptibility was assessed at grid-wise field measurements. The aim of the study was to develop a comprehensive spatial model of former fly ash depositions by using magnetic susceptibility as proxy indicator. The spatial variability of magnetic susceptibility was modeled, testing and using additional environmental parameters derived from geology, topography, and stand type. To improve the model precision with regard to small-scale variations of magnetic susceptibility, a spatial stratification of the model was tested. Finally, the stratified and the global models were cross-validated to test the model quality.

2 Material and Methods

2.1 Study Area

The case study was carried out in a regionally most important forested area in the eastern neighborhood of the industrial triangle Leipzig–Halle–Bitterfeld, the so called Dübener Heide (Fig. 1). The Dübener Heide was impacted by fly ash deposition from five large scale power plants mainly in Bitterfeld and Zschornewitz and a number of smaller fly ash emission sources in the whole industrial triangle. In the mid of the

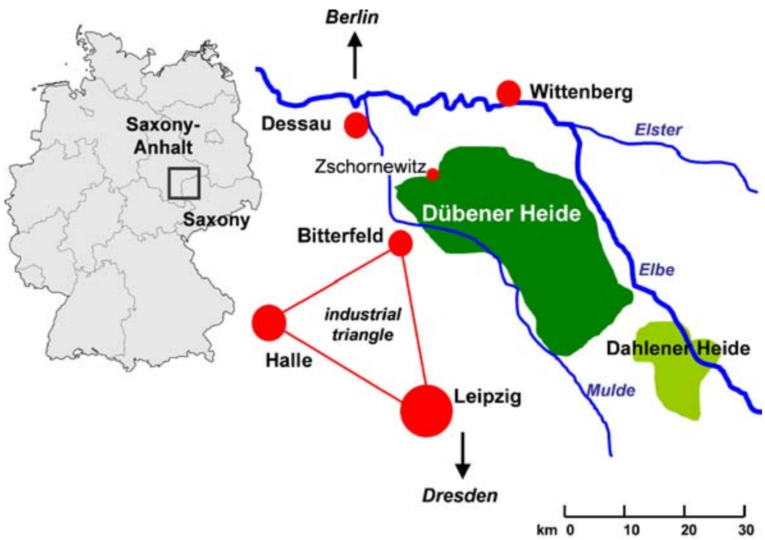


Fig. 1 Localization of the study area

1960s, the period of the highest emission activity, the average fly ash emission amounted to estimative 800 tons per day (Lux 1965), i.e., approximately 0.3 Mio. tons per year. Starting at the nearest power plant in Zschornewitz, Dübener Heide is situated in a horizontal distance of 8 km (western boundary)–50 km (eastern boundary) to the emitters. The area is known to be one of the most polluted forest ecosystems in Germany with more than 100 years history of industrial deposition: based on the available monitoring information, the deposition in the period 1910–2000 is estimated to amount to approximately 18 Mio. tons of fly ash and 12 Mio. tons of SO_2 (Fürst et al. 2007a, 2009). When extrapolating the above mentioned emission quantity of 0.3 Mio. tons of fly ash per year to a period of about 100 years, the real deposition amount could be even higher. However, respective data were hardly published and were partially lost after the German reunification.

An intensive fly ash impact on forest health and forest soil characteristics was observed since the 1960s up to a horizontal distance of 25–30 km to the emitters with decreasing intensity of the fly ash impact from the western to the eastern part of Dübener Heide. From the 1980s on, fly ash filters were introduced, and after the 1990s, the emitters were either closed or technically upgraded. In consequence, fly ash deposition plays no longer a role. However, the above-mentioned distance-dependent fly ash deposition gradient allowed for testing the spatial variation and performance of the proxy indicator magnetic susceptibility under more or less homogeneous environmental conditions (Fürst et al. 2007a, 2009).

2.2 Magnetic Susceptibility Measurements

Magnetic susceptibility field assessment was conducted in a 4×4-km^2 grid (38 plots) and a 1×1-km^2 grid (72 plots). Both grids were overlapping (nested approach). The 4×4-km^2 basic grid allowed for linking the magnetic susceptibility measurements to chemical soil data from level I monitoring. The 1×1-km^2 grid built on the basic grid. For the presented article, the 110 plots are jointly analyzed. The grid-wise measurements were done to map with sufficiently high resolution the spatial variation of magnetic susceptibility and to test if the formerly observed distance-dependent fly ash deposition gradient can be validated. Additional magnetic susceptibility laboratory measurements were carried out to adjust and correct the field assessments.

Magnetic susceptibility was measured with the MS2 meter susceptibility system of Bartington Instruments. The system is developed for detecting very low quantities of magnetic Fe-oxides in compact (rocks) or loose substrates (mineral soil, humus layer). The susceptibility meter has a sensitivity of $0.1-1\times10^{-5}$ SI units and can be used in a single readout mode or transfers the measured values to a PC, where the data can be processed with the software Multisus (© Bartington). The Multisus program uses the

Windows 3.1 or Windows 95/NT interface to record the magnetic susceptibility measurements of different field assessment sensors. The program allows for saving as file the results from a batch of individual samples or from a core. For single samples, the results can be volume or mass specific, and provision is made for automatic increments of depth for core measurements (source: Operation Manual of Multisus 2.0, Bartington Instruments Ltd.).

The MS2 meter susceptibility system comprises a portable measuring instrument, the MS2 meter, and a variety of sensors. The meter displays the magnetic susceptibility value of the tested substrates when these are brought within the influence of one of the sensors, which are each designed for a specific application and sample type (source: Operation Manual of the MS2 system, Bartington Instruments Ltd.).

At the field assessment, volume magnetic susceptibility was measured in 30-cm-deep boreholes with the MS2H down-hole-probe sensor. The MS2H is a subsurface probe for profiling the magnetic susceptibility of strata in 25-mm-nominal-diameter auger holes. Strata with a thickness down to 15 mm can be discriminated. The starting point 1 of the measurements was defined as first measurement after removing the litter (Oi). The Oi was removed, as a prestudy has shown that fly ash particles could never be detected in this layer. Magnetic susceptibility was measured centimeter wise at five bore holes per test plot (i.e., $N=150$/plot). If a soil profile was opened up (e.g., in the frame of the second level I assessment), the bore holes were installed along the head sides of the profiles in a distance of 0.5 m to the profile wall and a distance of 0.5 m between the single bore holes. In the case that no profile was opened up, four bore holes were oriented around one central bore hole with a radius of 0.5 m.

The described design with five repetitions/measurement plot was chosen to represent as best as possible small-scale spatial variations in the humus layer thickness (Oe, Oa) and the border zone to the mineral soil (A(h)), which occur often in Dübener

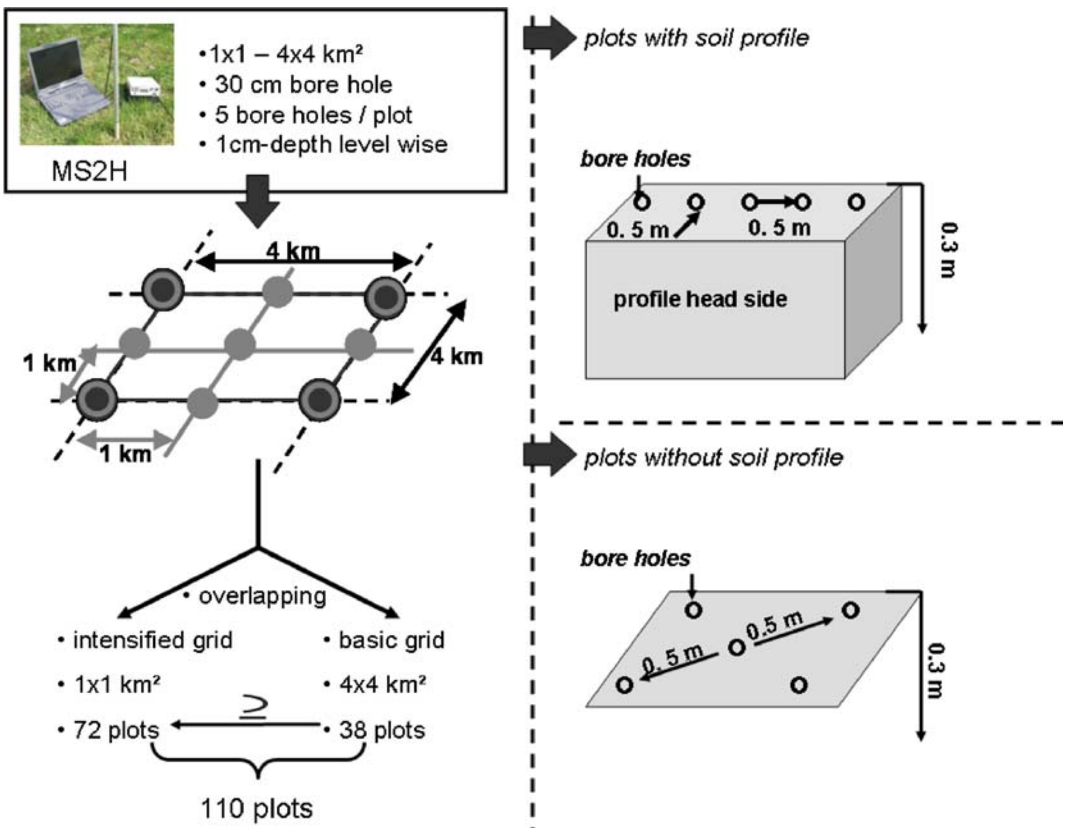


Fig. 2 Test design

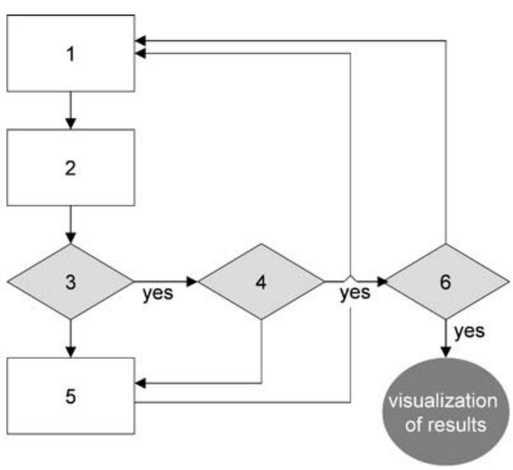
Heide due to extensive wild boar activities. Figure 2 illustrates the test design.

2.3 Regionalization Approach

For the regionalization of magnetic susceptibility, mean values of the measurements at three depth levels were used: Depth level 6–10 cm represents the zone in the humus layer, where in average, the highest magnetic susceptibility values were observed. In this zone, biased measurements which occur at the interface between airspace and humus layer due to technical particularities of the sensor can be excluded. Also, the likelihood of an impact of admixed particles from the mineral soil is low. Depth level 11–15 cm is situated in the transition zone between humus layer and upper mineral horizon, which is characterized by great local variation of the content of humus particles in mineral soil and vice versa due to bioturbation. In most cases, an absolutely clear and sharp border does not exist in the model area. In this zone, increased magnetic susceptibility values are still observed. Depth level 21–25 cm represents the local background value spectrum for the mineral horizon as reference for the height and indicative value of the magnetic susceptibility signal. At the same time, a possible falsification of the measurements due to organic material, which can drop down into the bore hole when taking out the auger, can more or less be excluded in this zone.

The three above-described depth levels are used in the context of the level I assessment and thus offer a good interface to a respective appraisal of soil chemical characteristics. In a horizon-oriented approach, a correlation of the magnetic susceptibility values with chemical values would not have been possible. Another reason for choosing this depth level oriented approach is the applied magnetic susceptibility assessment approach (MS2H down-hole-probe sensor). The data were assessed in 1-cm-depth level resolution in auger holes, and a direct assignment from the measured value to a humus or soil horizon was not always possible as soil profiles were not opened up at each of the 110 plots. The assignment of the above-described three depth levels to whether humus horizon, transition zone, or mineral soil was based on the existent soil profile descriptions, where with high accordance humus layers, thickness was almost never smaller than 10 cm and where the transition zone (11–15 cm) includes the regionally typical variability of sometimes even thicker humus layers.

The aim of the regionalization was to explain the spatial variation of the response variable magnetic susceptibility by auxiliary variables, which are characterized by a pertinent correlation with the response variable (Zirlewagen and von Wilpert 2004) and which are available in digital form. Examples for auxiliary variables are the horizontal distance to the former emitters, relief attributes, geological attributes (substrate/soil type), and stand attributes. The horizontal distance to the emitters, e.g., explains gradual differences in the magnetic signal along the deposition gradient. Topographical height and exposure give information on deposition intensity. Digital relief parameters, which describe convex or concave orography, can explain hydrological soil and site properties and support also the prediction of the response variable magnetic susceptibility (Zirlewagen and von Wilpert 2004). The soil type can give information on the water regime and matter dynamics and thus indicates how long fly ash is stored in the humus



(1) 0-hypothesis: identification of auxiliary variables.
(2) Model formulation by multiple regression analysis.
(3) Test of compliance of the model with model premises (0-hypothesis).
(4) Test of significance and relevance of the model.
(5) If auxiliary variables are added / deleted: re-formulation of the 0-hyothesis and repetition of the modelling.
(6) Plausibility test in the GIS; in case of implausible results, repetition of the steps 1 – 5.

Fig. 3 Flowchart of the iterative modeling procedure layers. Stand properties such as tree species composition include information on how intensive dust particles were combed out and—in coherence with the soil type—which humus dynamics can be expected. A preselection of auxiliary variables was based on experiences with the regionalization of soil chemical values in the federal state of Saxony (Zirlewagen et al. 2006, 2007).

For Dübener Heide, information from the digital elevation model (DEM; resolution 25 m) with the topographic position indices (TPI) grids TPI 500, TPI 1000, and TPI 2000 from the digital soil map (1:50,000), from Corine Landcover 1990 and 2000 and downscaled climate data from 1971–2000 were used. Based on the DEM, geomorphometric attributes, such as aspect, slope, and vertical, horizontal, and tangential curvature, were calculated from neighborhood relationships in geographic information system (GIS), while soil type attributes and hydrological properties could be taken directly from the digital soil map. Forest stand attributes were taken from the Corine Landcover 1990 and 2000, as digital maps for a comparable time frame could not be provided by forest inventory.

The selection of the variables and the formulation of the spatial model were carried out as combination of a multiple regression analysis and geostatistical analysis in six substeps (Zirlewagen and von Wilpert 2004; Zirlewagen et al. 2007). (a) The measurement results were processed and prepared for statistical analysis including a digital relief analysis. (b) An explorative data analysis was carried out including a control of the statistical distribution of the data with a set of statistical analysis methods (e.g., descriptive statistics, scatter plots, variograms, moving window statistics, etc.). Potential auxiliary variables were defined and their ranges were checked. The auxiliary variables with the highest predictive value were identified and integrated iteratively into the model. The number of model parameters was limited to maximally nine to avoid an overparameterization. (c) The formulation of the model itself was based on stepwise multiple linear regressions using the REG procedure of the SAS statistical package Release 9.2. In an iterative process, possible impact factors on the response variable were formulated and tested (Backhaus et al. 2000; Zirlewagen and von Wilpert 2004; see Fig. 3). An optimization of the model and a test of the model quality were done by selected statistical characteristics such as root mean square error (RMSE), R^2 and partial R^2 of the auxiliary variables, and numerous graphical analyses (residual plots, variogram plots, etc.). If necessary, a log-transformation of the data was carried out to improve the model quality (i.e., to achieve an approximate Gaussian distribution of the residuals). Variogram analyses of the residuals gave no indication of spatial dependence, which would have been

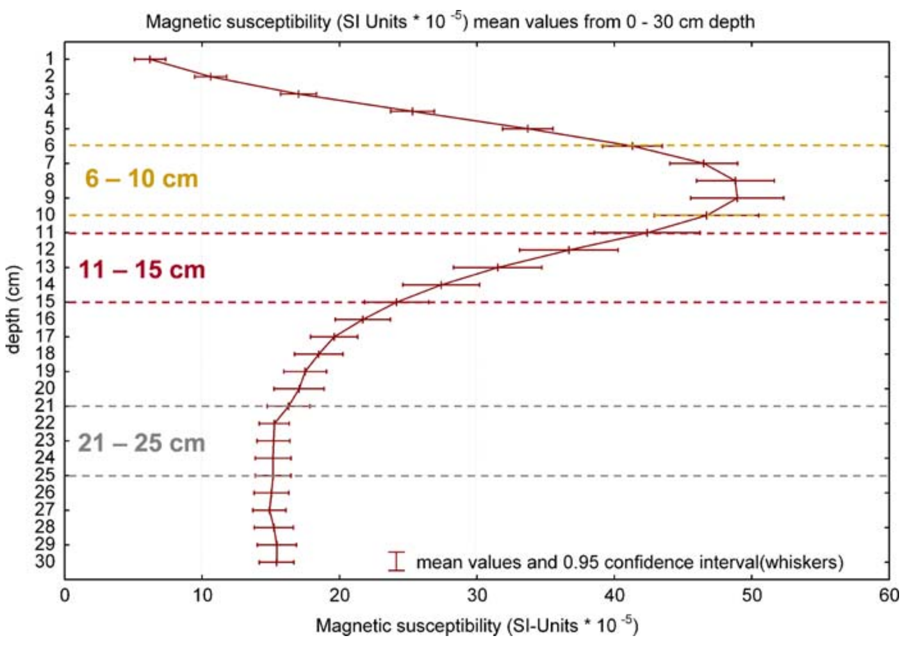


Fig. 4 Trend of magnetic susceptibility from 1 to 30 cm (mean values, *whiskers* 0.95 confidence intervals)

necessary for a kriging of residuals. Based on the intermediate results (e.g., spatial variation revealed by moving window statistics), a submodel was built for the spatial stratum up to 25 km distance to the emitters, which experienced a higher deposition impact than the rest of Dübener Heide. The prediction precision of this stratified model approach was compared with the respective characteristics of the global model without stratification. (d) To quantify the quality of the spatial prediction, a *k*-fold cross-validation with $k=5$ was carried out with the SAS 9.2 GMLSELECT procedure. (e) Finally, the regression equations were imported into ArcGIS, and the spatial distribution of magnetic susceptibility in different depth levels was mapped and visualized on the basis of these equations.

Figure 3 resumes the described procedure of an iterative model formulation according to Zirlewagen and von Wilpert (2004).

3 Results

3.1 Magnetic Susceptibility Values

Magnetic susceptibility (volume susceptibility) values in Dübener Heide ranged from 0 up to 565 SI units× 10^{-5}. Figure 4 shows the trend of magnetic susceptibility over depth (mean values, whiskers 0.95 confidence interval). The highest mean values were achieved in a depth of 8 and 9 cm. The highest variability of the measured values was observed in a depth from 10 to 12 cm. The lowest mean values were found in the upper humus layer from 1 to 4 cm depth and in the mineral horizon from 22 cm depth on. Going along with the lower absolute values, also the variability of the measured values was lower in these two depth levels. Table 1 gives an overview on the mean, minimum, and maximum values as well as on standard deviation and coefficient of variation of the measurement values in the three depth levels selected for regionalization. In depth level 6–10 cm, the highest mean values were observed, but standard deviation and coefficient of variation were lower compared to depth level 11–15 cm. Here, the value range is the highest and the statistical characteristics express the heterogeneity of this depth level. In depth level 21–25 cm, the low standard deviation of the measured values stands for a lower variability of the observed values, despite some outliers, such as the observed maximum value, which lead to a coefficient of variation, which is higher than the one observed in depth level 6–10 cm. The findings support the selection of the three depth levels for the regionalization of magnetic susceptibility.

Table 1 Overview on the mean values ($\bar{x}$), minimum, maximum values, standard deviation (σ), and coefficient of variation (vc (%)) of volume magnetic susceptibility (SI units× 10^{-5}) for the depth levels 5–10, 11–16, and 21–25 cm

Depth level (cm)	$\bar{x}$	Min	Max	σ	vc (%)
6–10	45.54	1	338	33.00	72.46
11–15	32.43	0	565	42.52	131.13
21–25	15.42	0	279	17.04	110.55

The high values especially in the depth level 11–15 cm result from regional fly ash deposition. Pure fly ash deposed directly in the neighborhood of the regional power plants reaches volume magnetic susceptibility values of up to 800 SI units× 10^{-5}

Considering the spatial variability of magnetic susceptibility, the highest single values were observed at the southwestern part of Dübener Heide, which was situated the nearest and in the major regional wind direction to the former power plants. Here, however, also the broadest variability of the measured values was observed, which is supported by previous findings (Fürst et al. 2009). The lowest values and the lowest variability were observed in the northeastern part of Dübener Heide, which is situated farthest from the power plants.

3.2 Selection of the Model Parameters (Auxiliary Variables)

A total number of 21 auxiliary variables resulted from the stepwise selection process, which includes a global modeling approach for the whole area of Dübener Heide and a stratified modeling approach for the near distance zone up to 25 km. Table 2 gives an overview on the selected auxiliary variables, their type, and a short explanation of their meaning.

Table 3 gives an overview on the statistical characteristics of the different variables related to the depth levels. It shows the results for the global model and the respective model validation, gives the results for the stratified model, and contains the results of the respective model validation.

Table 2 Auxiliary variables, which resulted from the step-wise selection process and were finally used for spatial modeling of magnetic susceptibility

Auxiliary variables	Type	Description	Indicative for
L-BITTERFELD-LOG	Metric	Logarithmic horizontal distance to the main emitters in Bitterfeld	Distance to emitters
L-ZSCHORNEW-LOG		Logarithmic horizontal distance to the main emitters in Zschornewitz	
MPV71-00		Mean precipitation in the vegetation period from 1971 to 2000	Hydrological dynamics
PODSOL		Podzol sites from the soil map 1:50,000 (surface area of the respective shape (0–100%))	Soil type, soil and site properties
SEMI-S		Semiterrestrial sites (alluvial sites, gley sites, and swamp sites from soil map 1:50,000, surface area of the respective shape (0–100%))	
SLOPE		Inclination (in degrees)	Orographic conditions: landscape form and surface dynamics, exposure
PRCURV		Surface curvature	
DIVCONV		Divergence–convergence index	
COS-ASP		Divergence from western aspect (cosinus transformation of the aspect)	
MFD-STRP		Stream power index (according to the multiple-flow-direction algorithm)	
BR-SLF		Slope length factor (according to the Braunschweig digital elevation model algorithm)	
MFD-TWI		Topographic wetness index (after the multiple-flow-direction algorithm)	
SLOPEPOS10_5_6	Binary	Slope position (lower slope/valley) derived from TPI 1000	
SLOPEPOS20_5_6		Slope position (lower slope/valley) derived from TPI 2000	
LFORM_4		Landform category—U-shaded valleys	
LFORM_5		Landform category—plains	
LFORM_10		Landform category—mountain tops, high ridges	
LF-MTOP		Landform category—mountain tops	
CONIF1990		Coniferous forest type, Corine Landcover 1990	Vegetation properties/forest stand properties
MIXED1990		Mixed forest type, Corine Landcover 1990	
MIXED2000		Mixed forest type, Corine Landcover 2000	

The application and explanatory value of each variable varies for the different depth levels, going along with the specific characteristics of each depth level, and varies also between global model and stratified model. The validation of the model parameters helped to exclude depth level wise variables, which do not contribute to a higher model quality or to include additional variables. The excluded and additionally included variables are marked in italics, bold, and bold italics in Table 3. Table 4 resumes the applicability and ranking of the single variables for the validated global and the validated stratified model and for each depth level. The ranking of the explanatory value of the variables was based on their partial R^2 and their significance.

Some variables, such as the logarithmic distance to Bitterfeld (L-BITTERFELD-LOG) and the stream power index (MFD-STRP), show for almost all depth levels and for global and stratified model a high explanatory value. In contrast to the logarithmic distance to Bitterfeld as regionally most important emitter, the logarithmic distance to Zschornewitz must have been rejected. Neither for the global nor for the

Table 3 Results of the stepwise selection of the auxiliary variables for the global model (total Dübener Heide) with differing explanatory value of the single variables for the different depth levels, validation of the global model variables, selected variables for the stratified model and statistical parameters for the depth levels, and validation of the variables for the stratified model

Variable name	Depth levels (cm)	Standardized estimate	Partial R^2	Significance
Global model				
L-BITTERFELD-LOG	6–10	−0.6564	0.5491	<0.0001
	11–15	−0.5861	0.4519	<0.0001
	21–25	−0.2818	0.1385	0.0003
MPV71-00	6–10	–	–	–
	11–15	–	–	–
	21–25	*0.1552*	*0.0276*	*0.0604*
PODSOL	6–10	0.1867	0.0302	0.0027
	11–15	*0.1406*	*0.0194*	*0.250*
	21–25	–	–	–
PRCURV	6–10	−0.1382	0.0103	0.0186
	11–15	**–**	**–**	**–**
	21–25	–	–	–
COS-ASP	6–10	–	–	–
	11–15	−0.1967	0.0220	0.0010
	21–25	−0.2900	0.0594	0.0002
MFD-STRP	6–10	0.1812	0.0087	0.0036
	11–15	0.4414	0.0277	<0.0001
	21–25	0.2130	0.0138	0.0131
BR-SLF	6–10	–	–	–
	11–15	−0.25893	0.0403	0.0013
	21–25	−0.1753	0.0212	0.0370
MFD-TWI	6–10	–	–	–
	11–15	−0.3338	0.0133	<0.0001
	21–25	–	–	–
LFORM_4	6–10	–	–	–
	11–15	–	–	–
	21–25	−0.3428	0.0677	<0.0001
LFORM_5	6–10	0.1788	0.0147	0.0058
	11–15	0.1806	0.0150	0.0139
	21–25	–	–	–
LFORM_10	6–10	0.0945	0.0072	0.1110
	11–15	0.1615	0.0262	0.0087
	21–25	–	–	–
LF-MTOP	6–10	–	–	–
	11–15	–	–	–
	21–25	*0.1933*	*0.0337*	*0.0129*
CONIF1990	6–10	–	–	–
	11–15	–	–	–
	21–25	−0.2606	0.0612	0.0004
MIXED2000	*6–10*	*0.0881*	*0.0075*	*0.1183*
	11–15	0.1024	0.0100	0.0747
	21–25	–	–	–

Table 3 (continued)

Variable name	Depth levels (cm)	Standardized estimate	Partial R^2	Significance
Global model validation				
L-BITTERFELD-LOG	6–10	−0.6618	0.5491	<0.0001
	11–15	−0.6488	0.4519	<0.0001
	21–25	−0.2372	0.1385	0.0018
MPV71-00	6–10	–	–	–
	11–15	–	–	–
	21–25	0.1552	0.0276	0.0604
PODSOL	6–10	0.1888	0.0302	0.0025
	11–15	–	–	–
	21–25	–	–	–
PRCURV	6–10	−0.1359	0.0153	0.0213
	11–15	0.1180	0.0122	0.0583
	21–25	–	–	–
COS-ASP	6–10	–	–	–
	11–15	−0.1793	0.0220	0.0029
	21–25	−0.2815	0.0594	0.0003
MFD-STRP	6–10	0.1684	0.0142	0.0066
	11–15	0.4469	0.0277	<0.0001
	21–25	0.2685	0.0234	0.0017
BR-SLF	6–10	–	–	–
	11–15	−0.3175	0.0456	0.0002
	21–25	−0.2215	0.0363	0.0080
MFD-TWI	6–10	–	–	–
	11–15	−0.3681	0.0117	<0.0001
	21–25	–	–	–
LFORM_4	6–10	–	–	–
	11–15	–	–	–
	21–25	−0.3330	0.0677	<0.0001
LFORM_5	6–10	0.1636	0.0042	0.0110
	11–15	0.1535	0.0145	0.0399
	21–25	–	–	–
LFORM_10	6–10	0.0907	0.0072	0.1277
	11–15	0.1623	0.0262	0.0088
	21–25	–	–	–
LF-MTOP	6–10	–	–	–
	11–15	–	–	–
	21–25	–	–	–
CONIF1990	6–10	–	–	–
	11–15	–	–	–
	21–25	−0.2768	0.0612	0.0002
MIXED2000	6–10	–	–	–
	11–15	0.1003	0.00960	0.0826
	21–25	–	–	–

Table 3 (continued)

Variable name	Depth levels (cm)	Standardized estimate	Partial R^2	Significance
Stratified model				
L-BITTERFELD-LOG	6–10	−0.5123	0.4090	<0.0001
	11–15	−0.5729	0.2901	<0.0001
	21–25	−0.4180	0.2019	<0.0001
L-ZSCHORNEW-LOG	***6–10***	***−0.1764***	***0.0176***	***0.0813***
	11–15	–	–	–
	21–25	–	–	–
MPV71-00	6–10	–	–	–
	11–15	–	–	–
	21–25	0.2094	0.0289	0.0434
PODSOL	6–10	0.1431	0.0407	0.0789
	11–15	0.2023	0.0202	0.0154
	21–25	–	–	–
SEMI-S	6–10	0.2579	0.0200	0.0054
	11–15	–	–	–
	21–25	–	–	–
SLOPE	6–10	–	–	–
	11–15	–	–	–
	21–25	−0.2768	0.0405	0.0044
DIVCONV	6–10	–	–	–
	11–15	0.1762	0.0149	0.0974
	21–25	–	–	–
COS-ASP	6–10	–	–	–
	11–15	−0.1721	0.0237	0.0242
	21–25	−0.2376	0.0261	0.0082
MFD-STRP	6–10	0.5770	0.0202	<0.0001
	11–15	0.6480	0.0943	<0.0001
	21–25	–	–	–
BR-SLF	6–10	−0.3262	0.0169	0.0039
	11–15	−0.5463	0.0381	<0.0001
	21–25	–	–	–
MFD-TWI	***6–10***	***−0.2767***	***0.0266***	***0.0136***
	11–15	−0.2333	0.0581	0.0358
	21–25	–	–	–
SLOPEPOS10_5_6	6–10	–	–	–
	11–15	–	–	–
	21–25	0.2145	0.0200	0.0223
SLOPEPOS20_5_6	6–10	−0.1805	0.0140	0.0353
	11–15	−0.1519	0.0141	0.0692
	21–25	–	–	–
LFORM_4	6–10	–	–	–
	11–15	–	–	–
	21–25	***−0.2208***	***0.0289***	***0.0439***

Table 3 (continued)

Variable name	Depth levels (cm)	Standardized estimate	Partial R^2	Significance
CONIF1990	6–10	–	–	–
	11–15	***0.1542***	***0.0667***	***0.0608***
	21–25	−0.3476	0.0802	0.0003
MIXED1990	***6–10***	***0.1766***	***0.0228***	***0.0326***
	11–15	–	–	–
	21–25	0.2099	0.0585	0.0495
Stratified model validation				
L-BITTERFELD-LOG	6–10	−0.5823	0.4090	<0.0001
	11–15	−0.5407	0.2901	<0.0001
	21–25	−0.4520	0.2019	<0.0001
L-ZSCHORNEW-LOG	6–10	–	–	–
	11–15	–	–	–
	21–25	–	–	–
MPV71-00	6–10	–	–	–
	11–15	–	–	–
	21–25	0.2108	0.0289	0.0463
PODSOL	6–10	0.1661	0.0244	0.0515
	11–15	0.2324	0.0555	0.0056
	21–25	–	–	–
SEMI-S	6–10	0.1546	0.0215	0.0810
	11–15	–	–	–
	21–25	–	–	–
SLOPE	6–10	–	–	–
	11–15	–	–	–
	21–25	−0.2701	0.0321	0.0066
DIVCONV	6–10	–	–	–
	11–15	0.1794	0.0154	0.0971
	21–25	–	–	–
COS-ASP	6–10	–	–	–
	11–15	−0.1889	0.0273	0.0146
	21–25	−0.2047	0.0345	0.0224
MFD-STRP	6–10	0.3465	0.0355	0.0015
	11–15	0.6678	0.0350	<0.0001
	21–25	–	–	–
BR-SLF	6–10	−0.1838	0.0320	0.0545
	11–15	−0.5638	0.0973	<0.0001
	21–25	–	–	–
MFD-TWI	6–10	–	–	–
	11–15	−0.2680	0.0728	0.0167
	21–25	–	–	–
SLOPEPOS10_5_6	6–10	–	–	–
	11–15	–	–	–
	21–25	0.1465	0.0200	0.0984

Table 3 (continued)

Variable name	Depth levels (cm)	Standardized estimate	Partial R^2	Significance
SLOPEPOS20_5_6	6–10	−0.1483	0.0035	0.0840
	11–15	−0.1931	0.0077	0.0196
	21–25	–	–	–
LFORM_4	6–10	–	–	–
	11–15	–	–	–
	21–25	–	–	–
CONIF1990	6–10	–	–	–
	11–15	–	–	–
	21–25	−0.3505	0.0802	0.0004
MIXED1990	6–10	–	–	–
	11–15	–	–	–
	21–25	−0.3195	0.0585	0.0009

The variables which were excluded in the global model validation are in italics, the variables which were integrated additionally after the validation are in bold, and the variables which were excluded after the validation of the stratified model are in bold italics

Table 4 Applicability and ranking of the auxiliary variables for the global and the stratified model after model validation and according to the different depth levels

Variable name	Depth levels (cm)	Global model		Stratified model	
		Applicability	Ranking	Applicability	Ranking
L-BITTERFELD-LOG	6–10	Yes	1	Yes	1
	11–15	Yes	1	Yes	1
	21–25	Yes	1	Yes	1
L-ZSCHORNEW-LOG	6–10	No	–	No	–
	11–15	No	–	No	–
	21–25	No	–	No	–
MPV71-00	6–10	No	–	No	–
	11–15	No	–	No	–
	21–25	No	–	Yes	6
PODSOL	6–10	Yes	2	Yes	4
	11–15	No	–	Yes	4
	21–25	No	–	No	–
SEMI-S	6–10	No	–	Yes	5
	11–15	No	–	No	–
	21–25	No	–	No	–
SLOPE	6–10	No	–	No	–
	11–15	No	–	No	–
	21–25	No	–	Yes	5
PRCURV	6–10	Yes	3	No	–
	11–15	Yes	7	No	–
	21–25	No	–	No	–
DIVCONV	6–10	No	–	No	–
	11–15	No	–	Yes	7
	21–25	No	–	No	–

Table 4 (continued)

Variable name	Depth levels (cm)	Global model		Stratified model	
		Applicability	Ranking	Applicability	Ranking
COS-ASP	6–10	No	–	No	–
	11–15	Yes	5	Yes	6
	21–25	Yes	4	Yes	4
MFD-STRP	6–10	Yes	4	Yes	2
	11–15	Yes	3	Yes	5
	21–25	Yes	6	No	–
BR-SLF	6–10	No	–	Yes	3
	11–15	Yes	2	Yes	2
	21–25	Yes	5	No	–
MFD-TWI	6–10	No	–	No	–
	11–15	Yes	8	Yes	3
	21–25	No	–	No	–
SLOPEPOS10_5_6	6–10	No	–	No	–
	11–15	No	–	No	–
	21–25	No	–	Yes	7
SLOPEPOS20_5_6	6–10	No	–	Yes	6
	11–15	No	–	Yes	8
	21–25	No	–	No	–
LFORM_4	6–10	No	–	No	–
	11–15	No	–	No	–
	21–25	Yes	2	No	–
LFORM_5	6–10	Yes	6	No	–
	11–15	Yes	6	No	–
	21–25	No	–	No	–
LFORM_10	6–10	Yes	5	No	–
	11–15	Yes	4	No	–
	21–25	No	–	No	–
LF-MTOP	6–10	No	–	No	–
	11–15	No	–	No	–
	21–25	No	–	No	–
CONIF1990	6–10	No	–	No	–
	11–15	No	–	No	–
	21–25	Yes	3	Yes	2
MIXED1990	6–10	No	–	No	–
	11–15	No	–	No	–
	21–25	No	–	Yes	3
MIXED2000	6–10	No	–	No	–
	11–15	Yes	9	No	–
	21–25	No	–	No	–

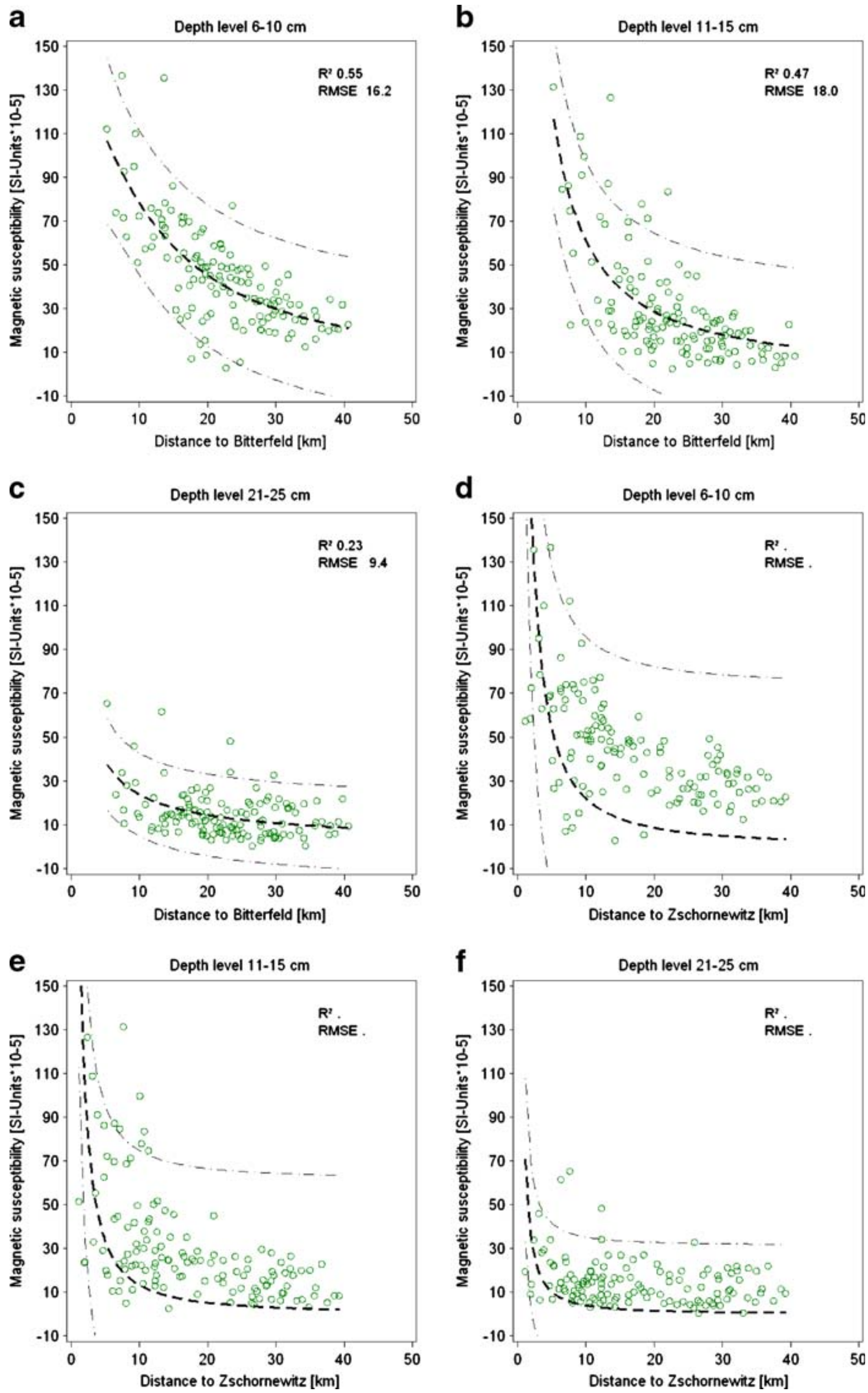


Fig. 5 a Dependence of magnetic susceptibility from the horizontal distance to Bitterfeld at depth level 6–10 cm. The *small dashed lines* show the approximate 0.95 confidence interval for an individual prediction. **b** Dependence of magnetic susceptibility from the horizontal distance to Bitterfeld at depth level 11–15 cm. The *small dashed lines* show the approximate 0.95 confidence interval for an individual prediction. **c** Dependence of magnetic susceptibility from the horizontal distance to Bitterfeld at depth level 21–25 cm. The *small dashed lines* show the approximate 0.95 confidence interval for an individual prediction. **d** Dependence of magnetic susceptibility from the horizontal distance to Zschornewitz at depth level 6–10 cm. The *small dashed lines* show the approximate 0.95 confidence interval for an individual prediction. **e** Dependence of magnetic susceptibility from the horizontal distance to Zschornewitz at depth level 11–15 cm. The *small dashed lines* show the approximate 0.95 confidence interval for an individual prediction. **f** Dependence of magnetic susceptibility from the horizontal distance to Zschornewitz at depth level 21–25 cm. The *small dashed lines* show the approximate 0.95 confidence interval for an individual prediction

stratified model a stable correlation was found. Figure 5a–f provides an overview on the depth level wise distance dependence of magnetic susceptibility. Figure 5a–c shows the results for the combination magnetic susceptibility—horizontal distance to Bitterfeld; Fig. 5d–f shows in comparison the findings for the combination magnetic susceptibility—horizontal distance to Zschornewitz.

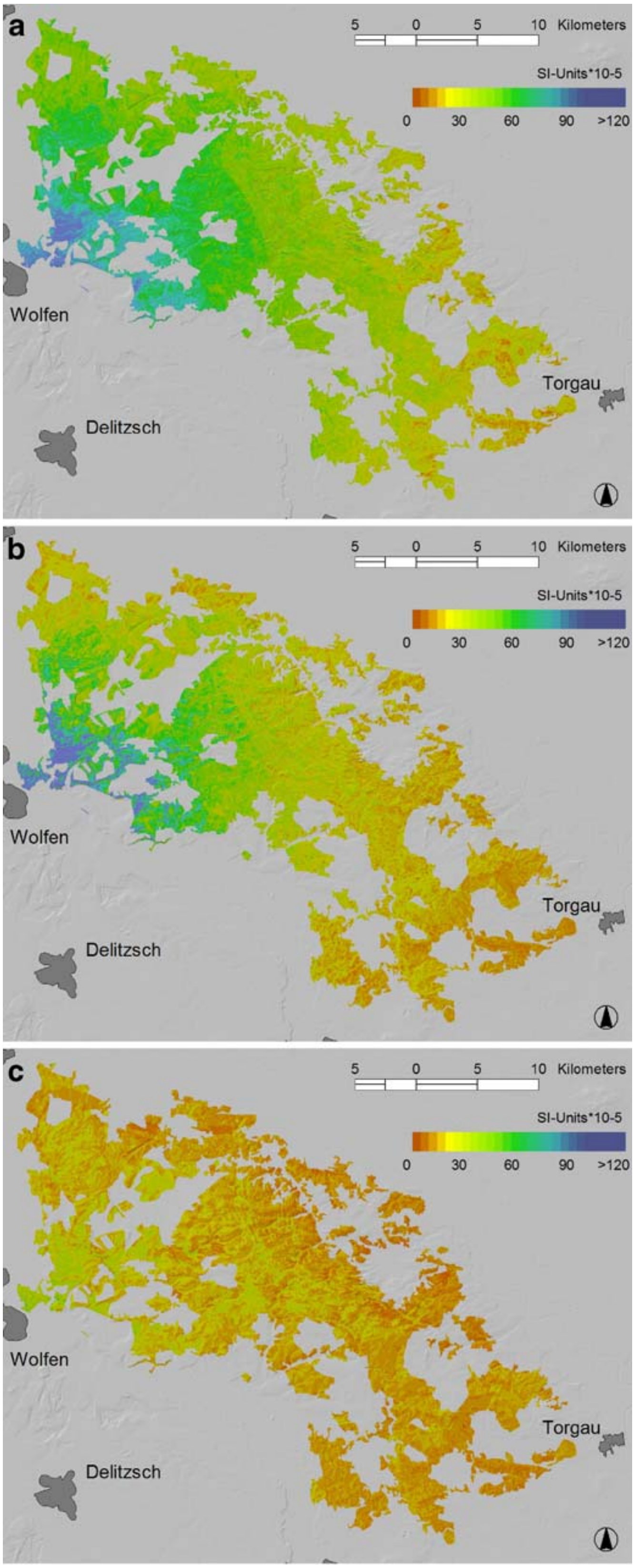


Fig. 6 **a** Spatial variability of magnetic susceptibility in the global model at depth level 6–10 cm. **b** Spatial variability of magnetic susceptibility in the global model at depth level 11–15 cm. **c** Spatial variability of magnetic susceptibility in the global model at depth level 21–25 cm. **d** Comparison of spatial variability of magnetic susceptibility in the global and stratified model at depth level 6–10 cm. **e** Comparison of spatial variability of magnetic susceptibility in the global and stratified model at depth level 11–15 cm. **f** Comparison of spatial variability of magnetic susceptibility in the global and stratified model at depth level 21–25 cm. **g** Zoom-in into differences between global and stratified model considering high resolution information on small-scale differences in magnetic susceptibility in the humus layer for the near distance zone of up to 25 km

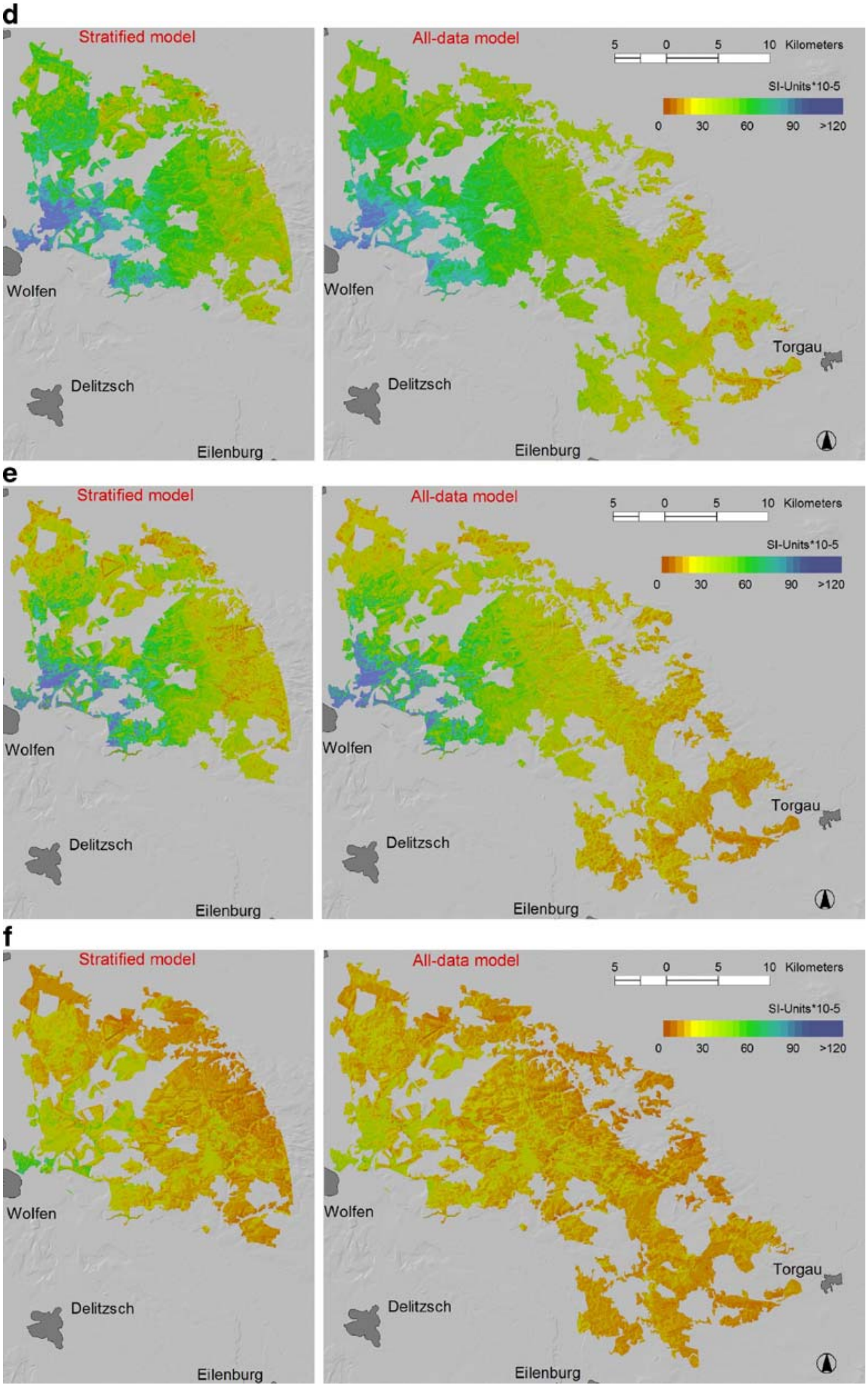
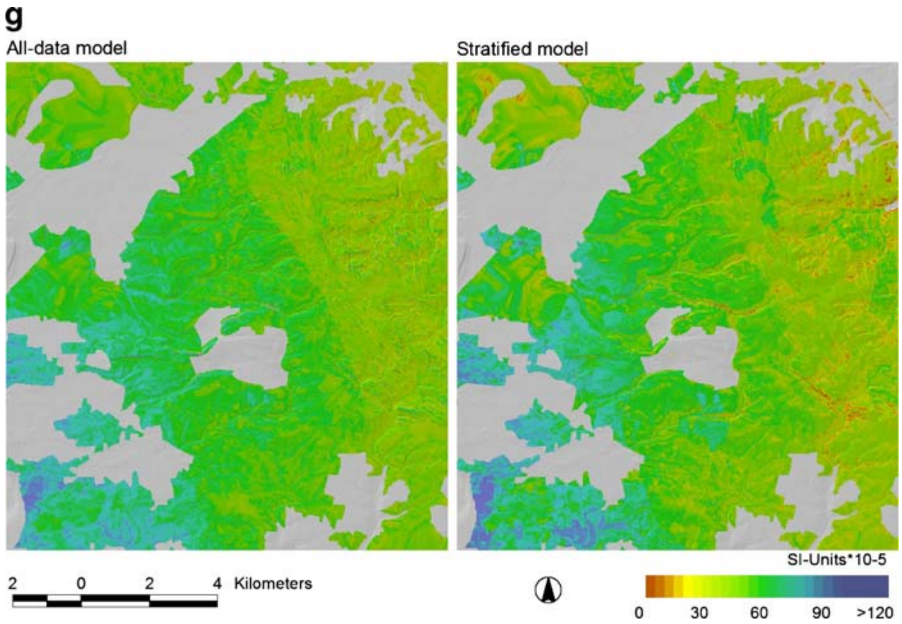


Fig. 6 (continued)

Fig. 6 (continued)



The impact of Bitterfeld becomes most evident in the depth levels 6–10 and 11–15 cm (Fig. 5a, b) and goes up to 40 km. However, up to a distance of about 10 km, the impact is also visible in the depth layer 21–25 cm (Fig. 5c). Considering the impact of the power plant in Zschornewitz, a rather small-scale impact can be detected up to a distance of maximally 10 km in the depth levels 6–10 and 11–15 cm (Fig. 5d, e), while the impact on the depth level 21–15 cm is almost not quantifiable (Fig. 5f). The missing R^2 and RMSE in Fig. 5d–f express the impossibility to fit a nonlinear regression between magnetic susceptibility and the horizontal distance to Zschornewitz. The nonlinear least-squares estimations did not converge, at least for the tested prediction equations. The higher emission quantity from a larger number of power plants in Bitterfeld with a larger spatial impact due to higher flues superposed evidently the influence of the single local power plant in Zschornewitz, despite this power plant was always assumed to be the major regional pollutant (see, e.g., Fritz and Makeschin 2007).

3.3 Spatial Transfer of Magnetic Susceptibility

Finally, the regression equations were imported into ArcGIS and the spatial variability of magnetic susceptibility in dependence on the model parameters was mapped and visualized for the different depth levels. Figure 6a–c shows the spatial variation of magnetic susceptibility in the three depth levels for the global model; Fig. 6d–f compares the information on spatial variability between global and stratified model. Figure 6g demonstrates for a selected section of the Dübener Heide near the former power plants the differences between global and stratified model considering high resolution information on spatial variability of magnetic susceptibility in the humus layer (depth level 6–10 cm).

The global model allows for identifying zones of more or less comparable height of the magnetic signal. These are especially evident in the depth level 6–10 cm (Fig. 6a) and become less pronounced with increasing depth (Fig. 6b, c). The maps show that fly ash was mostly deposed from western direction into the northeastern parts of Dübener Heide with a local peak above Bitterfeld-Wolfen, while the southeastern part of Dübener Heide is much less affected. By the use of topographical, geographical, and forest stand type parameters, also the spatial variability within the zones of comparable impact height can be modeled. This provides much more detailed information for forest management planning than a simple zoning as proposed by Lux (1965). Additionally, the improved representation of small-scale

Table 5 Statistical characteristics of the global and stratified model for the regionalization of ferrimagnetic susceptibility for the original model and for the cross-validated model

Model	Depth level (cm)	Original						Cross-validation					
		P	*FG*	R^2	Adj. R^2	RMSE	σ	*P*	*FG*	R^2	adj. R^2	RMSE	σ
Global	6–10	9	121	0.65 (0.43)	0.62 (0.37)	14.6 (18.1)	23.9 (25.4)	7	124	0.62	0.60	15.1	23.9
	11–15	10	120	0.63 (0.56)	0.60 (0.50)	0.46 (0.47)	0.72 (0.65)	10	121	0.62	0.59	0.46	0.72
	21–25	9	121	0.42 (0.36)	0.38 (0.29)	0.46 (0.51)	0.59 (0.62)	7	123	0.39	0.36	0.47	0.59
Stratified	6–10	10	73	0.59	0.54	17.30	25.4	7	76	0.53	0.49	18.10	25.4
	11–15	10	72	0.62	0.57	0.42	0.65	9	73	0.60	0.56	0.43	0.65
	21–25	9	75	0.49	0.43	0.47	0.62	8	76	0.46	0.41	0.48	0.62

The numbers in brackets at the global model are referred to the same data collective as the stratified model

P number of variables including the intercept, *FG* error degrees of freedom, R^2 coefficient of determination, *Adj.* R^2 adjusted R^2, *RMSE*, root mean square error, σ standard deviation of the measurements

differences by the stratified model becomes clear (Fig. 6d–g).

3.4 Model Quality Test

Table 5 compares finally some statistical characteristics of the global and the stratified model. The statistical characteristics for the global model are shown (a) on the basis of the complete data set of Dübener Heide and (b) on the basis of the same spatial data collective up to 25 km distance as it is used for the stratified model (numbers in brackets for R^2, adjusted R^2, root mean square error, and standard deviation). Comparing the statistical characteristics for global and stratified model for the same spatial data collective (numbers in brackets for global model), the stratified model led to an improvement of the model precision in the up to 25 km distance area at all depth levels: R^2 and adjusted R^2 are higher for the stratified model, while the root mean square error becomes lower and the standard deviation reaches identical values. This benefit of the model stratification is also supported by Fig. 6d–g.

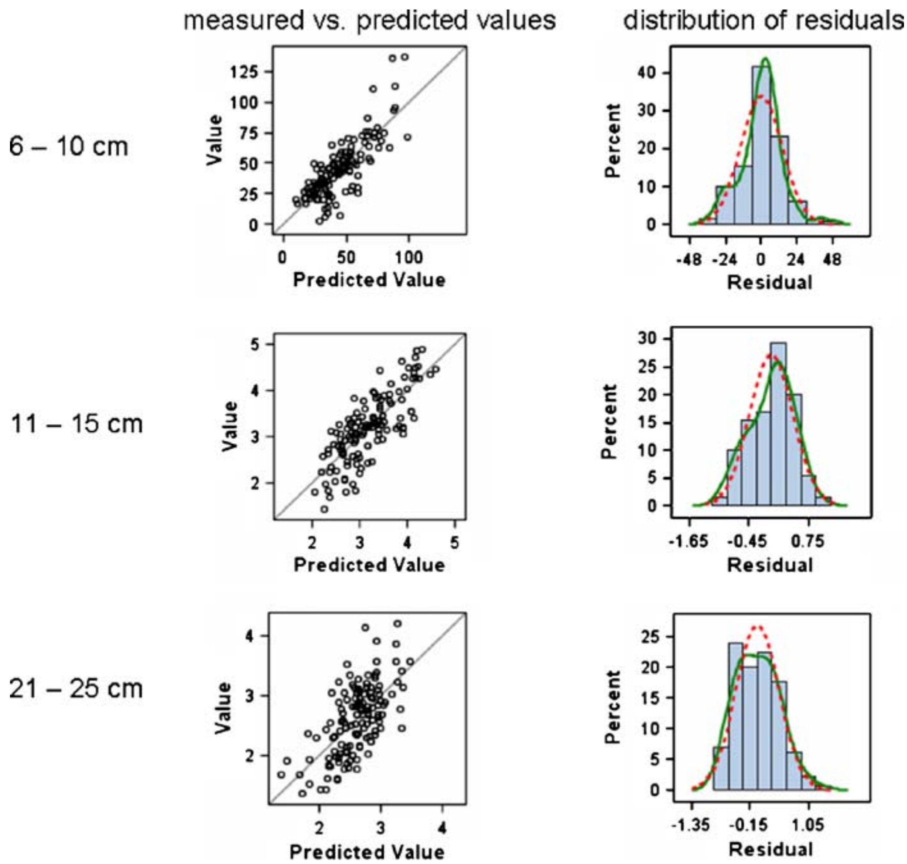
The fivefold cross validation was done to test the quality of the global and the stratified model for their proper spatial validity area, i.e., in this case, the spatial data sets are not identical and a comparison of the statistical characteristics is only possible between original and validated model. The statistical characteristics of the cross validation highlights the yet high quality of the original models and resulted in a reduced number of model parameters for depth level 6–10 and 21–25 cm at the global model and for all depth levels at the stratified model (see also Section 3.2).

The results of the fit diagnostics of the cross-validated models reveal some differences in the model quality between the different depth levels, which are in tendency equal for the global and the stratified model. The differences are exemplarily shown for the cross-validated global model (Fig. 7): In depth level 6–10 and 11–15 cm, a very narrow distribution of the measured and predicted values, and the residual plots indicate a high prediction quality which is lower in the depth level 21–25 cm, where the fly ash impact is minor compared to other factors. At depth level 6–10 cm, the residuals follow a normal distribution, while the residuals in depth level 11–15 cm are slightly right skewed and at depth level 21–25 cm, they are slightly left skewed. To achieve optimal results, a combination of the global model for the depth levels 6–10 and 11–15 with the stratified model for depth level 21–25 cm could be taken into consideration.

4 Discussion and Conclusions

The mapping of magnetic susceptibility in Dübener Heide delivered high resolution information on the range and spatial variation of this proxy indicator for fly ash deposition. The plot-wise assessment was regionalized by a multiple regression-based approach

Fig. 7 Fit statistics of the validated global model at depth levels 6–10, 11–15, and 21–25 cm



with a stepwise selection of highly indicative parameters for the magnetic signal in different depth levels.

In tendency, magnetic susceptibility values in the humus layer (depth level 6–10 cm) were best explained by the distance to Bitterfeld, the occurrence of the soil type podzol (PODSOL), and in the case of the stratified model also by the occurrence of semiterrestrial sites (SEMI-S). The properties podzol and semiterrestrial sites indicate a slowed down humus dynamics, which supports a long-term accumulation of fly ash (Magiera and Zawadzki 2007). Further variables, such as stream power index (MFD-STRP), surface curvature (PRCURV, global model), and slope length factor (BR-SLF, stratified model) indicate the probability of humus accumulation or humus erosion, which explains their high relevance for the model in this depth layer. Additionally, some few exposure variables (valleys (LFORM_4) and plains (L-FORM_5) in the global model and slope position (SLOPEPOS20_5_6) in the stratified model) play a role. They also explain the probability of a humus accumulation (see, e.g., McKenzie and Ryan 1999; Moore et al. 1993). In contrast, stand characteristics have no explanatory value for the magnetic signal in the depth level 6–10 cm. This is contradictory to findings from Zawadzki et al. (2007) which highlights the impact of the forest type on the magnetic signal. A reason might be that Zawadzki et al. (2007) did not differentiate the impact according to different depth levels. Also in the presented findings, stand properties play a role for magnetic susceptibility modeling, not for the humus layer (depth level 6–10 cm) but for the transition zone (depth level 6–11 cm) and especially for the mineral soil (depth level 21–25 cm). Probably, the stand type impact on the findings in the humus layer is by far superposed by soil type and orographic parameters, which decide upon the humus dynamics.

In the transition zone between humus layer and mineral soil (depth level 11–15 cm), variables which describe the orographic conditions gain in importance. New variables occur, such as the divergence from western aspect (COS-ASP), which indicates the exposure against the major wind direction and thus the probability of deposition. Also, stand properties (mixed forest—MIXED2000, global model) contribute to the model in this depth layer, though their explanatory value is lower compared to their importance for the model in the mineral horizon (depth level 21–25 cm).

In the mineral horizon (depth level 21–25 cm), variables indicating soil and site properties, such as PODSOL, disappear completely. Here, aspect (COS-ASP) and land surface characteristics (valleys—LFORM_4, global model, inclination—SLOPE, stratified model), which indicate the deposition probability, play a major role together with stand properties (CONIF1990, MIXED1990). The latter one can explain the probability that deposition was combed out by the stand. This, however, would raise the question why the stand type is not relevant for the model in the humus layer. Probably, in the case of depth level 21–25 cm, the stand type might indicate a vertical displacement of magnetic iron complexes together with sesquioxides and humus complexes by initial podzolization processes. This is supported by the findings that (a) only coniferous or mixed types show an explanatory value and not deciduous types and that (b) the elder Corine Landcover classification from 1990 contribute to the modeling in this depth layer and not the classification of 2000. Finally, also the precipitation amount from 1971 to 2000 (MPV71-00) contributed to the model in the mineral horizon. This could go along with the hypothesis formulated before: Locally, higher precipitation amounts can support podzolization processes.

Comparing the global and the stratified model, differences in some variables occur, which go along with the higher importance of small-scale variations of site, orographic, and stand properties in the stratified model. The parameters, which apply additionally in the stratified model or instead of variables in the global model, give more detailed information on the surface structure and exposure, such as the divergence–convergence index (DIVCONV) or the slope position (SLOPEPOS10_5_6 and SLOPEPOS20_5_6). Also, variables indicating specific hydrological frame conditions, such as the existence of semiterrestrial sites (SEMI-S) and the amount of precipitation in the vegetation period (MPV71-00) contribute exclusively in the stratified model to explain the height of the magnetic signal. This supports the assumptions that small-scale variations of the magnetic signal are also impacted by the hydrological dynamic of a site.

The high impact of the logarithmic distance to Bitterfeld (L-BITTERFELD-LOG) was unexpected in comparison to other findings (e.g., Fritz and Makeschin 2007), which assumed a major importance of the power plant in Zschornewitz due to its closeness to the study area and the high amounts of fly ash produced by this single power plant over more than a century. The power plant in Zschornewitz was one of the first and largest power plants in the region (Lux 1965). However, or despite of this fact, its minor impact on the study area compared to Bitterfeld might be a result of its ancient combustion technology, which produced much more coarse ash particles compared to more modern power plants in Bitterfeld. In the consequence, the fly ash particles of Zschornewitz were deposed primarily in the immediate vicinity of the power plant and not transported over longer distances (Fürst and Makeschin 2006). To differentiate the impact areas of Bitterfeld and Zschornewitz in Dübener Heide, a chemical analysis on the differences in the fly ash particles compared to the fly ash emitted by the different power plants would be necessary. This, however, is complicated by the fact that the yet stored fly ash particles in the forest soils were superposed at least for 20 years by weathering and decomposition processes. Furthermore, local fly ash composition variability is also impacted by historical and actual domestic fuel deposition (Strzyszcz and Magiera 2001).

In conclusion, spatial variation of magnetic susceptibility could be predicted with a high precision by the multiple linear regression model. The use of a slightly differing set of model parameters for the different depth levels according to their explanatory value improved the prediction quality and supported also the understanding of major drivers for magnetic particle deposition, storage, and vertical displacement in the forest soils.

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Testing the indicative value of magnetic susceptibility measurements for concluding on site potentials and risks provoked by fly ash deposition

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Abstract

The article presents results of testing the indicative value of magnetic susceptibility for fly ash deposition and its effects on forest site properties. Base saturation and concentrations of Ca and Mg were used as indicators for nutrient pools resulting from fly ash deposition. Concentrations of Fe, Al, Mn, Cd and Black Carbon were used as indicators for risks of leaching. The correlation of magnetic susceptibility with concentrations of nutrient, acidic cations, heavy metals, base saturation and Black Carbon was calculated. Additionally, we tested the suitability of magnetic susceptibility as parameter in a linear regression based model to predict the concentrations of Ca, Mg, Fe, Al, Mn, Cd and Black Carbon. We were able to prove a positive correlation between magnetic susceptibility and the selected indicators. In contrast to previous studies, we were also able to prove the suitability of magnetic susceptibility to predict the size of fly ash deposition influenced nutrient pools mainly for humus layers, especially for Oa horizons. The spatial distribution of magnetic susceptibility showed also a positive correlation with regionalized base saturation. However, caused by the data base and other factors impacting the measurement and modeling results, some shortcomings of using a linear regression model must be noticed. From these results, we concluded that magnetic susceptibility might be a valuable parameter in a multiple regression based approach, but should not be used alone for predicting effects of fly ash deposition.

Key words Magnetic susceptibility, fly ash deposition, predictive value of magnetic susceptibility, Level-I monitoring, linear regression based modeling, regionalization of fly ash deposition.

1. Introduction

The use of indicators to support ecosystem management is a widely used approach (Bockstaller and Girardin 2003, Cloquell-Ballester and others 2006). In forest ecosystem management soil vegetation and forest stand properties are used to conclude on forest health and forest growth and to adjust management targets (Brand 1997, Slocombe 1998, Hickey and others 2005). Indicators for atmospheric deposition and other forms of anthropogenic impacts are rarely used, although, it is well known that deposition might affect forest ecosystem development over decades (Fürst and others 2007 a, b). A possible reason might be that information on deposition is mostly not available on management planning unit level, but only on larger scales (see e.g. Lorenz and others 2008) or on monitoring plot level. The discussion on monitoring strategies and reduction of monitoring plots emphasizes the need for simple and low-cost approaches. To tackle this problem, advanced regionalization approaches were developed e.g. by Erhard and Flechsig (1998), Gauger and others (2002), Zirlewagen and others (2006, 2007), who used also data from soil monitoring programs as input. We tested for a fly ash impacted area if a combination of detailed measurements at few plots and spatial transfer by using grid-wise assessed proxies might be a suitable approach to transfer management information onto the target scale without loss of information depth (e.g. Percy and Ferretti 2004, Morvan and others 2008).

A major problem in the assessment of effects of atmospheric deposition is that agents with different relevance for forest management can be deposed at the same time. Taking fly ash as an example, the most important components are sulphur oxides and oxides of alkali and earth-alkali metals, metal and heavy metal oxides, and Black Carbon (Magiera and Strzyszcz 1999, Klose and Makeschin 2003). Fly ash deposition affects forests in all industrial influenced regions in Europe where unfiltered combustion residuals of fossil fuels have been or are still deposited. One of the most affected regions in Europe was the so called "Black Triangle", a heavily industrialized area in the Czech-German-Polish border region. For this area, fly ash deposition amounted up to 457 t km^{-2} a^{-1} (Upper Silesia, Poland) (Strzyszcz and others 1996, Strzyszcz and Magiera 2001, Klose and Makeschin 2003).

Fly ash particles might be stored in forest soils for many decades and might have a strong impact on humus properties and soil microbial communities as well as on the composition of the soil vegetation and forest growth (Koch and others 2002, Klose and Makeschin 2003, 2005, Klose and others 2001, 2003 a, b, 2004, Fürst and others 2007 b, 2009 a, b). Fly ash has ambiguous effects for the forest ecosystem: it might cause wider C:N and C:P ratios in forest soils, increase the pH-value and base saturation. As an additional effect, fly ash accumulation improves the nutrient pools of poor soils with consequences for composition and productivity of forest stands (Koch and others 2002, Klose and others 2001, 2003a, b, 2004, Fürst and others 2006 a, b). On the other hand, fly ash deposition might cause higher concentrations of Al, Fe, and heavy metal in forest soils. This can provoke a disturbance of litter decomposition and lead to the development of adverse humus forms (Strzyszcz and Magiera 1998, Magiera and others 2002, Koch and others 2002, Klose and others 2001, 2003 a, b, 2004). The deposed heavy metals can be mobilized by re-acidification of the soils, when fly ash deposition is stopped (Koch and others 2002, Klose and others 2003). Last but not least, Black Carbon might play a role in hindering the organic matter decomposition (Goldberg 1985).

Magnetic susceptibility has been used frequently as a proxy for the intensity of fly ash deposition (Strzyszcz and Magiera 1998, Magiera and Strzyszcz 1999, Klose and others 2001, Schibler and others 2002, Grimley and others 2004, Boyko and others 2004, Magiera and others 2006, Magiera and Zawadzki 2007). Magnetic susceptibility measures the magnetization of a material in dependence from the magnetic field strength. According to their magnetic properties materials are divided into diamagnetic, paramagnetic, ferrimagnetic, and ferromagnetic substances (Glaser 2001). The detection of fly ash by magnetic susceptibility is based on its content of ferrimagnetic Fe-oxides. These are mainly magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3). Magnetite occurs as natural component of lignite and both, magnetite and maghemite emerge from pyrite (FeS_2) oxidation during the combustion process (Strzyszcz and others 1996, Magiera and Strzyszcz 1999).

Magnetic susceptibility can be correlated with Fe, Al, Mn and other heavy metals (Goluchowska 2001, Schmidt and others 2005, Wang and Qin 2005, Lu and Bai 2006, Magiera and Zawadzki 2007, Zawadzki and others 2009). However, this correlation varies in dependence from geographic origin, type of combustion material (lignite or coal) and land use and might not be transferable (Strzyszcz and Magiera 1998, Fialova and others 2006, Magiera and Zawadzki 2007).

The detection of magnetic susceptibility is a suitable method for areas with a strong fly ash deposition, because a natural enrichment of magnetic substances due to geochemical and microbial processes is observed also in non-industrial areas and might superpose the effect of minor fly ash deposition (Le Borgne 1955, Scollar 1965, Thompson and Oldfield 1986, Faßbinder 1994, de Jong and others 2005, Zawadzki and others 2007). Therefore, the method is also not suitable for areas with high content of magnetic particles in the bedrock such as basalt (Fürst and others 2006 b).

The research hypothesis of our study is that magnetic susceptibility can be used as a proxy to predict the impact of fly ash deposition on site properties relevant for management, such as nutrient and heavy metal concentrations. Zawadzki and others (2009) used magnetic susceptibility as an indicator to predict the spatial extent of heavy metal pollution in two forested test areas. If our hypothesis is true, magnetic susceptibility might be used as fast and cost efficient indicator complementary to plot-wise monitoring to provide a broader basis for the regionalization of deposition driven changes of chemical site properties (Fürst and others 2009 a, b). In our study, field assessment was carried out for two test regions of different deposition intensity. We tested if differences of the magnetic signal reflect adequately the differences in deposition intensity. The correlation of magnetic susceptibility with base saturation, base cations Ca and Mg, acidic cations Fe, Al and Mn, the heavy metal Cd (humus layer) and with Black Carbon was tested. Base saturation and base cations are assumed to be an indicator for nutrient pools resulting from fly ash deposition. The mobilization of acidic cations, heavy metals and Black Carbon might be seen as a possible risk for (ground)water. Therefore, we assessed the suitability of magnetic susceptibility as predictor for the concentrations of the above mentioned elements and Black Carbon in a linear regression model.

2. Material and Methods

2.1 Test regions

The presented study was carried out in two test regions, the Dübener Heide and the Dahlener Heide. These regions are situated in different distance to the former industrial triangle Leipzig-Halle-Bitterfeld. Dübener Heide is located in direct neighborhood to this industrial area, with distances of 8 - 50 km to the nearest former power plants (Gräfenhainichen / Zschornewitz). In contrast, Dahlener Heide is located in greater distance, 50 - 75 km, to the industrial triangle.

In the industrial triangle Leipzig-Halle-Bitterfeld an intensive industrialization took place since almost 100 years and extensive deposition amounts resulted from lignite combustion for energy production. The estimated deposition for Dübener Heide amounts for the period 1910-2000 to 18 Mio. t fly ash and 12 Mio t SO_2. Only for the decade 1961-1970 the forest soils of the region received up to 3 t / ha * a fly ash (Klose and Makeschin 2004, Fürst and others 2007 b). Substantial impacts on forest health and forest soil characteristics was reported for the Dübener Heide up to a distance of 30 km to the industrial triangle since the 1960ies, while Dahlener Heide was not impacted (Lux 1965, Fürst and others 2007).

Dahlener Heide is characterized by comparable geological conditions and forest stand types as exist in the Dübener Heide. Therefore, we used this region as reference to assess the regional background value of magnetic susceptibility and to test if the correlation of magnetic susceptibility with the base cations, base saturation, metals, heavy metals and Black Carbon shows comparable or diverging trends to Dübener Heide.

Fig. 1 gives information on the localization of the two test regions and on the research plots used in the presented study (chapter 2.2).

Fig. 1.

Both test regions are characterized by geological frame conditions, which are representative for the lowlands of Middle and Eastern Europe (Fürst and others 2009 a). Dominant parent materials are pre-Weichsel glacial and glaciofluvial sands, which are covered by sandy to loamy periglacial deposits of the late Weichsel glacial. The predominant soil types are Eutric and Distric Cambisols with small areas of Glossic Podzo-Luvisols, Spodo-Dystric Cambisols and Orthic Podzols (Kopp and Schwanecke 1997). According to the national forest inventory, the main stand type is pure Scots pine (Pinus sylvestris, [L.]) plantation, partially in mixture with European beech (Fagus sylvatica [L.]), birch (Betula pendula [Roth]) and Sessile oak (Quercus petrea [(Matt) Liebl.]) from artificial or natural regeneration.

2.2 Test plots

Several types of plots were included in our study following a hierarchic approach (Fig. 2). Chemical soil properties and magnetic susceptibility were assessed at 12 project and 22 monitoring plots. These data were the basis for testing the correlation of magnetic susceptibility with chemical characteristics and for developing the linear regression based modeling approach. They formed also the basis for the regionalization of base saturation as integrative characteristic, which was used to test the quality of the regionalized magnetic susceptibility. For the regionalization of magnetic susceptibility, a grid wise assessment with 110 assessment plots was carried out additionally to the plot wise assessment to provide a broader data basis on its spatial variability.

Fig. 2.

The plot type properties are presented in the following and differences between the plot types are described as far as they are relevant for the interpretation of the results.

A. ENFORCHANGE plots: a subset of 12 plots was taken from the research project ENFORCHANGE (2005 - 2009, Fürst and Makeschin 2009) in Dübener Heide. The aim of this project was to assess the long-term influence of fly ash deposition on forest ecosystem development including soil and stand parameters. The plots were oriented along a distance dependent gradient of fly ash deposition, first described by Lux (1965), by using a part of his 150 original monitoring sites (Fürst and others 2009 a, b). The plots are located on the most important regional soil type (Eutric Cambisols) to minimize the influence of variable soil properties on the assessed chemical characteristics and the magnetic susceptibility. The influence of different stand types at the plots (pure Scots pine stands and mixed stands with English oak and European beech) might be not fully excluded (Zawadzki and others 2007).

   Only at the ENFORCHANGE plots it was possible to assess chemical parameters and magnetic susceptibility at identical sampling spots and soil samples. Magnetic susceptibility was first assessed in situ (i.e. volume magnetic susceptibility) at soil profiles at the same location where soil samples were taken.

In consequence, the plot collective delivered the most proper basis for correlating the content of Ca, Mg, Fe, Al, Mn, Cd and Black Carbon with magnetic susceptibility. A restriction for statistical analysis was the limited number of plots, which was predefined by the project frame. However, there were no reference plots in a non-fly-ash-impacted region, such as Dahlener Heide, in the ENFORCHANGE study.

To widen the data basis for spatial trend analysis, plot collective B was included in our study.

B. Monitoring plots: in Dübener Heide and Dahlener Heide, 20 plots from Level-I monitoring and two other plots from a prevailing study were included. The precondition for their selection was the availability of soil chemical data, which were assessed according to the same standard as at the ENFORCHANGE plots. The Level-I plots belong to a European wide network of 6,000 soil monitoring plots for the assessment of long range transboundary air pollution (see: www.icp-forests.org and BMELV 2006) with regular assessment of soil chemical values each five years. Two more monitoring plots were taken from a study by Lorz (2008) to broaden the data base for Dahlener Heide.

   Chemical parameters and field assessment of magnetic susceptibility (i.e. volume magnetic susceptibility) were carried out at the same plot, but sampling spots and soil samples for magnetic susceptibility and for the chemical analysis were not identical. Chemical analyses were carried out up to five years earlier than magnetic susceptibility assessment and original soil samples were not available anymore.

   Plot collective A and B formed the basis for testing the correlation between magnetic susceptibility and chemical soil parameters in Dübener Heide and Dahlener Heide. For the spatial transfer, which had to include other environmental parameters, a broader data base for magnetic susceptibility was needed (Fürst and others 2009 b). Therefore, plot collective C was established.

C. Grid-wise field-assessment plots: in Dübener Heide, a grid-wise assessment of volume magnetic susceptibility was conducted for a 1x1 km (110 plots) and a 4x4 km grid (38 plots, nested approach) as basis for a multiple regression based regionalization of the magnetic signal (Fürst and others 2009 b).

In our study the data material formed the basis for a depth level wise spatial regression of magnetic susceptibility and base. This was done to approve the quality of magnetic susceptibility as spatial indicator for chemical soil properties.

2.3 Assessment of soil chemical parameters and magnetic susceptibility

The concentrations of Ca, Mg, Fe, Al, Mn and Cd and base saturation were assessed at all plots according to the Level-I standard procedure (BMELV 2006). The design and the results of the chemical analysis are in detail described by Fritz and Makeschin (2007), Lorz (2008) and Fritz and others (2009). The Black Carbon content in the humus layer was assessed according to the method described by Glaser and others (1998, modified by Glaser 2008 non published, see Koschke and others [subm.] for details).

Magnetic susceptibility - the focus of the presented study - was measured with the MS2 meter susceptibility system of Bartington Instruments, Oxford (GB). The system was developed for detecting very low quantities of magnetic Fe-Oxides in compact (rocks) or loose substrates (mineral soil, humus layer). The susceptibility meter has a sensitivity of 0.1 - 1×10^{-5} S.I. units and can be used either in a single readout mode or can also transfer the data to a PC using a specially adapted software (Multisus). The system comprises a portable measuring instrument, the MS2 meter, and a variety of sensors. The meter displays the magnetic susceptibility value of the tested substrates when these are brought within the influence of one of the sensors, which are each designed for a specific application and sample type (source: Operation Manual of the MS2 system, Bartington Instruments Ltd., Oxford GB).

In situ, magnetic susceptibility was measured in 30 cm deep boreholes with the MS2H down-hole-probe sensor, where the starting point, i.e. depth = 0, was defined as first measurement after removing the Oi horizon. The material of this horizon was removed as pre-tests have shown that no ferrimagnetic particles could be detected in this layer (Fürst and others 2009 a) since fly ash deposition stopped around 20 years ago.

The MS2H sensor is a sub-surface probe for profiling the magnetic susceptibility of strata in 25 mm diameter auger holes. Strata with a thickness up to 15 mm can be discriminated. Volume susceptibility was measured centimeter wise at five bore holes per test plot (five bore holes * 30 measurements / hole => 150 measurements / plot). If a soil profile existed at the test plots (plot collectives A and partially B), the bore holes were drilled along the head sides of the profile in a distance of 0.5 m to the profile face and with a distance of 0.5 m between each bore hole. In case there was no profile (plot collective C and partially plot collective B), four bore holes were oriented around one central bore hole in a distance of 0.5 m (see Fig. 3)

The described field assessment design is a result of a pre-test series (Fürst and others 2009 a) and was chosen to compensate small scale variations in the humus layer thickness.
Additionally, at the 12 ENFORCHANGE plots and 7 Level-I plots samples were taken for laboratory analyses of magnetic susceptibility, which were carried out with the MS2B dual frequency sensor. These samples were used to derive a correction factor for in situ measurements of volume susceptibility (see chapter 2.4). The MS2B dual frequency sensor was used for mass or volume specific susceptibility measurements and accepts 10 ml and 20 ml cylindrical bottles. For our study, volume and mass susceptibility were measured in 10 ml bottles. Mixed samples of five samples per horizon for Oe, Oa, A(h) and B(w) horizon were measured, each with five repetitions. The Oi horizon was again excluded from measurements (see Fürst and others 2009 a). Also the C horizon was not included to achieve comparability with the field measurements.

Fig. 3.

2.4 Mathematical operations and statistics

The magnetic susceptibility field assessment delivers volume susceptibility values, which were corrected in a two step approach to mass susceptibility (1. field => laboratory, 2. volume => mass) on the basis of laboratory analysis (see Fig. 2). This was done, because previous studies had shown that correlation between mass susceptibility and acid or heavy metal cation concentrations is higher than between volume susceptibility and element contents or element stocks (Magiera and others 2007, Schmidt and others 2005). Studies for Ca, Mg, Black Carbon and base saturation do not exist.

A separate correction factor was calculated for Oe, Oa and mineral horizon ($r_{Oe, Oa}$ = 0.52 and r_{min} = 0.78). Comparative tests of the data quality and the correlation with soil chemical characteristics, supported the use of these factors, while a regression equation based correction resulted in higher variation and lower correlation. The findings in the results section (chapter 3) are based on measured or recalculated mass susceptibility values.

In a first step, the correlation between mass susceptibility and concentrations of Ca, Mg, Fe, Al, Mn, Cd and Black carbon was calculated by using Pearson's correlation coefficient (r). The calculation was done separately for the two plot collectives A and B to assess differences in the correlation quality, which result from the before described differences in sampling and which could indicate problems in using both data sets together.
Furthermore, r was also calculated for distance clusters < 10 km, < 20 km, < 30 km, < 50 km and < 75 km to test if evident spatial trends occur in dependence from increasing distance to

the emission source Leipzig-Halle-Bitterfeld. If such trends are found, they would question the indicative value of magnetic susceptibility. The test was carried out for the data sets of both plot collectives A and B together.

Based on plot collective C, magnetic susceptibility was regionalized by using a multiple regression approach (Fürst and others 2009 b). In a subsequent step, a spatial regression was calculated for regionalized base saturation (Zirlewagen 2009) and magnetic susceptibility (Fürst and others 2009 b). The test of the connectivity of these two spatial data sets by using the coefficient of determination R^2 as statistical indicator was done to evaluate if the proxy indicator magnetic susceptibility is suitable as model parameter to predict chemical soil properties in a spatial model. The regression was calculated for three depth level clusters, which are common in Level-I plot data analysis (BMELV 2006) 6 - 10 cm (humus layer), 11-15 cm (A horizon), 21 - 25 cm (B horizon) (see also Fürst and others 2009 b).

Linear regression based models were developed for predicting concentrations of Ca, Mg, Fe, Al, Mn, Cd and Black Carbon in the Oe and Oa horizons by magnetic susceptibility. The assessment was restricted to the humus layer for reasons of comparability, because concentrations of Cd and Black Carbon content were only assessed for the humus layer. For better visualization of the trends, mass susceptibility (abscissa) and the concentrations of Ca, Mg, Fe, Al, Mn, Mg, Cd and Black Carbon (ordinate) were transformed to natural logarithm.
The coefficient of determination (R^2) was calculated as indicator for linear regression between magnetic susceptibility and the element concentrations. This coefficient was used as indicator for the quality of predictions by the linear regression model. R^2 is the square of the sample correlation coefficient between the element contents and the predictor magnetic susceptibility. R^2 can take values between 0 (no linear regression) and 1 (perfect linear regression).
For evaluating the quality of the linear regression based predictions, the relation between measured and predicted values and the residuals were calculated.

Finally, a stratified approach was tested to try if the model quality can be improved. Linear regression based models were calculated separately for distance clusters (< 10 km, < 20 km, < 30 km, < 50 km and < 75 km) and for the two plot collectives A and B.
The correlation and regression analysis were carried out using the software Statistica 8.0. The multiple regression based regionalization of the base saturation and the magnetic susceptibility was performed using SAS 9.2 and ArcGIS 9.3.

3. Results

3.1 Magnetic susceptibility measurements

Magnetic susceptibility (mass susceptibility, $\chi * 10^{-8}$ m^3 kg^{-1}) of Oe, Oa and upper mineral horizon was highest for distance up to 10 km from the former fly ash emitters (Fig. 4). The means for the Oe horizon amounted up to 400 $\chi * 10^{-8}$ m^3 kg^{-1}, for the Oa horizon up to 500 $\chi * 10^{-8}$ m^3 kg^{-1}, and for the mineral horizon up to 20 $\chi * 10^{-8}$ m^3 kg^{-1}. Outliers for the Oa horizon reached values up to 800 $\chi * 10^{-8}$ m^3 kg^{-1} (not displayed in Fig. 4). For distance > 20 km, the value range for mineral soil showed only minor differences in Dübener Heide and Dahlener Heide. In the Oe and Oa horizon magnetic susceptibility decreased up to a distance of 30 km to mean values of up to 200 $\chi * 10^{-8}$ m^3 kg^{-1} in Oe and Oa.

For distances > 30 km, in most parts of Dübener Heide magnetic susceptibility values are on a comparable level to the value range in Dahlener Heide (50 and 75 km clusters). Comparing Oe and Oa horizon, values of regions in the Dübener Heide with a very strong impact of fly ash deposition were substantially higher for Oa horizons. For the Dahlener Heide, the differences between Oe and Oa horizons were in general smaller. For the greatest distances to the emitters (75 km) values for the Oe horizon were slightly higher than for Oa horizons. A slight trend of decreasing spatial variability of susceptibility indicated by a lower standard deviation was found for increasing distances to the industrial triangle. This was also supported by previous findings (Fürst and others 2009 a).

Fig. 4 resumes the measurement results and the spatial trends (box and whisker plots with mean value, 95 % confidence interval and standard deviation) for the Oe, Oa and mineral horizon.

Fig. 4.

3.2 Correlations and spatial trends

Tab. 1 provides an overview of results of correlation test at plot collectives A and B. The comparison between the two plot collectives A and B shows some differences. The correlation between mass susceptibility and concentrations of Ca and Mg is higher for the ENFORCHANGE plots except for Mg concentrations of Oe horizons. For concentrations of Fe, Al, Mn and Cd the results are the opposite. The correlation with Fe and Al (with exception of Oa horizons in case of Fe) is negative for all horizons at the ENFORCHANGE plots. For plot collective B this is only true for Fe in the mineral soil horizon 3 (21 - 30 cm) and for Al at all three mineral horizons.

The correlation with Black Carbon is negative for all plot types. For absolute values, the correlation with Black Carbon for the ENFORCHANGE plots is higher compared to plot collective B. The correlation of mass susceptibility over all horizons was higher at the

ENFORCHANGE plots for Ca, Mg, Cd and (absolute value) Black Carbon. The results are vice versa for Fe, Mn and Al.

For both plot collectives Pearson's correlation coefficient (r) between mass susceptibility and concentrations of Ca, Mg and Mn is in trend slightly lower for single horizons compared to the total correlation coefficients for each single plot collective. In contrast, r is higher for Fe, Al and Cd for the two humus horizons. For Black Carbon r reached values in between the two plot collectives.

When calculating r over all horizons, it is higher compared to each single plot collective for Ca, Mg and Fe and slightly lower for Al. The correlation coefficient for Mn and Black Carbon reached values in between both plot collectives and only for Cd it was considerably lower.

Tab. 1.

When calculating the correlation coefficients of all plots of collective A and B distance cluster-wise, no clear spatial trends were found. Figures 5a, 5b and 5c show exemplarily the results for Ca, Mg, Fe, Al, Cd and Black Carbon. The results for Mn were comparable to those of Ca and Mg and thus are not displayed.

The Pearson's correlation coefficient r for Ca and Mg (Fig. 5a) was slightly higher for nearest and farthest distances to former emitters than for intermediate distances. Although, variability expressed by standard error did not show a spatial trend. For Fe and Al (Fig. 5b) r remained on the same level for all distance clusters. Only the standard error reached higher values for clusters of nearest and farthest distances. For Cd and Black Carbon (Fig. 5c), which were both only analyzed for humus layers, no spatial trends were found for distances > 50 km. For distances of 10 - 30 km, r was substantially higher for Cd, but unstable for Black Carbon. The standard error for Cd showed a spatial trend, but nearer to former emitters it is lower than for distances > 50 km.

Fig. 5a.

Fig. 5b.

Fig. 5c.

The results of the spatial regression between ferrimagnetic susceptibility and base saturation and the coefficients of determination (R^2) for depth levels are displayed in Tab. 2. The coefficients of determination were highest for the combination of the depth levels 0-5, 6-10 and 11-30 cm (base saturation) with the depth levels 5-10 cm and 10-15 cm (magnetic susceptibility). This indicates that magnetic susceptibility values measured in humus layers (uppermost depth levels) are best suitable as model parameters and that their predictive value for chemical soil characteristics is also higher for the humus layer. Therefore, the following test of magnetic susceptibility as model parameter was restricted to the humus layer.

Tab. 2.

3.3 Linear regression based modeling

Following the findings of 3.1, a linear regression based model was calculated for Oe and Oa horizon, where the best modeling results were expected. Figs 6 a - 6c show exemplarily the results for Ca, Cd and Fe.

A distinct linear regression model with comparably high coefficients of determination (R^2) has been derived for Ca (Fig. 6a), Mg and Mn (without illustration). R^2 for Ca was 0.51, for Mg 0.52 and for Mn 0.37, with $\rho < 0.01$. For all three cases, also small 95 % confidence intervals were found, indicating a high precision of the linear regression model. In contrast, the linear regression was rather weak for Cd (Fig. 6b) and Black Carbon (without illustration). For both elements, R^2 was much lower (0.09) and the 95 % confidence intervals were much broader. No linear regression was found for Fe (Fig. 6c) and Al (without illustration). In both cases, R^2 was nearly 0 and the 95 % confidence intervals were very broad.

Fig. 6a.

Fig. 6b.

Fig. 6c.

Model quality was tested by using the relation between measured and predicted values (without illustration). Residuals showed an obvious coherence between measured and predicted values for Ca, Mg and Mn with small 95 % intervals. The test of model quality for Cd and Black Carbon showed a weaker coherence with broader 95 % intervals. In contrast, supported by previous findings, no such coherence was found for Fe and Al, which have also very broad 95 % intervals.

Residual histograms (without illustration), which were used as second indicator for model quality, were slightly right skewed for Ca, Mg and Mn. A good coherence with the expected distribution of the observations was given. Also for Cd, the distribution corresponded very well to a standardized normal distribution. For Fe, Al and Black Carbon the distribution of the residuals was left skewed and did not fit very well together with the expected distribution.

The stratification of regression models into distance clusters (without illustration) resulted in an improvement of R^2 for Fe and Al to 0.05 and 0.06, respectively. The coherence between measured and predicted values and the distribution of the residuals were also improved. However, rather small sample sizes within each of the distance clusters and broad 95 % confidence intervals question the quality of the respective models.
Contradictory results were obtained by a stratification of the regression models for the two plot collectives A and B. Taking Fe as an example, a linear regression was calculated for the subset of the ENFORCHANGE plots (plot collective A) with $R^2 = 0.43$. However, the 95 % confidence interval became very broad due to the low number of plots. In contrast, the linear regression for the subset of the monitoring plots (plot collective B) was rather weak ($R^2 = 0.12$), but the 95 % interval was smaller due to the higher number of plots. However, in both cases the distribution of the residuals fits not very well with a standardized normal distribution. The trends for Al were similar.

4. Discussion

Magnetic susceptibility is a well approved proxy indicator for fly ash deposition. Its suitability and application was subject of the EU project MAGPROX (http://www.geophysics.uni-tuebingen.de/index.php?id=54) and a great number of other studies (e.g. Blaha and others 2008, Fialova and others 2006, Magiera and others 2006, Boyko and others 2004). The here presented study intended to test the suitability of magnetic susceptibility as indicator for management relevant agents deposited with fly ash. In addition to previous studies, we tested, if the concentration of major nutrients such as Ca and Mg can be predicted.

The range of values of magnetic susceptibility is in agreement with previous studies in the test region Dübener Heide (Koch and others 2002, Klose and others 2001). Values for Dahlener Heide were not available. For humus layers of Dübener Heide magnetic susceptibility shows a distinct spatial trend for distances < 20 km (Fig. 4). For distances > 30 km magnetic susceptibility value ranges stayed more or less on the same level. There are no differences between the spatial clusters < 30 km, < 50 km (Dübener Heide) and < 75 km (Dahlener Heide). This indicates, in agreement with previous studies (Fürst and others 2009 a, b), that from a distance of 30 km on, detectable fly ash deposition plays an inferior role.

Correlation coefficients for magnetic susceptibility and concentrations of Fe and Cd were on a comparable level to data by Stryszcz and Magiera (1998) for highly polluted agricultural and forest soils in Southern Poland or by Wang and Qin (2005) and by Lu and Bai (2006) for urban soils in China. The correlation with Mn was slightly lower as found by Magiera and others (2007). In contrast to observations of Wang (2009) for urban roadside top soils, a weaker and negative correlation between magnetic susceptibility and Black Carbon was found. Data from other studies for comparing the correlation with the Al concentrations could not be found.

A comparison of the differences between the correlation for humus layers and mineral soils with published data was not possible, as this was not tested in other studies. In the presented study, the correlation between mass susceptibility and all horizons (*"total"*) was mostly higher than the mean value of the correlation coefficients for single horizons (Tab. 1). A reason might be that in situ assessment of magnetic susceptibility is done centimeter wise in bore holes and the values must have been assigned depth level wise to chemical characteristics assessed according to the Level-I standard depth levels. A problem in the correct matching of both data sets, especially at the plot collective B, is the unevenness of the soil surface at small distances due to a high variability of thickness of humus layers in Dübener and Dahlener Heide (Fürst and others 2009 a, b).

Also some differences in the correlation coefficients for the two plot collectives A and B were found (Tab. 1). These result from the difficulty to harmonize the sampling for the chemical analyses and the magnetic susceptibility measurements for the subset of the monitoring plots (plot collective B). Factors influencing the quality of magnetic susceptibility measurements such as differences in soil type, humus form and thickness of humus layers for the subset of monitoring plots could not be excluded (Kapicka and others 2001, Schibler and others 2002, Fialova and others 2006, Magiera and others 2006, Zawadzki and others 2007). The findings do not contradict the use of data from both plot collectives together as modeling basis, but indicate that the intention to get a broader data base for modeling might have caused some problems with model quality.

For the correlation of both plot collectives for distance clusters no spatial trends were found for Ca, Mg, Fe and Al. In contrast, spatial trends for Cd and Black Carbon for the distance clusters < 10 km, < 20km and < 30 km were found. Missing spatial trends support the use of magnetic susceptibility as model parameter. However, a missing trend could only be expected for the correlation with Fe as main source of magnetism but not for Ca or Mg. The observation allows several possible interpretations. The indicative value of magnetic susceptibility for fly ash and related nutrients and pollutants is superposed to a higher extend by natural humus properties, than assumed at the beginning of the studies (Faßbinder 1994, Zawadzki and others 2007). The humus layer in forests is an important nutrient reservoir and magnetizable Fe or Mn compounds occur also in "natural" humus layers (Faßbinder 1994, Scollar 1965, LeBorgne 1955). This is supported by the finding that for distances >30 km magnetic susceptibility levels are more or less the same for Dübener Heide and the reference region Dahlener Heide.

For Ca and Mg liming might also be of importance. Liming effects are likely for the zone >10 - 20 km distance, where the deposition of alkaline fly ash particles was only marginal (Fritz and Makeschin 2007). For this zone, acidic deposition components have caused even higher forest health damages than near to former emitters and in consequence extensive compensation measures were carried out (Fürst and others 2007 b). This might explain why the correlation between magnetic susceptibility and Ca and Mg in this zone was slightly lower and the standard error was slightly higher than for other distance clusters (Fig. 5a).

Finally, we cannot exclude that some fly ash fractions might be transported much wider than assumed before. In addition, deposits from domestic fuel from settlements in the vicinity of both test regions might have had an influence on the results. The latter is supported by observations on the spatial distribution of the Black Carbon content in the humus layers (Koschke and others subm.) in Dübener and Dahlener Heide, where also no clear dependence between distance to the emitters and Black Carbon concentrations was found.

Based on linear regression, the concentrations of important nutrients such as Ca (Fig. 6a.) or Mg and acidic cations such as Mn could be predicted. The quality of this prediction for the base cations Ca and Mg was even higher (higher R^2, smaller 0.95 confidence interval, better distribution of the residuals), than for Fe (Fig. 6c) and Al. In contrast, the prediction quality for Cd (Fig. 6b) and for Black Carbon as pollutants was lower. For Black Carbon the influence of the applied Black Carbon measurement method and the hereby isolated part of the Black Carbon combustion continuum (Masiello 2004, Koschke and others subm.) on the correlation with magnetic susceptibility, are not known. This aspect will be part of future research activities.

5. Conclusions and Perspectives

The results of our study have shown that magnetic susceptibility cannot exclusively be used as proxy for fly ash in soils. However, it might be used to a certain extent as model parameter to predict important fly ash components, which impact forest soils and forest ecosystem development. Following previous findings (e.g. Zawadzki 2009) magnetic susceptibility might be used to predict the spatial extent of heavy metal pollution as a major risk factor in fly ash impacted regions.

Our study supports the assumption that magnetic susceptibility might be also used as model parameter to predict the concentrations of Ca and Mg and pedo-chemical characteristics such as base saturation.

The high potential of magnetic susceptibility as spatial predictor is given by its high cost efficiency (Schibler and others 2002, Magiera and others 2007). Being used as predictor in a multiple regression approach, we were able to prove a very high sensitivity and indicative value for small scale variations of fly ash deposition in dependence from orographic and stand characteristics (Fürst and others 2009 b). The obtained data sets provide information with a high spatial resolution on fly ash deposition for different depth levels, which complements very well data sets from site classification (Zirlewagen and von Wilpert 2004, Fürst and others 2009 b).

The experiences obtained from the presented study and in modeling the spatial distribution of fly ash (Fürst and others 2009) lead to the conclusion that the applied linear regression based modeling approach should be transformed to a multiple regression approach. By using additional information on orographic, climatic or stand parameters together with magnetic susceptibility, the prediction quality of the deposed agents might be improved and small scale variations in nutrient potentials and risks driven by fly ash deposition could be better identified and used for forest management decisions.

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Figure Captions

Fig. 1: Map of the test regions including localization of the different test plot collectives.

Fig. 2: Research strategy of the study. The plot-wise and grid-wise assessment followed a hierarchical research approach, where each of the plot collectives contributed to the stepwise test of the suitability of magnetic susceptibility as spatial predictor for deposed nutrients, acid and heavy metals and Black Carbon.

Fig. 3: Test design at plots with / without soil profile in Dübener and Dahlener Heide.

Fig. 4: Spatial trend of magnetic susceptibility in the study areas Dübener and Dahlener Heide. The box and whisker plot show the mean value, the 0.95 confidence interval (box) and the standard deviation (whiskers) for the Oe, Oa and mineral horizons. The plots were bundled in 5 distance dependent clusters: Dübener Heide: up to 10 km distance, up to 20 km distance, up to 30 km distance, up to 50 km distance; Dahlener Heide: up to 75 km distance.

Fig. 5a: Spatial trend in correlation between magnetic susceptibility and Ca and Mg content for the plot collectives A and B.

Fig. 5b: Spatial trend in correlation between magnetic susceptibility and Fe and Al content for the plot collectives A and B.

Fig. 5c: Spatial trend in correlation between magnetic susceptibility and Cd and Black Carbon content for the plot collectives A and B.

Fig. 6a: Linear regression between magnetic susceptibility and the Ca content. Comparable results were obtained for Mg and Mn.

Fig. 6b: Linear regression between magnetic susceptibility and the Cd content. Comparable results were obtained for Black Carbon.

Fig 6c: Linear regression between magnetic susceptibility and the Fe content. Comparable results were obtained for Al.

Tables and table captions

Tab. 1: Pearsons correlation coefficient r for mass susceptibility ($\chi * 10^{-8}$ m³ kg^{-1}) and contents of Ca, Mg, Fe, Mn, Al, Cd, Black Carbon. The correlation was calculated for the total plot collective and separately for the collectives A (ENFORCHANGE plots) and B (monitoring plots) to test the quality of the correlation. The depth levels are oriented on the Level-I standard assessment approach (BMVEL 2006).

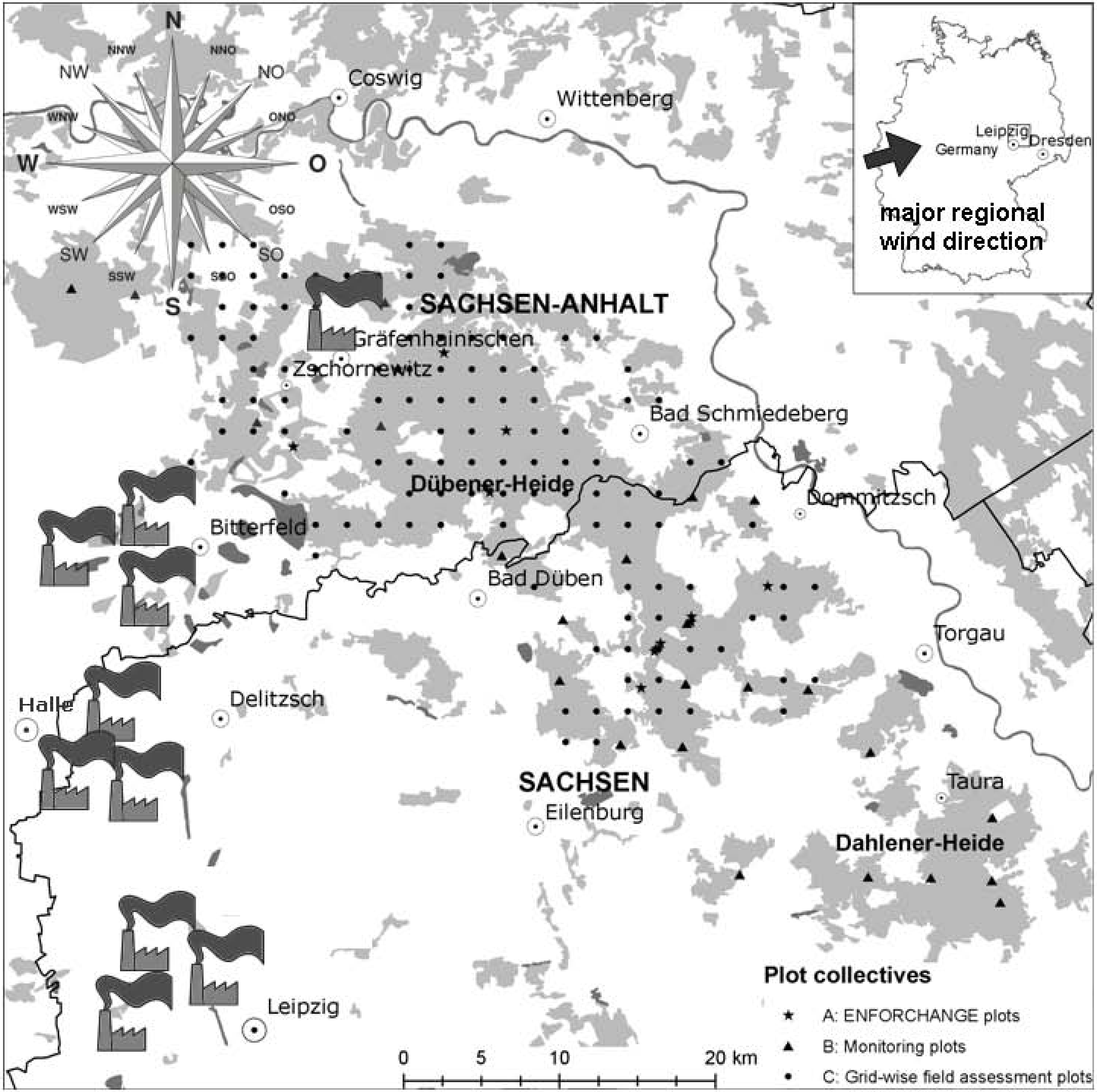
Depth (horizon)	**Correlation magnetic susceptibility (χ * 10^{-8} m³ kg^{-1})**						
all plots	*Ca*	*Mg*	*Fe*	*Mn*	*Al*	*Cd*	*Black Carbon*
Oe (0-5)	0.12**	0.33*	0.73*	-0.10	0.72*	0.58*	-0.09
Oa (6-10)	0.42**	0.64*	0.72*	0.55*	0.70*	0.53	-0.38
Mineral soil 1 (11 - 15)	0.50**	0.55	-0.18	0.19	-0.15		
Mineral soil 2 (16 - 20)	0.50*	0.42	-0.08	0.33*	0.06		
Mineral soil 3 (21 - 30)	0.26*	0.21	-0.29	0.36*	-0.03		
Total	*0.76***	*0.76**	*0.86**	*0.49**	*0.72**	*0.13*	-0.26
ENORCHANGE plots							
Oe (0-5)	0.49**	0.21*	0.38*	0.03	-0.26*	-0.48	-0.18
Oa (6-10)	0.90**	0.84*	-0.28	0.10*	-0.43*	-0.03	-0.45
Mineral soil 1 (11 - 15)	0.38**	0.51	-0.29	0.19	-0.42		
Mineral soil 2 (16 - 20)	0.71*	0.78	-0.07	0.09	-0.34		
Mineral soil 3 (21 - 30)	0.63*	0.84	-0.25	0.12	-0.44		
Total	*0.65***	*0.58***	*0.85**	*0.46**	*0.75**	*0.80**	-0.39
Level-I plots							
Oa (0-5)	0.39**	0.66*	0.66*	0.70	0.68*	0.55*	-0.04
Oe (6-10)	0.45**	0.57*	0.62*	0.70*	0.65*	0.46	-0.34
Mineral soil 1 (11 - 15)	0.08*	0.43	0.27	0.15	-0.41		
Mineral soil 2 (16 - 20)	0.00	0.06	0.10	0.37	-0.52		
Mineral soil 3 (21 - 30)	0.31	0.28	-0.19	0.43	-0.56		
Total	*0.52***	*0.52**	*0.75**	*0.75**	*0.74**	*0.51*	*-0.20*

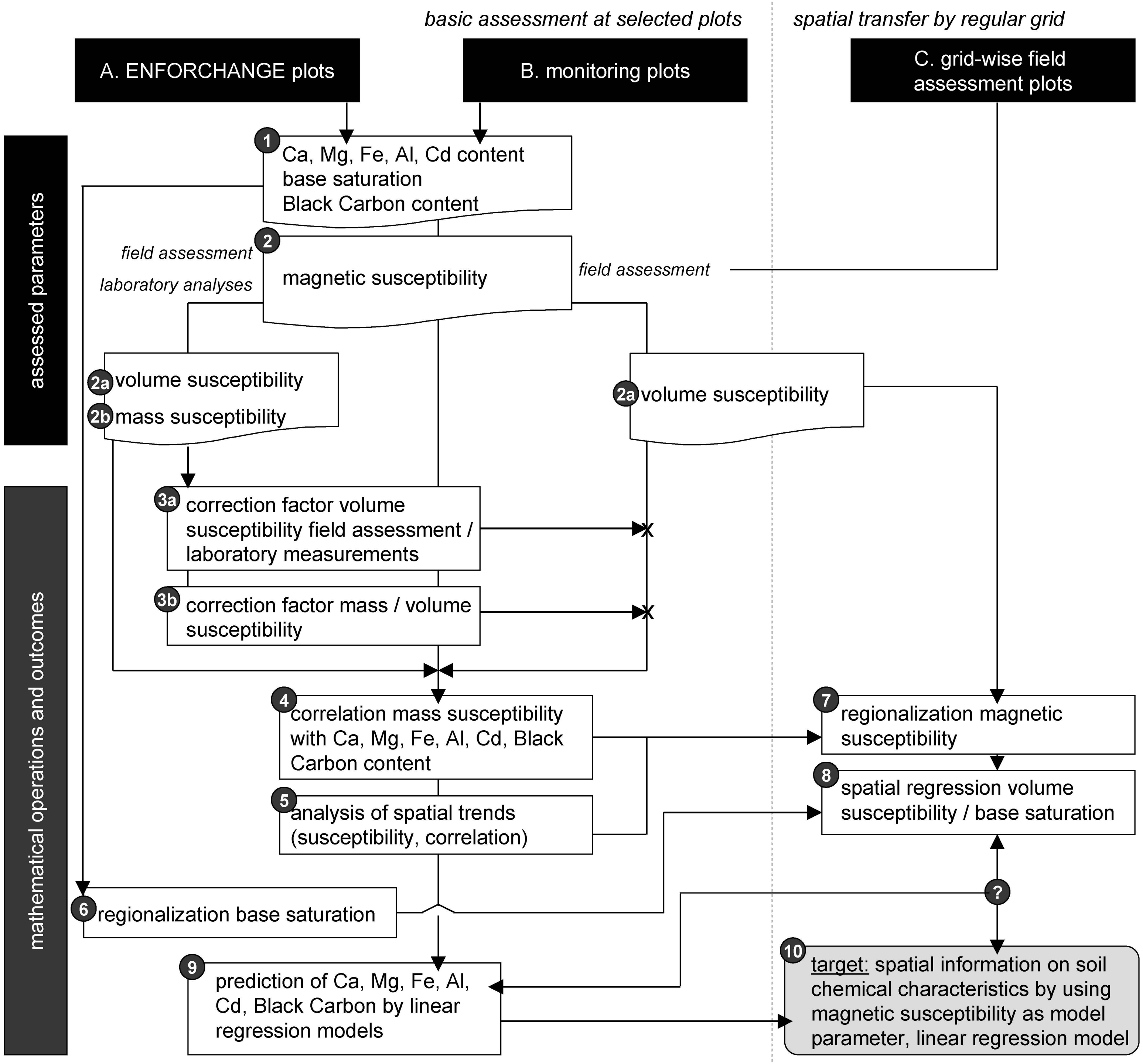
* $\rho < 0.05$, ** $\rho < 0.01$

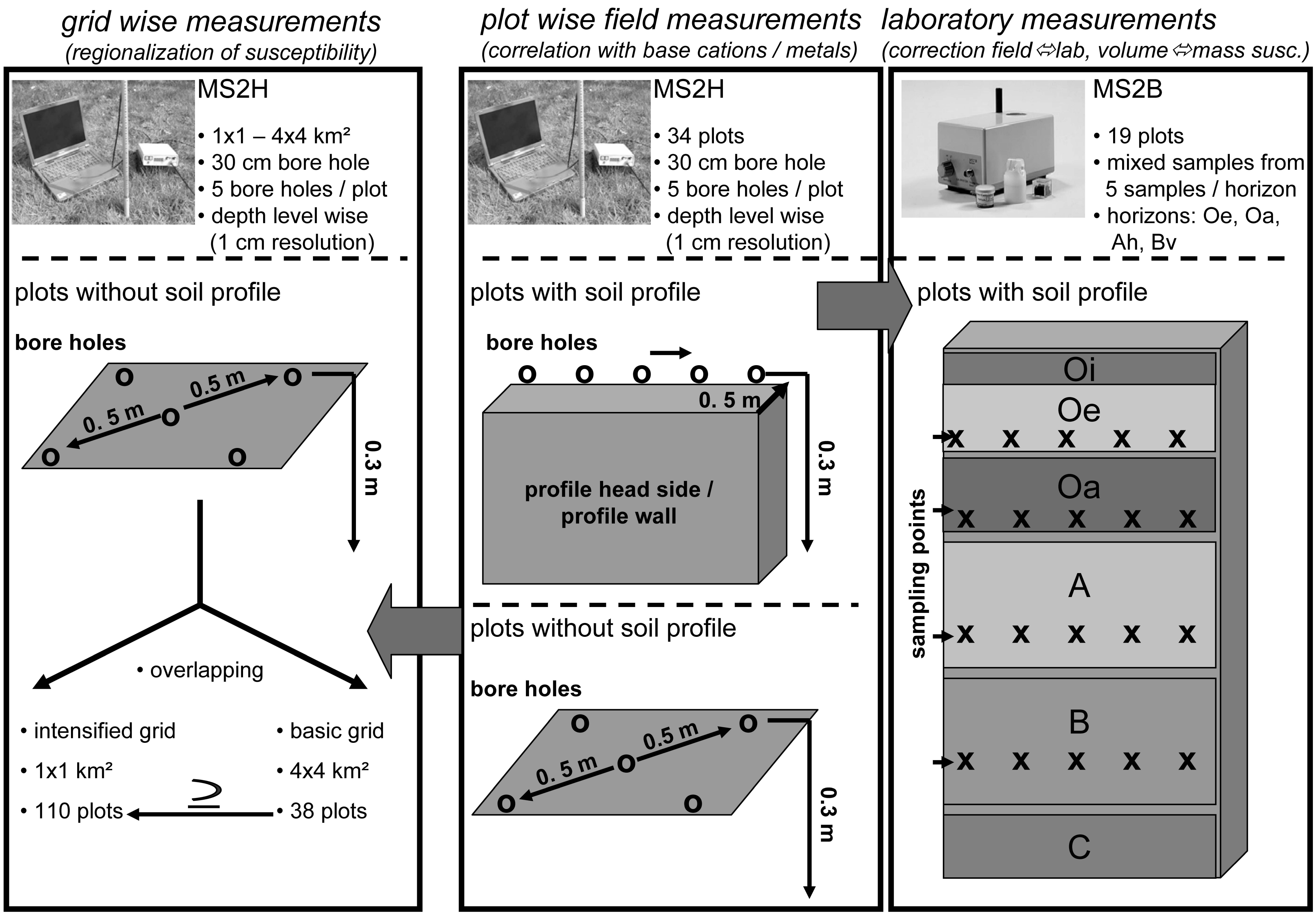
Tab. 2: Coefficients of determination (R^2) for the spatial regression of magnetic susceptibility against base saturation. The horizons with the highest R^2 are grey shaded.

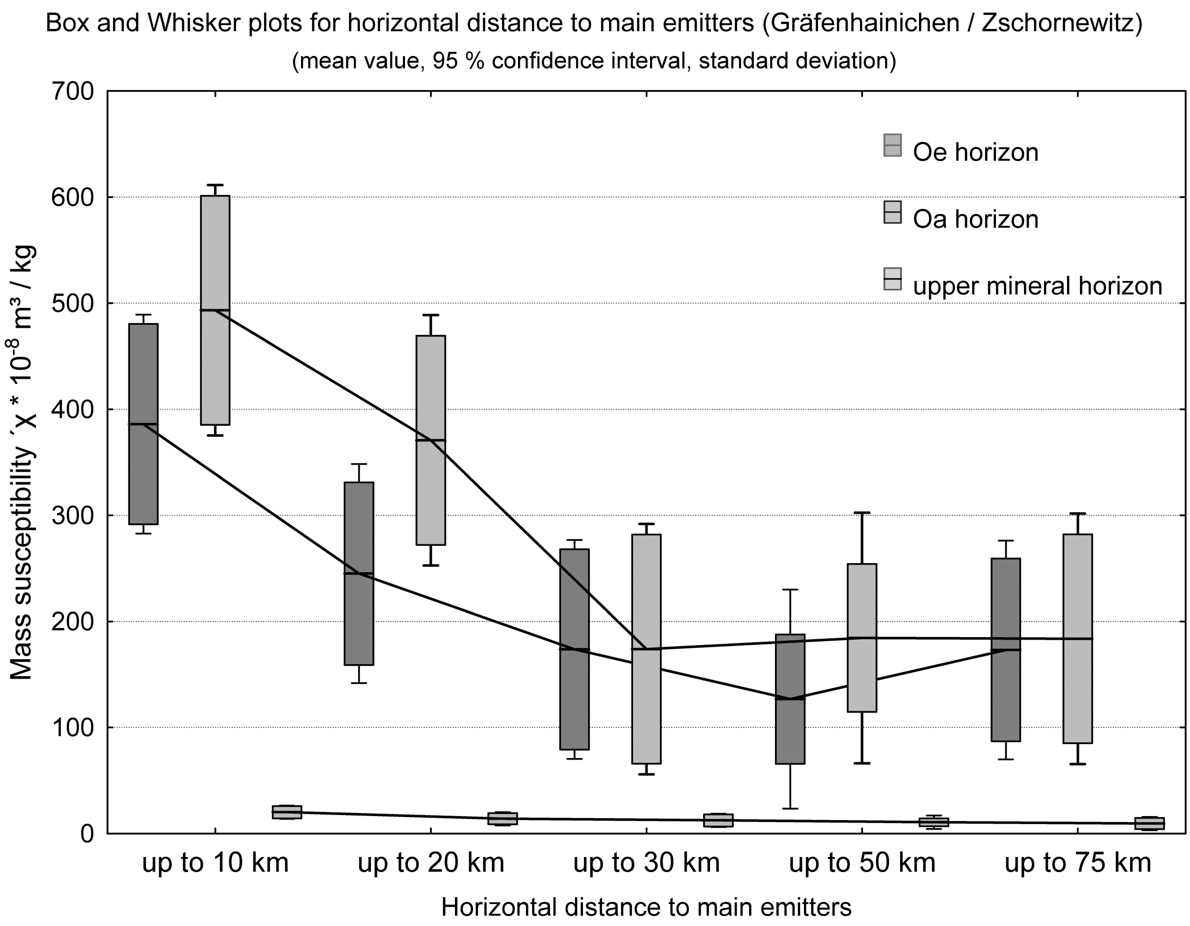
R^2		*Magnetic susceptibility*		
		6-10 cm	11-15 cm	21-25 cm
Base saturation	0 - 5 cm	0.3714**	0.3347**	0.0571*
	6 - 10 cm	0.3542**	0.2966**	0.0659*
	11 - 30 cm	0.4006**	0.3392**	0.0553*
	31 - 60 cm	0.2054*	0.1318*	0.0505*
	61 - 90 cm	0.0426*	0.0139*	0.0105*

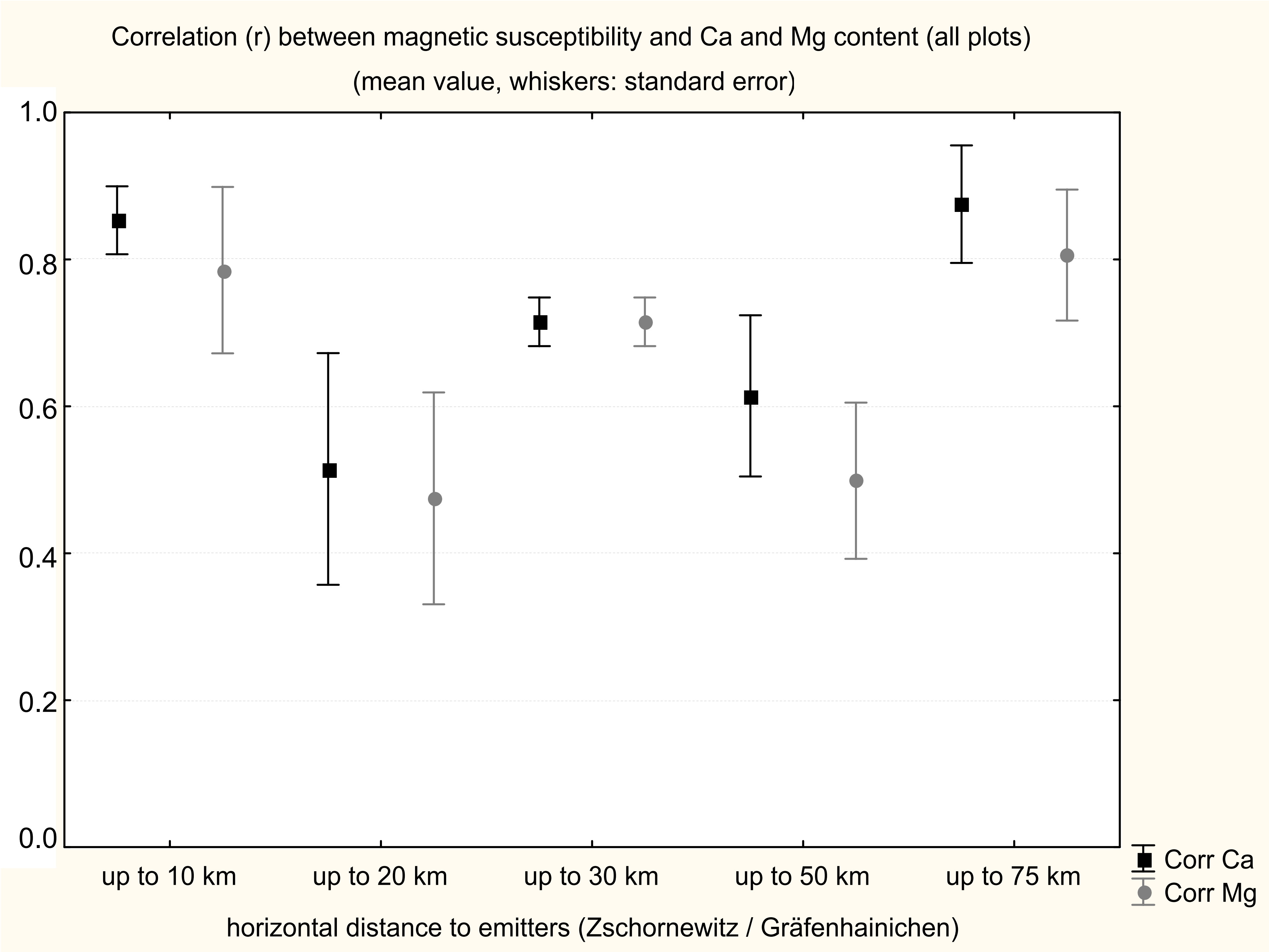
* $\rho < 0.05$, ** $\rho < 0.01$

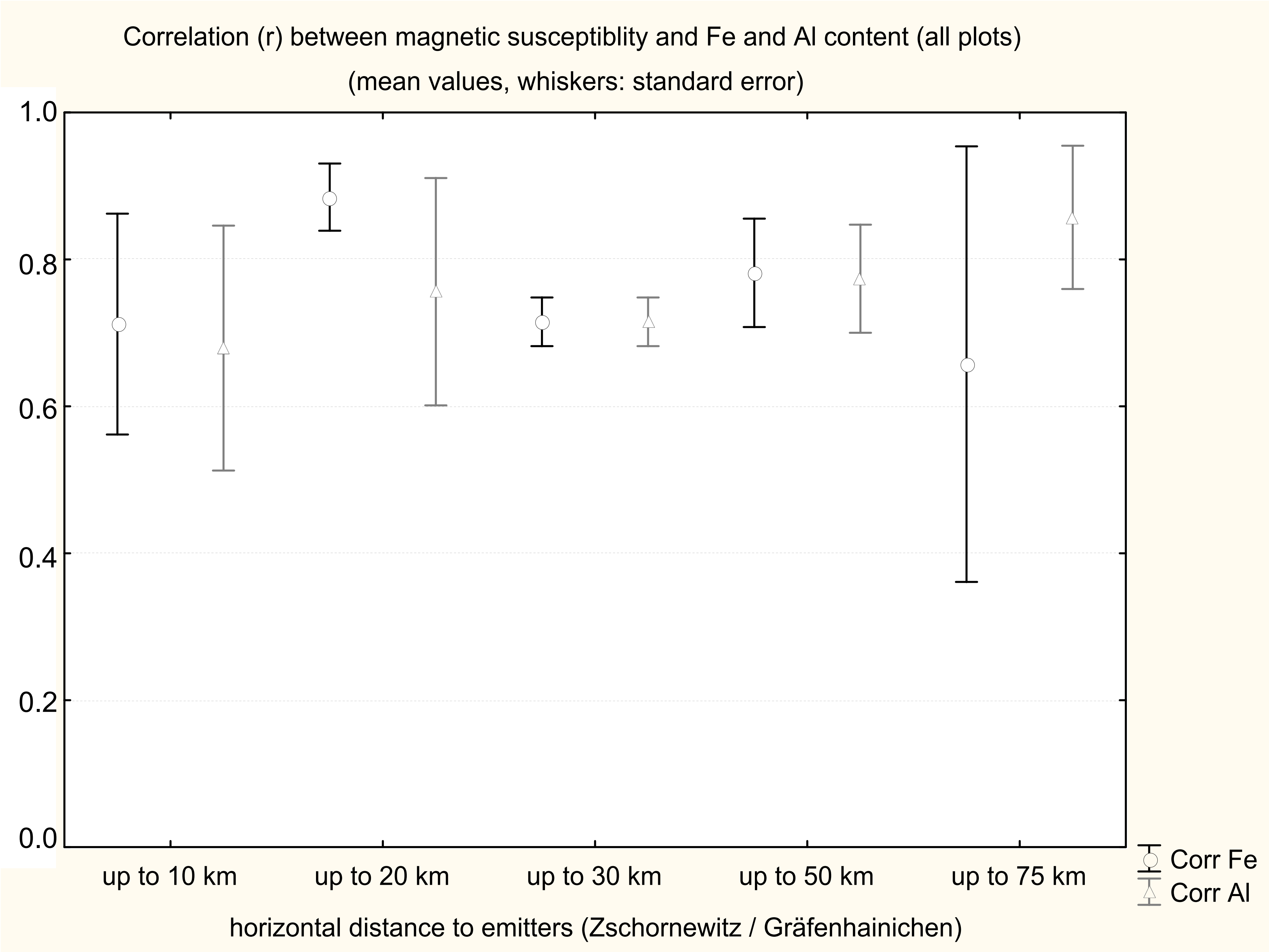

N
NNW
NNO
NW
NO
WNW
ONO
W
O
WSW
OSO
SW
SO
SSW
SSO
S
Coswig
Wittenberg
Leipzig
Germany
Dresden
major regional wind direction
SACHSEN-ANHALT
Gräfenhainichen
Zschornewitz
Bad Schmiedeberg
Dübener-Heide
Dommitzsch
Bitterfeld
Bad Düben
Torgau
Halle
Delitzsch
SACHSEN
Taura
Eilenburg
Dahlener-Heide
Leipzig
0
5
10
20 km
Plot collectives
A: ENFORCHANGE plots
B: Monitoring plots
C: Grid-wise field assessment plots

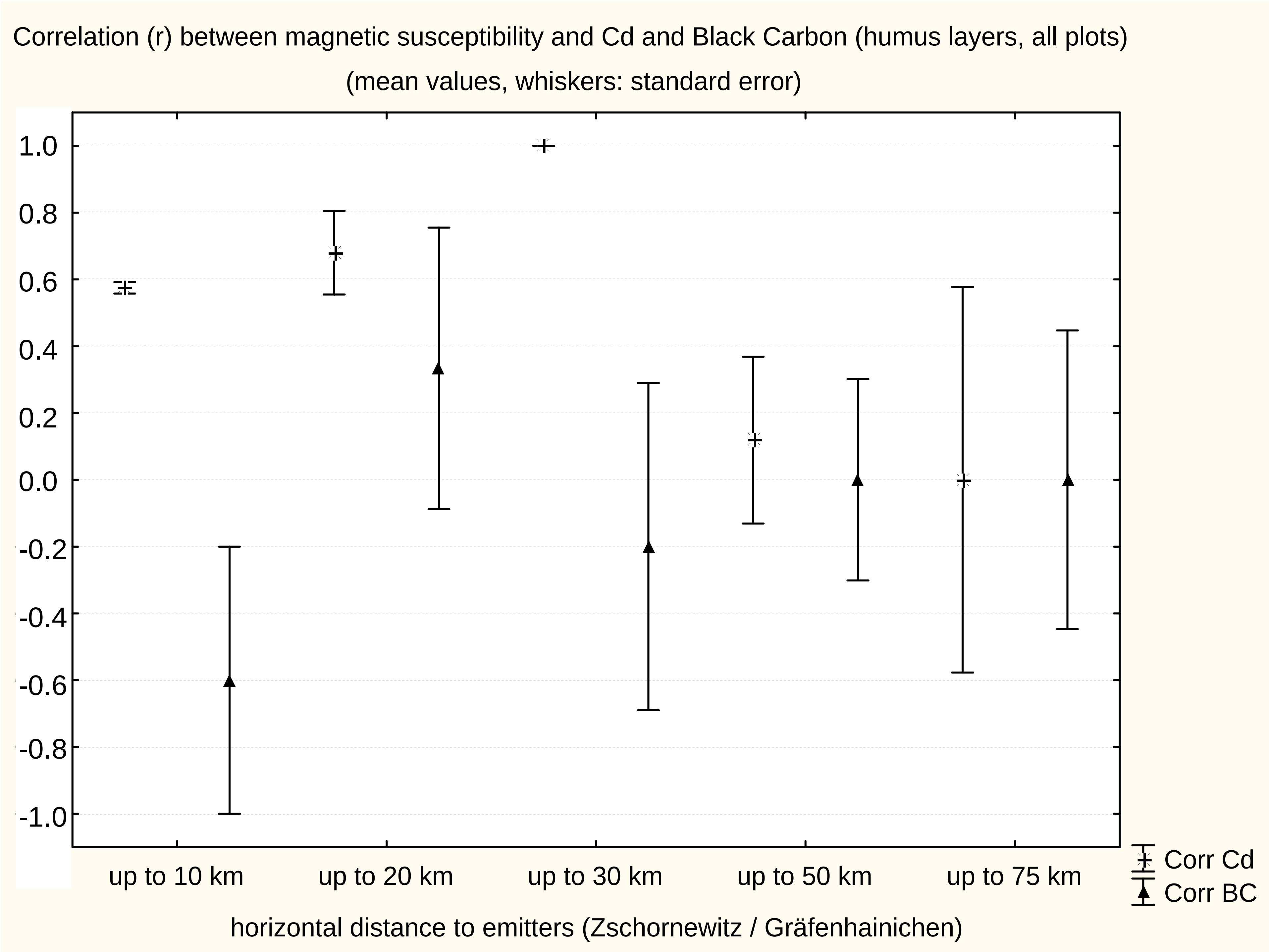

basic assessment at selected plots
spatial transfer by regular grid
A. ENFORCHANGE plots
B. monitoring plots
C. grid-wise field assessment plots
assessed parameters
1 Ca, Mg, Fe, Al, Cd content
base saturation
Black Carbon content
field assessment
laboratory analyses
2 magnetic susceptibility
field assessment
2a volume susceptibility
2b mass susceptibility
2a volume susceptibility
mathematical operations and outcomes
3a correction factor volume susceptibility field assessment / laboratory measurements
3b correction factor mass / volume susceptibility
4 correlation mass susceptibility with Ca, Mg, Fe, Al, Cd, Black Carbon content
5 analysis of spatial trends (susceptibility, correlation)
6 regionalization base saturation
7 regionalization magnetic susceptibility
8 spatial regression volume susceptibility / base saturation
?
9 prediction of Ca, Mg, Fe, Al, Cd, Black Carbon by linear regression models
10 target: spatial information on soil chemical characteristics by using magnetic susceptibility as model parameter, linear regression model

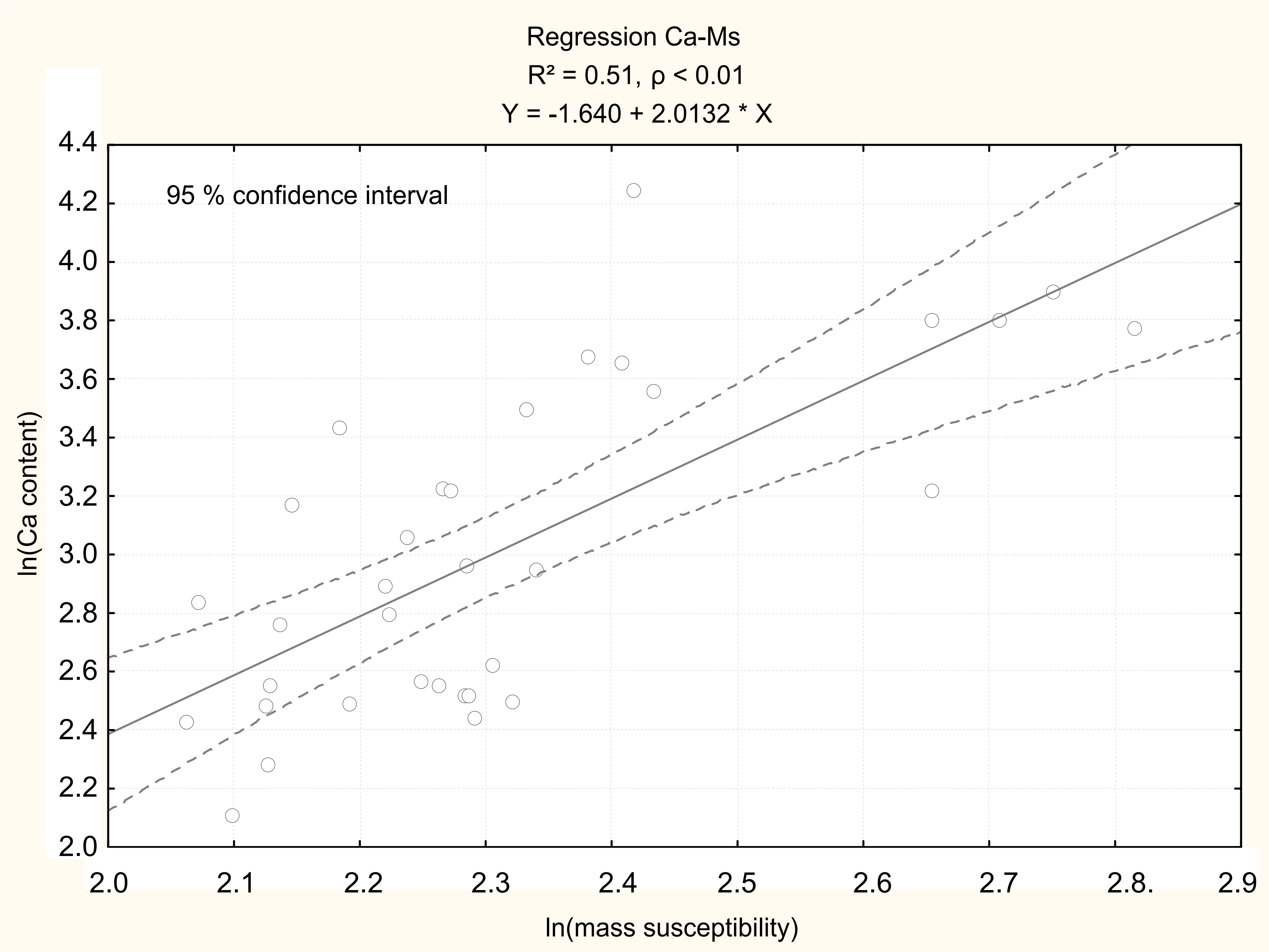

grid wise measurements
(regionalization of susceptibility)
plot wise field measurements
(correlation with base cations / metals)
laboratory measurements
(correction field⇔lab, volume⇔mass susc.)
MS2H
• 1x1 – 4x4 km²
• 30 cm bore hole
• 5 bore holes / plot
• depth level wise (1 cm resolution)
plots without soil profile
bore holes
0. 5 m
0.5 m
0.3 m
• overlapping
• intensified grid
• 1x1 km²
• 110 plots
• basic grid
• 4x4 km²
• 38 plots
MS2H
• 34 plots
• 30 cm bore hole
• 5 bore holes / plot
• depth level wise (1 cm resolution)
plots with soil profile
bore holes
0. 5 m
0.3 m
profile head side / profile wall
plots without soil profile
bore holes
0. 5 m
0.5 m
0.3 m
MS2B
• 19 plots
• mixed samples from 5 samples / horizon
• horizons: Oe, Oa, Ah, Bv
plots with soil profile
Oi
Oe
Oa
A
B
C
sampling points

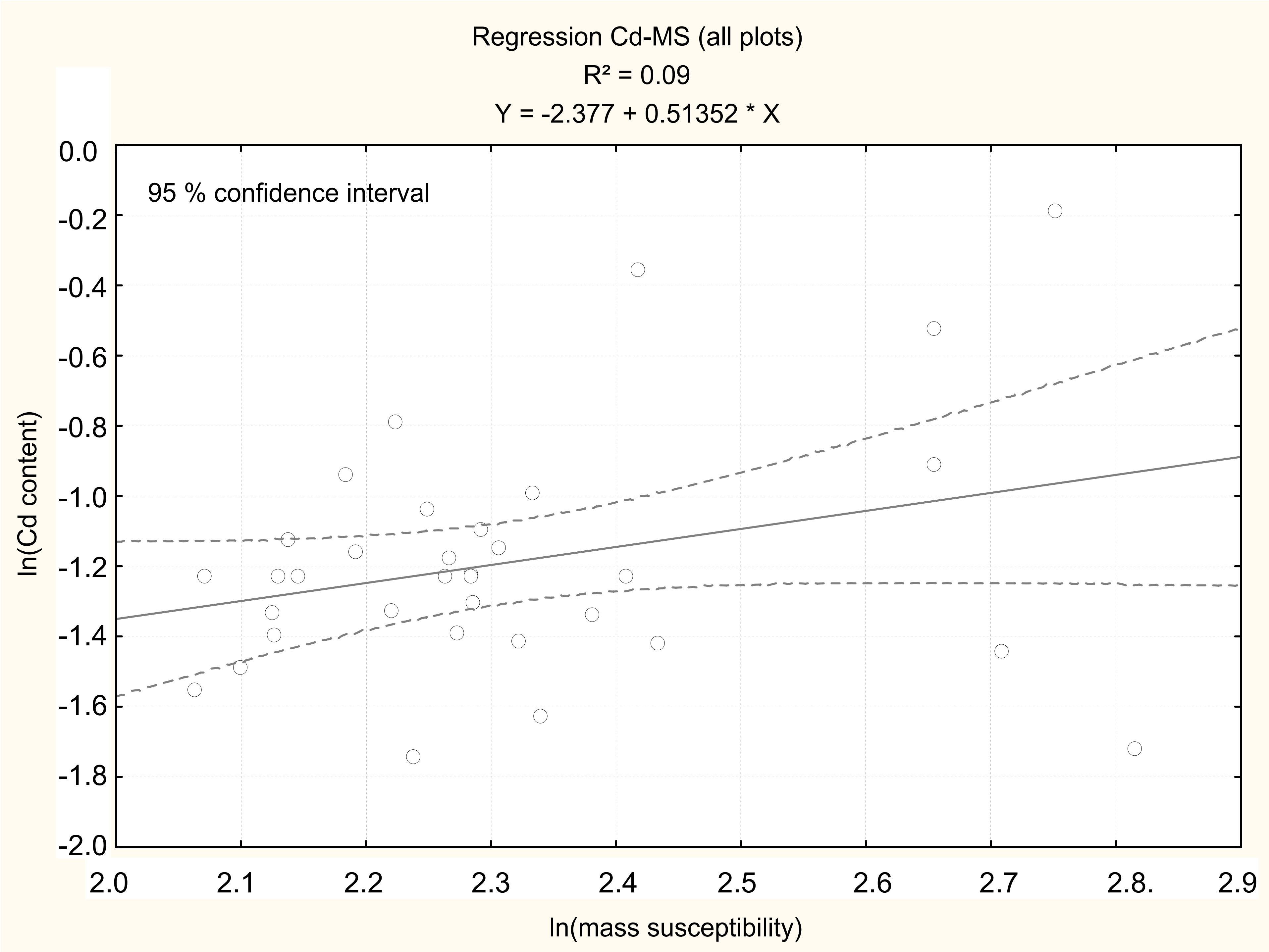

Box and Whisker plots for horizontal distance to main emitters (Gräfenhainichen / Zschornewitz)
(mean value, 95 % confidence interval, standard deviation)
700
600
500
400
300
200
100
0
Mass susceptibility ´χ * 10-8 m³ / kg
Oe horizon
Oa horizon
upper mineral horizon
up to 10 km
up to 20 km
up to 30 km
up to 50 km
up to 75 km
Horizontal distance to main emitters

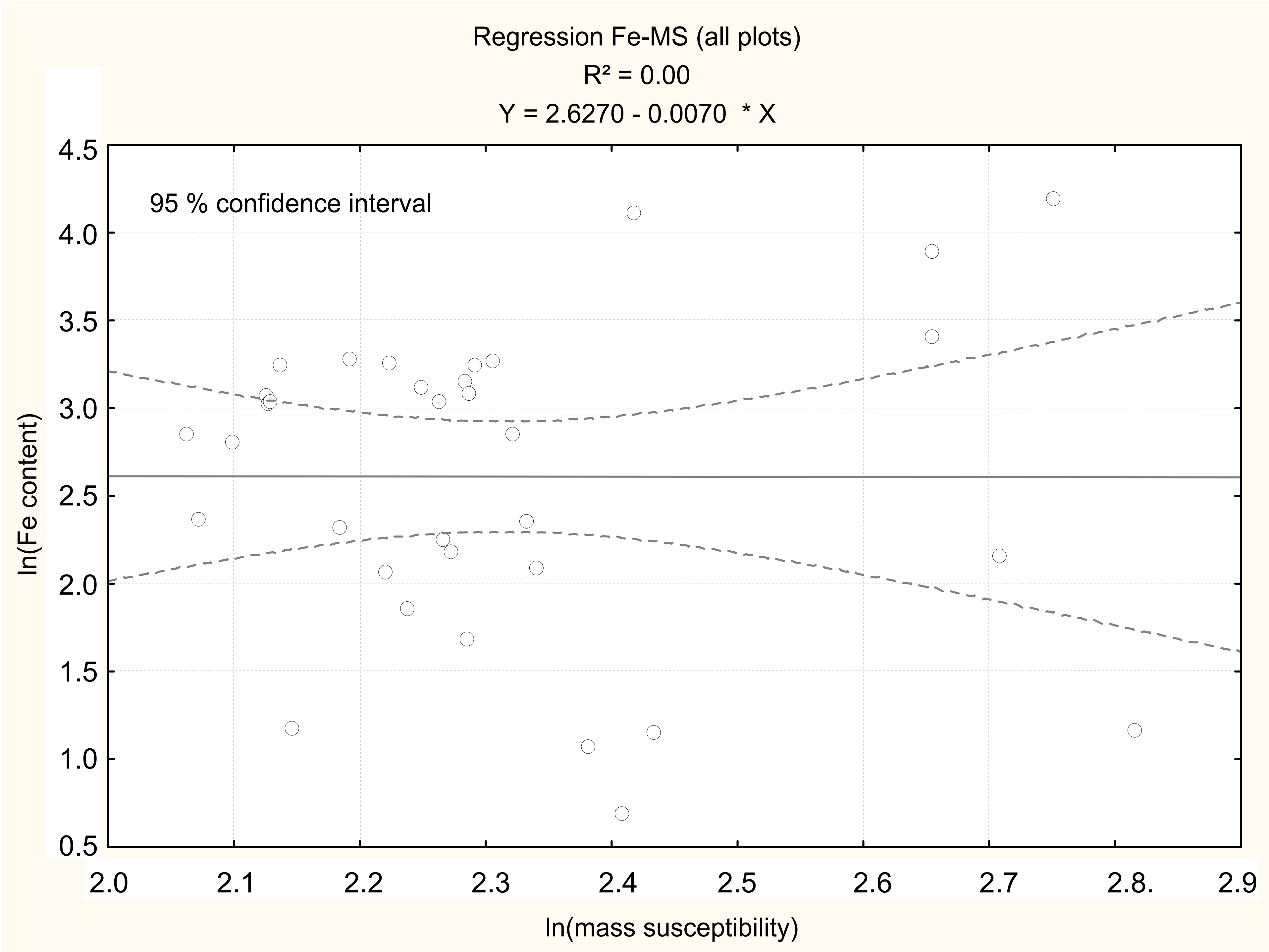

Correlation (r) between magnetic susceptibility and Ca and Mg content (all plots)
(mean value, whiskers: standard error)
1.0
0.8
0.6
0.4
0.2
0.0
up to 10 km
up to 20 km
up to 30 km
up to 50 km
up to 75 km
horizontal distance to emitters (Zschornewitz / Gräfenhainichen)
Corr Ca
Corr Mg


Correlation (r) between magnetic susceptiblity and Fe and Al content (all plots)
(mean values, whiskers: standard error)
1.0
0.8
0.6
0.4
0.2
0.0
up to 10 km
up to 20 km
up to 30 km
up to 50 km
up to 75 km
horizontal distance to emitters (Zschornewitz / Gräfenhainichen)
Corr Fe
Corr Al


Correlation (r) between magnetic susceptibility and Cd and Black Carbon (humus layers, all plots)
(mean values, whiskers: standard error)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
up to 10 km
up to 20 km
up to 30 km
up to 50 km
up to 75 km
horizontal distance to emitters (Zschornewitz / Gräfenhainichen)
Corr Cd
Corr BC


Regression Ca-Ms
R² = 0.51, ρ < 0.01
Y = -1.640 + 2.0132 * X
95 % confidence interval
ln(Ca content)
ln(mass susceptibility)
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8.
2.9


Regression Cd-MS (all plots)
$R^2 = 0.09$
$Y = -2.377 + 0.51352 * X$
95 % confidence interval
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
ln(Cd content)
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8.
2.9
ln(mass susceptibility)



Regression Fe-MS (all plots)
R² = 0.00
Y = 2.6270 - 0.0070 * X
95 % confidence interval
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ln(Fe content)
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8.
2.9
ln(mass susceptibility)