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**Detection of changes in soil using the long-term soil  
monitoring network Boden-Dauerbeobachtung Schleswig-  
Holstein (BDF-SH), Germany**

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*A rainbow of soil is under our feet:  
Red as a barn and black as a peat.  
It's yellow as lemon and white as the snow;  
Bluish gray ... so many colors below.  
Hidden in darkness as thick as the night:  
The only rainbow that can form without light.  
Dig you a pit, or bore you a hole,  
You'll find enough colors to well rest your soul.*

F.D. Hole, A Rainbow of Soil Words, 1985

## Summary

The regional long-term soil monitoring network Boden-Dauerbeobachtung Schleswig-Holstein (BDF-SH SMN) was established in the German federal state of Schleswig-Holstein in 1989. To date, no detailed investigation of its quality compared to national and international standards and its suitability to detect changes in soil and impacts of soil degradation has been undertaken. The so far collected data has partly been used for national and regional evaluations but is unpublished in international literature and no comprehensive scientific assessment has been undertaken. Hence, this thesis aims at evaluating the quality of the SMN for long-term soil monitoring and at examining selected existing results, especially in the context of soil degradation and carbon and nutrient changes due to management practices.

The basic BDF-SH SMN includes a broad range of chemical, physical and biological measurements in soil currently sampled every six and twelve years (biological measurements: three and six years) at currently 37 sites. The soil measurements are completed by groundwater level measurements and detailed farm management data. The intensive monitoring (I-BDF-SH) at five sites consists of additional annual measurements in soil as well as leachate and deposition data.

The assessments of the quality of the BDF-SH SMN compared to national and international standards revealed that the SMN largely fulfils the requirements of a soil and soil organic carbon (SOC) monitoring network. Apart from some limitations in the first years, the SMN has been assessed as highly suitable for detecting changes in soil. The evaluation of the, so far, existing results was done at first at two sites which had been converted from grassland/pasture into cropland. The study determined the impact of land use change as SOC loss, change of the pF curve, decrease of microbial biomass, earthworms, micro-annelids and other indicators. At the same time, the conversion impact could be distinguished from effects resulting from a lowering of the groundwater level, which also decreased the soil organic carbon stocks.

The second goal was to analyze the potential of the BDF-SH SMN to evaluate the impact of soil degradation using process-based modeling. For this purpose, two sites, differently affected by wind erosion, were studied in detail and evaluated with the wind erosion model SWEEP. The model was parameterized with local wind data in a high temporal resolution and the BDF monitoring data. Several modifications had to be included in the model to calibrate it for the BDF data, amongst others a model extension to quantify the SOC loss through wind erosion. The agreement of the measured and modeled SOC loss at the study sites was very good. The approach and the modifications were recommended for well-studied

sites without noteworthy SOC losses originating from other causes. It seems to be an adequate method for long-term periods where continuous erosion measurements are not available.

Third, the intensive soil monitoring (I-BDF-SH) was studied, focusing on its capability to depict changes in soil as a consequence of farm management practices. Using modeling (DNDC) and nutrient balancing, the aim was to determine whether and under which circumstances annual soil carbon and nutrient measurements are more beneficial for soil monitoring compared to the common five- to ten-year measurement intervals. The results underline that when using five- or ten-year measurement intervals as a base for the DNDC model, the long-term trend of SOC and  $N_{tot}$  measurements were well reproduced, but this could also have been by coincidence as the type of trendline depended on the choice of the modeled starting year in DNDC.  $NO_3-N$  leaching was overestimated. Measured short-term changes in soil could not be depicted neither by the model results nor by the nutrient balances. The reason was that variations in spatial and temporal patterns of fertilization, tillage and yield were measured as the sites are not fully controlled experimental fields, but rather managed by independent farmers. This means that the I-BDF SH measured true short-term variations of soil properties. Under these conditions, annual soil property measurements can depict the soil's variability and contribute to the identification of the true long-term trend.

The conclusions stress that the basic BDF-SH and the I-BDF-SH SMN complement each other well. It was shown that the quality of the SMN is in accordance with national and international standards for detecting changes in soil and establishing time series. The BDF-SH SMN can additionally serve to parameterize and validate process-based models. It was also determined how the broad range of data can be used to detect changes in soil resulting from degradation and how process-based modeling can be of use for this purpose. By using the SMN data, the effects of different types of soil degradation could be quantified considering the statistical uncertainties. The assessment also revealed some limitations of the BDF-SH SMN. Considering some other SMNs, there are relatively few sites in the BDF-SH SMN due to high financial and administrative efforts. Secondly, the comparability between the first and the second sampling campaign can be partly limited due to changes of analytical methods and the depth increment sampling method. The preliminary study resulted in recommendations which were widely implemented into the SMN. For future measurement campaigns, suggestions for some new measurements were included.

The applied methodology of this thesis can be used for the evaluation of other SMNs on a regional, a national and an international scale. With the results of the thesis, the value of the BDF-SH SMN is more accessible to international scientific studies and networks and can be used easier as its quality level and its characteristics were described in a research context.

This also applies to the use of the SMN with process-based models for studies focusing on changes in soil and soil degradation. The thesis also stresses how the broad range of observed data might create synergies, thus recommending the inclusion of the measured soil properties also for other SMNs on an international scale.

## Zusammenfassung

Das regionale Boden-Dauerbeobachtungsnetzwerk Schleswig-Holstein BDF-SH SMN (engl. Long-term soil monitoring network Schleswig-Holstein) wurde 1989 im deutschen Bundesland Schleswig-Holstein eingerichtet. Bisher lagen keine detaillierten Untersuchungen zu seiner Qualität im Vergleich zu nationalen und internationalen Standards vor. Das Gleiche betrifft seine Eignung zur Erfassung der Auswirkungen von Bodenveränderungen und Bodendegradation. Die erhobenen Daten wurden teils in nationalen und regionalen Auswertungen verwendet, sind jedoch in der internationalen Literatur nicht veröffentlicht, und es wurde keine umfassende wissenschaftliche Bewertung vorgenommen. Ziel dieser Arbeit ist es daher, die Qualität des SMN für eine langfristige Bodenüberwachung bzw. -beobachtung zu evaluieren und ausgewählte vorhandene Ergebnisse zu untersuchen, insbesondere im Zusammenhang mit Bodendegradationen sowie Kohlenstoff- und Nährstoffänderungen im Boden als Folge von Bewirtschaftungspraktiken.

Das Basis-BDF-SH SMN umfasst ein breites Spektrum chemischer, physikalischer und biologischer Messungen im Boden, die momentan in Intervallen von sechs und zwölf Jahren (biologische Messungen: drei und sechs Jahre) an derzeit 37 Standorten durchgeführt werden. Die Bodenmessungen werden durch Grundwasserstandmessungen und detaillierte Schlagkarteidaten ergänzt. Das Intensivmonitoring I-BDF-SH (engl. Intensive) an fünf Standorten umfasst zusätzlich jährliche Messungen im Boden, in Düngern und im Erntegut sowie Sickerwasser- und Depositionsdaten.

Die Bewertung der Qualität des BDF-SH SMN im Vergleich zu nationalen und internationalen Standards ergab, dass das SMN die Anforderungen eines Monitoringnetzwerks für Boden und Bodenkohlenstoff (SOC, engl.: Soil organic carbon) weitgehend erfüllt. Abgesehen von einigen Einschränkungen in den ersten Jahren wurde festgestellt, dass sich das SMN hervorragend zum Nachweis von Bodenveränderungen eignet. Die Auswertung der bisherigen Ergebnisse erfolgte zunächst an zwei Standorten, die von Grünland/Weideland in Ackerland umgewandelt worden waren. Die Studie ermittelte die Auswirkungen von Landnutzungsänderungen wie Kohlenstoffverlust, Änderung der pF-Kurve,

Abnahme von mikrobieller Biomasse, Regenwürmern, Kleinringelwürmer und anderen Indikatoren. Gleichzeitig konnten die Auswirkungen der Landnutzungsänderung von Effekten unterschieden werden, die sich aus einer Absenkung des Grundwasserspiegels ergaben und ebenfalls zu einer Verringerung der Bodenkohlenstoffvorräte führten.

Das zweite Ziel bestand darin, das Potenzial des BDF-SH SMN zu analysieren, um die Auswirkungen der Bodendegradation mithilfe prozessbasierter Modelle zu bewerten. Zu diesem Zweck wurden zwei Standorte, die unterschiedlich stark von Winderosion betroffen sind, detailliert untersucht und mit dem Winderosionsmodell SWEEP ausgewertet. Das Modell wurde mit lokalen Winddaten in hoher zeitlicher Auflösung und den BDF-Monitoringdaten parametrisiert. Dem Modell wurden mehrere Modifikationen hinzugefügt, um es für die BDF-Daten zu kalibrieren, unter anderem eine Modellerweiterung, um den Kohlenstoffverlust durch Winderosion zu quantifizieren. Die gemessenen und modellierten Bodenkohlenstoffverluste an den Untersuchungsstandorten stimmten weitgehend überein. Der Ansatz und die Modifikationen wurden für ähnlich gut untersuchte Standorte ohne sonstige nennenswerte Bodenkohlenstoffverluste empfohlen. Daher scheint dies eine adäquate Methode für Langzeitbeobachtungen zu sein, in denen kontinuierliche Erosionsmessungen nicht verfügbar sind.

Als dritter Schritt wurde das intensive Bodenmonitoring (I-BDF SH) untersucht, wobei der Schwerpunkt auf dessen Qualität lag, Bodenveränderungen als Folge von Bewirtschaftungspraktiken darzustellen. Mithilfe von Instrumenten der Modellierung (DNDC) und der Nährstoffbilanzierung sollte ermittelt werden, ob und unter welchen Umständen jährliche Messungen von Kohlenstoff und Nährstoffen im Boden sinnvoller sind als die üblichen Messintervalle von fünf bis zehn Jahren. Die Ergebnisse zeigen, dass der Langzeittrend von SOC- und  $N_{\text{tot}}$ -Messungen gut reproduziert werden konnte, wenn Fünf- oder Zehnjahresmessungen als Grundlage für das DNDC-Modell verwendet wurden. Dies könnte jedoch auch zufällig gewesen sein, da die Art der Trendlinie abhing von der Wahl des modellierten Startjahres in DNDC. Die  $\text{NO}_3\text{-N}$ -Auswaschung wurde im Modell überschätzt. Gemessene kurzfristige Veränderungen im Boden konnten weder durch die Modellergebnisse noch durch die Nährstoffbilanzen abgebildet werden. Der Grund war, dass Variationen der Ausprägung von Bodeneigenschaften gemessen wurden, die durch räumliche und zeitliche Unterschiede in Düngung, Bodenbearbeitung und Ertrag bedingt waren. Die Ursache ist, dass die BDF-Standorte keine vollständig kontrollierten Versuchsfelder sind, sondern von unabhängigen Landwirten bewirtschaftet werden. Das bedeutet, dass beim I-BDF SH tatsächliche, kurzfristige Schwankungen der Bodeneigenschaften gemessen wurden. Unter

diesen Bedingungen können jährliche Messungen der Bodeneigenschaften die Variabilität des Bodens abbilden und dazu beitragen, den tatsächlichen langfristigen Trend zu erkennen.

Die Schlussfolgerungen ergaben, dass sich das Basis-BDF-SH und das I-BDF-SH SMN gut ergänzen. Es wurde gezeigt, dass die Qualität des SMN den nationalen und internationalen Standards für die Erfassung von Bodenveränderungen und die Erstellung von Zeitreihen entspricht. Das BDF-SH SMN kann außerdem zur Parametrisierung und Validierung prozessbasierter Modelle dienen. Es wurde ebenso bestimmt, wie das breite Datenspektrum zum Nachweis von durch Degradation verursachten Bodenveränderungen verwendet werden kann und wie eine prozessbasierte Modellierung für diesen Zweck von Nutzen sein kann. Durch die Nutzung der SMN-Daten konnten die Auswirkungen verschiedener Arten der Bodendegradation unter Berücksichtigung der statistischen Unsicherheiten quantifiziert werden. Die Bewertung ergab auch einige Einschränkungen des BDF-SH SMN. Zum einen beinhaltet das SMN, gemessen an einigen anderen Messnetzen, aufgrund des hohen finanziellen und administrativen Aufwands relativ wenige Standorte. Zweitens kann die Vergleichbarkeit zwischen der ersten und der zweiten Probenahmekampagne teilweise eingeschränkt sein aufgrund von Änderungen der Analysemethoden und der Beprobungstiefen. Die Ergebnisse der Vorstudie führte zu Empfehlungen, die im SMN weitgehend umgesetzt wurden. Für zukünftige Messkampagnen wurden Vorschläge für einige neue Messgrößen entwickelt.

Die angewandte Methodik dieser Arbeit kann für die Bewertung anderer SMNs auf regionaler, nationaler und internationaler Ebene verwendet werden. Mit den Ergebnissen der Dissertation ist der Wert des BDF-SH SMN für internationale wissenschaftliche Studien und Netzwerke besser zugänglich und kann leichter genutzt werden, da sein Qualitätsniveau und seine Eigenschaften in einem Forschungskontext beschrieben wurden. Dies gilt auch für die Verwendung prozessbasierter Modelle für Studien zu Bodenveränderungen und Bodendegradation. Die Dissertation zeigt ebenfalls, wie das breite Spektrum der beobachteten Daten Synergien schaffen kann, und empfiehlt daher, die im BDF-SH SMN gemessenen Bodeneigenschaften auch für andere SMNs auf internationaler Ebene zu berücksichtigen.



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## Abbreviations

BDF	Long-term soil monitoring (Boden-Dauerbeobachtung)
BDF-SH	Long-term soil monitoring Schleswig-Holstein (Boden-Dauerbeobachtung Schleswig-Holstein)
BDF-SH SMN	Long-term soil monitoring network Schleswig-Holstein (Boden-Dauerbeobachtungsnetzwerk Schleswig-Holstein)
BDF site	Long-term soil monitoring site (Boden-Dauerbeobachtungsfläche)
CFE	Chloroform-fumigation extraction
$C_{mic}$	Microbial biomass
$C_{org}$	Organic carbon concentration
DIN	German Industry Standard (Deutsches Institut für Normung)
DNDC	DeNitrification DeComposition Model
DOC	Dissolved organic carbon
DWD	German Meteorological Service (Deutscher Wetterdienst)
E	Relative modeling error
EF	Modeling efficiency
ER	Enrichment ratio
GASI	German Agricultural Soil Inventory
GMD	Geometric mean diameter
GSD	Geometric standard deviation
I-BDF	Intensive long-term soil monitoring (Intensiv-Boden-Dauerbeobachtung)
I-BDF-SH	Intensive long-term soil monitoring Schleswig-Holstein (Intensiv-Boden-Dauerbeobachtung Schleswig-Holstein)
LKSH	Landwirtschaftskammer Schleswig-Holstein
LLUR	Landesamt für Landwirtschaft, Umwelt und Ländliche Räume Schleswig-Holsteins
LTSE	Long-term soil experiment
LUC	Land use change
LUCAS	Land Use and Coverage Area frame Survey
MgO	Magnesium oxide
$NH_4^+$	Ammonium
$NH_4^+-N$	Ammonium-Nitrogen
$NO_3^-$	Nitrate
$NO_3^- - N$	Nitrate-Nitrogen
$N_{tot}$	Total nitrogen
$P_2O_5$	Phosphorus pentoxide
$qCO_2$	Metabolic ratio
$RESP_{basal}$	Basal respiration



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RMSE	Root mean square error
SAI	Stem area index
SIR	Substrate-induced respiration
SMN	Soil monitoring network
SOC	Soil organic carbon
SOM	Soil organic matter
SWEEP	Single-event Wind Erosion Evaluation Program
TEAM	Texas Tech Erosion Analysis Model
WEPS	Wind Erosion Prediction System



# 1 Introduction

## 1.1 Motivation

Soil degradation and changes in soils over time are constant challenges for worldwide agriculturally used areas. These changes are triggered through land use change, erosion, compaction, contamination, climate change and the quality of farming practices. To measure and observe their impact, agriculturally used soils need to be monitored (Jandl et al., 2014). Long-term soil monitoring networks (SMNs) are well known in literature, e.g. Morvan et al. (2008), who defined them as “a set of sites/areas where changes in soil characteristics are documented through periodic assessment of an extended set of soil parameters”. Arrouays et al. (2012) and van Wesemael et al. (2011) described general requirements of SMNs. There are two basic requirements for a soil monitoring network. On the one hand, the quality of the SMN must be adequate to obtain significant results and suitable timelines. On the other hand, the monitoring must be long-term, as many soil properties change slowly.

A soil monitoring network is used for the development of sustainable management strategies against soil degradation, such as erosion, compaction, contamination, organic carbon decline and fertility decrease. This can be done short term or rather long term. It is also an instrument to study long-term changes which are not direct soil degradations. These are, for example, climate change effects, organic carbon changes, soil water variations or soil biodiversity alterations. An example on the European scale is the Land Use/Cover Area frame statistical Survey Soil (LUCAS Soil) implemented by the Statistical Office of the European Union (EUROSTAT) (Orgiazzi et al., 2018) since 2009.

Soil monitoring is often organized on a national or an international scale. Due to its federal structure, Germany is an exceptional case. Each federal state implements its own regional long-term SMN. From 2011 to 2017, the first nation-wide standardized soil organic carbon monitoring campaign, the German Agricultural Soil Inventory (Bach et al., 2011) has taken place. However, it only covered soil organic carbon and bulk density. A full range of soil variables is only measured in the regional BDF SMNs. The long-term soil monitoring network Boden-Dauerbeobachtung (BDF-SH) is a compilation of 14 different regional SMNs. These regional monitoring programs vary slightly in the type of studied parameters, applied methods and their monitoring focus.

SMNs as the BDF-SH study long-term sites in depth using a large variety of examinations methods which can be rarely be found in other SMNs, but rather in, so-called, long-term soil experiments (LTSEs; Jandl et al., 2014). The LTSEs, however, focus on specific

research questions and do not cover all the landscape units of a region. Thus, the BDF-SH benefits from both the in-depth and the comprehensive observation of a comparatively large site set. It has been installed from 1989 onwards (Table 1), while especially the first ten years have been characterized by changes of analytical methods and depth increment sampling.

To date, no full scientific assessment of a German SMN like the BDF-SH has been undertaken, which is due to the relatively short time since they have been installed. Thus, after 25 to 30 years for the first time there is the opportunity to evaluate the first long-term results. The focus is to (1) assess the quality and design of the BDF-SH to detect changes in soil and (2) evaluate the results within case studies of soil degradation or other changes in soil.

### **1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area**

The German long-term soil monitoring network Boden-Dauerbeobachtung (BDF SMN) (Prechtel et al., 2009; Schröder et al., 2003, 2004; Kaufmann-Boll et al., 2012; Nerger, 2010, 2016; Barth et al., 2001) exists since 1985. The aim of the BDF SMN is a detailed long-term observation of all changes in soil, especially those resulting from soil degradation. It is not a national SMN but consists of 14 regional SMNs (Table 1), among them the regional BDF SMN of the federal state Schleswig-Holstein (BDF-SH SMN). The monitored sites are called Boden-Dauerbeobachtungsflächen (long-term soil monitoring sites; BDF sites). All BDF SMNs use standard soil monitoring techniques, e.g. site installation and maintenance, composite sampling, sampling intervals, permanent laboratory, farming management questionnaires and the documentation of changed methods. This is described within the main BDF installation and monitoring guideline (Barth et al., 2001). However, this guideline can be implemented flexibly by the different federal states (Nerger, 2010).

In the federal state of Schleswig-Holstein, the 38 BDF study sites were installed by the LLUR state agency and their predecessors' representative to landscape units (Figure 2), soil types, land use forms and pollution level (Nerger, 2010; Schröder et al, 2003; 2004). Despite the deviations among the different German regional SMNs, the methods of the BDF-SH network were shown as comparable to those of the other German regional SMNs (Nerger, 2010). In the same study, it was also determined that the BDF-SH can be compared to SMNs outside of Germany, such as the national long-term soil monitoring of Switzerland (Nationale Bodenbeobachtung der Schweiz (NABO); Desaules et al., 2010). In Schleswig-Holstein, the BDF 01 to 33 have been installed between 1989 and 1993, while the sites 34 to 39 have been installed at a later stage (Table 2).

## 1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area

Table 1: Basic data of regional BDF SMNs in Germany in 2012 (source: modified after Kaufmann-Boll et al., 2012)

	Established since	Total	Basic BDF only	I-BDF	Cropland	Grassland	Forest	Specialized crop	Urban	Other
Baden-Württemberg	1986	39	33	6	12	7	20	0	0	0
Bayern	1985/86	271	249	22	97	50	101	10	0	13
Brandenburg	1990	36	30	6	23	7	6	0	0	0
Hamburg	1992	3	3	0	0	0	0	0	3	0
Hessen	1992	67	66	1	25	17	22	2	0	1
Mecklenburg-Vorpommern	1993	34	34	0	23	10	0	0	1	0
Niedersachsen	1991/92	90	72	18	48	18	20	1	0	3
Nordrhein-Westfalen	1992	21	21	0	0	2	16	0	0	3
Rheinland-Pfalz	2008	16	0	16*	0	0	16	0	0	0
Saarland	1990	11	11	0	4	1	4	1	0	1
Sachsen-Anhalt	1990	70	67	3	33	10	24	0	0	3
Sachsen	1993	61	50	11	52	3	6	0	0	0
Schleswig-Holstein	1989	38	34	4	15	14	5	0	1	3
Thüringen	1993/95	32	27	5	13	4	9	0	0	6
<b>Sum</b>		<b>789</b>	<b>697</b>	<b>92</b>	<b>345</b>	<b>143</b>	<b>249</b>	<b>14</b>	<b>5</b>	<b>33</b>

## 1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area

Table 2: Basic data of the BDF-SH monitoring sites sorted by land use

BDF name and number	Land use	Monitoring type	Landscape	Installed	Soil type (Ad-Hoc-AG Boden, 2005)
Stadum/Goldelund <b>04</b>	cropland	basic	Lower Geest	1990	Gley-Podsol
Gintoft <b>05</b>	cropland	basic	eastern uplands	1990	Pseudogley-Parabraunerde
Sönke-Nissen-Koog <b>06</b>	cropland	basic / intensive	marshland	1989	(Norm-) Kalkmarsch
Schuby <b>09</b>	cropland	basic / intensive	Lower Geest	1990	Gley-Podsol
Maasleben <b>10</b>	cropland	basic	eastern uplands	1991	Parabraunerde-Pseudogley
Vadersdorf/Fehmarn <b>12</b>	cropland	basic	eastern uplands	1990	(Norm)- Pseudogley
Hohenschulen <b>15</b>	cropland	basic	eastern uplands	1990	Kolluvisol über Pseudogley
Schönberg/Schwartbruck <b>16</b>	cropland	basic	eastern uplands	1991	Pseudogley-Parabraunerde
Dannau <b>17</b>	cropland	basic	eastern uplands	1991	Pseudogley-Parabraunerde
Gut Siggen <b>18</b>	cropland	basic	eastern uplands	1989	pseudovergleyte Parabraunerde
Mörel/Nindorf <b>19</b>	cropland	basic	High Geest	1990	Pseudogley-Parabraunerde
Bornhöved <b>24</b>	cropland	basic	eastern uplands	1989	Braunerde
Lebatz/Tankenrade <b>27</b>	cropland	basic	eastern uplands	1992	Pseudogley-Parabraunerde
Hamberge/Niederbüssau <b>29</b>	cropland	basic	eastern uplands	1990	Braunerde-Pseudogley
Lindhof 2 <b>36</b>	cropland	basic / intensive	eastern uplands	2001	(Norm-) Parabraunerde
Schwabstedt/Lehmsiek <b>11</b>	grassland / cropland	basic	High Geest	1991	Pseudogley
St. Peter Ording/Kleihof <b>13</b>	grassland / cropland	basic	marshland	1991	(Norm-) Knickmarsch
Hedehusum/Föhr <b>03</b>	grassland/pasture	basic (closed and replaced by 38)	marshland / Lower Geest	1990	Podsol-Braunerde
Havetoftloit <b>08</b>	grassland/pasture	basic	eastern uplands	1991	Parabraunerde
Meggerdorf <b>14</b>	grassland/pasture	basic	Lower Geest	1991	Mulm-Niedermoor
Hindorf <b>22</b>	grassland/pasture	basic	High Geest	1991	vergleyter Pseudogley-Podsol
Bokhorst <b>23</b>	grassland/pasture	basic / intensive	High Geest	1992	podsolierte Braunerde
Kudensee/Landscheide <b>25</b>	grassland/pasture	basic	marshland	1990	Mulm-Niedermoor
Karkendamm <b>26</b>	grassland/pasture	basic	Lower Geest	1989	Gley-Podsol
Groß Offenseth-Aspern <b>28</b>	grassland/pasture	basic	High Geest	1990	(Norm-) Pseudogley
Altendeich/Neuendorf <b>30</b>	grassland/pasture	basic	marshland	1992	Flusskleimarsch
Hellbachtal <b>33</b>	grassland/pasture	basic	eastern uplands	1993	Erd-Niedermoor
Lindhof 1 <b>35</b>	grassland/pasture	basic / intensive	eastern uplands	2001	(Norm-) Parabraunerde

## 1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area

Witsum/Föhr <b>38</b>	grassland/pasture	basic	marshland / Lower Geest	2002	Podsol
Süderlügum <b>02</b>	forest	basic	High Geest	1989	Podsol
Wüstenfelde <b>20</b>	forest	basic	eastern uplands	1989	Braunerde-Pseudogley
Pobüller Bauernholz <b>07</b>	forest (protected)	basic	Lower Geest	1989	Pseudogley-Podsol
Hevenbruch <b>39</b>	forest (protected)	basic	eastern uplands	2005	podsolierte Braunerde
Hahnheide <b>32</b>	forest (protected)	basic	eastern uplands	1992	podsolierte Braunerde
Sylt <b>01</b>	nature reserve	basic	marshland / Lower Geest	1989	podsolierter Regosol
Speicherkoog Dithmarschen <b>21</b>	nature reserve	basic	marshland	1989	Kalkmarsch
Hamburger Hallig <b>37</b>	nature reserve	basic	marshland	2001	(Norm-) Rohmarsch
Pinneberg <b>31</b>	tree nursery	basic	Lower Geest	1991	Hortisol über Braunerde
Kiel <b>34</b>	urban park	basic (closed)	eastern uplands	1996	Pararendzina



Figure 1: Left: Field of BDF site 35 (Lindhof 1), right: Field of BDF site 6 (Sönke-Nissen-Koog); pictures: R. Nерger, October 2007

## 1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area

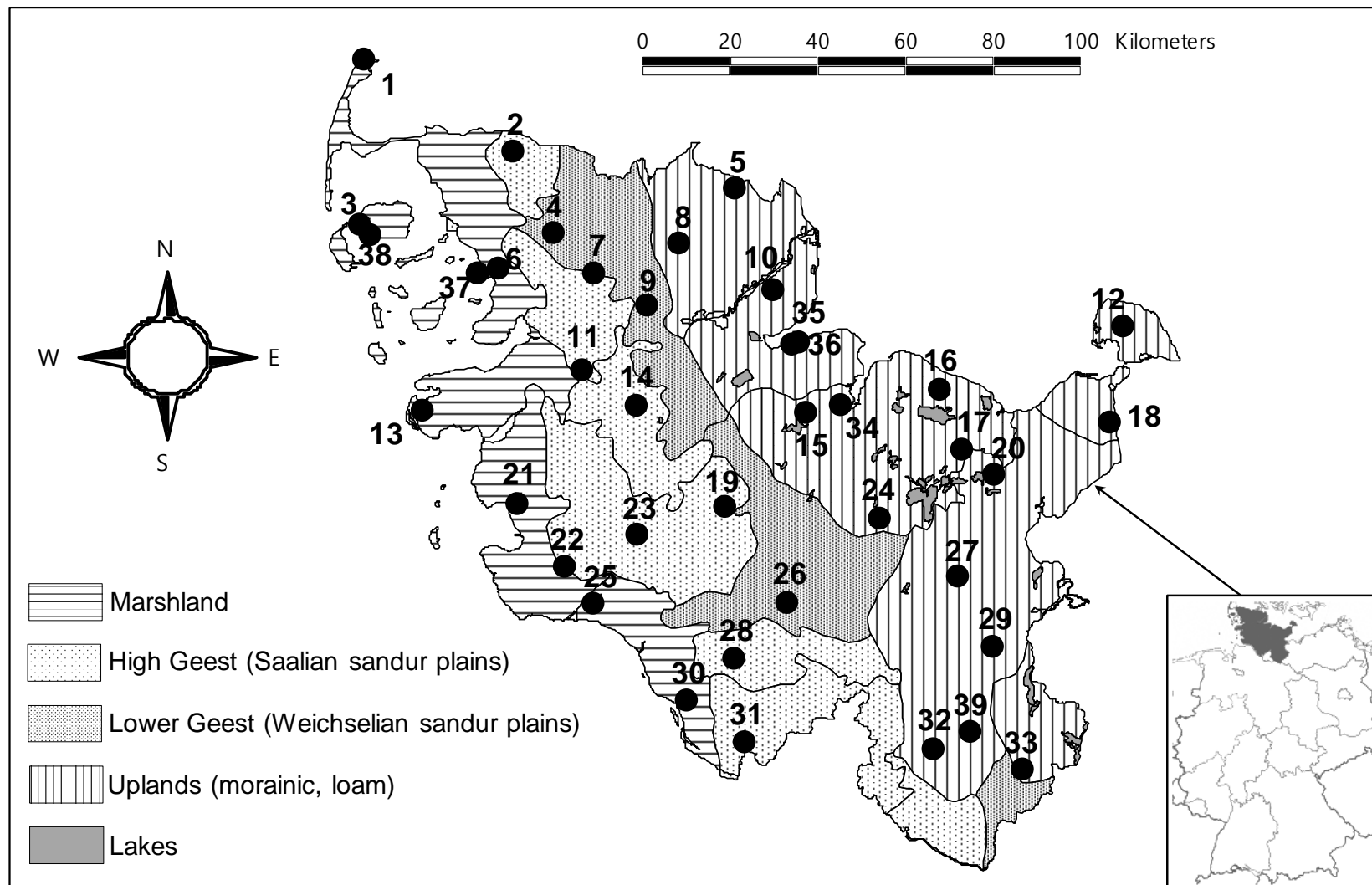


Figure 2: Map of the landscape units in Schleswig-Holstein, Germany, and the locations of the BDF monitoring sites



The intensive monitoring (I-BDF-SH) currently consists of five sites (BDF 6, 9, 23, 35, 36). These intensive monitoring sites (I-BDF) are basic BDFs, which were later established with annual soil sampling, weekly leachate sampling and bi-weekly deposition measurements. Table 3 below shows the use of basic and intensive monitoring sites within different functions and processes.

Table 3: Function and process of the long-term soil monitoring (Barth et al., 2000)

<b>Monitoring functions</b>	<b>Basic BDF</b>	<b>Intensive BDF</b>
Early warning system	+	++
Control tool	+	+
Evidence	++	+
Environment-monitoring	++	++
Reference for soil loads	++	–
Test platform	+	+
Reference for site survey	++	–

*Legend: ++ well suited, + suited, - not suited*

The BDF-SH SMN includes a large variety of measured soil properties and additional data (Table 4). Additionally, different analytical methods were used. Thus, the very first step was to establish a comprehensive overview of the SMN (section 1.3 Preliminary study) before more detailed research questions could be answered (sections 2 to 4).

## 1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area

### Measured properties

The measured properties, currently and in the past, are indicated in Table 4.

Table 4: Measured properties within the BDF-SH SMN

Type	Basic SMN	Intensive SMN	Measured properties
Chemical inorganic in soil	every ten years, from 2014: every 12 years	annual until 2013	pH, N <sub>tot</sub> , C <sub>org</sub> , CaCO <sub>3</sub> , P <sub>2</sub> O <sub>5</sub> , K <sub>2</sub> O, MgO, CEC (Ca <sup>2+</sup> , Mg <sup>2+</sup> , Na <sup>+</sup> , K <sup>+</sup> , Al <sup>3+</sup> , Fe <sup>2+</sup> , H <sup>+</sup> , Mn <sup>2+</sup> ), NaCl, As, Cd, Cr, Cu, Ni, Hg, Pb, Zn, Mg, Ca, S, K, P, Na, Al, Fe, Mn, Ba, Mo, Al <sub>oxal</sub> , Al <sub>dith</sub> , Fe <sub>oxal</sub> , Fe <sub>dith</sub> , Mn <sub>oxal</sub> , Mn <sub>dith</sub>
	every ten years, from 2014: every 6 years	-	pH, N <sub>tot</sub> , C <sub>org</sub> , CaCO <sub>3</sub> , P <sub>2</sub> O <sub>5</sub> , K <sub>2</sub> O, MgO, NaCl, Mg, Ca, S, K, P, Na, Al, Fe, Mn, As, Cd, Cr, Cu, Ni, Hg, Pb, Zn, Th, U, Be, Mo, Co, Sb, V, Se
	-	annual from 2014	pH, N <sub>tot</sub> , C <sub>org</sub> , CaCO <sub>3</sub> , P <sub>2</sub> O <sub>5</sub> , K <sub>2</sub> O, MgO, NaCl, Mg, Ca, S, K, P, Na, Al, Fe, Mn, As, Cd, Cr, Cu, Ni, Hg, Pb, Zn, Th
	-	three times a year	NO <sub>3</sub> -N, NH <sub>4</sub> -N, N <sub>org</sub> , N <sub>tot</sub>
Chemical organic in soil	irregular (1990, 2009, 2014, ...)	-	PAHs, PCBs, chlorobenzenes, chlorophenols, organochlorine pesticides, triazines, PCDDs, PCDFs, other hydrocarbons (AHCs, CHCs), etc.
Groundwater levels	biweekly	-	measured groundwater well levels
Chemical in leachate	-	weekly	leachate amount (calculated), NO <sub>3</sub> -N, NH <sub>4</sub> -N, N <sub>org</sub> , N <sub>tot</sub> , ortho-PO <sub>4</sub> , total-PO <sub>4</sub> , K <sub>2</sub> O
	-	weekly from 2012 onwards	As, Cd, Cr, Cu, Ni, Hg, Pb, Zn, U, Be, Mo, Co, Sb, V, Se
Deposition	-	biweekly	sample weight, rainfall, pH, Elec. conductivity, NO <sub>3</sub> -N, NH <sub>4</sub> -N, NO <sub>2</sub> -N, N <sub>tot</sub> , PO <sub>4</sub> -P, P <sub>tot</sub> , DOC, Cl <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup> , Ca <sup>2+</sup> , Mg <sup>2+</sup> , Na <sup>+</sup> , K <sup>+</sup> , Fe, Mn, Al, Cr, Ni, Cu, Zn, As, Cd, Hg, Pb
Physical	every ten years, from 2014: every 12 years	-	particle size distribution and texture
	every ten years, from 2014: every 6 years	-	rock fraction, dry bulk density, saturated water conductivity, total pore volume, pF curve, soil content (weight)
	-	annual	dry bulk density
Microbiological	every 3-4 years, from 2013: every 3 years	-	pH, N <sub>tot</sub> , C <sub>org</sub> , N <sub>min</sub> , dry bulk density, basal respiration, microbial biomass (SIR / CFE), enzyme activities (still active): arginine ammonification, enzyme activities (not active anymore): arylsulfatase, alkaline

## 1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area

			phosphatase, beta-glucosidase, cellulase, dehydrogenase, alphanmino nitrogen
Faunistic	every 3-6 years, from 2013: every 6 years	-	lumbricoids (epigeic, endogeic, anecic), microannelids. For all species: number of individuals, species identification, number of species, weight, age, socialization
Vegetation	every 3-8 years, from 2013: every 6 years on non-intensively managed sites	-	Complete list of vascular plants, stand structure, vitality and phenological state of development, permanent areas (coverage, vitality, Londo scale), mapping (degree of coverage, homogeneity, stature height, number of species, species power, phytosociological classification, Braun-Blanquet scale), forest tree mapping (forest only), moss (forest only), surrounding areas of the BDF sites (biotope equipment, species list vascular plants)
Lichen	every 3-4 years, closed since 2013	-	lichen species identification, coverage (Braun-Blanquet 1964, modified to Barkmann 1958 and Reichelt & Wilmanns 1975), lichen vitality, carrier trees: type, height, bark texture, stem slope, exposure, moss
Harvest products, organic fertilizers	-	annually since 2012	As, Cd, Cr, Cu, Hg, Ni, Pb, Zn
Mineral K and P fertilizers and lime	-	annually since 2015	As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, Th

### Sampling

The different types of sampling campaigns will be described in more detail in the sections 2 to 4. The following pictures illustrate the sampling process and devices for the main sampling campaigns (Figure 3), the soil faunistic sampling (Figure 4) and the intensive monitoring (Figure 5).

## 1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area



Figure 3: Main sampling campaign at forest BDF site 39: Main soil profile (upper left, picture: M. Filipinski), sampling procedure and soil description (pictures upper right to lower right, R. Nerger)

## 1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area



Figure 4: Devices used in the soil faunistic sampling campaign, pictures: R. Nерger, November 2007

## 1.2 The SMN Boden-Dauerbeobachtung Schleswig-Holstein and study area



Figure 5: Devices used in the intensive monitoring: Installation of leachate samplers (upper left, picture: D. Elsner), leachate collection box (upper right), wet-only collector for deposition (lower left), deposition measurement station (lower right), pictures except upper left: R. Nerger, 2007-2008

### 1.3 Preliminary study

The three-year preliminary study period of this dissertation was compiled in the expertise assessment report “Boden-Dauerbeobachtung Schleswig-Holstein: Auswertung der Projektergebnisse im Hinblick auf Aussagen zu Veränderungen von Böden, Aussagefähigkeit und Optimierung der eingesetzten Untersuchungsverfahren“ (Nerger, 2010). This assessment presented the development, the current status of and recommendations for the BDF-SH SMN in a broader and more generic way. Its main purpose was to evaluate and optimize this regional SMN within a regional and national context. Study sites, sampling campaigns and analytical methods were documented from the beginning in 1989 up to the year 2008. This timeframe included only the first two main sampling campaigns. The assessment consisted of three full annual reports and an additional report on a comparison between organically and conventionally farmed BDF sites.

The main outcomes of this preliminary study and the associated reports were the following:

- According to national standards (Barth et al., 2000), the BDF-SH SMN was assessed as suitable as a long-term soil monitoring for the detection of changes in soil. This applied to the sampling strategy and design, the implementation, the farmer management questionnaire, the analytical methods and the quality and permanence of the same soil laboratory and sampling staff.
- Between the first and the second measurement campaign, there were some differences in the analytical methods (especially heavy metals) and the sampling depth increments (layer-specific, and, later, mainly depth-specific with a consideration of the layers). Although most of the different methods were regarded as comparable to each other and most of the differences in depth increments were negligible, this might potentially limit the comparability of the results of these campaigns.
- All kinds of measurement results, analytical methods, changes in methods and data collections, were depicted in a systematic way. The implemented methods were compared to the requirements of the LABO (Barth et al., 2000).
- Development of a concept for uncertainty determination and evaluation of spatial and temporal variability.
- All SMN-specific data and all measured and collected data was fully illustrated in figures and tables. Statistical land-use-specific evaluations were calculated and shown with

the software “R”. Nutrient balances and soil organic matter balances were calculated for the cropland sites.

- The measured and calculated results were partially analyzed in terms of first results, the significance of changes in soil, the nutrient balances and the impact of site-specific conditions. Although there were some single site-specific results, the main result was that most of the present timelines were still too short at the time (two main measurement campaigns) for the detection of significant changes in soil.
- Detailed comparison of organically and conventionally managed sites.
- Optimization approach: Elaborate recommendations for the future of the BDF-SH SMN. These comprised general and analytical methods, soil properties, the sampling strategy, single BDF sites and the data management. Most of the suggested recommendations were implemented from 2012 onwards.

These results were the base for four more specific research questions and studies as shown in the next section.



### 1.4 Research questions and outline

The overall aim was to (a) assess the quality of both the basic and the intensive BDF-SH SMN with national and international standards, (b) to evaluate the capability of the SMN to detect and assess soil changes and impacts of soil degradation and (c) to test its capability using process-based modeling. To date, no detailed evaluation of a regional German soil monitoring network exists. Thus, information on the quality and the capabilities of a regional German SMN would be valuable for its usefulness to detect and assess changes in soil. This especially applies to the detection and evaluation of long-term and short-term impacts of soil degradation. Based on this information, long-term soil monitoring networks as instruments to observe soil degradation and changes in soil could be used in a more adequate way. This research gap led to four central research questions.

After evaluating the BDF-SH in a regional and national context (section 1.3 Preliminary study), the first research question is meant to evaluate the quality of the BDF-SH SMN compared to international standards and international SMNs:

- **What is the quality of the BDF-SH soil monitoring network compared to international standards?**

This research question will be addressed in sections 2 and 4. Based on these findings, the BDF-SH was tested for its capability to detect and assess changes of soil properties resulting from soil degradation. Thus, the next step was to evaluate the SMN's quality in a case study related to soil degradation. Hence, research question 2 is:

- **How suitable is the specific design of the BDF-SH SMN to detect and assess impacts of soil degradation, on the base of the example of land use change from grassland to cropland?**

This research question will be answered in section 2. The aim was to determine whether the BDF-SH SMN can provide high-quality soil monitoring data to assess impacts of soil degradation. This shall be shown with the degradation example of land use change from grassland to cropland at two SMN sites. Once the question on whether the SMN is capable to provide this data can be answered positively, the next question is how the BDF-SH can provide

such monitoring data on soil degradation for process-based models. This is of special importance because modeling is a key instrument in the development of sustainable management strategies against soil degradation and because process-based environmental models rely on ground truth data. Thus, the third research question that needs to be answered concerns the inclusion of process-based modeling:

- **How can process-based modeling be combined with the BDF-SH SMN monitoring data to detect and assess effects of soil degradation on the base of the example of wind erosion?**

This research question will be investigated in section 3. The process-based wind erosion model SWEEP will be modified and used to determine whether measured long-term SOC losses at two SMN sites can be explained by wind erosion. The previous steps focus on the basic SMN. However, at five sites, an intensive soil monitoring (I-BDF-SH) exists where soil changes are measured in a higher temporal resolution. Hence, reviewing the intensive soil monitoring and testing its capability using process-based modeling raises the following question:

- **How suitable is the specific design of the intensive I-BDF-SH SMN to detect and assess soil property changes and which benefits does it have compared to process-based modeling approaches and basic soil monitoring?**

The main focus will be to investigate whether and under which circumstances annual soil carbon and nutrient measurements are more beneficial within this the BDF-SH SMN than common five- to ten-year measurement intervals using modeling and nutrient balances. This research question will be addressed in section 4. In the end, the quality of the basic and the intensive long-term soil monitoring of Schleswig-Holstein will have been evaluated, including their capacities for process-based modeling. Having addressed these central research questions, the conclusion (section 5) discusses the research questions, the possibilities and limitations and will give an outlook.



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## 2 Long-term monitoring of soil quality changes in Northern Germany

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### Abstract

The German regional long-term soil monitoring network (SMN) BDF-SH (Boden-Dauerbeobachtung Schleswig-Holstein) was assessed focusing on the quality of this soil monitoring network to detect and evaluate impacts of land-use change (LUC) from pasture to arable land on soil organic carbon (SOC) and biological soil properties. This included a review and evaluation of the monitoring methods to detect long-term SOC changes over time. Two loamy LUC study sites were selected from the monitoring program. The BDF-SH is not only focusing on monitoring of soil organic carbon but also on a wide range of data of soil chemistry, physics, biology and management at field scale. The quality of the SMN as a SOC monitoring was assessed using a catalogue of essential soil monitoring requirements which resulted in a classification of monitoring levels for each parameter. A SMN-specific method is given how to calculate SOC stock changes over time. Within seven and one year(s) respectively the conversion from pasture to arable land resulted in significant SOC losses of 19.4 Mg ha<sup>-1</sup> (19.8%) at the sandy loam site 11 and 27.2 Mg ha<sup>-1</sup> (20.2%) at the clay loam site 13. SOC measurements and microbiological parameters of the soil microbiological program confirmed and defined the results of the main program more precisely. Soil faunistic results underlined the impact of LUC on the soil ecosystem. Using evaluation schemes of the literature the quality of the SMN was evaluated as highly suitable to detect and evaluate SOC stock changes over time and further LUC impacts on the soil. Most of the assessed monitoring parameters of the SMN were evaluated as fulfilling the highest level. However, a SOC fractionation method could be included in the SMN to enable an even more thorough evaluation of SOC stock changes using SOC fraction measurements in process-based SOC modeling.

**Keywords**

Long-term soil monitoring; soil monitoring network; soil sampling design; land-use change; soil organic carbon; SOC loss; Schleswig-Holstein, soil biology; Northern Germany; Stagnosols; Planosols

**2.1 Introduction****2.1.1 Introduction to long-term soil and soil organic carbon (SOC<sup>1</sup>) monitoring types**

Changes of soil properties over time, e.g. SOC loss, as a consequence of soil degradation are focal points in recent literature (FAO & ITPS, 2015; Lal, 2014; BIO Intelligence Service, 2014; Louwagie et al., 2009). Soil degradation can develop through land-use change (LUC), erosion, compaction or contamination and may have impact on soil properties. Therefore, soil properties have to be monitored (Jandl et al., 2014). As soil properties change slowly, a long-term monitoring is essential for the assessment of changes in soil and the development of sustainable management strategies against soil degradation.

Long-term soil monitoring systems are well known in literature. Morvan et al. (2008) showed the concept of soil monitoring networks (SMNs). The authors defined them as “a set

**<sup>1</sup> Abbreviation list:**

BDF	Long-term soil monitoring (Boden-Dauerbeobachtung)
BDF-SH	Long-term soil monitoring of Schleswig-Holstein (Boden-Dauerbeobachtung Schleswig-Holstein)
BDF site	Long-term soil monitoring site (Boden-Dauerbeobachtungsfläche)
CFE	Chloroform-fumigation extraction
$C_{mic}$	Microbial biomass
$C_{org}$	Organic carbon concentration
DIN	German Industry Standard (Deutsches Institut für Normung)
LTSE	Long-term soil experiments
LUC	Land-use change
$qCO_2$	Metabolic ratio
$RESP_{Basal}$	Basal respiration
SIR	Substrate-induced respiration
SMN	Soil monitoring network
SOC	Soil organic carbon

of sites/areas where changes in soil characteristics are documented through periodic assessment of an extended set of soil parameters". The term SMN is used as well by Arrouays et al. (2012) and van Wesemael et al. (2011) who described general requirements of soil monitoring systems. Jandl et al. (2014) and Richter et al. (2007) use the term LTSE (long-term soil experiments) for a set of single long-term sites. They define LTSEs as "field experiments with permanent plots that are periodically sampled to quantify soil change across decadal time scales" (Jandl et al., 2014). Both authors see LTSEs as highly relevant for a SOC monitoring.

### **2.1.2 Introduction to the SMN "Boden-Dauerbeobachtung"**

The German long-term soil monitoring program "Boden-Dauerbeobachtung" (BDF) (Prechtel et al., 2009; Schröder et al., 2003, 2004; Kaufmann-Boll et al., 2012; Nерger, 2010; Barth et al., 2001; Huschek and Krenzel, 2004) is a SMN existing since 1985. The monitored sites are called "Boden-Dauerbeobachtungsflächen" (long-term soil monitoring sites; BDF sites), which are 0.1 ha sized squares inside a field. Agriculturally used BDF sites are managed by farmers with contractual obligation to report all management actions to the responsible regional authorities (Huschek and Krenzel, 2004). The topsoil material of the BDF sites is sampled at regular time intervals (6 to 10 years) using standard soil monitoring techniques. Additionally, at currently five sites there is an intensive monitoring, which includes an annual soil sampling, a biweekly atmospheric deposition sampling and a weekly leachate sampling.

The focus of this study is the long-term soil monitoring program in Schleswig-Holstein (BDF-SH) (Nерger, 2010; Cordsen, 1993). Within the BDF-SH program there are currently 37 BDF sites monitored, which were selected representatively based on landscape units, soil types and land use management (Nерger, 2010; Schröder et al., 2003, 2004). The recent literature for SOC and soil monitoring mainly describes monitoring aims for accomplishing information on the regional scale (e.g. Morvan et al., 2008; Jandl et al., 2014; Arrouays et al., 2012; van Wesemael et al., 2011; Prechtel et al., 2009). Opposite to that the main focus of the BDF-SH program lies on the observation of site-specific soil properties and processes which shall be representative for the related landscape unit, soil type and land use management.

In addition to the BDF-SH program there are further regional BDF programs in Germany (e.g. Bavaria, Lower Saxony). They follow the same main guideline (Barth et al., 2001) which includes site installation and maintenance, major sampling strategies, etc., but specific rules (e.g. amount of composite samples, sampling intervals) can be implemented flexibly. Furthermore, the BDF-SH program can be compared to other SMNs, such as the national long-

term soil monitoring of Switzerland (Nationale Bodenbeobachtung der Schweiz (NABO); Desaules et al., 2010; Nерger, 2010).

### **2.1.3 Focal points of a soil/SOC monitoring**

Jandl et al. (2014) state that for the assessment of SOC pool changes and even ecosystem processes soil monitoring programs or repeated soil inventories are necessary. Thereby, the benefit of SMNs/LTSEs increases with their age (Richter et al., 2007). Therefore, a reliable database for quantifications of SOC and other soil chemical, physical and biological properties is essential to assess soil degradations and long-term changes of soil properties. Especially in the context of climate change long-term observations become indispensable. A long-term soil monitoring features several focal elements (Jandl et al., 2014; Arrouays et al., 2012; van Wesemael et al., 2011; Morvan et al., 2008). Among them are the specific sampling design (sampling depth, amount of composite samples, etc.), aspects of SOC change detection (measurement method, SOC stock calculation method, uncertainty determination, sampling interval, trend, etc.) and other topics (e.g. sampling archives and change of staff for field survey and laboratory).

Specifically focusing on a long-term soil carbon monitoring system the most important requirement is its capability to detect changes in SOC stocks. Ellert and Bettany (1995) proposed a basic method for the calculation of SOC stocks. They found that when comparing temporal changes of SOC stocks the soil mass needs to remain equivalent, if there is no erosion influence. Ellert et al. (2002) confirmed this finding with the measurement of coal dust addition to soils of microsites. The subsequently measured effective SOC recovery did not result from the fixed volume (fixed depth without considering soil thickness or mass) method, but from using the equivalent soil mass method described in Ellert and Bettany (1995). Mikha et al. (2012) focused on the differences in fixed-depth and equivalent soil mass sampling as well and concluded that the equivalent soil mass approach is more exact. The sample depth was also a central point in the study of VandenBygaart et al. (2011), the authors found that land management induced changes (tillage, forage, crop types) of SOC stocks of  $5 \text{ Mg ha}^{-1}$  can be assessed correctly only with samples of  $> 15 \text{ cm}$  depth.

### **2.1.4 Land-use change – grassland to cropland**

Land-use change (LUC; conversion) in general is closely connected to SOC balances (Poeplau et al., 2011). Whereas LUC from cropland to pasture or forest serves positive SOC balances through SOC sequestration, LUC to cropland usually results in SOC loss (Guo &

Gifford, 2002). Therefore, LUC to cropland can be a cause of soil degradation and SOC loss its effect. LUC from grassland to cropland can result in a loss of up to ~50 % (Guo & Gifford, 2002) for sites of >35 years of pasture prior to LUC and >500 mm precipitation. A recent review of Wei et al. (2014) revealed Other authors found average SOC losses of  $36.1 \pm 4.6$  % within 17 years to equilibrium (Poeplau et al., 2011) and  $24 \pm 5$  Mg C ha<sup>-1</sup> for a depth of 0-30 cm (Poeplau & Don, 2013). Soussana et al. (2004) collated results of SOC loss by LUC in France from the INRA database and showed an average loss of 19 Mg C ha<sup>-1</sup> (32% of the initial average SOC stock) for a period of 20 years. A recent study for a poorly drained clay loam in Ireland (Necpalova et al., 2014) resulted in a SOC loss of ~22 % ( $32.2$  Mg C ha<sup>-1</sup>) during 2.5 years. For Northern Germany Strebel et al. (1988) studied a sandy soil in Lower Saxony and found a SOC loss of 58% ( $100$  Mg C ha<sup>-1</sup>) after 2-4 years of LUC. The soil properties affected by land-use change have been observed on the long-term monitoring BDF sites in Schleswig-Holstein (Germany) since two decades (LLUR, 2010).

### 2.1.5 Research gap and aims

To date there is neither an international publication presenting a specific regional long-term soil monitoring network in Germany and evaluating its quality, nor a peer-reviewed result of long-term SOC loss through LUC from such a SMN. This study aims to evaluate the specific design and structure of the BDF-SH program regarding its suitability to assess effects of soil degradation - exemplarily SOC loss and further impacts on soil water parameters and microbiologic and faunistic soil properties - through LUC considering different sampling and analytical methods at two study sites. Additionally, other impacts on SOC stocks shall be determined. Furthermore, the quality of the monitoring program will be assessed using scientific characteristics suggested in the relevant literature (Arrouays et al. (2012), Jandl et al. (2014), van Wesemael et al. (2011) and Morvan et al. (2008). The analysis of these focal points shall elaborate how the BDF-SH program may be used to assess long-term changes of soil properties and monitor land-use change impacts on soil. An associated topic is the optimization of the program. Which measures should be undertaken to make the program more adequate to answer these questions?



## 2.2 Material and Methods

### 2.2.1 Evaluation of the monitoring network

As a first step essential requirements and sampling effort parameters of soil and soil carbon monitoring networks which were realized in the BDF-SH SMN or described in the literature (Jandl et al., 2014; Arrouays et al., 2012; van Wesemael et al., 2011; Morvan et al., 2008) were evaluated for the BDF-SH program. Among them were the specific sampling design (samples per plot, sampling depth, bulk density, soil biology, stoniness, etc.), aspects of SOC change detection (measurement method, SOC stock calculation method, uncertainty determination, sampling interval, trend, fractionation, etc.) and other topics (e.g. management database, sampling archives and change of field survey and laboratory staff).

The second step was to rank the sampling effort parameters of the BDF-SH program using the proposed hierarchy of sample effort levels of SMNs/LTSEs of Jandl et al. (2014). The authors pointed out four different effort levels, ranging from Level 1 with no statistical design to Level 2 (random sampling), to Level 3 (stratified random sampling) and Level 4 (nested sampling design). The further monitoring parameters were ranked due to the recommendations of the literature (Arrouays et al., 2012; van Wesemael et al., 2011; Morvan et al., 2008) or of this study.

### 2.2.2 LUC study sites

Figure 6 shows the localization of all BDF sites in the federal state of Schleswig-Holstein. The LUC study sites BDF 11 (Lehmsiek) and BDF 13 (St. Peter-Ording) are located in the High Geest region and the Marshland region respectively.

## 2.2 Material and Methods

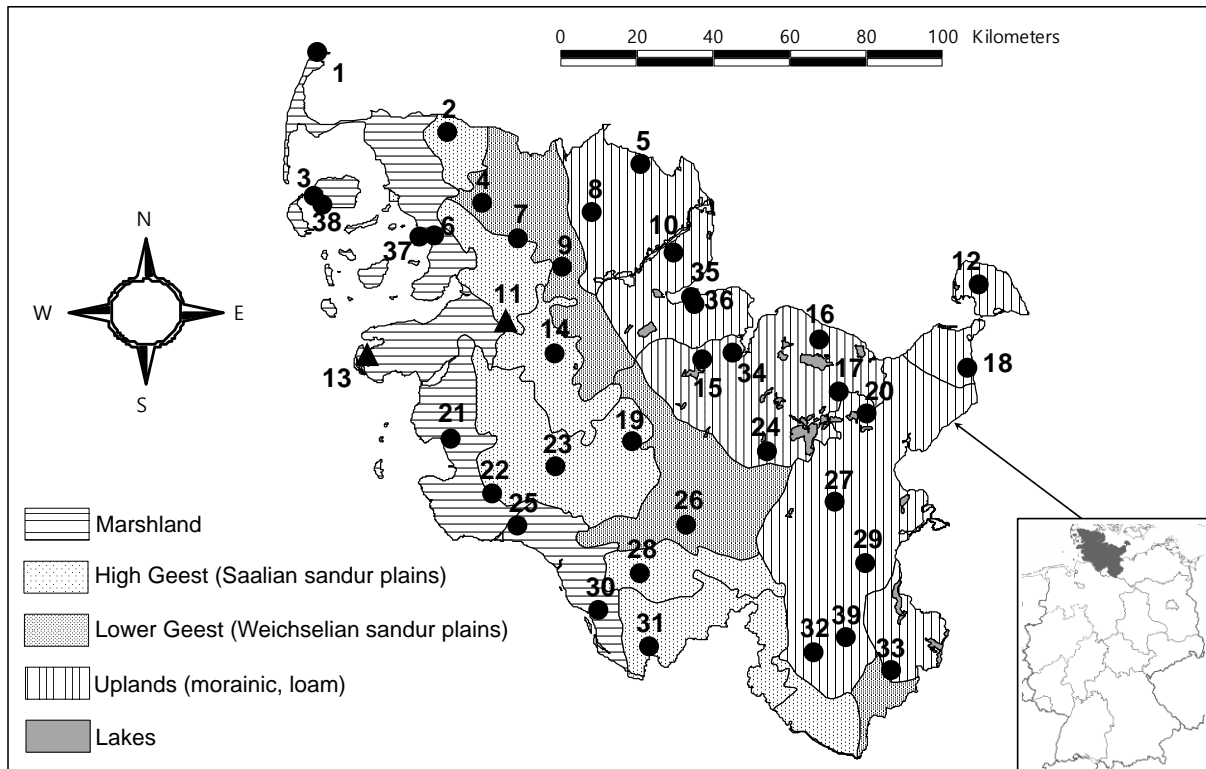


Figure 6: Natural landscape units of Schleswig-Holstein (Northern Germany) and localization of the long-term soil monitoring sites. The sites 11 and 13 (triangle symbols) are the LUC study sites described in detail in this study; database: LLUR (2010)

Table 5 shows basic characteristics of the LUC study sites. They differ largely in their parent material and soil texture. Site 11 is dominated by a sandy loam texture originated from a glacial (Saalian stage) moraine ridge, whereas site 13 (land diked in 1150 AD) is characterized by Holocene marine silt and clay material. Both sites are influenced by groundwater or temporary stagnating water.

The sites were used as pasture a long time period. From 2002 (site 11) and 2009 (site 13) the fields were converted to arable land and are mainly cultivated with maize. Site 11 features a subterranean drainage since 1976. Site 13 is drained by surface ditches, additionally a wastewater treatment plant was installed at the end of the year 1995 directly adjacent to the monitoring site, which led to a lowering of the groundwater table (LLUR, 2010).

Table 5: Basic characteristics of the study sites for land-use change; database: LLUR (2010)

	site 11	site 13
location	Lehmsiek	St. Peter-Ording
landscape unit + (subunit)	High Geest (Bredstedt-Husumer Geest)	Marshland (Eiderstedter Marsch)
mean annual temp. (°C) 1981-2010	8.7	9.2
local geological situation	Saalian moraine ridge (Drenthe substage)	Holocene Marshland
parent material	loamy periglacial flow till over glacial loam and clay	tidal-brackish loam over tidal-brackish clay
soil texture*	sandy loam (64% sand, 23% silt, 13% clay)	clay loam (21% sand, 41% silt, 38% clay)
soil type class*	Stagnosols	Planosols
historic land use	pasture (at least since 1930)	pasture (at least since 1945)
conversion date (dd/mm/yyyy)	24/03/2002	25/04/2009
present land use	maize monoculture since 2002 and maize-wheat rotation since 2007	maize 2009, grassland 2010
ploughing	annually (since 2002, except 2009) in spring; 1993 ploughing (no conversion) with immediate land packer compaction	2009 spring only (ploughing up grassland)
organic fertilizers	annually, ~0.1-0.2 Mg C ha <sup>-1</sup> y <sup>-1</sup>	annually, ~0.2-0.4 Mg C ha <sup>-1</sup> y <sup>-1</sup>

\* (IUSS, 2006)

### 2.2.3 Sampling campaigns and strategies

#### 2.2.3.1 Campaigns and sampling intervals

The measurement campaigns and the sampling depths for each program are shown in Table 6. The measurement campaigns consist of the main program ( $C_{org}$ , dry bulk density and soil chemistry), the microbiological program ( $C_{org}$ , dry bulk density, soil microbiology) and the faunistic program (earthworms and microannelids).

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Table 6: Sampling programs, campaigns and characteristics of the study sites for land use; database: LLUR (2010)

programs and campaigns	site 11						site 13					
	sampling dates	land use	amount of sample depth increments		average undermost sampling depth in topsoil [cm]		sampling dates	land use	amount of sample depth increments		average undermost sampling depth in topsoil [cm]	
			SOC calculation	sam-pled	sam-pled	sam-pled			SOC calculation	sam-pled	sam-pled	sam-pled
Main program					CH	PH					CH	PH
1 <sup>st</sup>	15-27 Oct 1992	PA	2-3	2-3	29.8	30	02-08 Jul 1991	PA	3-6	3-6	10	30
2 <sup>nd</sup>	26 Jul 1999	PA	3-4	1*	5	5	28 Jul 1999	PA	4-7	1*	5	5
3 <sup>rd</sup>	14 Oct 2009	CL	1	1	28.4	5	19 Mar 2009	PA	4-7	1*	5	5
4 <sup>th</sup>	-	-	-	-	-	-	10 May 2010	CL	1	1*	30	5
Micro-biological program												
1 <sup>st</sup>	20 Mar 1996	PA	3-4	1*	10	5	20 Mar 1996	PA	3-4	1*	10	5
2 <sup>nd</sup>	31 Mar 1999	PA	3-4	1*	10	5	31 Mar 1999	PA	3-4	1*	10	5
3 <sup>rd</sup>	06 Mar 2002	PA	3-4	1*	12.3	5	06 Mar 2002	PA	3-4	1*	10.5	5
4 <sup>th</sup>	21 Mar 2005	CL	1	1	30	5	07 Apr 2006	PA	3-4	1*	10	5
5 <sup>th</sup>	01 Apr 2010	PA/CL	1	1	30	5	01 Apr 2010	CL	1	1	30	5
Faunistic program												
			EWs	MAAs	EWs	MAAs			EWs	MAAs	EWs	MAAs
1 <sup>st</sup>	27 Oct 1994	PA	1	4	20	10	24 Oct 1995	PA	1	4	20	10
2 <sup>nd</sup>	27 Nov 2000	PA	1	4	20	10	30 Oct 2002	PA	1	4	20	10
3 <sup>rd</sup>	05 Dec 2007	CL	1	4	20	24	28 Nov 2008	PA	1	4	20	10
4 <sup>th</sup>	15 Nov 2013	PA	1	4	20	10	-	-	-	-	-	-

Legend: 1\* = the uppermost layer; CH = chemistry; PH = physics; PA = pasture; CL = cropland; EWs = earthworms; MAAs = microannelids

### 2.2.3.2 Sampling scheme and composite samples

The general sampling scheme of a long-term soil monitoring site with its sample points for soil chemistry, physics, microbiology, fauna and vegetation is shown in Figure 7. Each point on the two crossing diagonals was sampled twice using core samplers of 1 m depth driven into the soil with a motor hammer. The soil material in the sample cores was described and sampled according to the instructions of the soil mapping manual of Ad-Hoc-AG Boden (1982, 1994, 2005). This included the identification and description of numerous soil horizon properties, inter alia the averaged soil horizon depths from the two sample cores, the rock fraction and the identification of non-topsoil horizon material, which was excluded from the sample cores. The subsequent main sampling campaigns were realized as shown in Figure 7b. For each sampling point the adjacent spot in 1 m distance from the original point in northern direction was sampled. For the respective following campaign, the same scheme was applied, rotating 45° clockwise.

Topsoil chemistry (pH, concentrations of organic carbon ( $C_{org}$ ), nutrients, heavy metals) and particle-size distribution (soil texture) sampling within the main campaigns was performed at each of the 18 points. Referring to the composition pattern in Figure 7 six of the 18 samples at a time were mixed to the respective composite sample for the respective soil horizon. In total three composite samples were analyzed in the laboratory within each campaign.

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Figure 7a: Design for the first sampling campaign (all sample points)

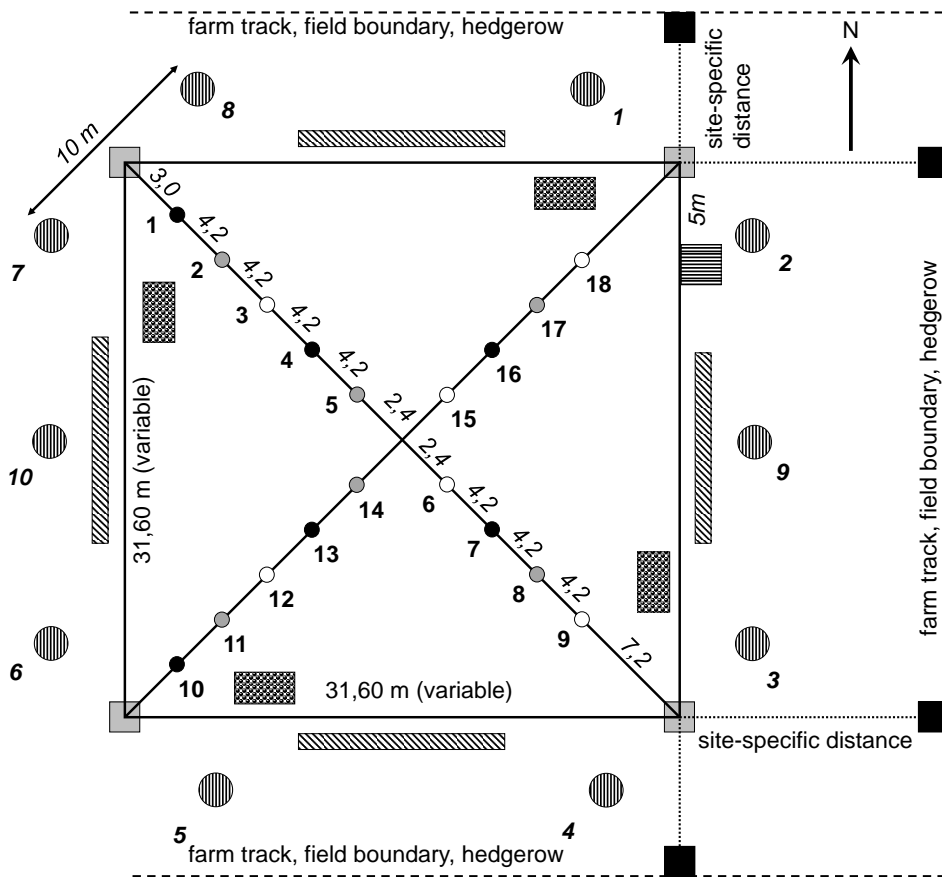
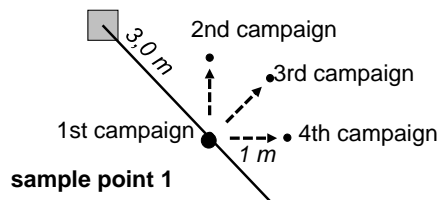


Figure 7b: Design for subsequent sampling campaigns (sample point 1)



- granite stone marks
- paving stone with magnet 50cm below surface
- main monitoring area (0.1 ha)
- ▨ main soil profile (2 m site lengths)
- sample points soil chemistry and physics (partly), composite sample 1
- sample points soil chemistry and physics (partly), composite sample 2
- sample points soil chemistry and physics (partly), composite sample 3
- ↔ distance [m] between sample points or to central marks
- ⊖ sample points (01-10): soil fauna
- ▨ sample points (01-04): soil microbiology (2m besides main monitoring area)
- ▣ sample points (01-04): vegetation (position variable depending on site)

Figure 7: Sampling design for the first and repeated sampling campaigns (main program) at the monitoring sites

Within the 1<sup>st</sup> main campaign the bulk density was sampled in the main soil profile and was adopted for the corresponding horizons of the composite sample profiles. For the 2<sup>nd</sup> campaign there was one value for each composite sample and within the 3<sup>rd</sup> campaign the six single points of the second composite sample were sampled. In this case the average results were adopted for the first and third composite sample.

For analysis of dry bulk density and saturated hydraulic water conductivity undisturbed samples in cylindrical core-cutters of 100 cm<sup>3</sup> were taken. Bulk dry density was measured gravimetrically after drying the samples at 105 °C until they reached constant weight (ISO 11272-01). The particle-size distribution was determined by gravimetric measurements based on sieving and sedimentation according to the Köhn-pipette technique (ISO 11277-08). The rock fraction was determined by volume in the field and converted to mass fractions using conversion tables in Ad-Hoc-AG Boden (2005). Within the sieving process rock fraction by mass was measured. Soil chemistry composite samples were analyzed for C<sub>org</sub> by oxygen combustion (ISO 10694:08 and previously destroyed carbonates) and measured with a Leco RC 412 apparatus.

### 2.2.3.3 SOC stock calculation und uncertainty determination

SOC stocks were generally calculated from SOC concentrations and soil masses (including bulk density, topsoil depth and rock fraction). Soil masses were calculated for each depth increment of a single sample point (equation 1) and multiplied with the measured carbon concentration as a fraction to obtain SOC stocks (equation 2). After that the depth increments of a single sample point were added (equation 3). The six single sample point results of a composite sample were averaged (equation 4) and the three composite samples as well to an average SOC stock of the site (equation 5).

$$SOIL_{A/Ap,Layer} = BD_{A/Ap,Layer} \times DEP_{A/Ap,Layer} \times (1 - RM_{A/Ap,Layer}) \times 100 \quad (1)$$

$$SOC_{A/Ap,Layer} = SOIL_{A/Ap,Layer} \times C_{A/Ap,Layer} \quad (2)$$

$$SOC_{A/Ap,SSP} = \sum_{i=1}^n SOC_{A/Ap,Layer} \quad (3)$$

$$SOC_{A/Ap,CS} = \frac{1}{6} \times \sum_{i=1}^6 SOC_{A/Ap,SSP} \quad (4)$$

$$SOC_{A/Ap} = \frac{1}{3} \times \sum_{i=1}^3 SOC_{A/Ap,CS} \quad (5)$$

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Where:

Layer = Layer/Horizon of the depth increments in a soil profile of a single sample point

$SOIL_{A/Ap,Layer}$  = Layer-specific soil mass in A/Ap horizon [ $Mg\ ha^{-1}$ ];

$BD_{A/Ap,Layer}$  = Layer-specific dry bulk density in A/Ap horizon [ $g\ cm^{-3}$ ];

$DEP_{A/Ap,Layer}$  = Layer-specific depth of sampled A/Ap horizon material [cm];

$RM_{A/Ap,Layer}$  = Layer-specific rock fraction by mass in A/Ap horizon [fraction];

$SOC_{A/Ap,Layer}$  = Layer-specific SOC stock in A/Ap horizon [ $Mg\ ha^{-1}$ ]

$C_{A/Ap,Layer}$  = Layer-specific SOC concentration in A/Ap horizon [fraction];

$SOC_{A/Ap,SSP}$  = Soil mass in A/Ap horizon of a single sample point within a composite sample [ $Mg\ ha^{-1}$ ];

$SOC_{A/Ap,CS}$  = SOC stock in A/Ap horizon of a composite sample [ $Mg\ ha^{-1}$ ]

$SOC_{A/Ap}$  = Soil mass in A/Ap horizon [ $Mg\ ha^{-1}$ ];

The determination of SOC stock changes after LUC refers to Ellert & Bettany (1995) and Poeplau et al. (2011) using the concept of equivalent soil masses (equation 6) as land-use change often involves a change of bulk density and a change of topsoil depth (Poeplau et al., 2011). The equation is suitable for samples after LUC taken as one depth increment as in this study.

$$SOC_{corr,Ap} = \frac{BD_A \times SOC_{Ap}}{BD_{Ap}} \quad (6)$$

Where:

$SOC_{corr,Ap}$  = Corrected SOC stock in Ap horizon after LUC using equivalent soil masses [ $Mg\ ha^{-1}$ ];

$BD_A$  = Dry bulk density prior to LUC [ $Mg\ ha^{-1}$ ];

$BD_{Ap}$  = Dry bulk density after LUC [ $Mg\ ha^{-1}$ ];

$SOC_{Ap}$  = SOC stock in Ap horizon after LUC [ $Mg\ ha^{-1}$ ];

### Uncertainty determination

Uncertainty of the three (main program) or four (microbiological program) composite samples or the ten single samples (faunistic program) was determined calculating the standard deviation of the respective measurement values for the composite samples and realized as



error bars within the bar charts. The comparison of standard deviations for two average values of a time series gives information about the significance of temporal differences in the results. When the limits of the standard deviations are not overlapping each other, there is a significant temporal difference between two values.

#### 2.2.3.4 Soil biology

##### Microbiology sampling and analysis

The soil microbiological sampling (LLUR, 2010) was carried out at four lines adjacent to the borders outside of the monitoring sites (Figure 7). The sampling depths were 10 to 12.25 cm for grassland soils and 30 cm for cropland soils. In each of the sampling campaigns of 1996 and 1999 the soil material from all four sampling lines in the field was mixed to one composite sample and analyzed whereas in the subsequent campaigns four composite samples resulted for each sampling line. Therefore, the standard deviation of four analytical values (of each composite sample) is known for the sampling campaigns from 2002 only. All analytical measurements included three replicates.

Microbial biomass ( $C_{mic}$ ) was measured using two analytical techniques, on the one hand after Vance et al. (1987) with the chloroform-fumigation extraction method (CFE) and on the other hand after Anderson & Domsch (1978, cited in Heinemeyer et al., 1989) with the substrate-induced respiration method (SIR). The SIR method is of limited suitability for determining inactive biomass in water-logged soils (ISO 14240-1).

$C_{org}$  was measured after destruction of carbonates in dry combustion and thermal conductivity detection with a Variomax C/N analyzer (Elementar Analysesysteme, Germany). Bulk density was determined after Schlichting et al. (1995). For grassland soils prior to LUC the SOC stocks in the first part of the topsoil were determined as in the equations (1) and (2) and for deeper zones using the SOC stock calculations from the last complete sampling until 30 cm. After LUC the SOC stocks in cropland soils (depth 30 cm) were corrected as indicated in the equation (3).

The  $C_{mic}/C_{org}$  ratio giving information about the biological activity of the microorganisms and the C-enrichment was calculated for both  $C_{mic}$ -CFE and  $C_{mic}$ -SIR. Basal respiration ( $RESP_{basal}$ ) was measured after Heinemeyer et al. (1989) and is an indicator for the activity of the microorganisms. The metabolic ratios ( $qCO_2 = RESP_{basal}/C_{mic}$ -CFE/SIR) can indicate soil pollution, compaction or energy inefficiency of microorganisms (Tischer, 2005).

### **Soil faunistic sampling and analysis**

The soil faunistic analyses included earthworm and microannelid sampling at ten points (Figure 7) adjacent to the borders outside of the study sites (Beylich and Graefe, 2009). The earthworms were sampled by formalin extraction on a soil surface area of 0.25 m<sup>2</sup> (ISO 2006) in combination with hand-sorting. For hand-sorting two samples were taken at each sampling point using a corer of 250 cm<sup>2</sup> to a depth of 20 cm. The samples were hand-sorted in the laboratory and subsequently underwent a Kempson extraction to be sure that all individuals were found. The earthworm results comprise density/amount of individuals, biomass, species composition and composition of functional types (life forms: epigeic, endogeic, anecic).

Microannelids were sampled using a split soil corer (diameter 3.8 cm in cropland soils or 5 cm in grassland soils) (ISO, 2007; Beylich and Graefe, 2009). Each sample was divided into four subsamples (every 6 cm, in total 24 cm, in cropland soils, and every 2.5 cm, in total 10 cm, in grassland soils). The individuals were counted and identified *in vivo* after extracting the soil samples for 48 h by a wet-funnel technique without heating (following Graefe, 1984, as cited in Dunger & Fiedler, 1997, 1999; DIN ISO 2007). The results were analyzed with respect to species composition, total abundance and vertical distribution of the community as well as dominance, frequency and functional traits of individual species according to Graefe & Schmelz, 1999.

## **2.3 Results and Discussion**

### **2.3.1 Monitoring evaluation**

The comparison of the BDF-SH long-term soil monitoring revealed that it corresponds largely to the level 4 of soil sampling effort levels of Jandl et al. (2014) which the authors mentioned as necessary to allow conclusions of the SOC pool change over time (Table 7). Additionally, there was an evaluation of further important monitoring parameters (Table 7), realized in the BDF-SH SMN or highlighted in relevant studies (Arrouays et al., 2012; Morvan et al., 2008; van Wesemael et al., 2011).

Table 7: Evaluation of the BDF-SH soil monitoring network (SMN) with the monitoring effort level evaluation of Jandl et al. (2014) and further important monitoring parameters

<b>Sampling effort parameters</b>	<b>BDF-SH sampling effort using modified terms of Jandl et al. (2014)</b>	<b>BDF-SH sampling effort level</b>
	Main program	na = no comparison possible 1 = lowest, 4 = highest
Monitoring description	Nested sampling design	4
Samples per plot	>3 (18)	4
Sampling device	Pit excavation (main soil profile) and window samplers driven into the soil with a motor hammer	4
Depth	Mineral soil to bedrock	4
Layers	Several layers and pedological classification	4
Bulk density	Measurement	4
Stoniness	Visual estimation and volume measurement	3 and 4
Roots	Visual estimation	na
Superficial obstacles	Visual estimation	2
Pooling	Individual and bulk samples	2 and 4
Carbon content	Dry combustion	4
Fractionation	None	1
IR spectroscopy	-	na
Texture	Texture analysis	4
<b>Further important monitoring parameters</b>	<b>BDF-SH situation</b>	<b>BDF-SH monitoring level</b>
Site heterogeneity	minimal	highest
Topsoil sampling avoiding inclusion of subsoil material	yes	highest
No change of field survey staff	yes	highest
No change of laboratory staff	yes	highest
Sample archive	yes	highest
Site history and surrounding conditions	yes, once	high
Detailed management data on a daily base	yes	highest
Detailed soil biology and other properties (e.g. nutrients, pH, soil water)	yes	highest
Sampling interval	10 years, from 2014: 6 years	highest
Intensive monitoring	yes, at 5 sites out of 37	high
Intensive monitoring intervals		
Soil	annual	highest
Atmospheric deposition	biweekly	highest
Leachate	weekly	highest
Regional scale results	site scale only	[level depends on monitoring focus]

The results show that the BDF-SH SMN is capable to detect and evaluate SOC stock changes over time as these criteria were described in the relevant literature of Arrouays et al. (2012), Jandl et al. (2014), van Wesemael et al. (2011) and Morvan et al. (2008). Almost all relevant monitoring parameters (Table 7) are at the highest level and characterize not only a SOC but a soil monitoring network (SMN) which fulfills the requirements of a long-term monitoring of various soil properties.

Until present a carbon fractionation is not included in the BDF-SH SMN and might reveal more details of the causes of SOC changes. However, within a complete soil monitoring the interpretation of the carbon data is mainly drawn upon additional measured or gathered data as site surroundings mapping, soil biology, nutrients, soil water, groundwater and detailed management data.

### 2.3.2 SOC stock changes through LUC

Figure 9 and Table 8 show the SOC stocks measured within both the main program and the microbiological program at the study sites 11 and 13. At site 11 the results of the different analytical methods (LECO infrared detection vs. VARIOMAX thermal conductivity detection) show comparable values. At site 13 the results of the VARIOMAX method are about 20-25% lower than those of the LECO method. However, both methods show the same trend in every respect. For the pasture phase both sites show a SOC stock increase of 3.0 Mg C ha<sup>-1</sup> (site 11) and 4.8 Mg C ha<sup>-1</sup> (site 13 between 1999 and 2009). The conversion from grassland to arable land led to significant SOC stock decreases on both sites. At site 11 the SOC stock decreased about 19.4 Mg ha<sup>-1</sup> from 1999 to 2009 (main program) which corresponds to a loss of 19.8% (Table 8). The measurements within the microbiological program showed losses of 18.0 Mg ha<sup>-1</sup> (19.2%) between 2002 and 2005.

At site 13 the SOC stock loss through conversion was 27.2 Mg ha<sup>-1</sup> (20.2%) within the measurements of the main program and 28.4 Mg ha<sup>-1</sup> (26.0%) in the measurements of the microbiological program. However, as the conversion date at site 13 was in spring 2009 and the last soil samplings in spring 2010 the SOC loss might be quantified more intense in later measurement campaigns. At site 13 there is a further and earlier significant SOC loss between the years 1996 and 1999. As described in section 2.2.2 a wastewater treatment plant was installed adjacent to the site in autumn 1995, which led to a lowering of the groundwater table between 1995 to 2000 (Figure 8). Whereas in prior years the groundwater reached the surface and the topsoil for various week, from 1995 to 2000 it was few weeks only.

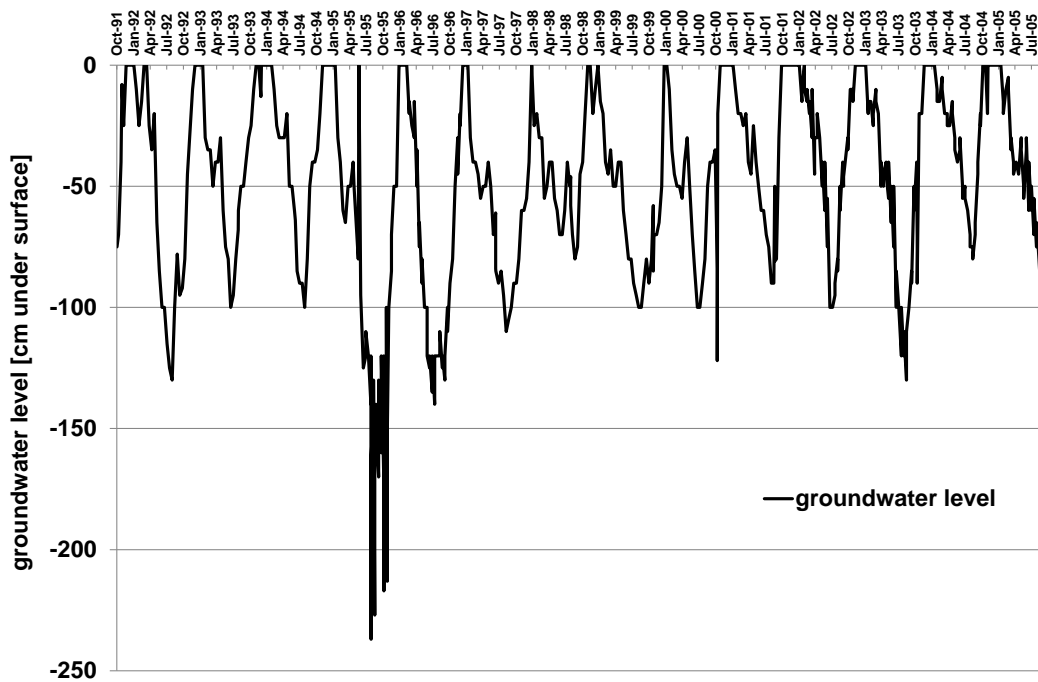


Figure 8: Measured groundwater levels of the measurement campaigns (measured biweekly) within the main program at site 13; database: LLUR (2010)

Thus, the measured SOC losses at both measurement programs at site 13 show the SOC loss which occurred through the lowering of the groundwater table until 1999 and which had larger dimensions ( $28.4 \text{ Mg ha}^{-1}$  corresponding to 18.0% in the main program and  $32.2 \text{ Mg ha}^{-1}$  corresponding to 24.3% in the microbiological program (Table 8) compared to the SOC loss by conversion. Combining the total time span including both types of SOC loss, at site 13 there was a SOC loss of  $50.8 \text{ Mg ha}^{-1}$  (32.1%) and  $51.7 \text{ Mg ha}^{-1}$  (38.9%) respectively, from 1991-2010. For the pasture phases prior to LUC both sites show SOC stock increases (at site 13 from 1999).

## 2.3 Results and Discussion

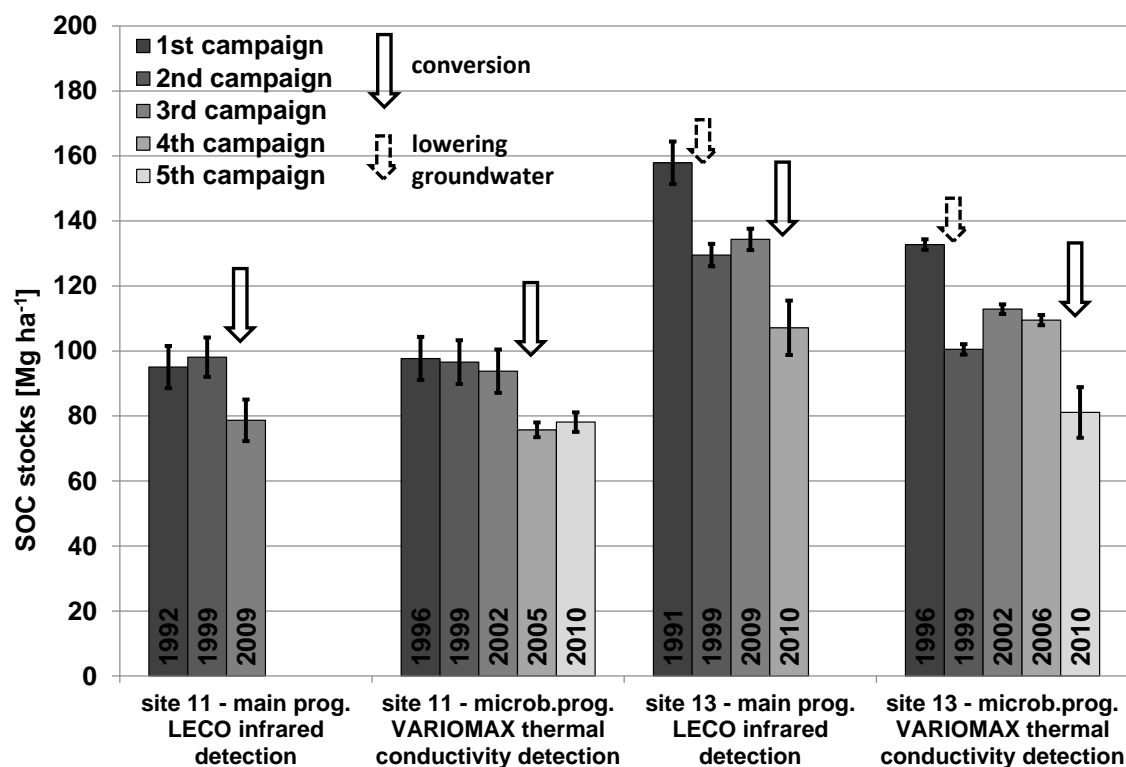


Figure 9: Measured SOC stocks of the measurement campaigns with standard deviations within the main program and the microbiological program at the LUC study sites; database: LLUR (2010)

Table 8: Measured SOC stock changes of the main program (all changes) and microbiological program (losses only) and relation to agricultural management at the LUC study sites 11 and 13

campaigns and years		SOC loss		relation	
		Mg ha <sup>-1</sup>	%		
site 11 main program	1st to 2nd	1992 to 1999	3.0	3.2	grassland SOC increase prior to conversion
	2nd to 3rd	1999 to 2009	<b>-19.4</b>	<b>-19.8</b>	<b>conversion</b>
	1st to 3rd	1992 to 2009	-16.4	-17.2	conversion incl. prior SOC increase
site 11 microbiol. program	3rd to 4th	2002 to 2005	<b>-18.0</b>	<b>-19.2</b>	<b>conversion</b>
	3rd to 5th	2002 to 2010	-15.7	-16.7	conversion incl. later management
site 13 main program	1st to 2nd	1991 to 1999	-28.4	-18.0	lowering groundwater table
	2nd to 3rd	1999 to 2009	4.8	3.7	grassland SOC increase prior to conversion
	3rd to 4th	2009 to 2010	<b>-27.2</b>	<b>-20.2</b>	<b>conversion</b>
	2nd to 4th	1999 to 2010	-22.4	-17.3	conversion incl. prior SOC increase
	1st to 4th	1991 to 2010	-50.8	-32.1	conversion incl. prior SOC loss by lowering groundwater table
site 13 microbiol. program	1st to 2nd	1996 to 1999	-32.2	-24.3	lowering groundwater table
	4th to 5th	2005 to 2010	<b>-28.4</b>	<b>-26.0</b>	<b>conversion</b>
	1st to 5th	1996 to 2010	-51.7	-38.9	conversion incl. prior SOC loss by lowering groundwater table

The results of SOC losses through LUC from pasture to cropland are comparable to the literature as the following literature study results show. The loss of  $24 \pm 5 \text{ Mg C ha}^{-1}$  for six sites (two in Northern Germany) presented by Poeplau & Don (2013) is quite close to the results of this study. In their review article Poeplau et al. (2011) collated average SOC losses through LUC from a large amount of study sites, including several sites in Germany. Although including a wider range of site conditions the results can be used as background levels. Poeplau et al. (2011) found an average SOC loss of 36% but mentioned a duration of 17 years until an equilibrium of the SOC stock was reached. The sites in our study were sampled seven and one year after conversion, therefore it seems possible that a higher SOC loss might occur in the future. This could be the reason why the results of our study do not correspond to the findings of Guo & Gifford (2002), who reported SOC losses of ~50 % for sites of >35 years of pasture prior to LUC and >500 mm precipitation. The results from Necpalova et al. (2014) resulted in a SOC loss of ~22 % ( $32.2 \text{ Mg C ha}^{-1}$ ) during 2.5 years are for similar soil conditions (clay loams) as site 13 and fit almost exactly to the results of site 13 (~20 % ( $27.2 \text{ Mg C ha}^{-1}$ )). Furthermore, the authors mentioned that 86% of the loss has been taken place within the first four months, thus it fits even better to the 20% loss at site 13 after one year. Some high SOC losses from LUC studies of Northern Germany (Strebel et al., 1988; Springob et al., 2001) can be adopted only partially, because the studied sites were largely sandy.

The BDF-SH SMN does not rely on SOC measurements only, but as well on further soil properties as soil physics and biological measurements. Figure 10 shows that after LUC the water content at wilting point ( $pF > 4.2$ ) decreased significantly at both study sites. On the other hand, the macropores ( $pF < 1.8$ ) increased.

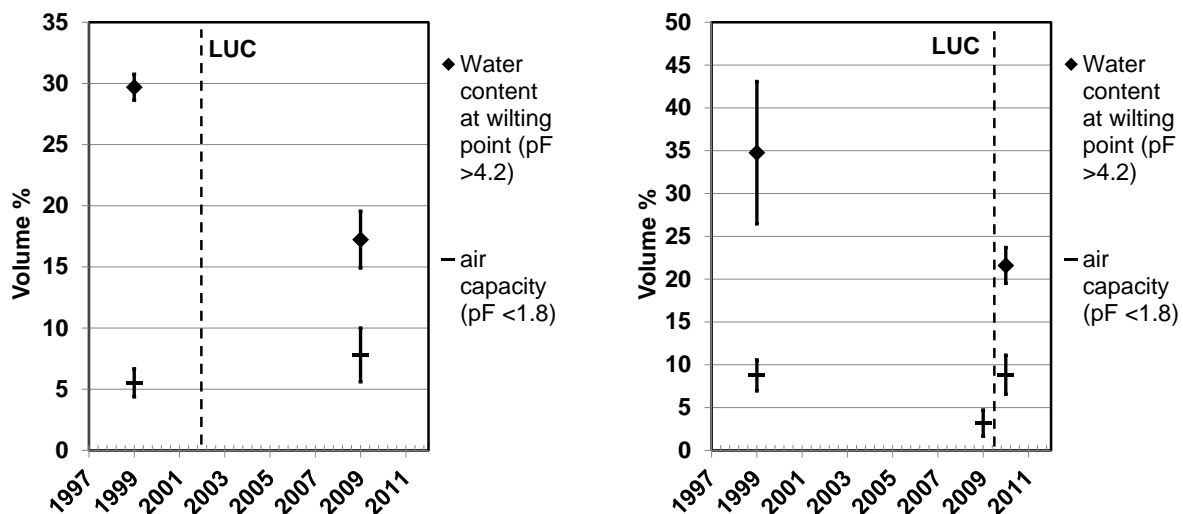


Figure 10: Measured water contents at the permanent wilting point and air capacity within the main program at the LUC study sites 11 (left) and 13 (right); database: LLUR (2010)

## 2.3 Results and Discussion

Strebel et al. (1988) showed that LUC impacts the soil water properties. The relative share of micro-pores, i.e. soil water content at permanent wilting point and higher, decreases while air capacity increases. Kuka et al. (2007) described that the stabilized soil carbon is mainly localized in these micro-pores. Therefore, the decrease of micro-pores through LUC shows that after conversion less stabilized carbon was available, which probably contributed to the total SOC decrease after LUC.

### 2.3.3 LUC impacts on soil microbiologic and faunistic parameters

Table 9 shows the measurements of microbial biomass ( $C_{mic}$ ; CFE and SIR methods) in the same years as the SOC stocks of the microbiological program mentioned above. The values show similar tendencies as the SOC stocks but are more distinct. The conversion from grassland to arable land was associated with a significant lowering of microbial biomass for both analytical methods, CFE and SIR. Thus,  $C_{mic}$  is a fast indicator for changes in soil. At site 11 the second measurement after conversion shows slight but significant increases of  $C_{mic}$  which could be probably due to a recuperation of the microbial community after the conversion.

Table 9: Measured microbiological parameters at the monitoring sites 11+13 within the microbiological measurement campaigns 1996-2010; database: LLUR (2010)

parameters	unit	site	1 <sup>st</sup> campaign		2 <sup>nd</sup> campaign		3 <sup>rd</sup> campaign		4 <sup>th</sup> campaign		5 <sup>th</sup> campaign			
			mean	$\pm$ SD	mean	$\pm$ SD	mean	$\pm$ SD	mean	$\pm$ SD	mean	$\pm$ SD		
$C_{mic}$ (CFE)	$\mu\text{g C g}^{-1}$ soil d. m.	11	1004	-	259	-	623	20	318	*	19	364	*	12
		13	2104	-	263	-	1087	177	1775	*	190	399	*	30
$C_{mic}$ (SIR)	$\mu\text{g C g}^{-1}$ soil d. m.	11	-	-	529	-	699	81	302	*	13	492	*	31
		13	-	-	670	-	924	302	1228		84	406	*	17
RESP <sub>basal</sub>	$\mu\text{g CO}_2 \text{ g}^{-1}$ soil d.m. h <sup>-1</sup>	11	-	-	0.61	-	1.29	0.12	0.50	*	0.04	0.70	*	0.07
		13	-	-	0.70	-	2.29	0.36	1.43	*	0.13	0.53	*	0.07
$C_{mic}/C_{org}$ (CFE)	[dimension- less]	11	3.03	-	0.85	-	2.00	0.15	1.60	*	0.06	1.78	*	0.09
		13	2.89	-	0.81	-	2.07	0.41	3.00	*	0.21	1.76	*	0.15
$C_{mic}/C_{org}$ (SIR)	[dimension- less]	11	-	-	1.75	-	2.24	0.40	1.52	*	0.09	2.40	*	0.20
		13	-	-	2.06	-	1.76	0.53	2.07		0.27	1.79		0.23
qCO <sub>2</sub> (CFE)	[dimension- less]	11	-	-	2.36	-	2.06	0.17	1.57	*	0.21	1.91	*	0.25
		13	-	-	2.06	-	1.76	0.53	2.07		0.27	1.79	*	0.23
qCO <sub>2</sub> (SIR)	[dimension- less]	11	-	-	1.15	-	1.84	0.24	1.66		0.06	1.42	*	0.11
		13	-	-	1.04	-	2.48	1.63	1.17		0.17	1.29		0.23

SD = standard deviation; \* = significant change (data available from 3rd to 4th and 4th to 5th campaign only)



The following measured parameters and indicators of the microbiological program confirm the  $C_{mic}$  measurements. Basal respiration and  $C_{mic}/C_{org}$  ratio decreased significantly after conversion at both study sites, which indicated a lowered microbiological activity. On the other hand, the metabolic ratio ( $qCO_2$ ) increased after conversion at both study sites, pointing out a disorder of the microbiological community. The results show a disturbed soil ecosystem and correspond to the changes of the chemical and physical soil properties.

A further proxy of the soil ecosystem change after the conversion is provided by the soil fauna (Figure 11 and Figure 12). At site 11 earthworm density and biomass decreased significantly after conversion (sampling 2007). This is mainly attributed to the disturbance caused by tillage (Ernst & Emmerling, 2009) and to changed food supply (Van Capelle et al., 2013). While the earthworm population in general is damaged directly by tillage, ploughing reduces food availability on the soil surface thus impairing in particular the surface feeding species (epigeic and anecic life form type). Further, ploughing disrupts repeatedly the permanent burrows of anecic species. The conversion from grassland to arable land therefore strongly affected the anecic and epigeic species, resulting in a higher percentage of endogeic biomass after conversion (Table 10). In 2013 the lumbricidae population had recuperated and showed levels as prior to the conversion. While earthworm abundance and biomass were rather high for the first two sampling campaigns in comparison with reference values for grassland sites, in 2007 the values were rather low, but still within the reference range for agricultural field site after LUC (Beylich and Graefe, 2009).

The total number of microannelids also decreased significantly at site 11 after LUC. The decline was especially pronounced in the uppermost 6 cm (Figure 12). This was accompanied by a partial shift of microannelids to lower horizons (12 to 24 cm), which are not sampled at grassland soil monitoring sites, assuming a very low amount of soil fauna there. After conversion, due to tillage the organic material (i.e. food resources) was distributed in the whole plough layer. Subsequently there was a considerable amount of microannelids also in the deeper parts of the topsoil.

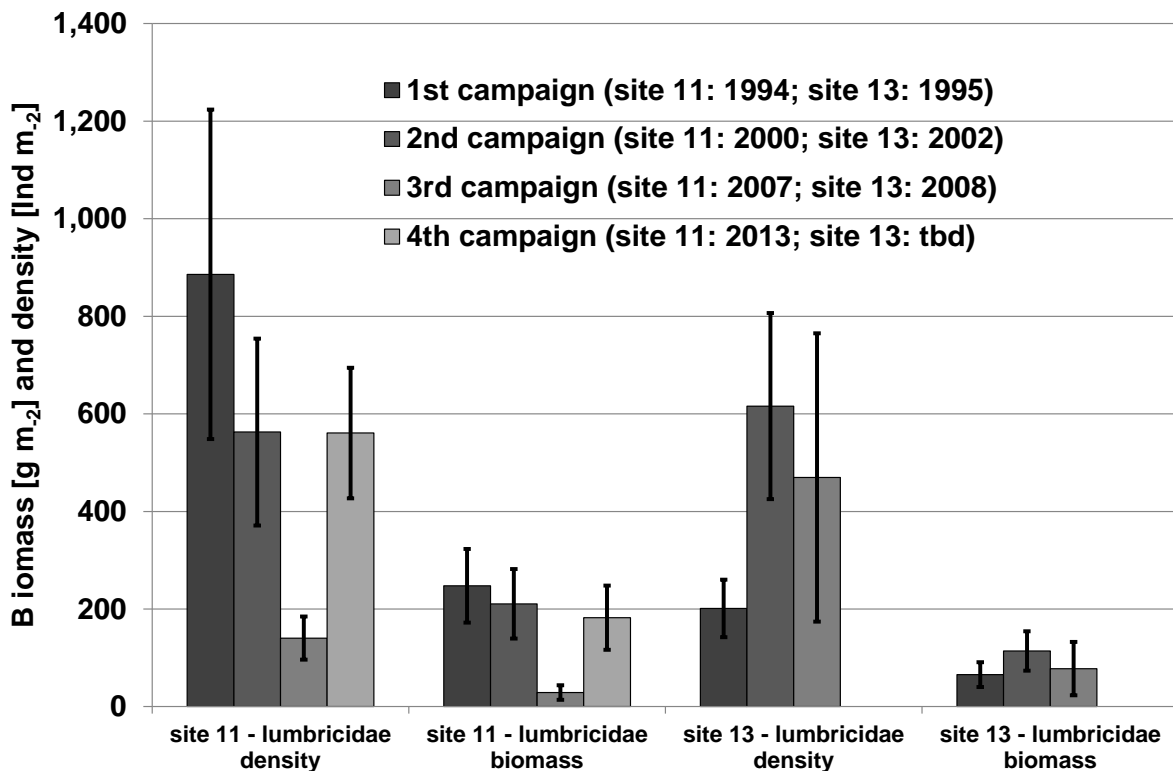


Figure 11: Lumbricidae densities and biomasses for the study sites 11 and 13 within the soil faunistic measurement campaigns 1994-2013; database: LLUR (2010)

Table 10: Lumbricidae life form types for the study sites 11 and 13 within the soil faunistic measurement campaigns 1994-2013; database: LLUR (2010)

sampling campaign	epigeic %	endogeic %	aneic %
1994	5.9	51.8	42.3
2000	5.5	53.1	41.3
conversion 2002			
2007	5.2	77.6	17.2
2013	10.6	74.7	14.7

The species composition changed after conversion (Figure 12). The abundances of most species decreased after conversion (especially *Fridericia*-species), whereas one species (*Marionina argentea*), indicating wet conditions and oxygen deficiency, increased. This is possibly induced by an increase of stagnant moisture due to soil compaction by more frequent traffic. Four years after reconversion to grassland, the vertical distribution resembles the situation found for the first two samplings under grassland. The total microannelid abundance was even higher in 2013, as compared to the years 1994 and 2000 prior to conversion (not significant). Especially individuals of *Enchytraeus*-species increased in comparison to the

years 1994 and 2000. These species are generally considered as r-strategists, showing high reproduction rates after food supply, as organic fertilizers, or following a disturbance. As they

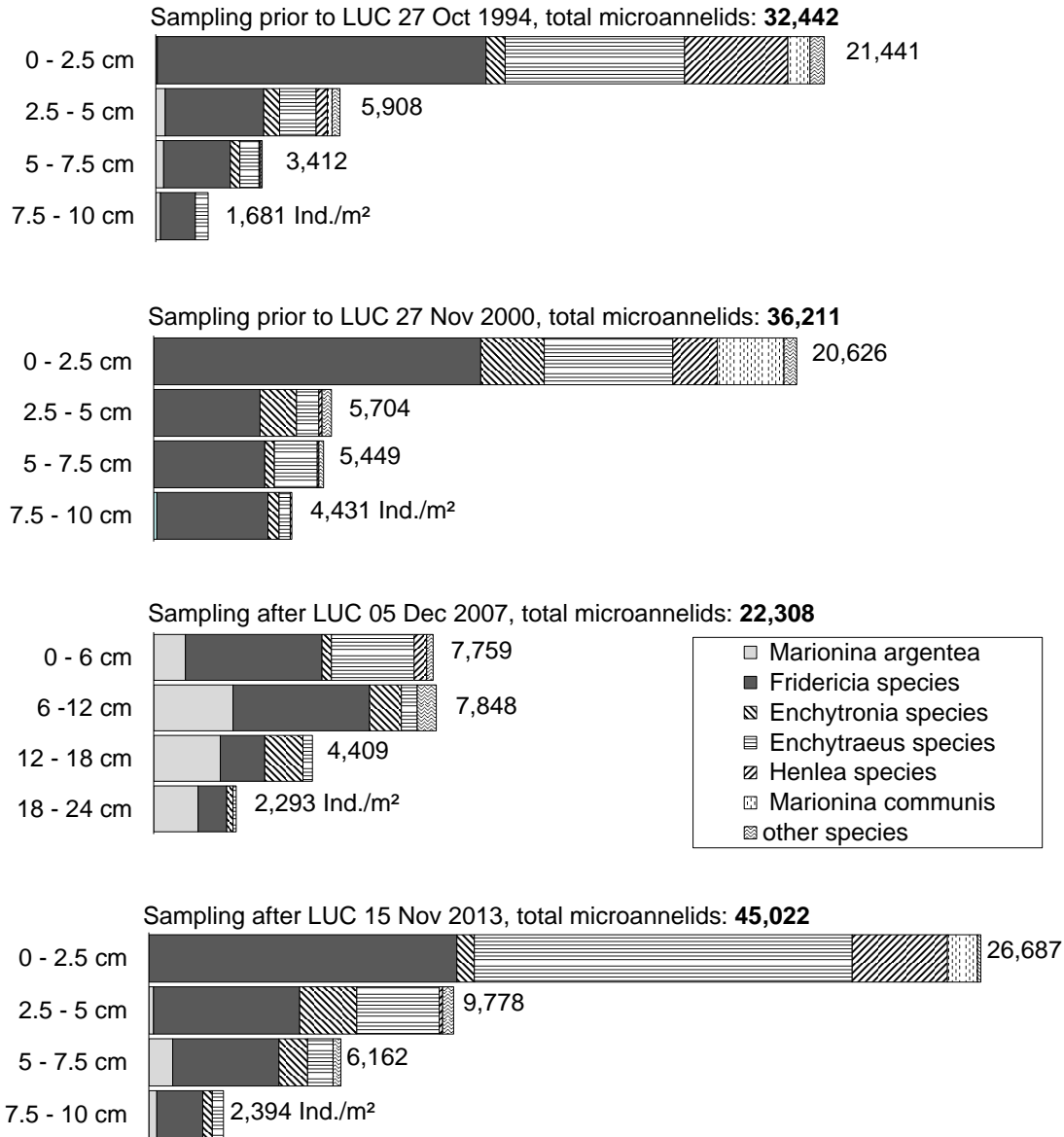


Figure 12: Microannelid results of site 11: total amount and horizon-specific amounts and species distribution for the sampling years 1994, 2000, 2007 and 2013; database: LLUR (2010)

react within months, their high proportion in 2013 was not necessarily induced by the LUC. It is difficult to detect to which extent the decline in earthworm and enchytraeid activity after LUC is not only caused by the consequences of mechanical disturbance by tillage but also by the loss of SOC and microbial biomass, being food resources for soil fauna.

## 2.4 Conclusions

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At site 13 there was still no soil faunistic sampling after conversion. In autumn of 1995 the lumbricidae density was significantly lower compared to 2002 and much lower than in 2008, whereas lumbricidae biomasses and microannelid densities (data not shown) feature this trend to a lesser extent.

### **2.4 Conclusions**

To date there was no study evaluating the quality of a regional German long-term soil monitoring network regarding its capability to detect long-term SOC losses and further impacts on physical and biological soil properties. The BDF-SH as a soil monitoring network (SMN) was evaluated as largely fulfilling the requirements of a SOC monitoring as stated in the relevant literature. The ability of the SMN to detect SOC stock changes over time was found as highly suitable. It focuses on the site scale and does not allow valid information for the regional scale. However, a soil monitoring includes not only carbon data but more detailed data of management, soil chemistry, soil physics, groundwater and soil biology which allowed a thorough interpretation and evaluation of the SOC stock changes over time and LUC impacts on further essential soil properties.

By means of the monitoring methods significant SOC stock changes by LUC were detected and evaluated with the large amount of the available data. The results might be valuable for further LUC studies and the inclusion of LUC in process-based SOC models. Soil biology and groundwater results were valuable to detail the changes of SOC stocks over time and further LUC impacts on the soil. A SOC fractionation could be included in the SMN and might reveal more detailed relationships between SOC stock changes and its causes. Furthermore, the determination of SOC fractions would be advantageous for the usage of the SMN data in process-based SOC models.

### **2.5 Acknowledgments**

We would like to thank the Department Geology and Soil, Soil Conservation of the State Agency of Agriculture, Environment and Rural Areas of the Federal State Schleswig-Holstein (LLUR) and the Ministry of Energy, Agriculture, the Environment and Rural Areas of the Federal State Schleswig-Holstein (MELUR) for the financial support (grant number: 4121-3-2007-440F), the good cooperation and the data supply.



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### 3 Application of a modeling approach to designate soil and soil organic carbon loss to wind erosion on long-term monitoring sites (BDF) in Northern Germany

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#### Abstract

Soil organic carbon (SOC) loss is a serious problem in maize monoculture areas of Northern Germany. Sites of the soil monitoring network (SMN) “Boden-Dauerbeobachtung” show long-term soil and SOC losses, which cannot be explained neither by conventional SOC balances nor by other non-Aeolian causes. The main objective was to determine whether these losses can be explained by wind erosion shown on the use of a process-based model.

In the long-term context of 10 years wind erosion was not measured directly but often observed. A suitable estimation approach was linking high-quality soil/farming monitoring and wind speed data with modeling results. The model SWEEP, validated for German sandy soils, was used. Two similar local SMN study sites were compared. Site A was characterized by high SOC loss and often affected by wind erosion; the reference site B was not.

At site A soil mass and SOC stock decreased by 49.4 and 2.44 kg m<sup>-2</sup> from 1999 to 2009. Using SWEEP, a total soil loss of 48.9 kg m<sup>-2</sup> resulted for 16 erosion events (max. single event 12.6 kg m<sup>-2</sup>). A share of 78 % was transported by suspension with a SOC enrichment ratio (ER) of 2.96 (saltation ER 0.98), comparable to the literature. At the reference site measured and modeled topsoil losses were minimal.

The good agreement between measurements and modeling results suggested that wind erosion caused significant long-term soil and SOC losses. The approach uses results of prior studies and is applicable to similar well-studied sites without other noteworthy SOC losses.

**Keywords:** long-term soil monitoring; BDF; SOC loss; wind erosion modeling; SWEEP; Northern Germany

## 3.1 Introduction

### 3.1.1 Background and research gap

Soil organic carbon (SOC<sup>2</sup>) loss of arable soils is one of the main impacts of land degradation, triggered by a variety of physical and chemical factors, but finally caused by inappropriate land use (FAO & ITPS, 2015; Lal, 2014, 2003; Louwagie et al., 2009; Verheijen et al., 2009). Wind erosion can be a reason of gradual soil degradation, but the processes themselves are difficult to recognize or measure in the field.

In the flat sandy lowlands of Schleswig-Holstein in Northern Germany wind erosion is also a common process (Hassenpflug, 1998; Duttmann and Bach, 2006; Duttmann et al., 2011). SOC-rich sandy soils were developed on formerly heathland by Plaggen fertilization of livestock residues from stables (Giani et al., 2014; Blume, 2004; Springob et al., 2001; Springob and Kirchmann, 2002), characterized as Plaggic Anthrosols (IUSS, 2006). Used as arable land these sites are highly susceptible to wind erosion (Riksen and Graaff, 2001). Quantitative and qualitative effects of wind erosion on these soils were investigated sporadically only in a few studies. Direct field measurements of wind erosion are sparsely available for the region (Funk et al., 2004; Goossens and Gross, 2002; Goossens, 2004), even less is known about the amount of SOC loss by wind erosion (Bach, 2008) and nothing about the long-term losses over decades. For the latter, the most plausible reasons are the high technical and organizational efforts to measure wind erosion over long periods.

However, some soils exhibit decreased soil mass and SOC stock in the topsoil, i.e. the Ap horizon (LLUR, 2010; Ad-Hoc-AG Boden, 2005). Several authors recommend considering these changes for estimating erosion losses in combination with modeling approaches (e.g. Post et al., 2001; Kibblewhite et al., 2012; Lal, 2005). Kibblewhite et al. (2012) state that soil erosion reduces topsoil depth, soil mass and SOC in the Ap horizon and suggests the use of long-term soil monitoring data to identify these changes. Even without direct measurements of

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#### <sup>2</sup> Abbreviation list:

BDF	Boden-Dauerbeobachtungsfläche (long-term soil monitoring site)
DIN	German Industry Standard (Deutsches Institut für Normung)
DWD	German Meteorological Service (Deutscher Wetterdienst)
ER	Enrichment ratio
GMD	Geometric mean diameter
GSD	Geometric standard deviation
LAI	Leaf area index
LLUR	State Agency
SAI	Stem area index
SMN	Soil monitoring network
SOC	Soil organic carbon
SWEEP	Single-event Wind Erosion Evaluation Program
TEAM	Texas Tech Erosion Analysis Model
WEPS	Wind Erosion Prediction System

wind erosion, the long-term monitoring of these soil parameters enables the assessment of the changes over decades (Post et al., 2001). Chappell & Viscarra Rossel (2013) and Chappell & Baldock (2016) describe the importance of soil monitoring, sampling design on the detection of wind erosion and the absence of aeolian SOC losses from management focused SOC balances. To conclude all these studies; reproducing measured SOC changes with a process-based wind erosion model may help to identify the contribution of wind erosion on SOC losses, which is not included in SOC balances so far. Using this approach, it is necessary to exclude other possible sources of SOC loss. Dust emission by tillage, was considered negligible for typical soil moisture conditions in the periods of wind erosion (Öttl and Funk, 2007; Funk et al., 2008), and water erosion has no relevance in the flat lowlands. A possible thinning effect resulting of an intrusion of subsoil material by tillage can lead to an underestimation of SOC in the topsoil. Therefore, topsoil and tillage depths need to be observed to exclude such causes of detected SOC changes.

To link topsoil measurements with Aeolian losses previous region-specific direct wind erosion measurements and other erosion studies are advantageous to define a range of usual soil and SOC loss. Bach (2008) measured soil and SOC losses by saltation in laboratory wind tunnel experiments investigating sandy topsoil material from the same erosion-affected site as reported in this study. Using the TEAM model (Gregory et al., 2004) the author determined a high erodibility of that soil material resulting in a total soil loss of  $13.08 \text{ kg m}^{-2}$  within four days in March 1969, and a maximum single-event loss of  $5.49 \text{ kg m}^{-2}$ . Hassenpflug (1998) estimated a total soil loss of  $10.0\text{--}15.0 \text{ kg m}^{-2}$  by aerial photograph analysis for the same erosion events and in the same area. In Northwestern Germany Goossens (2004) found  $> 5 \text{ kg soil m}^2$  eroded at a sandy field (lengths  $125\text{--}200 \text{ m}$ ) during an erosion event of 11 h. Studying an alluvial sandy soil in Northeastern Germany Funk et al. (2004) determined surface roughness and measured and simulated up to  $10.5 \text{ kg m}^{-2}$  of single-event total soil loss blown by erosive west winds. The study used the process-based erosion model SWEEP (Hagen et al., 1995) which was validated successfully for German sandy soils (Funk et al. 2004). Measurements and modeling on a  $150 \text{ m}$  long field resulted in 35 and 46 % of suspension, respectively. It was possible to show, that after setting the initial conditions very carefully, changing soil surface conditions and corresponding soil losses could be modelled by SWEEP with good accuracy. The studies of Bach (2008) and Funk et al. (2004) are the only available comparisons between measured and modelled soil losses by wind erosion in Germany.

To avoid wind erosion, the surface application of cattle slurry is a widely used erosion control method in agricultural areas with high wind erosion risk in Northern Germany (Duttmann et al., 2011; Bach, 2008; Riksen et al., 2003). Especially liquid cattle manure contains many



fibers and adhesive substances forming a stable crust after drying (Riksen et al. in Warren, 2003). Heavy rainfall can destroy the protective effect of these crusts. Alternatively, erosion control by surface-applied solid manure or dung (Blanco-Canqui and Lal, 2008; de Rouw and Rajot, 2004b) can be used.

### 3.1.2 SOC and wind erosion

Wind erosion is a very effective material sorting and SOC-removing process; as a result, fine particles in the suspension transport can be enriched in organic matter (Zobeck and Fryrear, 1986). This is expressed through enrichment ratios (ERs), the ratio of SOC content in the eroded material to the SOC content in the parent soil (Sterk et al., 1996). ERs for SOC are expected to be  $\leq 1$  in the saltation layer ( $< \approx 30$  cm) and  $\geq 1$  in the suspension layer ( $> \approx 30$  cm). Bach (2008) derived an ER of 0.98 in the saltation layer by wind tunnel studies using soil material of site A and surroundings.

A comprehensive overview of the importance of SOC enrichment in dust emissions on a continental scale was provided by Chappell et al. (2013). The authors present results from soil sampling and modeling. In the semiarid Canadian prairies Larney et al. (1998) reported ERs for saltation ranging between 1.02 and 1.05 (25 cm height). At semiarid environments in southwest Niger Sterk et al. (1996) found a saltation ER of 1.33 at 5 cm height. Funk et al. (2004) described increasing ER with height, ranging from 0.92 to 1.7 from 5 to 45 cm height at a sandy test site of low SOC stock in Eastern Germany. Similar was observed by Mendez et al. (2011) presenting measured ERs of 0.97 (5 cm height), 1.03 (15 cm), 3.7 (45 cm) and 4.6 (80 cm). Sterk et al. (1996) stated ERs of 2.39 and 3.02 for heights of 26 and 50 cm, respectively. They remarked that those heights include material transported by both, saltation and suspension processes.

Studying the arid region of southern New Mexico Li et al. (2007) found ERs (1.2 m height) between 3.24 without coverage, increasing continuously to 6.33 (75% cover). Ramsperger et al. (1998) measured ERs of SOC of 3 - 4 for dust samples trapped in 2 and 4 m height, Funk (1995) estimated an ER of 5 for dust sampled in 6 m height. ERs depend as well of the parent material's SOC content. For Australia Webb et al. (2012) reported suspension ERs (2 m height) of 1.67 in grass downs, 3.63 at a sand plain and  $\sim 7$  at a dune. Analyzing the SOC losses per area requires greater efforts and is based on flux measurements with a high spatial resolution (Buschiazzo and Funk, 2015) or indirect evidences as radionuclide concentration of  $^{137}\text{Cs}$  (Funk et al., 2012). For Australian soils Harper et al. (2010) found average losses of 0.36 and 0.51 kg C m<sup>-2</sup> eroded by wind, for 1 or 2 years, respectively.

### 3.1.3 Soil monitoring

The soil properties affected by environmental impacts, e.g. wind erosion, have been observed on long-term soil monitoring sites (“Boden-Dauerbeobachtungsflächen”, BDF sites) in Germany since 1985 (Nerger et al., 2016; Prechtel et al., 2009; Schröder et al., 2004; Barth et al., 2001). A detailed description of the BDF-SH SMN (Boden-Dauerbeobachtung Schleswig-Holstein soil monitoring network) methods and quality was provided in Nerger et al. (2016). The BDF-SH SMN was evaluated as highly suitable to detect long-term changes in soil and in farming management.

The BDF sites are part of larger fields and managed by farmers with contractual obligation to report all realized management actions. The topsoil material of the BDF is sampled and analyzed at regular time intervals. These sites offer the unique opportunity to study long-term effects on soil properties, especially the gradual degradation by wind erosion, which is difficult to detect at a site itself through short-term measurements. On an international scale, comprehensive wind erosion monitoring networks which include soil and farming monitoring are still in the build-up phase (Webb et al., 2016). Thus, the already existing soil monitoring networks could be used to study the past impact of wind erosion on the soil.

### 3.1.4 Objectives

The main objective of this study was to investigate whether long-term soil and SOC losses measured at sites of a high-quality soil monitoring network can be explained by wind erosion shown on the use of a process-based wind erosion model. In this long-term context of 10 years wind erosion events were often observed but continuous direct measurements were not possible. Instead, measured long-term soil monitoring and farming data of the peer-reviewed BDF-SH SMN were used for study sites without other noteworthy causes of soil and SOC losses, except wind erosion. As the data situation was adequate the use of a physical based wind erosion model, considering both saltation and suspension transport process, was possible. The most important input parameters were determined in the field, including high-resolution wind speed data. Finally, the potentials, uncertainties and limitations of the approach will be discussed.

## 3.2 Material and Methods

### 3.2.1 Description of the study sites

The monitoring site Leck (site A) was characterized by high SOC losses, possibly due to wind erosion, and therefore selected as a study site. The reference site Schuby (site B) was selected because it features similar soil properties and farming management. Both sites are located in the Geest region in Northern Germany (Table 11 and Figure 13).

Table 11: Basic geographical and management characteristics of the monitoring sites A and B (LLUR, 2010)

site	A	B
location	Leck	Schuby
short coordinates (GK) <sup>a</sup>	35066, 60621	35282, 60452
landscape unit	Geest (Schleswiger Vorgeest)	Geest (Schleswiger Vorgeest)
annual mean temp. (°C) 1981-2010	8.2	8.6
parent material	Weichselian glaciifluvial sands	Weichselian sandur sands
soil texture <sup>b</sup>	sandy sand (93% sand, 4% silt, 2% clay)	sandy sand (87% sand, 9% silt, 4% clay)
soil type <sup>c</sup>	Plaggic Anthrosol	Plaggic Anthrosol
historic land use	heathland / plaggen	heathland / plaggen
present land use	maize monoculture	crop rotation (maize, grain crops)

<sup>a</sup> Gauß-Krüger system, Bessel, Potsdam: easting and northing, <sup>b</sup> (Ad-Hoc-AG Boden, 2005), <sup>c</sup> (IUSS, 2006)

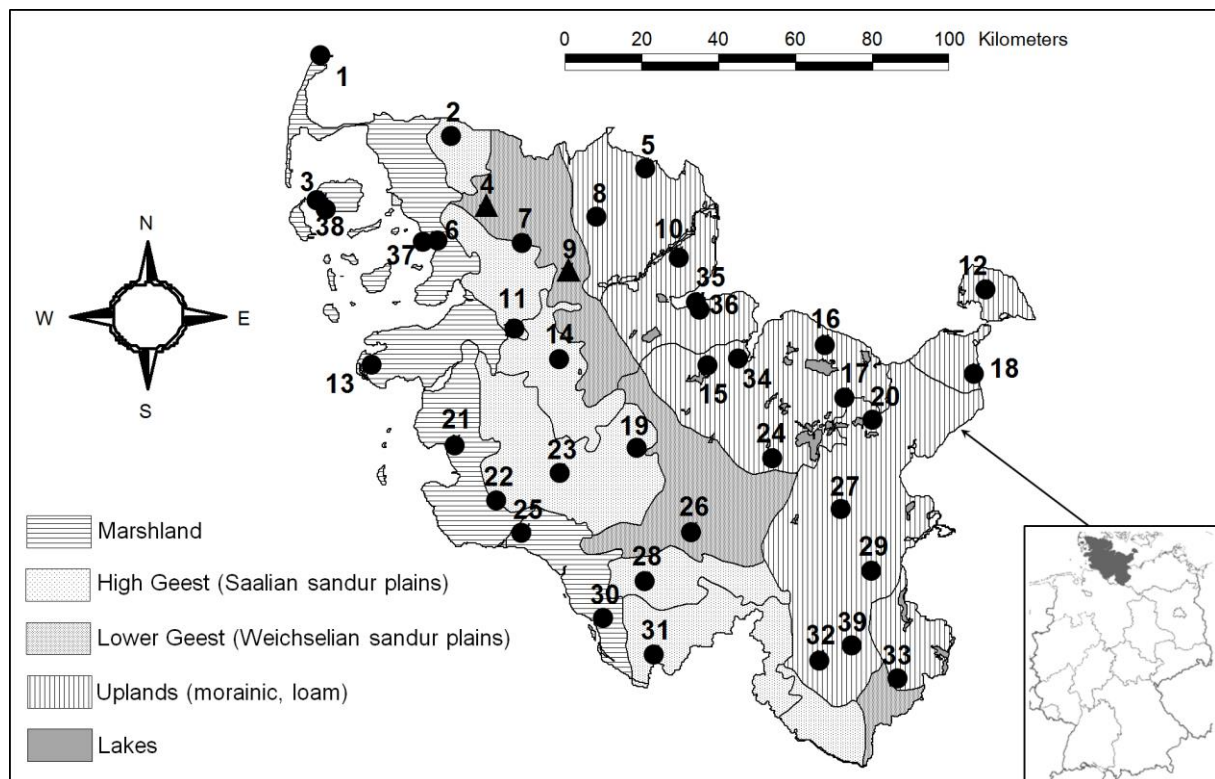


Figure 13: Natural landscape units of Schleswig-Holstein (Northern Germany) and localization of the long-term soil monitoring sites. The study sites A and B are the sites 4 and 9 in the figure (triangle symbols)

## 3.2 Material and Methods

The monitoring sites with a size of 0.1 ha are managed in the same manner as the larger field of which they are part of (Figure 14). The boundaries of the BDF are geodetically marked positions of rocks and magnets in the deeper subsoil. Thus, at the surface there is a continuous transition of the soil from the monitoring sites to the surrounding field.

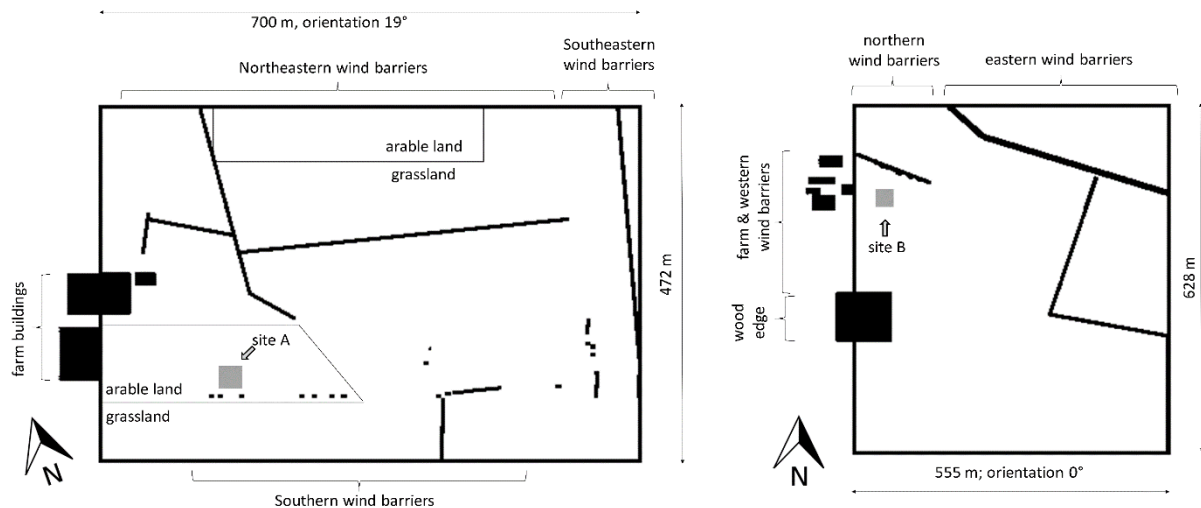


Figure 14: Monitoring sites A (left), B (right) and surrounding areas

Site A is located in the center of a sandy maize monoculture field. The effective field length to the east, the direction where the erosive winds are from, is 125 m. Adjacent to the east there is pasture and finally wind barriers; the total length from site A to the wind barriers in the east is 545 m. Site B has a similar soil texture, more wind barriers close to the monitoring site and tillage perpendicular to the main erosive wind directions. The field length to the east is 340 m. The surrounding situation of both sites remained constant over the time periods considered for modeling.

Erosion control measures were realized using the crust formation effect of surface-applied slurry at site A (Table 12). In some years, the slurry was not applied immediately after sowing, thus, on a few days high wind speeds coincided with uncovered soil. Heavy rainfall was able to destroy the adhesive effect, as documented by the farmer in the management database (LLUR, 2010) and regarded in the calculations. Referring to German Meteorological Service (DWD) heavy rainfall is defined as daily precipitation amount exceeding 25 mm, a value which was used in the study to consider the slurry crust as ineffective. After harvest crop residues remained on the field. In addition to the natural weed infestation it formed a soil cover until stubble cultivation in spring. Since 2007 solid cattle manure was surface-applied as erosion control at site A. This cover was not affected by heavy rainfall (LLUR, 2010). In

contrast, at site B no erosion control took place and the farming management was partly different (Table 12).

Table 12: Selected major management characteristics of the monitoring sites A and B from 1991 – 2009 (LLUR, 2010)

site	A	B
main crops	silage maize monoculture	crop rotation including maize; years 2002 to 2005 and 2008: wintercrops only, no crop cultivation in spring
catch crops and mulch	none	none
crop residues	remained on the field in winter; incorporated in spring by cultivator or disk harrow (before ploughing)	surface-applied in autumn
ploughing	annually, from 2007 conservation tillage	1-2 times per year
ploughing depth	30 cm until 2002; 25 cm since 2003	25 cm in spring, 30 cm in autumn (some years)
sowing time	1-5 days after seedbed preparation	2-6 days after seedbed preparation
tillage spacing and orientation	75 cm, WNW-ESE	75 cm, N-S
incorporated organic fertilizer	35-45 m <sup>3</sup> ha <sup>-1</sup> a <sup>-1</sup>	35-40 m <sup>3</sup> ha <sup>-1</sup> a <sup>-1</sup>
erosion control after sowing	always on the same day or 1 day after sowing; surface fixation by cattle slurry (5-15 m <sup>3</sup> ha <sup>-1</sup> a <sup>-1</sup> ) until 2006; from 2007 surface application of solid manure	none
potential erosion exposure	spring: time from stubble cultivation, ploughing, sowing, until 2 months after; in total about 2.5 to 3 months; coincides with dry and strong eastern winds	

### 3.2.2 Soil sampling strategy and laboratory work within the SMN

All laboratory results are obtained from the long-term soil monitoring program BDF-SH SMN (LLUR, 2010). Data of three sampling campaigns between October to November in 1990, 1999 and 2009 were used for the analysis. The sampling and measurement procedure followed standardized and scientific soil monitoring techniques and was described in detail in Nerger et al. (2016). Basically, three composite samples were taken from 18 single points per campaign and study site. Only topsoil material was taken, and depths documented. The rock fraction was determined by volume in the field and converted to mass fractions using conversion tables in Ad-Hoc-AG Boden (2005). SOC stock calculation, uncertainty determination and laboratory procedures were as described in Nerger et al. (2016). Additionally, saturated hydraulic water conductivity was measured in constant-head mode after DIN 19683-9:1998-05.

### 3.2.3 Calculation of management SOC balances

Conventional management SOC balances were calculated annually using the site-adjusted method of Kolbe (2010). The calculation is based on the management documentation of main crops, residue management and organic amendments. Cultivated crops are considered as a SOC-draining factor whereas catch crops, organic amendments and residues left on the field increase SOC balance. The method offers default values for these factors, derived from German long-term field trials.

The method was chosen because it is a substantial improvement to former methods and has been site-specific adjusted. SOC/N<sub>tot</sub> ratio and texture as soil-borne input are considered, referring to Springob and Kirchmann (2003) who stated this ratio as an indicator for the high inert SOC pool of sandy soils of heathland and Plaggen history which are present at the study sites A and B.

### 3.2.4 The wind erosion model SWEEP

#### 3.2.4.1 Brief description of the model and its application

To reproduce the measured topsoil loss, the model SWEEP (Single-event Wind Erosion Evaluation Program; version 1.2.12; Hagen, 2004) was chosen, because it was validated successfully for sandy soils of Northeastern Germany by Funk et al. (2004), which are comparable to those of Schleswig-Holstein. SWEEP is an advancement of the stand-alone erosion submodel of WEPS (Hagen et al., 1995, 1991; Hagen, 2004; Li et al., 2014). The site-specific total soil loss and deposition are modelled, and creep/saltation and suspension transport are distinguished. Data input and output is from sub-hourly (e.g. wind speed) to daily (e.g. erosion results) time steps.

The model runs cover the time periods of topsoil measurements from 1999 to 2009. Each year the relevant model period started at the first day of tillage in the year and lasted until 60 days after sowing, thus up to 75 days per year in total. Days featuring erosion control measures were not erosive (LLUR, 2010) and thus not modeled. Dust emissions by tillage were excluded, because they were considered as negligible (cf. section 3.1.1).

### 3.2.4.2 Field geometry and wind barriers

The entire field, neighboring areas and wind barriers of the study sites (Figure 14) were included in the spatial model setup. A grid size was chosen in which each BDF site was represented of nine grid cells (3x3) as part of the total modeling area. As modeling results solely the grid cells of the monitoring sites (0.1 ha) were used. The different height, length, width and porosity of wind barriers were also characterized. For grass, tree lines and shrubs the porosity was set to 0.5, according to Vigiak et al. (2003) and Hagen et al. (1981); farm buildings, wood and solid barriers were considered with lesser porosities or were set to zero. Height, length and width of hedges and trees were determined in field campaigns. The wind barriers were constantly present over the monitored time period, although tree growth was not considered in this study.

### 3.2.4.3 Weather related parameters

The weather station in Leck (distance: 14 km) was selected for site A, data from the urban station in Schleswig (distance: 7 km) were used at site B. The stations are equivalent for the study sites as the comparison with verified and region-specific data of wind maps of a 200 m resolution (DWD, 2010) revealed that both sites and stations are characterized by a long-term average annual wind speed of 5.1 - 5.4 m/s. Wind speed data were available as 10-minute- and wind direction as hourly averages supplied by the German Meteorological Service (DWD). Aerodynamic roughness was estimated according to the classification of Traup and Kruse (1996) and aerial photos of the surroundings of the station.

The surface water content was calculated hourly from precipitation data of both weather stations. According to the very sandy soil texture and high soil hydraulic conductivity values of both sites (2.2–8.8 cm h<sup>-1</sup>), precipitation was assumed to infiltrate immediately (Blume et al., 2002) and the soil surface to be dried up within two hours from the surface. Surface water content of the upper 5 mm (Hagen et al., 1995) of soil layer was calculated as follows:

$$SWC = \frac{0.1 * CUMP_h}{0.5 * DBD} \quad (7)$$

Where: SWC = surface water content [g g<sup>-1</sup>]; CUMP<sub>h</sub> = hourly precipitation amount [mm] equivalent to [l m<sup>-2</sup>] or [kg m<sup>-2</sup>]; DBD = dry bulk density [g cm<sup>-3</sup>]

## 3.2 Material and Methods

### 3.2.4.4 Soil layer, surface and biomass parameters

Many constant SWEEP input parameters (Table 13) were determined in the field or in the laboratory, others calculated due to reliable sources. The study of Funk et al. (2004) for German sandy soils was important to confirm the field-determined range of initial random roughness and oriented roughness (ridge height) as well as the description of their declines after precipitation and erosion events.

Table 13: Setup of selected constant input parameters in SWEEP of the monitoring sites A and B

constant parameters	unit	site A	site B	calculation/estimation method; source	
initial random roughness	mm	4	6	field observation; Funk et al. (2004)	
initial ridge height	mm	25	35		
row spacing	m	0.75	0.75	LLUR (2010)	
ridge orientation	deg	109	0		
ridge spacing	mm	150	150	LLUR (2010), Hagen et al. (1995)	
ridge width	mm	100	100		
aerodynamic roughness	mm	40	300	estimation according to Traup and Kruse (1996) and aerial photos	
rock volume fraction	m <sup>3</sup> m <sup>-3</sup>	0	0.15	field measurement	
initial very fine sand fraction	Mg Mg <sup>-1</sup>	0.2	0.1	estimation from grain-size distribution curve (Blume et al. 2002)	
initial aggregate density	Mg m <sup>-3</sup>	1.80	1.80	Skidmore and Layton (unpub.) in: Hagen et al. (1995)	
initial dry aggregate stability	ln (J kg <sup>-1</sup> )	1.17	1.42	Skidmore and Layton (1992) in: Hagen et al. (1995)	
initial GMD of aggregate sizes	mm	1.02	3.19	Farres (1978) in: Hagen et al. (1995)	
initial GSD of aggregate sizes	mm mm <sup>-1</sup>	10.30	14.76		
initial minimum aggregate size	mm	0.01	0.01		
initial maximum aggregate size	mm	16.44	75.20		
adjusted sand fraction (after prev. erosion event = a.p.e.e.)	Mg Mg <sup>-1</sup>	1.00	1.00	equations (2; 3) of this study	
adjusted very fine sand fraction (a.p.e.e.)	Mg Mg <sup>-1</sup>	0	0		
adjusted aggregate density (a.p.e.e.)	Mg m <sup>-3</sup>	1.80	1.80		
adjusted dry aggregate stability (a.p.e.e.)	ln (J kg <sup>-1</sup> )	0.85	0.85		
adjusted GMD of aggregate sizes (a.p.e.e.)	mm	1.00	1.00		
adjusted GSD of aggregate sizes (a.p.e.e.)	mm mm <sup>-1</sup>	1.01	1.01		
adjusted minimum aggregate size (a.p.e.e.)	mm	0.10	0.10		
adjusted maximum aggregate size (a.p.e.e.)	mm	2.00	2.00		
Soil wilting point water content	Mg Mg <sup>-1</sup>	0.09	0.16		LLUR (2010), field measurement
effective crust after applying slurry as erosion control (until 2006)	m <sup>2</sup> m <sup>-2</sup>	1.0	-		LLUR (2010), field observation; soil cover of solid manure comparable to Wagner and Nelson (1995)
residue flat cover after applying solid manure as erosion control (from 2007)	fraction	1.0	-		
residue flat cover of flat maize stubbles	fraction	0.25	-		
surface crust density	Mg m <sup>-3</sup>	1.80	1.80	Skidmore and Layton (unpub.) in: Hagen et al. (1995)	
surface crust stability	ln (J kg <sup>-1</sup> )	1.17	1.42	Zobeck (1991) in: Hagen et al. (1995)	



Some variable parameters (Table 14) were determined following the contributions of various authors as documented in the WEPS technical manual (Hagen et al., 1995). Events of erosion and precipitation >10 mm affect soil layer and surface properties. Thus, after each event some soil layer and surface parameters had to be updated (Hagen, 2008) using the SWEEP update function.

Table 14: Sources of selected variable input parameters in SWEEP for the monitoring sites A and B

variable parameters	unit	calculation/estimation method; source
decline of random roughness (after precipitation)	mm	Potter (1990) in: Hagen et al. (1995)
decline of ridge height (after precipitation)	mm	Lyles and Tatarko (1987) in: Hagen et al. (1995)
decline of random roughness (after erosion event)	mm	SWEEP subdaily results (update function)
decline of ridge height (after erosion event)	mm	
initial surface crust thickness	mm	Farres (1978) in: Hagen et al. (1995)
initial surface crust fraction	m <sup>2</sup> m <sup>-2</sup>	Zobeck and Popham (1992) in: Hagen et al. (1995)
initial loose erodible fraction	m <sup>2</sup> m <sup>-2</sup>	
initial loose erodible mass	kg m <sup>-2</sup>	
decline of surface crust thickness	mm	SWEEP subdaily results (update function)
decline of surface crust fraction	m <sup>2</sup> m <sup>-2</sup>	
decline of loose erodible fraction	m <sup>2</sup> m <sup>-2</sup>	
decline of loose erodible mass	kg m <sup>-2</sup>	
changed loose erodible mass	kg m <sup>-2</sup>	equations (2; 3) of this study
residue flat cover	m <sup>2</sup> m <sup>-2</sup>	Wagner and Nelson (1995); field observation
growing crop height	m	sowing and yield data of the management database (LLUR, 2010); growth stages of maize plants of Armbrust and Lyles (1985); growing degree days concept of Hagen et al. (1995)
SAI (incl. stem diameter, plants per m <sup>2</sup> )	m <sup>2</sup> m <sup>-2</sup>	
growing crop leaf area index	m <sup>2</sup> m <sup>-2</sup>	

However, not all necessary updates for the needs of this study are included in the update function, e.g. the changed texture in the uppermost centimeter after erosion events. If such events were characterized by high suspension loss and low saltation loss, soil texture near surface shows depletion of material susceptible to suspension transport (López, 1998; de Rouw and Rajot, 2004a). These losses were subtracted from soil stocks of those materials. As a first step material susceptible for suspension was defined according to Hagen et al. (1995) as the clay, silt and very fine sand fraction (Table 15).

## 3.2 Material and Methods

Table 15: Estimated stocks of process-specified susceptible material for the uppermost layer of 1 cm from Ap horizon of the monitoring sites A and B

	unit	site	value
stock of material susceptible for suspension (very fine sand, silt, clay) of the uppermost layer of 1 cm	kg m <sup>-2</sup>	A	3.47
		B	3.10
stock of material susceptible for saltation (sand without very fine sand) of the uppermost layer of 1 cm	kg m <sup>-2</sup>	A	9.53
		B	10.20

The SWEEP model is actually not applicable for multiple soil layers. Thus, the resulting superficial sand layer was modeled as loose erodible mass (LEM) above an impermeable crust (L.E. Wagner, 2011, personal communication). The calculation for the thickness of the remaining pure sand layer and the LEM was derived as follows:

$$T_{LAYER} = \frac{SOIL\_LOSS_{SUSP}}{SOIL\_STOCK_{SUSP}} - \frac{SOIL\_LOSS_{SALT}}{SOIL\_STOCK_{SALT}} \quad (8)$$

$$LEM = SOIL\_STOCK_{SUSP} * T_{LAYER} \quad (9)$$

Where:  $T_{LAYER}$  = Thickness of remaining pure sand layer [fraction of 1 cm],  $SOIL\_LOSS_{SUSP}$  = soil loss by suspension [kg m<sup>-2</sup>],  $SOIL\_STOCK_{SUSP}$  = soil stock of material susceptible to suspension [kg m<sup>-2</sup>],  $SOIL\_LOSS_{SALT}$  = soil loss by creep/saltation [kg m<sup>-2</sup>],  $SOIL\_STOCK_{SALT}$  = soil stock of material susceptible to creep/saltation [kg m<sup>-2</sup>], LEM = loose erodible mass of remaining pure sand layer [kg m<sup>-2</sup>]

### 3.2.5 Comparing SOC losses from measurement, balances and modeling results

As a first step topsoil SOC stocks at the beginning and the end of the test period were calculated as described in section 3.2.2. The annually calculated SOC balances were cumulated for the test period and added to the topsoil SOC stock losses (Equation 10) resulting in the total SOC loss through wind erosion. Calculating SOC transport by saltation of each event the ER of 0.98 derived from wind tunnel experiments for local soil material from Bach (2008) was multiplied with the modeled soil losses (Equation 11). The resulting sum of SOC loss by saltation of the whole test period was subtracted from overall SOC loss (Equation 12). The remaining SOC loss was regarded to be lost by suspension. Assigning the entire measured topsoil SOC loss to wind erosion was possible as all other causes of SOC loss could be excluded (cf. section 3.1.1).

SOC loss by suspension was allocated weighted to the suspension soil loss of each erosion event. Thus, a suspension ER resulted for the whole test period whereas SOC loss was pointed out for single events considering reduced SOC contents after every erosion event.

$$SOC\_LOSS_{TOTAL} = SOC\_CHANGE_{Ap;1999\ to\ 2009} + \sum_{year\ 1}^{year\ 10} SOC\_BALANCE_{ANNUAL} \quad (10)$$

$$SOC\_LOSS_{SALT} = \sum_{i=1}^n SOIL\_LOSS_{SALT} * (SOC\_CONC_{Ap;1999} * ER_{SALT}) \quad (11)$$

$$SOC\_LOSS_{SUSP} = SOC\_LOSS_{TOTAL} - SOC\_LOSS_{SALT} \quad (12)$$

Where:

$SOC\_LOSS_{TOTAL}$  = sum of total SOC loss of the test period [t];  $SOC\_CHANGE_{Ap;1999\ to\ 2009}$  = topsoil SOC stock change of the test period, means from 1999 to 2009 [t];  $SOC\_BALANCE_{ANNUAL}$  = annual SOC balances of the test period [t];  $SOC\_LOSS_{SALT}$  = sum of SOC loss by saltation of the test period [t];  $SOIL\_LOSS_{SALT}$  = soil loss by saltation as SWEEP result of one event [t];  $SOC\_CONC$  = initial SOC concentration measured at the beginning of the test period [%];  $ER_{SALT}$  = enrichment ratio saltation (=0.98; Bach (2008));  $SOC\_LOSS_{SUSP}$  = sum of SOC loss by suspension of the test period [t]

### 3.2.6 Modeling variations

Modeling variations were assessed for the most sensitive parameters mentioned in Hagen et al. (1999) and Feng & Sharratt (2005) for site A. Using the SWEEP threshold friction speed of  $8\ m\ s^{-1}$  the effect of wind speed variations of  $\pm 5\%$  on wind values was calculated, whose relation is similar between wind speed and soil loss (Fryrear et al., 1998). The resulting wind value deviations represent the potential total soil loss deviations. In a second run, random and oriented roughness were varied by 25 and 20%, respectively. Finally, the time needed to dry up the soil surface after an erosion event was varied from two hours to four hours.

## 3.3 Results

### 3.3.1 Results of topsoil measurements

The results of the topsoil measurements (LLUR, 2010) are listed in Table 16. Grain size distribution shows an erosion-susceptible fine sand fraction of 50 % at site A. It declined from 1999 to 2009. In accordance with the very sandy texture of the sites, hydraulic water conductivity was high and reached  $2.2\text{--}8.8\ cm\ h^{-1}$ .

### 3.3 Results

Table 16: Laboratory characterization of topsoil samples of the monitoring sites A and B. Measurement campaigns in October/November of the years 1990 (1<sup>st</sup>), 1999 (2<sup>nd</sup>) and 2009 (3<sup>rd</sup>)

soil property	unit	site	1 <sup>st</sup> campaign		2 <sup>nd</sup> campaign		3 <sup>rd</sup> campaign	
			mean	± SD	mean	± SD	mean	± SD
Ap horizon soil mass (excluding rocks)	kg m <sup>-2</sup> (for 0.1 ha)	A	429.3	15.82	390.0	23.43	340.6	14.25
		B	344.3	0.00	338.3	10.31	335.9	3.46
SOC concentration	%	A	2.53	0.10	2.27	0.09	1.88	0.04
		B	3.64	0.32	4.02	0.22	3.70	0.25
SOC/N <sub>tot</sub> ratio	dimension- less	A	13.9	-	15.2	-	13.4	-
		B	15.5	-	20.5	-	17.4	-
sand (63 - <2000 µm)	Vol%	A	92.63	0.48	93.23	0.38	90.67	0.55
		B	87.13	0.78	86.73	0.68	87.93	0.40
fine sand (63 - <200 µm)	Vol%	A	49.97	2.51	51.07	1.42	47.13	2.15
		B	29.63	1.66	31.50	2.04	28.10	1.25
silt (2 - <63 µm)	Vol%	A	4.52	0.44	4.40	0.36	-	-
		B	8.50	0.55	9.30	0.26	8.07	0.47
clay (<2 µm)	Vol%	A	2.85	0.36	2.27	0.64	-	-
		B	4.37	0.37	4.03	0.81	4.00	0.10
silt+clay (<63 µm)	Vol%	A	-	-	-	-	9.33	0.55
		B	-	-	-	-	-	-
dry bulk density	g cm <sup>-3</sup>	A	1.37	-	1.30	0.08	1.21	0.05
		B	1.35	-	1.33	0.04	1.33	0.05
topsoil depth	cm	A	31.3	1.2	30.0	1.3	28.2	1.2
		B	30.0	0.3	30.0	0.3	29.8	0.3
hydraulic water conductivity	cm h <sup>-1</sup>	A	-	-	8.8	7.3	6.3	2.4
		B	-	-	2.2	0.4	2.5	1.2

SD = standard deviation

Originally both sites were characterized by high SOC stocks of over 10.0 kg m<sup>-2</sup> (Figure 15). From 1999 to 2009 averaged topsoil depth, dry bulk density and SOC concentration declined at site A. Thus, soil mass declined by 49.37 kg m<sup>-2</sup> and SOC stocks significantly by 2.44 kg m<sup>-2</sup>. Considering standard deviation minimum, loss of SOC stock was 1.76 kg m<sup>-2</sup>. Already prior to the modeling period (1990 to 1999) the significant loss of SOC stock was 2.01 kg m<sup>-2</sup>. At the reference site B the averaged topsoil depths and dry bulk density remained nearly constant. Thus, only a very small soil loss of 2.42 kg m<sup>-2</sup> was measured; SOC changes were insignificant.

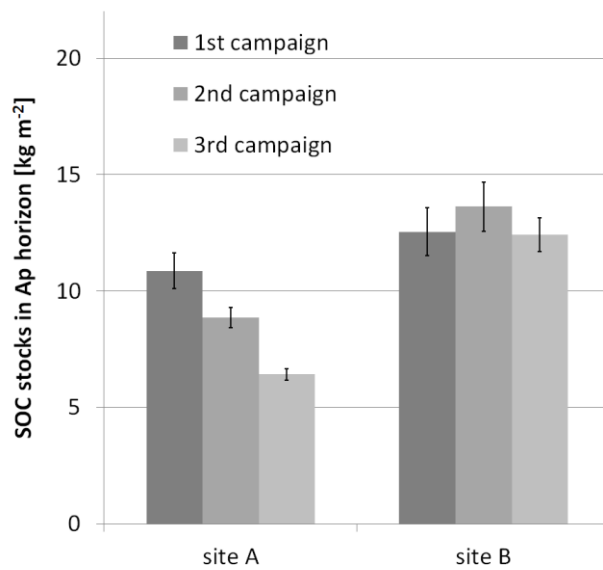


Figure 15: SOC stocks in  $\text{kg m}^{-2}$  for the study sites A and B. Measurement campaigns in October/November of the years 1990 (1<sup>st</sup>), 1999 (2<sup>nd</sup>) and 2009 (3<sup>rd</sup>)

### 3.3.2 Results of management SOC balances

Table 17 shows calculated conventional annual farming management SOC balances based on main crops of the study sites. The total sum of SOC balances for all years was  $0.15 \text{ kg m}^{-2}$  at site A and  $0.35 \text{ kg m}^{-2}$  at site B. The method of site-adjusted SOC balance (Kolbe, 2010) implies that SOC-consuming crops influence sandy sites to a lesser extent because they have a high turnover of organic carbon. Additionally, organic fertilizers were applied regularly by the farmers. Therefore, these sites mostly feature neutral or positive SOC balances. Compared to the SOC losses the applied amount of organic carbon by liquid and solid manure is low ( $<0.05 \text{ kg m}^{-2} \text{ a}^{-1}$ ).

### 3.3 Results

Table 17: Main crops and SOC balances in kg m<sup>-2</sup> 1999-2009 for the monitoring sites A and B; calculated using the management data of LLUR (2010) with the side-adjusted method (Kolbe, 2010)

<b>site A</b>										
year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
main crop	sm <sup>a</sup>	sm	sm	sm	sm	sm	sm	sm	sm	sm
	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031
catch crop										
crop residues										
solid manure								0.048	0.028	0.028
liquid manure	0.032	0.032	0.032	0.032	0.049	0.045	0.032	0.036	0.032	0.032
sewage sludge										
<b>TOTAL</b>	0.001	0.001	0.001	0.001	0.018	0.014	0.001	0.053	0.029	0.029
<b>site B</b>										
year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
main crop	sm	oa <sup>b</sup>	ww <sup>c</sup>	wb <sup>d</sup>	wr <sup>e</sup>	ww	sm	sm	wry <sup>f</sup>	sm
	-0.031	-0.003	-0.003	-0.003	-0.003	-0.003	-0.031	-0.031	-0.003	-0.031
catch crop										
crop residues			0.032	0.036	0.031					0.040
solid manure										
liquid manure	0.028	0.024	0.028	0.028	0.023	0.024	0.020	0.028	0.016	0.028
sewage sludge	0.056				0.045					
<b>TOTAL</b>	0.053	0.021	0.057	0.061	0.095	0.021	-0.011	-0.003	0.013	0.037

legend: <sup>a</sup> silage maize; <sup>b</sup> oat; <sup>c</sup> winter wheat; <sup>d</sup> winter barley; <sup>e</sup> winter rape; <sup>f</sup> winter rye

#### 3.3.3 SWEEP modeling results

Model results for site A (Table 18) found 16 erosion days within a ten-year period. The majority of erosion events (10 out of 16) and the highest calculated single event soil loss of 12.64 kg m<sup>-2</sup> were related to easterly winds. In the whole test period 48.93 kg m<sup>-2</sup> of soil was estimated to be eroded by wind from the 0.1 ha monitoring site. This is in very good agreement with the balanced topsoil loss of 49.37 kg m<sup>-2</sup> for the ten-year period (1999–2009). Excluding negligible erosion events of 100 % creep/saltation transport, soil loss through easterly winds was transported between 61–99 % by suspension. Due to a smaller effective field length and/or more wind barriers saltation's share was higher (20-50%) at erosion events of southerly, westerly and northeasterly winds. The overall weighted creep/saltation to suspension ratio was 22:78.

### 3.3 Results

Table 18: Estimated variable parameters, model results and projected SOC loss for the test period 1999-2009 of the monitoring sites A and B

date	DALTO <sup>a</sup>	soil surface properties					biomass properties				weather related properties			predicted soil loss for the study sites (0.1 ha)						est. SOC loss		
		random roughness	ridge height	surface crust fraction	loose erod. fraction	loose erod. mass	residue flat cover	grow. crop height	stem area index	leaf area index	CUMP <sup>b</sup>	SWC <sup>c</sup>	wind direction	mean total soil loss	grid variability	creep / saltation loss	suspension loss	T <sub>LAYER</sub> <sup>d</sup>	saltation ER=0.98	suspension ER=2.96		
DD/MM/YYYY		mm	mm	m <sup>2</sup> /m <sup>2</sup>	m <sup>2</sup> /m <sup>2</sup>	kg/m <sup>2</sup>	m <sup>2</sup> /m <sup>2</sup>	m	m <sup>2</sup> /m <sup>2</sup>	m <sup>2</sup> /m <sup>2</sup>	mm	Mg/Mg <sup>-1</sup>	deg	kg/m <sup>2</sup>	%	kg/m <sup>2</sup>	% of total	kg/m <sup>2</sup>	% of total	cm	kg/m <sup>2</sup>	kg/m <sup>2</sup>
<b>site A - 2000 - 2009</b>																						
09/05/2001	0	4.00	25.00	0	0	0	0	0	0	0	0	70	2.1	5.9	0.4	18	1.7	82	0.45	0.01	0.12	
09/05/2002	0	4.00	25.00	0	0	0	0	0	0	0	0	57	8.4	3.5	4.3	51	4.1	49	0.72	0.10	0.27	
10/05/2002	0	4.00	25.00	0	0	0	0	0	0	0	0	83	12.6	1.7	0.3	2	12.3	98	3.53	0.01	0.80	
03/05/2003	0	4.00	25.00	0	0	0	0.25	0	0	0.3	0.05	250	0.8	25.1	0.4	53	0.4	47	0.06	0.01	0.02	
09/06/2003	32	1.53	6.66	0.62	0.25	0.01	0	0.38	0.03	0.25	0	235	0.3	75.2	0.2	50	0.2	50	0.00	0.00	0.01	
11/06/2003	34	1.50	6.66	1.00	1.00	0.03	0	0.41	0.03	0.31	4.5	0	240	0.0	60.2	0.0	100	0.0	0	0.00	0.00	
29/04/2004	2	4.00	25.00	0	0	0	0.25	0	0	0	0	100	0.0	0.2	0.0	23	0.0	77	0.01	0.00	0.00	
30/04/2004	3	3.98	24.91	0	0	0	0.25	0	0	0	0	85	4.0	1.2	1.6	39	2.5	61	0.54	0.03	0.15	
09/05/2006	0	4.00	25.00	0	0	0	0	0	0	0	0	80	3.0	2.5	0.1	5	2.8	95	0.79	0.00	0.17	
19/04/2007	4	4.00	25.00	0	0	0	0.25	0	0	0	1.1	0	250	0.0	35.9	0.0	56	0.0	45	0.00	0.00	
20/04/2007	0	4.00	25.00	0	0	0	0	0	0	0.4	0.05	307	3.6	2.4	1.8	50	1.8	50	0.71	0.04	0.11	
22/04/2008	0	4.00	25.00	0	0	0	0	0	0	0	0	80	7.6	2.2	0.3	4	7.3	96	0.21	0.01	0.43	
23/04/2008	1	1.50	9.90	1.00	1.00	1.98	0	0	0	0	0	93	0.0	89.8	0.0	100	0.0	0	0.00	0.00	0.00	
25/04/2009	1	4.00	25.00	0	0	0	0	0	0	0	0	97	4.1	0.5	0.0	1	4.0	99	1.16	0.00	0.23	
27/04/2009	0	4.00	25.00	0	0	0	0	0	0	0	0	195	2.4	18.2	1.4	58	1.0	42	0.01	0.03	0.06	
28/04/2009	1	1.50	6.57	1.00	1.00	0.14	0	0	0	0.4	0	80	0.0	72.1	0.0	100	0.0	0	0.00	0.00	0.00	
TOTAL													<b>48.9</b>		<b>10.8</b>	<b>22<sup>e</sup></b>	<b>38.1</b>	<b>78<sup>e</sup></b>		<b>0.226</b>	<b>2.369</b>	
																				<b>2.595<sup>f</sup></b>		
<b>site B - 2000 - 2009</b>																						
04/06/2006	24	2.85	13.99	0.53	0.21	0.64	0	0.13	0.00	0.04	72.5	0	310	0.4	97.7	0.3	73	0.1	27	0.00	0.01	0.01
11/05/2007	19	2.88	20.04	0.38	0.39	0.17	0	0.09	0.00	0.02	2.7	0.02	250	0.0	75.0	0.0	80	0.0	20	0.00	0.00	0.00
17/05/2007	25	1.85	14.15	0.40	0.16	0.64	0	0.13	0.00	0.04	14.6	0	300	0.4	89.9	0.3	75	0.1	25	0.00	0.01	0.01
15/05/2009	25	3.49	21.53	0.40	0.16	0.64	0	0.14	0.00	0.05	0	0	90	0.0	27.5	0.0	73	0.0	27	0.00	0.00	0.00
22/05/2009	32	2.46	16.99	0.40	0.56	0.61	0	0.22	0.01	0.10	21.6	0	260	0.0	72.9	0.0	80	0.0	20	0.00	0.00	0.00
26/05/2009	36	1.90	14.69	0.40	0.57	0.60	0	0.28	0.01	0.14	4.1	0	250	0.1	51.3	0.1	79	0.0	21	0.00	0.00	0.00
28/05/2009	38	1.87	14.56	0.40	0.49	0.46	0	0.31	0.02	0.17	6.1	0	300	0.0	119.4	0.0	75	0.0	25	0.00	0.00	0.00
TOTAL													<b>1.0</b>		<b>0.8</b>	<b>75<sup>e</sup></b>	<b>0.3</b>	<b>25<sup>e</sup></b>		<b>0.031</b>	<b>0.031</b>	

<sup>a</sup> day after last tillage operation

<sup>b</sup> cumulative depth of precipitation since last tillage or erosion event

<sup>c</sup> relevant cumulated hourly surface water content during erosion event

<sup>d</sup> thickness of new pure sand horizon after this event

<sup>e</sup> calculation of creep/saltation-suspension ratio using total values of the test periods

<sup>f</sup> Total SOC loss in test period: saltation + suspension = SOC loss Ap horizon ± ∑ SOC balances

### 3.3 Results

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In years with more than one erosion event and without tillage random and oriented roughness decline was considered. As a consequence of the decline also less erosive winds were able to initiate erosion at site A. This was mostly the case when random roughness and ridge height were  $<2$  mm and  $<10$  mm, respectively. The crust caused by surface fixation by cattle slurry ( $5 \text{ m}^3 \text{ ha}^{-1}$ ) was sufficient protective against wind erosion and no erosion was modeled. In 2003 the slurry crust was destroyed by heavy rainfall of 27.1 mm on 08/06/2003. Thus, the soil surface was susceptible to wind erosion and erosive winds could erode soil material on two days. As a consequence of 110 mm of precipitation since the last tillage operation, random and oriented roughness decreased to a minimum, so that erosion could take place even though wind speeds were relatively low.  $0.32 \text{ kg m}^{-2}$  of total soil loss through westerly winds was modeled at site A. In 2004 the slurry crust was destroyed again, but a new slurry layer was applied immediately. Therefore, more slurry was utilized ( $15 \text{ m}^3 \text{ ha}^{-1}$ ) in 2005, which could resist heavy rainfall of 29.3 mm without losing the crust.

Precipitation was typically related to westerly winds reducing susceptibility to erosion by increased surface water contents. Mostly, precipitation sums after last tillage operations were quite low ( $<10$  mm); thus, on 15 out of 16 days no surface crusts by precipitation developed. At five events of westerly winds a total soil loss of  $4.74 \text{ kg m}^{-2}$  occurred at site A, whereas at easterly wind events  $41.81 \text{ kg m}^{-2}$  were modeled. Three erosive days were characterized by pure sand layers which developed on the surface by high suspension loss, i.e. especially loss of parts of the fine sand and silt fractions (see Table 16). In each case model results of the following erosive day stated that these sand layers were not completely eroded; indicating that the underlying fine soil material was not susceptible to erosion.

At site B, featuring closer wind barriers to the northeast, the average total soil losses were much smaller, and the variability of the SWEEP grid cells was higher. Most of the erosive days coincided with a crusted surface or growing crops. 7 erosive days were modeled, resulting in  $1.0 \text{ kg m}^{-2}$  of total soil loss and a saltation/suspension ratio of 75:25. This total soil loss of ten years corresponds to the measured topsoil loss ( $2.4 \text{ kg m}^{-2}$ ). The maximum total soil loss of a single event was  $0.4 \text{ kg m}^{-2}$ , eroded by northwesterly winds. All erosive days showed average loss in both creep/saltation and suspension. Some events were characterized by very small deposition at the western part of the monitoring site.



### 3.3.4 Comparing SOC losses from measurement, balances and modeling results

At site A a SOC stock decrease of  $2.44 \text{ kg m}^{-2}$  was measured in the topsoil within the period 1999–2009. The total conventional SOC balance method resulted in an increase of  $0.15 \text{ kg m}^{-2}$ . Based on the wind erosion modeling results SOC loss by creep/saltation was quantified to  $0.23 \text{ kg m}^{-2}$  for all 16 erosion events of the test period. Considering reduced SOC contents in the uppermost layer after each erosion event the remaining sum of  $2.37 \text{ kg m}^{-2}$  was estimated to be transported by suspension with an ER of 2.96. Highest SOC loss by creep/saltation was on 09/05/2002 ( $0.10 \text{ kg m}^{-2}$ ) and by suspension on 10/05/2002 ( $0.80 \text{ kg m}^{-2}$ ). SOC losses at site B were low. Developing ER's for site B from the present data of very few soil loss would feature a large uncertainty. Therefore, the same ERs as at site A were used, as it is geographically very close. Using these ERs,  $0.031 \text{ kg m}^{-2}$  of SOC was eroded by creep/saltation and  $0.031 \text{ kg m}^{-2}$  by suspension in the test period.

### 3.3.5 Modeling variations

The calculated soil losses using variations of sensitive parameters (Table 19) show that varying wind speed had the largest effect on the modeling results of site A (-44% and +62%). A roughness variation impacted the total soil loss also significantly (-33% and +11%) while a longer dry-up time had a negligible effect because most erosion events were days without rain close to the erosive hours (15 of 16).

### 3.4 Discussion

Table 19: Calculated modeling soil losses using wind speed, surface roughness and surface dry-up variations for the test period 1999-2009 of the monitoring site A

event no.	date	without variation	Wind speed variation		Roughness variation		Surface water drying up
		-	-5%	+5%	+20 to +25%	-20 to -25%	after 4 hours instead of 2 hours
		kg m <sup>-2</sup>	kg m <sup>-2</sup>	kg m <sup>-2</sup>	kg m <sup>-2</sup>	kg m <sup>-2</sup>	kg m <sup>-2</sup>
1	09/05/2001	2.1	0.4	4.4	0.0	3.1	2.1
2	09/05/2002	8.4	3.4	15.3	0.1	8.0	8.4
3	10/05/2002	12.6	8.2	18.1	12.3	12.8	12.6
4	03/05/2003	0.8	0.6	1.0	0.3	1.6	0
5	09/06/2003	0.3	0.2	0.4	0.3	0.4	0.3
6	11/06/2003	0.0	0.0	0.0	0.0	0.0	0.0
7	29/04/2004	0.0	0.0	0.0	0.0	0.3	0.0
8	30/04/2004	4.0	3.0	5.2	2.9	5.1	4.0
9	09/05/2006	3.0	1.3	5.3	2.2	3.2	3.0
10	19/04/2007	0.0	0.0	0.0	0.0	0.3	0.0
11	20/04/2007	3.6	0.8	10.0	2.7	4.1	3.6
12	22/04/2008	7.6	5.2	10.3	6.8	7.8	7.6
13	23/04/2008	0.0	0.0	0.0	0.0	0.0	0.0
14	25/04/2009	4.1	2.5	6.0	3.7	4.2	4.1
15	27/04/2009	2.4	1.7	3.2	1.5	3.7	2.4
16	28/04/2009	0.0	0.0	0.0	0.0	0.0	0.0
<b>SUM</b>		<b>48.9</b>	<b>27.3</b>	<b>79.3</b>	<b>32.7</b>	<b>54.5</b>	<b>48.2</b>
<b>Differences in %</b>		<b>-</b>	<b>44</b>	<b>62</b>	<b>33</b>	<b>11</b>	<b>2</b>

### 3.4 Discussion

#### 3.4.1 Soil loss by wind erosion

The comparison of two study sites influenced by wind erosion to a different extent showed a very good agreement between measured and modeled topsoil loss. Within the ten-year-period the measured topsoil loss at site A corresponds almost exactly to the modeled soil loss. For the reference site B, the modeled very small soil and SOC losses are as well in accordance with the topsoil measurements. The absolute loss of 49 kg m<sup>-2</sup> over ten years (4.9 kg m<sup>-2</sup> a<sup>-1</sup>) at site A can be considered as very high but not unusual; Zhang et al. (2017) worked as well with SWEEP and determined 4-5 kg m<sup>-2</sup> per year for an entire field. The maximum single-event soil loss of 12.64 kg m<sup>-2</sup> was caused by dry easterly winds, which is comparable to other measured very strong wind erosion events; e.g. 17 kg m<sup>-2</sup> in German Lower Saxony (Schäfer and Neemann, 1990) at sites with similar soil and environmental conditions. Not focusing on

the center part but on the entire field Bach (2008) modeled with another process-based model (TEAM, Gregory et al., 2004) a total soil loss of  $13.08 \text{ kg m}^{-2}$  for four days in March 1969 at the same area as in this study (site A).

The relatively long field length to the east, in main wind direction, explains proportions of 99 % suspension in some erosion events at the monitoring site in this study. After a field length of approx. 100 m the maximum transport capacity of saltation is reached – erosion and deposition are in equilibrium – whereas suspension transport is constantly increasing and never reaches saturation (Hagen et al., 1995). The results of Funk et al. (2004) are supporting the modeling results of this study. For their validation of the SWEEP model in Germany the authors reported an excellent agreement between measured and simulated soil loss, especially for large erosion events. Model results confirm that wind erosion is much higher at site A compared to site B. Without erosion control by cattle slurry and solid manure (cf. Funk & Riksen, 2007; Riksen et al., 2003) soil and SOC loss would have been extraordinarily high at site A.

The strong decline of the topsoil mass at site A over ten years shows the erosion impact, whereas soil mass at site B (less affected by erosion) remained nearly constant. This relation is in accordance with the literature (cf. Ellert and Bettany, 1995; Kibblewhite et al., 2012). Another indication for the wind erosion impact is the declined fine sand fraction at site A from 1999 to 2009 (cf. Li et al., 2009). Particles of this size are preferably transported in wind erosion events (Hagen et al., 1995). The analytical and modeling results bear also given uncertainties. This was shown e.g. in Table 16 and Table 19). In the recent literature for SWEEP the model was evaluated to overestimate the threshold friction velocity, which is necessary to initiate wind erosion (Zhang et al., 2017; Pi et al., 2014; Feng & Sharratt, 2007, 2009). This is especially important for smaller erosion events. However, most of the soil and SOC loss reported in this study was caused by large erosion events of high wind speeds. Smaller events could be affected; this might be the reason for the difference of  $1.4 \text{ kg m}^{-2}$  between measured topsoil loss and modeled loss at site B. Once SWEEP detected erosion it overpredicted the modeled soil loss in the Columbia Plateau (USA) by  $200\text{-}700 \text{ kg ha}^{-1}$  (Feng & Sharratt, 2007) which translates to  $0.02\text{-}0.07 \text{ kg m}^{-2}$  and is therefore negligible for this study, as  $48.9 \text{ kg m}^{-2}$  were modeled and its aim was to designate the main part of the measured topsoil SOC loss to wind erosion.

### 3.4.2 SOC loss by wind erosion

The SOC loss determined by measurements and modeling at site A corresponds to the high soil loss. The SOC loss of  $2.44 \text{ kg m}^{-2}$  in ten years is an important degradation factor reducing soil fertility at the study site. The determination of a considerable change of SOC (10 – 15 %) in soils requires an adequate sample size. This size was determined as  $n=16$  (Garten and Wulschleger, 1999). Considering the 18 sampling points in the BDF program, each containing two cores, this size is clearly reached (cf. Nерger et al., 2016). Using standardized sampling and laboratory methods all three composite samples of site A showed significantly declined SOC stocks. To assign the estimated SOC losses to wind erosion other possible SOC losses have to be excluded. Water and tillage erosion were not relevant (cf. sections 3.1 and 3.2.4.1). Tillage depth changed 2003 at site A from 30 to 25 cm as documented in the management data base. Thus, a possible thinning effect from subsoil material intermixed with topsoil material can be excluded.

SOC losses were considered separately by using different ER for the saltation and suspension part of the soil losses. ERs can vary in space and time as indicated by Webb et al. (2012) or in consecutive measurements as well by sampler type (Funk, 1995). Nevertheless, over a long-term period these variations are minimized (Figure 16). ERs for saltation transport were derived from wind tunnel experiments (Bach, 2008) with soil material from Site A. The chosen ER of 0.98 for saltation fits very good to the function derived from data of several authors (Figure 16). The same applies to the suspension ER found in this study (2.96). It is very similar to the ER of 3.02 found by Sterk et al. (1996) and the ERs of 3.02 and 3.63 of Webb et al. (2012) and can therefore be considered as a reasonable value for SOC loss mainly by suspension.

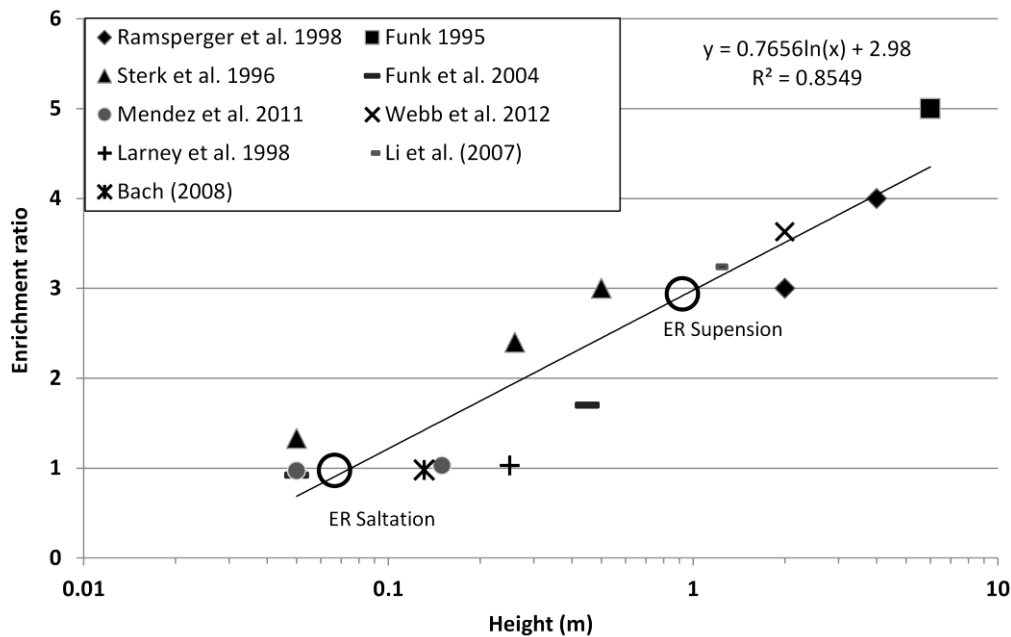


Figure 16: Comparison of the enrichment ratios found in the present study with those of the literature

### 3.4.3 Significance and limitations of the study approach

The results are of relevance for evaluating long-term soil and SOC losses by wind erosion. Wind erosion measurements are not feasible for such long-term periods, therefore, approaches using modeling (Post et al. 2001), long-term soil monitoring (Lal, 2005) or soil sampling and modeling (Chappell et al., 2013; Chappell & Viscarra Rossel, 2013) may be more appropriate. The selected approach to combine topsoil measurements, detailed management data and process-based modeling allows to quantify the impact of wind erosion as land degradation process. To date there is no similar approach quantifying these long-term impacts of wind erosion. The presented approach is limited to sites without noteworthy SOC changes due to other processes such as water erosion and without presence of a thinning effect.

Adequate region-specific and characterization studies are necessary if the SWEEP model is applied without direct measurements of wind erosion. The estimation of all main input parameters in the model setup is based on field observations or measurements of the study site or on adequate validation studies (Funk et al., 2004; Hagen, 1995; Bach, 2008; references in Table 13). This covers the most sensitive parameters mentioned in Hagen et al. (1999) and Feng & Sharratt (2005) and enables to conclude that the study reconstructs reasonable erosion events and SOC loss even without direct erosion measurements in sandy soils of Northern Germany. However, the exact results bear also an uncertainty. This was shown in

Table 16 and section 3.3.5. Especially wind speed variations may have a large impact on the result, therefore, this study benefits from the used official and quality-proved 10-minute wind speed data set. Although a given uncertainty remains, the importance of the presented study lies more in the reliable designation of the main part of the measured SOC losses to wind erosion.

### **3.5 Conclusions**

The applied approach, combining high-quality long-term monitoring data of soil and farming management as well as high-resolution wind speed data with a process-based wind erosion model, was successful. The measured SOC losses could be designated to wind erosion and confirms the impact of this soil degradation in arable sandy soils of Northern Germany. Although based on measured data it is an indirect estimation approach as wind erosion was not measured directly. However, it seems to be an adequate method to estimate wind erosion induced soil and SOC loss, especially for long-term periods (decades) where continuous erosion measurements are not possible

The key data is the BD-SH SMN using consistent sampling and laboratory methods of standardized monitoring routines allowing the determination of uncertainties and thus significant changes in time for long-term periods (Nerger et al., 2016). Although the results are limited to the study sites in Northern Germany, the presented procedure could be interesting for similar environments when long-term soil monitoring data are available and non-Aeolian causes for SOC loss can be excluded. The application of ER factors for SOC losses by saltation and suspension could improve carbon accounting systems and wind erosion models, following the recommendation of Webb et al. (2012).

### **3.6 Acknowledgments**

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## 4 Intensive long-term monitoring of soil organic carbon and nutrients in Northern Germany

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### Abstract

Since 2003, the regional long-term soil monitoring network (SMN) Schleswig-Holstein (SH) includes an intensive monitoring program (I-BDF) with (sub-)annual measurements at four sites. This is the first study investigating the benefits of this SMN where study sites are no experiments but managed by independent farmers. The main objective of this study was to investigate whether, and under which circumstances, annual soil carbon and nutrient measurements are more beneficial within a soil monitoring network than common five- to ten-year measurements using modeling and nutrient balances. Soil measurements (stocks of soil organic carbon (SOC),  $N_{\text{tot}}$ , P and Mg), weekly leachate- $\text{NO}_3\text{-N}$  and management data were used for comparison. C and N changes were modeled with DNDC (DeNitrification-DeComposition); P and Mg were calculated as full nutrient balances and compared to the observations using performance metrics. The results show that DNDC could reproduce the long-term trend of SOC and  $N_{\text{tot}}$  well, but this could also be by coincidence as the type of trendline depended on the starting year. The model results could not depict measured short-term variations in soil which were due to field heterogeneities caused by farm management.  $\text{NO}_3\text{-N}$  leaching was strongly overestimated when organic fertilization and stronger rainfall occurred. Comparing stock changes with nutrient balances revealed that, in several cases, long-term trends could be shown to a limited extent and reproduced only very few short-term changes and variations. The results suggest that only annual soil property measurements can depict the soil's variability and contribute to the identification of the true long-term trend.

**Keywords:** long-term soil monitoring; I-BDF; SOC change; soil modeling; DNDC; nutrient balances; Schleswig-Holstein



## 4.1 Introduction

Long-term soil monitoring networks are important to observe changes of soil properties and agroecosystems (Jandl et al. 2014; Nерger et al. 2016; van Leeuwen et al. 2017). However, different soil properties require different monitoring frequencies. For example, soil organic carbon is a less fluctuating variable, whereas plant-available nutrient stocks are subject to faster changes (Nерger 2010), e.g. to short-term fertilization inputs or weather conditions.

Most long-term SMNs exclusively use monitoring frequencies of five to ten years, e.g. the NRI SMNs in the US (Ogle et al. 2010), the RMQS SMN in France (Arrouays et al. 2002, Louis et al. 2014) or the NABO SMN in Switzerland (Gubler et al. 2015). This is due to the high organizational and financial efforts associated with annual monitoring, especially for more fluctuating variables like plant-available nutrients which would require a shorter monitoring frequency. Likewise, from European soil monitoring networks such as NABO, it is known that measurement variability can be quite high (Desaules 2012). The author states that at least three observations are needed in a time span of five years to establish a time series, i.e. to evaluate a trend. The NABO SMN uses such a five-year interval for resampling campaigns and uses matter balances to get from trend to process analysis (Gubler et al. 2015).

Since 2009, the Land Use/Cover Area frame statistical Survey Soil (LUCAS Soil) is a monitoring project implemented by the Statistical Office of the European Union (EUROSTAT), which uses 3-year resampling intervals (Orgiazzi et al., 2018). Within LUCAS, ~20,000 soil sampling points were measured in each campaign using a stratified random sampling approach based on remote sensing (Montanarella et al., 2011). A topsoil sampling depth of 0.2 m was used for SOC and nutrients. Farm management data was not recorded, and bulk density was measured in 2018 only (Orgiazzi et al., 2018). A process or intensive monitoring analysis would involve an SMN measuring the soil properties annually and, even more frequently, the leachate, etc. Process SMNs using such annual monitoring frequencies like the Chinese SMN (van Wesemael et al. 2011) or the regional I-BDF SMNs in Germany (Prechtel et al. 2009; Kaufmann-Boll et al. 2012) are rare worldwide.

Starting between 2003-2008, monitoring by the I-BDF in Schleswig-Holstein (SH) was established as an add-on to the basic BDF-SH SMN (Boden-Dauerbeobachtung Schleswig-Holstein soil monitoring network), which was described in Nерger et al. (2016). The basic BDF-SH SMN measured basic soil properties every ten years until 2012 and every six years since 2013. The locations of basic and I-BDF sites are identical. On the contrary to long-term soil experiments (LTSEs), the (I-)BDF-SH SMN is not an experiment where all farm management activities were controlled. All agronomic activities and decisions remained with the farmers who

only have the obligation to report their management activities. The I-BDF SMN includes annual observations of soil properties and farm management, biweekly nutrient and heavy metal deposition measurements, and weekly leachate measurements. The amount of measured soil indicators covers most of the quality indicators presented by Bünemann et al. (2018, Fig. 4). Hence, the I-BDF SMN was created to observe soil properties and quality and to detect short-term changes in soil. Such SMNs can also help to assess the performance of process-based soil models such as the DNDC model (Li et al. 1992a) or the CANDY model (Franko et al. 1995).

However, there is a lack of assessments identifying those variables and purposes for which the intensive SMNs are more useful than standard SMNs. Since 2015, the present I-BDF SMN data from Schleswig-Holstein collected eight to eleven years of measured data. Thus, this time span enables the first study investigating its benefits. Thus, the main objective of this study was to investigate whether, and under which circumstances, annual soil carbon and nutrient measurements are more beneficial within a soil monitoring network than common five- to ten-year measurements using modeling and nutrient balances. The analysis will include further SMN data, such as farm management and leachate measurements, and the use of the process-based model DNDC (SOC and  $N_{\text{tot}}$  stocks) for the cropland sites.

## 4.2 Material and Methods

### 4.2.1 Description of the study sites

The monitoring sites 6, 9, 35, and 36 are located in Schleswig-Holstein, Northern Germany (Supplementary Table 1). Supplementary Figure 1 shows the natural and management characteristics of the sites. The I-BDF sites cover all landscape units present in Schleswig-Holstein, i.e. loamy uplands, sandy Geest, and clayey marshland. All I-BDF sites are also regular BDF, i.e. soil measurements every five or ten years take place (Nerger et al. 2016). The four I-BDF sites were established between 2005 and 2008 (Supplementary Table 1). Of particular interest is that the field at site 6 is tile-drained and has soils rich in carbonates due to the fact that it was reclaimed by the sea in 1925. At site 9, the historic land use was Plaggen farming causing high soil organic carbon stocks in these sandy soils (Giani et al. 2014). Two I-BDF sites are managed using organic farming (35, 36) and two with conventional cropland farming (6, 9). The monitoring sites with a size of 0.1 ha are managed in the same way as the

larger field of which they are part of. Thus, at the surface, there is a continuous transition of the soil from the monitoring sites to the surrounding field.

Four to six permanent leachate ceramic samplers are located in four clusters close to the corners of each monitoring site. The clusters are at a depth of 0.75 m and are connected via vacuum leachate wires with sampling bottles, an overflow container, and a vacuum pump in a leachate box outside of the site (Supplementary Figure 2). A deposition measurement station is also located close to each monitoring site.

#### 4.2.2 Soil sampling strategy and laboratory work within the SMN

All laboratory results are obtained from the long-term soil monitoring program BDF-SH SMN (LLUR 2017). Data of the annual sampling campaigns between 2005 and 2016, measured always in March or April, were used for the analysis. From 2005 to 2011, the 18 single samples were taken and analyzed within the I-BDF program (Supplementary Figure 2). From 2012 to 2015, the three composite samples were taken from 18 single points per campaign and study site. In each campaign, the exact sampling spot was selected 1 m adjacent to the original spot and rotated 45° clockwise in each subsequent campaign. This is identical to the procedure within the regular BDF monitoring sampling, described in detail in Nerger et. al. (2016). Within all campaigns, only topsoil material was taken by horizon (usually ~0.3 m in cropland and 50 mm in grassland) and depths were documented. The rock fraction was determined by volume in the field and converted to mass fractions using conversion tables in Ad-Hoc-AG Boden (2005).

Soil chemistry composite samples were analyzed for organic carbon ( $C_{org}$ ) by dry combustion with previously destroyed carbonates and measured with a Leco RC 412 apparatus (Germany). Total Nitrogen ( $N_{tot}$ ) was analyzed using the Dumas combustion method with a Vario MAX cube (Germany). Phosphorous (P) in the soil was measured as Phosphorus pentoxide ( $P_2O_5$ ) using the double lactate extraction method after Egner. Magnesium (Mg) in the soil was determined as Magnesium oxide (MgO) with the  $CaCl_2$  method after Schachtschabel (1956). The pH value was analyzed in a 0.01 M  $CaCl_2$  solution. Cylindrical core-cutters of 100 cm<sup>3</sup> were used to sample bulk density, saturated hydraulic water conductivity, and pore space distribution in undisturbed samples. Bulk density was measured gravimetrically after drying the samples at 105 °C. Pore space distribution resulted from the measurement of the pF curve or water retention curve via ceramic pressure plates. Field capacity was determined as the total capacity of all water-filled pore spaces. Porosity was determined as follows:

## 4.2 Material and Methods

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$$P_{A/Ap} = 1 - (BD_{A/Ap} / PD_{A/Ap}) \quad (13)$$

Where:

$P_{A/Ap}$  = Horizon-specific porosity in A/Ap horizon [fraction];

$BD_{A/Ap}$  = Horizon-specific dry bulk density in A/Ap horizon [ $\text{g cm}^{-3}$ ];

$PD_{A/Ap}$  = Generic particle density in soils:  $2.66 \text{ [g cm}^{-3}\text{]}$ ;

The Köhnpipette technique, which applies sieving and sedimentation, was used to determine the particle-size distribution. The rock fraction was determined by volume in the field and converted to mass fractions using conversion tables in Ad-Hoc-AG Boden (2005). Stocks were calculated for each measurement value as follows (equations 14 to 15), representatively for SOC:

$$SOIL_{A/Ap} = BD_{A/Ap} \times DEP_{A/Ap} \times (1 - RM_{A/Ap}) \times 100 \quad (14)$$

$$SOC_{A/Ap} = SOIL_{A/Ap} \times C_{A/Ap} \quad (15)$$

Where:

$SOIL_{A/Ap}$  = Horizon-specific soil mass in A/Ap horizon [ $\text{Mg ha}^{-1}$ ];

$BD_{A/Ap}$  = Horizon-specific dry bulk density in A/Ap horizon [ $\text{g cm}^{-3}$ ];

$DEP_{A/Ap}$  = Horizon-specific depth of sampled A/Ap horizon material [cm];

$RM_{A/Ap}$  = Horizon-specific rock fraction by mass in A/Ap horizon [fraction];

$SOC_{A/Ap}$  = Horizon-specific SOC stock in A/Ap horizon [ $\text{Mg ha}^{-1}$ ]

$C_{A/Ap}$  = Horizon-specific SOC concentration in A/Ap horizon [fraction];

The final results were the averages of the resulting stocks of each measurement value (18 single values for the years 2005 to 2011 or three composite values for the years 2012 to 2015). The uncertainty of the plotted values was represented by the standard deviation.

In the leachate sampling, there were measurements of  $N_{\text{tot}}$  and P (measured as elementary P) but not of  $C_{\text{org}}$  and Mg. The leachate samples were collected on a weekly basis from the sampling bottles in the leachate box. The samples were in a cooling chain from the

point of collection until the analysis in the laboratory. After storage, the samples were left to thaw overnight at 5°C and then analyzed with the Autoanalyzer (Skalar, Germany) for NO<sub>3</sub>-N, NH<sub>4</sub>-N, N<sub>tot</sub>-N, and PP at the Institute of Crop Science and Plant Breeding of the Kiel University. P<sub>2</sub>O<sub>5</sub> was converted to P using the factor 0.436 and MgO was converted to Mg multiplying with 0.603. The content of N<sub>org</sub>-N was determined as the difference between N<sub>tot</sub>-N and the mineral N fractions. The amount of leachate was calculated using the climatic water balance (DVWK 1996) and corrected with the calculated leachate amounts from DNDC in order to have an identical basis for the NO<sub>3</sub>-N leaching. The evaporation was calculated after Wendling et al. (1991), a method which is adjusted for zones near coasts. At all four plots there is a groundwater level measurement station which is measured every 2 weeks.

### 4.2.3 Nutrient balances

The measurement data of those nutrients not fully covered in the DNDC model runs (P, Mg) were evaluated against full nutrient balances based on farm management (fertilization, crop residues, N fixation, yield loss, catch crops), deposition input, and leachate loss data, while measured SOC and N<sub>tot</sub> stocks were evaluated with the DNDC model (Li et al. 1992a, b). As for fertilization, the applications of manure, slurry, biogas digestate, and chemical fertilizers were considered.

All farm management data, nutrient deposition input, and leachate loss data were recorded in the SMN's database (LLUR 2017). The fertilization dates were synchronized with the sampling dates so that sampling takes place first and fertilization later. However, as previously described, the SMN is not a fully controlled experiment but, rather, the fields are managed independently by individual farmers. Organic and inorganic fertilizer nutrient contents as well as nutrient contents in cut grass were taken from LKSH (2009). For nutrient contents in crops and crop residues as well as crop-specific nitrogen fixation national reference data of the German Fertilizer Ordinance were used (LfL 2013). Crop yield fresh and dry mass and deposition input data was derived from the database of LLUR (2017). Nutrient loss through grazing at site 35 was not considered.

### 4.2.4 The model DNDC

#### 4.2.4.1 Brief description of the model and its application

The DNDC (DeNitrification-DeComposition) model is a process-based model simulating the C and N turnover in cropland and grassland. This includes the modeling of soil pool changes, greenhouse gas emissions, leaching, erosion, inputs from farm management (crop residues, organic and inorganic fertilization, tillage, cutting, grazing), crop growth prediction, and soil temperature and moisture (Li 2012). The primary ecological drivers are climate, soil, vegetation, and management practices (Li 1998). There are four pools of soil organic matter: Plant residues/manure, microbial biomass, humads, and passive humus (Li 1998). Each pool consists of sub-pools with different specific decomposition rates (Li 2012). For nitrogen, nitrification, and denitrification as well as mineralization, ammonium adsorption/volatilization, leaching, crop N uptake, and fixation are included.

DNDC was first described in Li et al. (1992a, b) and validated in many parts of the world (Gilhespy et al. 2014; Giltrap et al. 2010). It was also often used in model comparison studies, e.g. in Brillì et al. (2017) who compared nine different process-based models. For Germany, only few studies are available for grassland or cropland soils, mostly focusing on N<sub>2</sub>O emissions (Ludwig et al. 2011a, b; Jäger et al. 2011; Li et al. 1997; Frolking et al. 1992; Li et al. 1992b) from long-term trials in Central Germany. The model version 9.5 (downloaded on 07 Mar 2018) was used to simulate the changes of SOC and N<sub>tot</sub> stocks and NO<sub>3</sub>-N leaching in soil.

#### 4.2.4.2 Parameterization

The model was parameterized with soil data from the first I-BDF sampling campaign of each site (Supplementary Table 1). For the SOC partitioning the DNDC texture-specific default values were used to determine the size of the SOC pools. Farm management data (main crops and catch crops, yield, fertilization, tillage, grazing, cutting) was available for actual dates.

The weather input data of daily maximum and minimum temperature, daily precipitation, relative humidity, and wind speed were obtained for site 6 from the weather stations of Strucklahnungshörn, Hattstedt, and Bordelum, for site 9 from the station Schleswig, and for the sites 35/36 from the stations Kiel-Leuchtturm, Schönhagen, and Osdorf (DWD 2017).

The soil physical and chemical input parameters were measured as shown in section 4.2.2 The SOC pool distribution was not measured but the DNDC default values for each texture (e.g. sandy loam) were used. For the Plaggen soil at site 9, literature sources, e.g.

Springob & Kirchmann (2002), state that these topsoils contain large fractions of refractory organic matter. The authors show the proportion of this resistant pool of up to 90%. The DNDC default value for the passive humus pool was about 95%. The Supplementary Table 2 shows the starting values used for the DNDC soil variables and its parameters. The amount and application method of organic fertilization input was determined via the data of LLUR (2017). The DNDC default share values were used for the  $\text{NH}_4^+$  and  $\text{NO}_3^-$  input.

#### 4.2.5 Comparing SOC losses from field measurement and modeling results

The DNDC model results are stock changes which cannot be compared directly with the measured stock changes as the DNDC model does not deduct the mass of stones from the soil mass, nor from the carbon stocks. Therefore, the model results of the stocks were re-calculated to the soil mass, deducted of stones, and re-calculated as stocks. Bulk density does not change over time within the DNDC model, while measured bulk density does slightly change. This represents a small source of uncertainty when comparing measured and modeled stocks.

#### 4.2.6 Model performance metrics

The performance of the model was evaluated via the root mean square error (RMSE), the model efficiency (EF) calculated after Loague & Green (1991), and via the relative error (E) after Addiscott & Whitmore (1987). The calculation was shown in the following equations 16 to 18.

$$RMSE = \frac{100}{\bar{O}} \sqrt{\sum_{i=1}^n \frac{(P_i - O_i)^2}{n}} \quad (16)$$

$$EF = \frac{\sum_{i=1}^n (O_i - \bar{O})^2 - \sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (17)$$

$$E = \frac{100}{n} \sum_{i=1}^n \frac{O_i - P_i}{O_i} \quad (18)$$

Where:  $O_i$  is the observed (measured) value,  $P_i$  is the predicted value,  $\bar{O}$  is the mean of the observed data, and  $n$  is the number of paired values. RMSE ranges from 0 to  $\infty$ , EF from  $-\infty$  to 1, and E from  $-\infty$  to  $\infty$ . For an ideal fit, RMSE and E equal zero and EF equals 1. EF values  $<0$  indicate that a mean of the observations describes the data better than the simulated values.

### 4.3 Results

#### 4.3.1 Measured and modeled SOC and N<sub>tot</sub> stocks

The comparison of measured SOC and N<sub>tot</sub> stocks with modeled SOC and N<sub>tot</sub> stocks in cropland soils is shown in Figure 17 and the modeling statistics can be seen in Table 20. These results show that the DNDC model predicted very smooth time series, whereas the observed time series were more variable, especially at BDF09 where the highest carbon input from organic fertilization occurred. The modeled trend matched with the observations. While the trends at site 6 were slightly increasing, at site 9 and 36 they were constant.

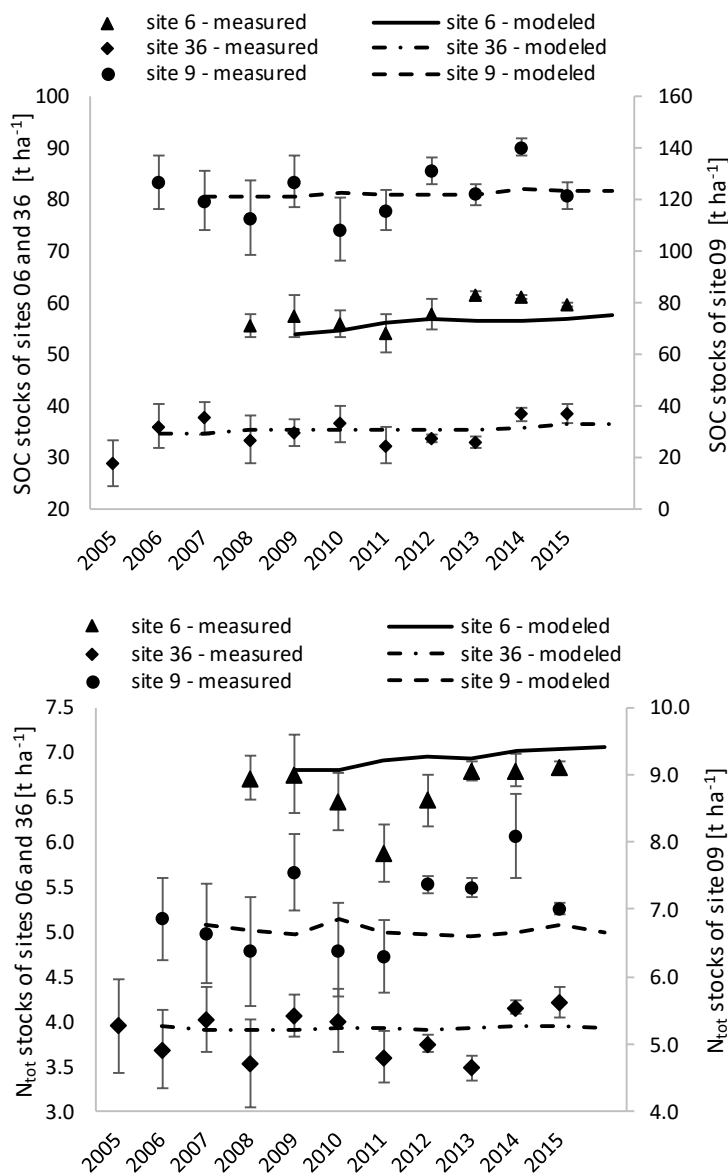


Figure 17: Measured and DNDC-modeled cropland SOC and N<sub>tot</sub> stocks for the period of 2005 to 2015 and modeling statistics



Table 20: Modeling statistics (RMSE in  $\text{t ha}^{-1}$ , EF, E) of the measured and DNDC-modeled SOC and  $\text{N}_{\text{tot}}$  stocks of the sites 6, 9, and 36

	site	RMSE	EF	E
C	6	5.14	-0.41	3.10
	9	6.91	0.07	-0.29
	36	7.33	0.15	-2.31
	site	RMSE	EF	E
N	6	7.18	-1.39	-5.65
	9	8.55	-0.16	3.74
	36	6.49	-0.06	-2.03

The model was not able to reproduce measured short-term changes. These short-term changes cannot be explained by the calculated average balances but instead by true field heterogeneities in the soil and farm management and only slightly by measurement uncertainty. Figure 18 shows selected years of SOC stock measurements which are part of the entire measured 10-year period. The trendline after 10 years (Figure 17) shows that SOC stock remained relatively constant. However, the selected 5-year periods show different trendlines depending on which 5-year period was selected. Using just four consecutive starting years of 5-year periods, the trendlines vary between strong increase and decrease.

## 4.3 Results

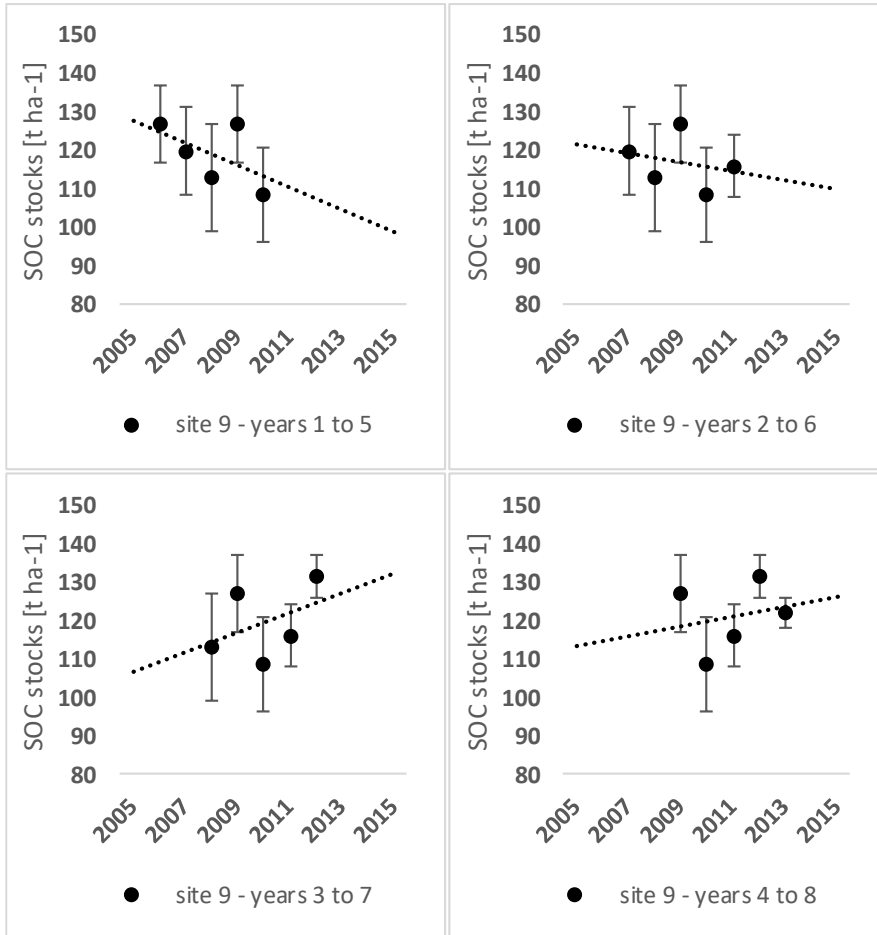


Figure 18: Measured SOC stocks at site 9 for selected 5-year periods between 2005 to 2015

The modeling statistics in Table 20 show a good modeling efficiency for SOC but lower efficiency and higher error levels for  $N_{tot}$ . SOC and  $N_{tot}$  stocks were not modeled for site 35 as the samples were taken from 0-50 mm, whereas the DNDC models were taken in steps of 100 mm soil depth increments. The cropland sites were sampled horizon-specific to ~0.3 m depth. Modeling  $NO_3$ -N leachate loss with the DNDC model resulted in large deviations from the measured outputs as shown in Table 21. The best agreement resulted for the grassland at site 35 where  $NO_3$ -N leaching was slightly underestimated. The DNDC model overestimated leached  $NO_3$ -N especially at the tile-drained clay loam site 6 and at the sandy site 9. Adjusting the drainage efficiency in DNDC resulted in no changes. The change of the depth of the water-retention layer option in DNDC to 0.5 m or below caused a stop of leachate water, a change below 0.5 m showed no changes in leached  $NO_3$ -N output. It was also observed that the overestimation of  $NO_3$ -N leaching was modeled especially for the summer half of the year (April to September). The measured values show always maximums in winter (November to

February) because temperature and, thus, evaporation are low in winter. The model shows strong nitrate leaching when slurry and, to a lesser extent, manure was applied during a rainy period. Figure 19 shows an example at site 9 for the year 2007. There were two applications of cow slurry in April and June combined with high precipitation. These were exactly the dates where modeled  $\text{NO}_3\text{-N}$  increased significantly but not the measured  $\text{NO}_3\text{-N}$ . Similar trends were observed for all sites throughout the model runs.

Table 21: Measured and DNDC-modeled  $\text{NO}_3\text{-N}$  leaching ( $\text{kg ha}^{-1}$ ) at the cropland I-BDF and modeling statistics (RMSE in  $\text{t ha}^{-1}$ , EF, E)

year	site 6		site 9		site 35		site 36	
	measured	modeled	measured	modeled	measured	modeled	measured	modeled
2005					11	7	42	14
2006			91	252	5	11	8	6
2007			66	309	21	13	19	3
2008	77	20	37	58	11	10	35	2
2009	40	53	17	73	3	6	28	86
2010	24	75	32	412	11	4	10	12
2011	6	94	75	165	6	7	29	3
2012	11	77	42	199	1	11	17	102
2013	29	110	14	334	3	7	57	155
2014	28	111	6	353	5	20	20	12
2015	17	124	20	211	4	21	26	4
<b>SUM <math>\text{NO}_3\text{-N}</math></b>	<b>233</b>	<b>664</b>	<b>400</b>	<b>2367</b>	<b>81</b>	<b>117</b>	<b>291</b>	<b>397</b>
RMSE		251		521		115		164
EF		-12		-76		0.8		-10
E		-413		-1145		-160		-18
<b>SUM calculated leachate</b>	<b>2892</b>		<b>3403</b>		<b>3524</b>		<b>3925</b>	

### 4.3 Results

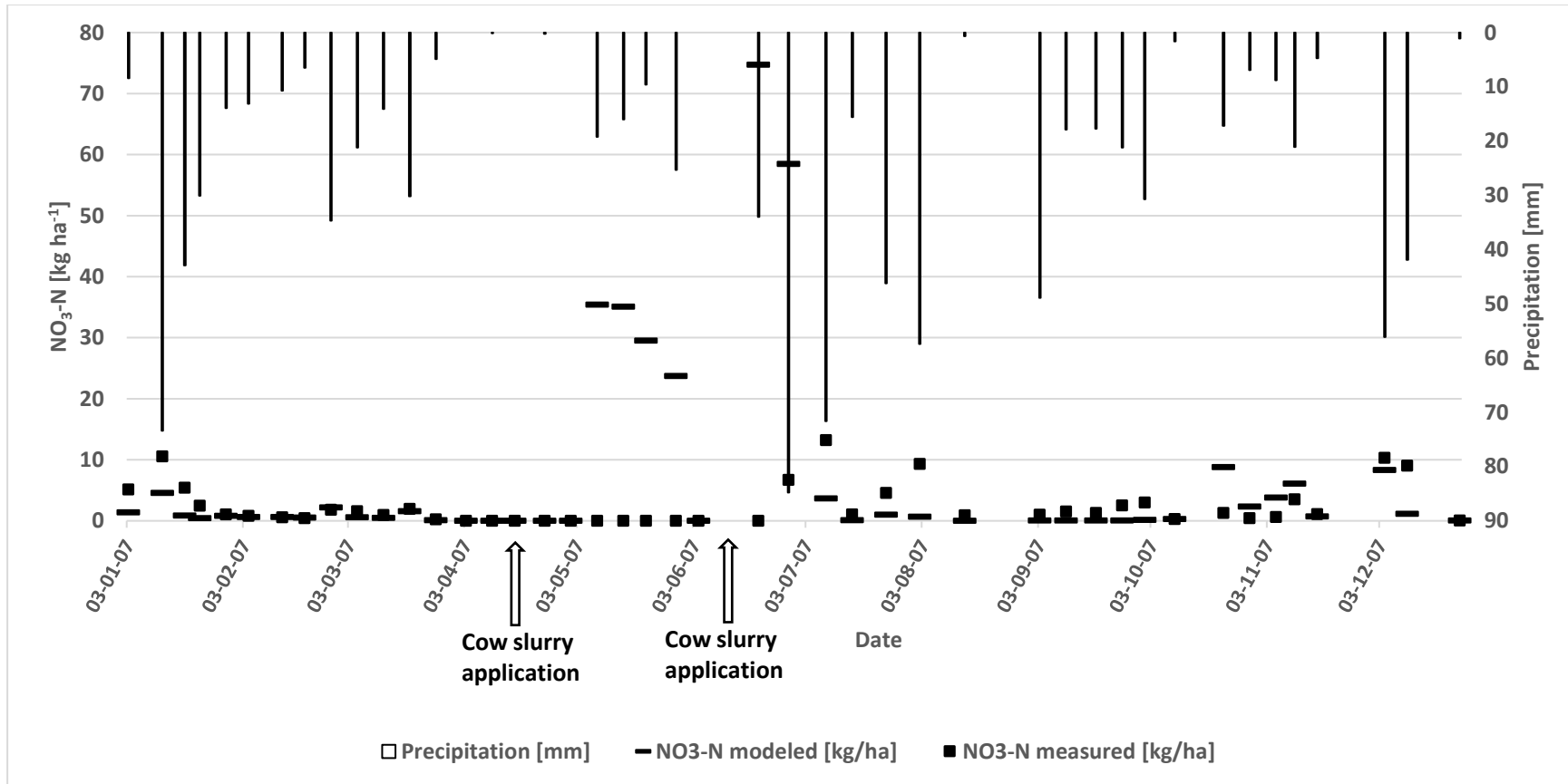


Figure 19: Intra-annual measured and modeled NO<sub>3</sub>-N fluxes including measured precipitation at site 9 (year 2007). NO<sub>3</sub>-N was measured in a weekly interval except during longer dry times in summer (44 measured values). Daily modeled NO<sub>3</sub>-N was adjusted to this approximate weekly interval

There was no such effect in years of solely chemical fertilization nor in years of organic fertilization without rain. Adjusting the manure options in DNDC (application method and depth) resulted in only very slight changes of the modeled  $\text{NO}_3\text{-N}$ . Removing the total  $\text{NO}_3\text{-}$  and  $\text{NH}_4\text{+}$  input in  $\text{kg ha}^{-1}$ , which were determined via default values, decreased the modeled  $\text{NO}_3\text{-N}$  loss by ~30%. The presumably most impactful manure option was the total nitrogen input in  $\text{kg ha}^{-1}$ .

At site 9, measured  $\text{NO}_3\text{-N}$  leaching was constantly decreasing from 2009 to 2014 which was at the same time when winter catch crops were used for the first time. The main proportion of leaching is in winter and the catch crops reduced it effectively.

#### 4.3.2 Measured nutrients compared with full nutrient balances

The modeled P stock curves (Figure 20 and Table 22) based on the calculated full balances fit the trend only to a limited extent. The best agreement was determined at site 36 where the balance line mainly followed the measured stock timeline. The small peak of phosphorous input at this site is reflected in the measurements of the following year, as they were prior to the fertilizer application. At site 6 and 9, the balances overestimate the stock development and significant short-term increases are not depicted.

At the grassland site 35, the small P stock value was due to the sampling until 50 mm depth only. The modeled stocks follow the measured stocks but from 2013 onwards they underestimate the measurements. The last fertilizer application was in 2011. RMSE, EF, and E as discrepancy indicators of the balance curve show an inadequate agreement at this site.

For Mg (Figure 20 and Table 22), there are good agreements between measured and calculated curves at the sites 6, 9, and 36 (low EF values). At the grassland site, 35 measured and predicted stocks seemed to be in accordance, however, deviations at a very low absolute level ( $<0.2 \text{ kg ha}^{-1}$ ) caused relatively high statistical error indicators.

4.3 Results

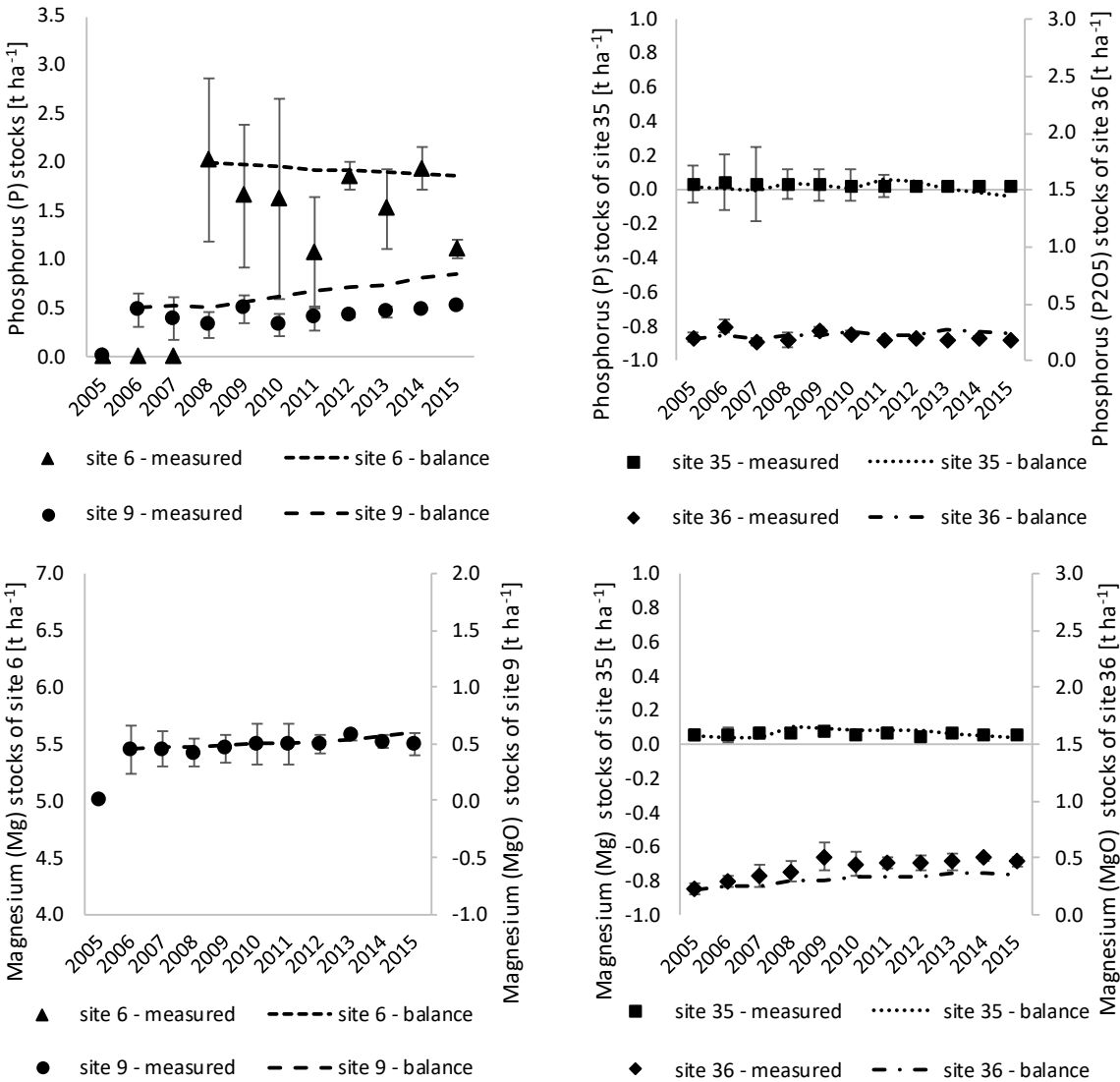


Figure 20: Measured and calculated P and Mg stocks of the sites 6 and 9 (left) and 35 and 36 (right)

Table 22: Performance metrics (RMSE in t ha<sup>-1</sup>, EF, E) of the measured and calculated P stocks (above) and Mg stocks (below) of the sites 6, 9, 35, and 36

	site	RMSE	EF	E	site	RMSE	EF	E
P	6	28	-0.9	-26	35	159	-41	135
	9	58	-15	-53	36	25	-0.66	-14
Mg	6	10	-0.2	3.6	35	39	-11	-8
	9	9.1	-0.1	-5.8	36	28	-0.7	23

## 4.4 Discussion

### 4.4.1 Modeling with DNDC

For both modeled variables (SOC and  $N_{tot}$ ), the modeling results show similar trends that the agreement of measured and modeled data was satisfactory as can be seen looking at the RMSE, modeling efficiency, and relative error. For SOC, this was also observed for example by Jarecki et al. (2018) and Chen et al. (2018). This is desirable for basic soil monitoring focusing on the detection of long-term trends and changes and using five- or ten-year measurement intervals. However, the DNDC model could not reproduce the measured short-term variations of SOC stock and  $N_{tot}$  stock at the study sites. Likewise, measurements every five or ten years could not reveal them. The reason is that, apart from the measurement uncertainty, the true field heterogeneity of the soil was measured. Fertilization is not always applied homogeneously, and topsoil depths are not always exactly identical. As previously stated, the BDF-SH monitoring takes place on fields managed by independent farmers. Thus, a certain spatial heterogeneity can develop due to fertilization dates and amounts but also different tillage activities. These aspects were not recorded in the farm management database and the DNDC model is not capable of considering them. For example, it is possible that fertilization was not fully homogeneously applied on the field or that it took place before sampling. Moreover, average fertilization inputs used in the model and balances can be much higher or lower than the true values at certain spots on the field. Tillage activities, e.g. preparing the soil with ridges and furrows, can have an impact on the carbon and nutrient stock calculation. If the soil was sampled in one year without previous tillage and in the following year after tillage or if ridges and furrows were deeper or shallower, the soil mass and, thus, carbon/nutrient stocks could have varied from one year to the other.

All of these factors lead to zig-zag curves in the laboratory results which were also described by Desaules (2012). Aside from these short-term variations, the trends were mostly constant. The short-term variations are especially present at site 9. In Figure 18, the different trendlines in 5-year periods which are very close to each other were shown. The type of trendline – strong increase, slight increase, strong decrease, and slight decrease – strongly depended on which 5-year period was selected. This variety in trendlines could also potentially occur in different 10-year periods. Thus, the benefits of annual soil property measurements are within the full documentation of the soil's variability. It suggests that for these soil variables, i.e. carbon and nutrients, annual or more frequent measurements have more benefits compared to modeling or measurements every five or ten years. The purpose of building up

time series can also be fulfilled with measurements in a lower temporal resolution, preferably five years in order to establish a time series as soon as possible (Desaules 2012).

Focusing on an improved use of DNDC, especially the parameterization the different soil carbon pools, the consideration of a soil organic carbon fractionation method would suit the I-BDF SMN. There is recent literature (Wiesmeier et al. 2019; Trigalet et al. 2017; van Wesemael et al. 2019) showing the benefits of simplified fractionation methods, analyzing also labile carbon fractions which are sensitive to farm management practices. For the purpose of establishing complete carbon balances, the inclusion of dissolved organic carbon (DOC) measurements in leachate samples would be a benefit to the I-BD-SH in the future.

The modeling of the leached  $\text{NO}_3\text{-N}$  showed large discrepancies to the measured values, except for the grassland site. A contributing reason could be that in DNDC models the leached  $\text{NO}_3\text{-N}$  is measured at a 0.5 m depth, whereas the measurements actually took place at a 0.75 m depth. At site 6, the presence of the tile-drainage could also be responsible. The main reasons for the discrepancies between modeled and measured  $\text{NO}_3\text{-N}$  were application of organic fertilization combined with precipitation or, to a lesser extent, when strong precipitation occurred without organic fertilization. As organic fertilization was applied almost always in the summer half of the year, the overestimation of  $\text{NO}_3\text{-N}$  leaching mostly occurred in this part of the year (April to September). In the literature, DNDC overestimations were found by several authors (Kröbel et al. 2010; Congreves et al. 2016), also in relation to tile-drained fields (Tonitto et al. 2007, 2010). There were also findings that the soil water content was not simulated well (Zhang et al. 2015 and Uzoma et al. 2015). In East Canada, Guest et al. (2017) found in a model comparison that only DNDC modeled a relatively high  $\text{NO}_3\text{-N}$  leaching already in summer months (although not higher than in winter), similarly as in this study.

The differences of measured and modeled  $\text{NO}_3\text{-N}$  seasonal leaching patterns also represent a significant error source. Such differences were also found in Vogeler et al. (2013) and Tonitto (2007, 2010) who emphasized that the DNDC model represents seasonal water fluxes, denitrification, and nitrate leaching only to a low extent. In German sandy soils, Ludwig et al. (2011b) found that the seasonal dynamics of  $\text{N}_2\text{O}$  emissions after a model calibration were still not well-predicted. The constant decrease of measured  $\text{NO}_3\text{-N}$  leaching at site 9 between 2009 and 2014 showed the effect of the first use of winter catch crops during the main leaching season. Thus, catch crops could reduce winter leaching effectively. This effect did not result using the DNDC model, thus, it is an advantage only visible using measurements.



#### 4.4.2 Measured nutrients compared with full nutrient balances

The data show that for cropland sites and nutrients (P, Mg) the balances can explain the measured stock changes to a limited extent only. The agreement for Mg was shown as better compared to P. It is not known whether interchanging processes from the subsoil to the topsoil via the plants could be responsible as the nutrient concentrations in the subsoils were not measured.

Yield loss has a significant impact on the balance curves, thus, the accuracy of the farmer's annual documentation plays an important role. Weather and hydrologic/groundwater regime variations can impact the sequestration, plant uptake or loss of nutrients. Similarly, fertilizer input can cause discrepancies between measured and calculated values. At site 9, the introduction of catch crops was identified to decrease nitrate leaching. But there are also measurement peaks (P at site 6 and 9, Mg at site 6) which could not be explained by fertilization nor harvesting.

Thus, nutrient balances were determined to only partly show the main trend. As the balances are based on average numbers (fertilization amount, crop yield, tillage depth, etc.) they cannot depict the short-term variations which were measured. Especially at the tile-drained site 6 and at the grassland site, the approach of balancing combined with five- or ten-year measurements cannot replace the annual soil measurements.

## 4.5 Conclusions

The applied approach to determine whether, and under which circumstances, annual measurements and other more frequently measured I-BDF data are more beneficial for soil monitoring compared to measurements every five or ten years was successful.

Except of some basic SMNs, the use of modeling with DNDC and full nutrient balances can help to show a long-term trend or changes, which is the main purpose of soil monitoring networks. However, it was also shown that the documented trend strongly depends on the choice of the modeled starting year. Shifting from year 1 to year 2 as the starting year can show an entirely different trend in 5-year periods. It could be similar for 10-year periods. The I-BDF SH measures true short-term variations of soil properties which occurred due to variations in fertilization, tillage, and yield causing a change in carbon or nutrient stocks. This is not a weakness of the I-BDF SH but a strength, as the study sites are not fully controlled experimental fields but managed by independent farmers. Thus, they show the topsoil status

## 4.6 Acknowledgments

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of real farms. Under these conditions annual soil property measurements can depict the soil's variability and contribute to the identification of the true long-term trend.

The I-BDF-SH uses consistent sampling and laboratory methods of standardized monitoring routines allowing the determination of uncertainties and, thus, significant nutrient changes also in short-term periods. There is also a variety of additional data such as groundwater levels, leaching, and deposition as well as nutrient content measurements in crops from other regional SMNs which are very helpful to analyze and evaluate the annual soil data of the I-BDF SMN. One variable which has not yet been measured is DOC in leachate samples and a fractionation of SOC; this should be included into the I-BD-SH in the future. Although, there are few sites studied in such detail and as an intensive soil monitoring is costly, it complements the basic long-term soil monitoring network.

### **4.6 Acknowledgments**

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## 4.7 Supplementary information

### **Intensive long-term monitoring of soil organic carbon and nutrients in Northern Germany**

in Nutrient Cycling in Agroecosystems

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## 4.7 Supplementary information

Supplementary Table 1: Basic geographical and selected major management characteristics of the monitoring sites between 2005-2015 (sites 35/36), 2006-2015 (site 9), and 2008-2015 (site 6) (LLUR, 2017)

site	6	9	35	36
location	Sönke-Nissen-Koog	Schuby	Lindhof grassland	Lindhof cropland
short coordinates (WGS84) <sup>a</sup>	54°36 N, 8°53 E	54°32 N, 9°26 E	54°27 N, 9°57 E	54°27 N, 9°58 E
landscape unit	marshland	Geest (Schleswiger Vorgeest)	eastern uplands	eastern uplands
annual mean temp. (°C) 1981-2010	8.7	9.3	8.9	8.9
climate	temperate oceanic	temperate oceanic	temperate continental	temperate continental
parent material	Holocene marine silt and clay	Weichselian sandur sands	Weichselian glacial cover sand over Weichselian boulder clay	Weichselian glacial cover sand over Weichselian boulder clay
soil texture <sup>b</sup>	loam (32% sand, 47% silt, 21% clay)	sandy sand (87% sand, 9% silt, 4% clay)	sandy loam (65% sand, 30% silt, 6% clay)	sandy loam (62% sand, 28% silt, 9% clay)
soil type <sup>c</sup>	Calcaric Gleysol	Plaggic Anthrosol	Haplic Luvisol	Haplic Luvisol
stones in topsoil	0%	15%	15%	15%
slope	0°	0°	2°	2°
potential erosion risk	none	wind erosion (very low)	none	water erosion (very low)
historic land use	cropland (part of the sea until 1925)	heathland / plaggen	grassland/pasture	cropland

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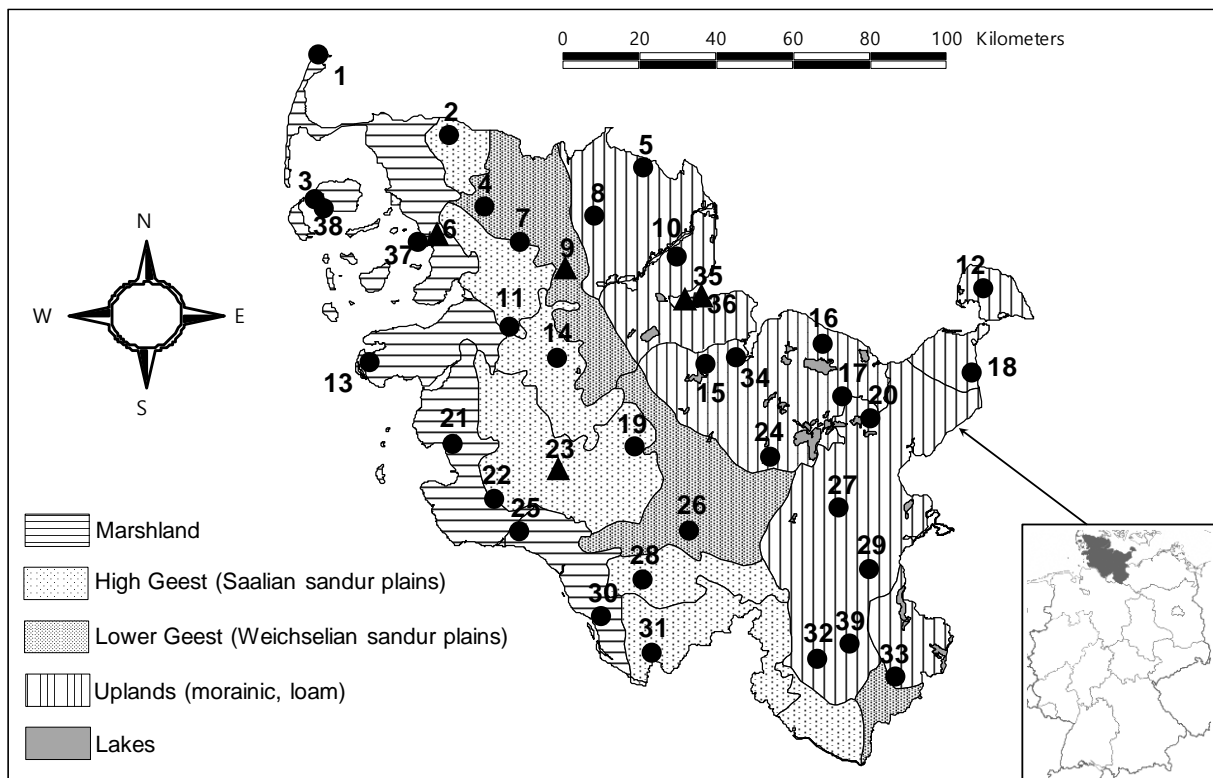
present land use	crop rotation (wheat, rape, wheat)	crop rotation (maize, maize, rye, maize)	grassland/pasture	crop rotation (potato, legume, wheat, clover, oat)
drainage	tile-drained	none	none	none
irrigation	none	none	none	none
catch crops	none	2013-15: rye grass, rye	none	few: rye grass, rye
winter soil cover	yes, main crop	yes, crop residues	yes	in some years
crop residues	incorporated, sometimes exported off-field	left on field	-	exported off-field, sometimes incorporated
ploughing (0.25-0.3 m depth)	1 time per year	1 time per year	never	~1 time per year (every 4 years no ploughing)
main org. fertilizer	pig slurry	cattle slurry (until 2007), digestate (from 2009 onwards)	none	cattle slurry (in 3 of 11 years only)
org. amount fertilized	~18 m <sup>3</sup> ha <sup>-1</sup> a <sup>-1</sup>	~31 m <sup>3</sup> ha <sup>-1</sup> a <sup>-1</sup>	none	~28 m <sup>3</sup> ha <sup>-1</sup> a <sup>-1</sup> (if applied)
main chem. fertilizer	Urea, CAN, S, (low: B)	Urea, DAP, (low: K, CaO)	none	(low: PK, Mg, S, CaO)
nitrogen fertilized	~150 kg N ha <sup>-1</sup> a <sup>-1</sup>	~90 kg N ha <sup>-1</sup> a <sup>-1</sup>	none	none
standard soil monitoring since	1989	1990	2000	2000
intensive soil monitoring since	2008	2006	2005	2005

<sup>a</sup> WGS84 system degrees and minutes, <sup>b</sup> (Jahn et al. 2006), <sup>c</sup> (IUSS 2006), not included: I-BDF site 23 (recently established as I-BDF site)

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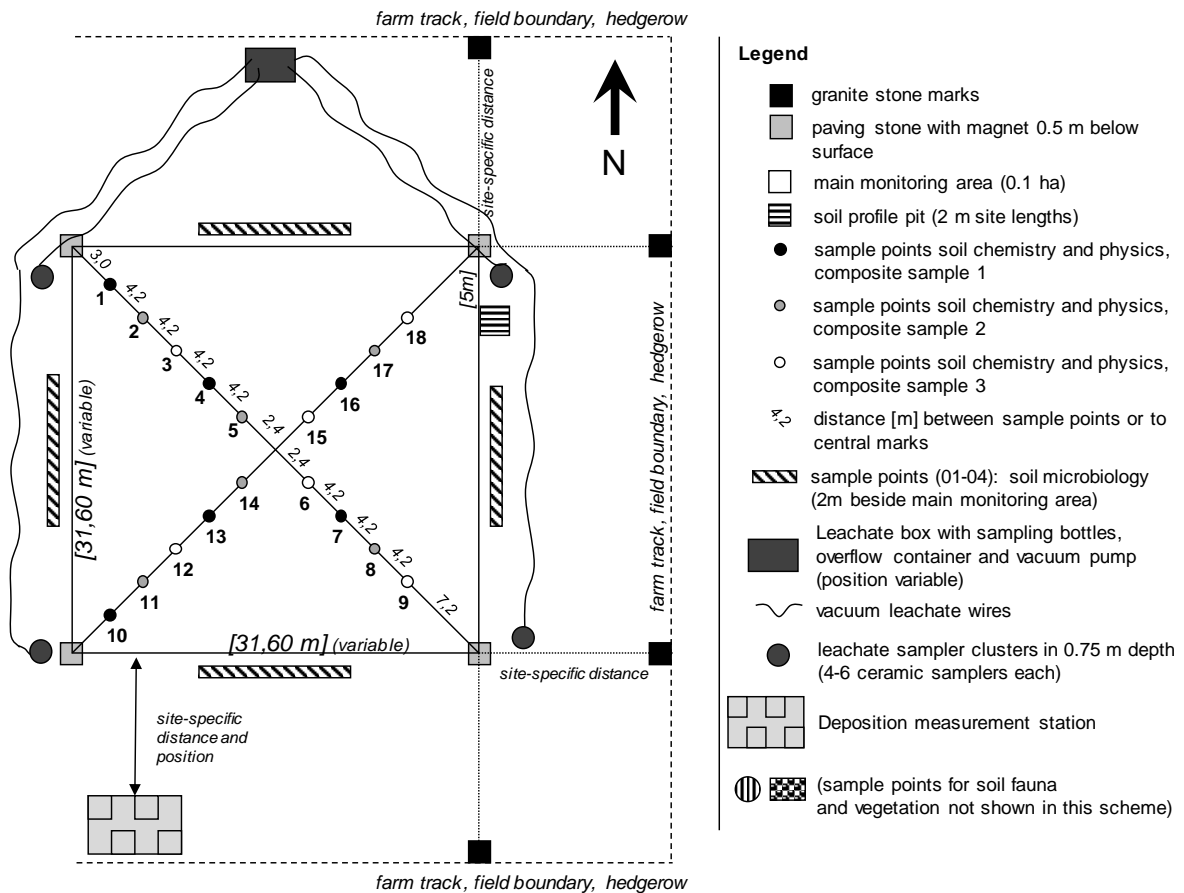
Supplementary Table 2: DNDC soil input variables parameters used

site	6	9	35	36
Land use	Upland crop field	Upland crop field	Dry grassland	Upland crop field
texture	Silt loam	Sand	Sandy loam	Sandy loam
Clay fraction	0.2073	0.04	0.0592	0.0923
Bulk density (g cm <sup>-3</sup> )	1.41	1.192	1.29	1.5617
Field capacity (wfps)	0.4272	0.3751	0.4696	0.3351
Hyd. conductivity (m/hr)	0.0415	0.0445	0.0981	0.0528
Soil pH	7.27	5.19	5.40	6.60
Wilting point (wfps)	0.1913	0.0629	0.1795	0.121
Porosity (0-1)	0.4991	0.5254	0.4947	0.3803
Depth of water-retention layer (m)	0.61	1.2	0.89	1.0
Drainage efficiency (0-1)	1	1	1	1
SOC (kg C kg soil <sup>-1</sup> )	0.0134	0.0408	0.0244	0.0093
Depth uniform SOC (m)	0.295	0.3	0.05	0.295
SOC decrease rate below topsoil	3	1.5	1.5	3
Bulk C/N	8.38	18.67	10.90	9.28
Very labile litter	0	0	0	0
Labile litter	0	0	0	0
Resistant litter	0.01	0.01	0.01	0.01
Humads	0.02	0.0326	0.0251	0.0181
Humus	0.97	0.9574	0.9649	0.9719
Biochar	0	0	0	0
Initial nitrate (mg N kg <sup>-1</sup> )	1.758	0.924	0.5	1.662
Initial ammonium (mg N kg <sup>-1</sup> )	0.630	3.482	0.05	0.563
SCS/MUSLE functions use	no	no	no	yes



Supplementary Figure 1: Landscape units of Schleswig-Holstein (Northern Germany) and localization of the long-term soil monitoring sites (LLUR 2017). The study sites 6, 9, 23, 35, and 36 are represented as triangle symbols

## 4.7 Supplementary information



Supplementary Figure 2: Sampling design of the I-BDF monitoring sites from 2012 to 2015 (ongoing). From 2005 to 2011, there was no composite sampling. All soil chemistry and physics subsamples were analyzed separately





# 5 Conclusions

## 5.1 Summary of key results

The preliminary study (section 1.3) showed that the methods used in the BDF-SH SMN were comparable to national standards and resulted in recommendations which were widely implemented into the SMN. Sections 2 to 4 fulfilled the main objective of this thesis, namely evaluating the quality of the BDF-SH SMN to provide reliable and relevant information for the long-term monitoring of soils and soil degradation. This was done by using different case studies and process-based modeling. To test the BDF-SH SMN in these case studies, its quality based on international standards was investigated.

- **What is the quality of the BDF-SH soil monitoring network compared to international standards?**

The SMN was evaluated as “largely fulfilling the requirements of a soil and SOC monitoring as stated in the relevant literature” and highly suitable to detect changes in soil. Amongst others, these requirements were: a nested sampling design, an adequate number of single sample points for composite sampling, field survey and laboratory conditions, sampling intervals and a variety of measured variables. As different kinds of data were recorded on a long-term basis, changes in soil could be interpreted and evaluated. These were related to the soil chemistry and physics, groundwater levels, the faunistic and microbiological data as well as the farming management on a daily base. The data was used in the first case study on the impact of land use change on SOC stocks and on further essential soil properties.

- **How suitable is the specific design of the BDF-SH SMN to detect and assess impacts of soil degradation on the base of the example of land use change from grassland to cropland?**

The results showed that the BDF-SH is able to detect the severe impacts of deep ploughing, i.e. LUC, on soil properties. Within seven years and one year respectively, the conversion from grassland/pasture to cropland at a sandy loam site and at a clay loam site resulted in significant SOC losses of 19.4 Mg ha<sup>-1</sup> (19.8 %) at a sandy loam site and 27.2 Mg ha<sup>-1</sup> (20.2 %) at a clay loam site. The lowering of the groundwater level was identified as an accompanying consequence of the LUC, contributing to decreasing SOC levels, but it was also found that the

lowering of the groundwater, caused by the installation of a wastewater treatment plant, can cause SOC losses, similar to LUC. The impact of LUC was also seen on soil physics as in the pF curve, the air capacity increased and the water content at permanent wilting point decreased. Faunistic results showed that earthworm and microannelid populations were heavily impacted by deep ploughing. Especially, the anecic and endogeic earthworm biomass and the density decreased, the same applied to surface-near microannelids. The species composition was similarly impacted. The results also stressed that in the next sampling campaign six years later, the soil fauna had recuperated and returned to levels prior to the conversion. Microbiological results showed that the microbial biomass and the basal respiration decreased by over 50 % and recuperated much less compared to the soil fauna. Further indicators, as the  $C_{mic}/C_{org}$  ratio and the metabolic quotient, were also influenced and showed values indicating a disorder of the microbiological community. In total, the results revealed the severe impact of LUC on the entire agroecosystem. Especially due to the high variety of measurements, the BDF-SH is highly suited to detect and evaluate the impact of this kind of soil degradation. As such, since LUC sites are rarely studied with such a large variety of different measurements, the results are highly valuable as data source for other studies, models and policy makers. The next step was to determine whether the BDF-SH monitoring data can also provide a valuable database for process-based modeling.

- **How can process-based modeling be combined with the BDF-SH SMN monitoring data to detect and assess effects of soil degradation on the base of the example of wind erosion?**

For this purpose, a complex methodological approach was developed, combining high-quality long-term monitoring data of soil and farming management as well as high-resolution wind speed data with a process-based wind erosion model (SWEET) at two BDF sites. The model runs on a daily base and requires daily (soil, crop, management, weather) and subdaily data (wind speed). It was found that, excluding the external weather data, the BDF-SH can provide all necessary data to either be used directly in SWEET or to be the base for an estimate equation. This approach of using long-term soil monitoring data has not yet been published in other studies. One of the further methodological outcomes of the study was a guidance on how to update several model parameters after one model run. The modeling results were an indirect estimation approach as wind erosion was not measured directly. They modeled results were compared to the measured SOC losses in soil for a period of ten years, where SOC changes

## 5.1 Summary of key results

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through farming practices and other sources were considered. Including the use of enrichment rations, this development was another methodological outcome.

In the field measurements, it was determined that at the site with high wind erosion, the soil mass decreased by 49.4 kg m<sup>2</sup>, while SOC stock declined by 2.44 kg m<sup>2</sup> within ten years. For this time period, modeling with SWEEP resulted in a total soil loss of 48.9 kg m<sup>2</sup> as a total of 16 erosion events. The agreement between measured and modeled data was very good and implied that these significant long-term losses were caused by wind erosion. 78 % of the soil loss was transported by suspension. The SOC enrichment ratio of the eroded soil material in suspension was 2.96 (saltation ER: 0.98), which was comparable to the findings in the literature. At the reference BDF site, characterized by low wind erosion, measured and modeled results of topsoil loss were equally comparable. The developed approach was shown to be applicable to well-studied sites where soil organic carbon is not lost by other causes on a noteworthy scale. The approach seems to be an adequate method to estimate aeolian soil and SOC loss, especially for long-term periods (decades), where continuous erosion measurements are not feasible. The application of ER factors for SOC losses by saltation and suspension might improve carbon accounting systems and wind erosion models.

The above-mentioned research covered the basic BDF-SH monitoring. However, in terms of an intensive soil monitoring, measuring in a higher temporal resolution, another assessment of the monitoring quality, shown in a case study, was implemented.

- **How suitable is the specific design of the intensive I-BDF-SH SMN to detect and assess soil property changes and which benefits does it have compared to process-based modeling approaches and basic soil monitoring?**

The measured soil carbon and nutrient changes of four studied I-BD sites were modeled with DNDC and compared to full nutrient balances using statistical indicators. The results show that DNDC could reproduce the long-term trend of SOC and N<sub>tot</sub> well, but this might also have been by coincidence as the type of trendline depended on the modeled starting year. Shifting from year 1 to year 2 as the starting year can show an entirely different trend in 5-year periods. This might be similar for 10-year periods. The model results could not depict measured short-term variations in soil which were due to field heterogeneities caused by farm management. Likewise, measurements every five or ten years could not reveal short-term variations. The I-BDF SH measures true short-term variations of soil properties which occurred due to variations in fertilization, tillage and yield, caused a change in carbon or nutrient stocks.

For example, it was possible, that the fertilization was not fully homogeneously applied to the field or that it had taken place before the sampling. Also, changes within the tillage activities (tillage depth, tillage time) might have an impact on the soil mass, and, thus, on carbon and nutrient stocks, from one year to another. Thus, the true field heterogeneity of the soil was measured and caused measured zig-zag timelines. These aspects were not recorded in the farm management database and the DNDC model is not capable of considering them. The study sites are not fully controlled experimental fields but rather managed by independent farmers. Thus, the measured results of the study sites show the topsoil status of real farms. Under these conditions, annual soil property measurements can depict the soil's variability and contribute to the identification of the true long-term trend.

NO<sub>3</sub>-N leaching was strongly overestimated when organic fertilization and stronger rainfall occurred. The seasonal leaching pattern of measured and modeled NO<sub>3</sub>-N represented a significant error source. The main reasons for the discrepancies between modeled and measured NO<sub>3</sub>-N were the application of organic fertilization combined with precipitation, or, to a lesser extent, when strong precipitation occurred without organic fertilization. Comparing stock changes with nutrient balances revealed that, in several cases, long-term trends could be shown to a limited extent and reproduced only very few short-term changes and variations. Beyond fertilization input, yield loss, catch crop introduction and weather, the impact factors on the balance curves could not be fully determined. However, as the balances are based on average numbers (fertilization amount, crop yield, tillage depth, etc.) they cannot depict the short-term variations which were measured.

Apart from these limitations, the I-BD SH was assessed as highly suitable to detect and assess short-term changes in soil. This especially applies to the annual soil measurements and the weekly NO<sub>3</sub>-N measurements in leachate. The consideration of a soil organic carbon fractionation method and the inclusion of dissolved organic carbon (DOC) measurements in leachate samples would be a benefit to the I-BDF SMN in the future.

## **5.2 Capabilities, limitations and outlook**

### **5.2.1 BDF-SH Soil Monitoring Network**

The SMN includes a wide range of observed variables and indicators. 37 sites, representatively selected based on landscape units, soil types and land use management, are monitored in high detail in terms of chemical, physical, biological and management data. High monitoring quality standards were used to ensure that uncertainty can be determined, and time series

established. Therefore, the BDF-SH SMN can be considered as a long-term soil monitoring network, mainly fulfilling the highest level of SMN standards (Jandl et al., 2014; Nerger et al., 2016). This is the base for the SMN to be used by national and international surveys, programs and studies. This thesis proved that the BDF-SH SMN can additionally serve to parameterize and validate process-based models. It was also determined how basic and intensive monitoring provide the base for different monitoring aspects, on the one hand the establishment of long-term trends and time series, and, on the other hand, the detection of short-term variations in soil. The BDF-SH SMN is, furthermore, suitable for setting up basic and full carbon and nutrient balances, considering all relevant input and output variables.

The limitations of the BDF-SH SMN are that, even though selected representatively, there are relatively few sites when compared to the site density of other SMNs as LUCAS Soil. This is due to the relatively high financial and administrative efforts of maintaining a SMN of this kind of comprehensiveness. Furthermore, within the first ten years of the SMN, there were some changes within the depth increment sampling method and of some analytical methods. Although most of the different methods were regarded as comparable to each other and most differences in depth increments were negligible, this might potentially impede the comparability of the first two sampling campaigns with each other. The comparison of each of the 13 regional BDF SMNs in Germany with each other is limited concerning certain aspects. The reason are differently interpreted guideline norms. However, they all fulfill the main quality criteria of the national main monitoring guideline (Barth et al., 2001). Another limitation is that calculated full nutrient balances could not depict measured short-term variations in soil.

The assessment of this thesis determined that there two additional analytical methods might be used; on the one hand, a fractionation of soil organic carbon in the basic and in the intensive monitoring. On the other hand, a measurement of dissolved organic carbon in leachate would be beneficial to the intensive monitoring. Furthermore, the use of the BDF-SH monitoring data in combination with process-based modeling should be strengthened. This was determined as a mainly successful approach in this thesis. The BDF-SH data should be further harmonized with the other German regional SMNs by using the methodological code (Kaufmann-Boll et al., 2011). This code allocates all used analytical methods to a logic code abbreviation. The SMN should also be compared to the results of recent raster-based soil monitoring networks like the German Agricultural Soil Inventory (GASI; Bach et al., 2011) and LUCAS Soil (Orgiazzi et al., 2018) to determine the comparability of the sites with similar landscape unit, soil type and land use management. This would be the base to allocate soil properties, measured only in the BDF-SH SMN, to the GASI and LUCAS Soil sites.

### 5.2.2 Thesis approach

The applied methodology of this thesis evaluated the quality level of the BDF-SH SMN and showed the comparability to other national and international SMNs and standards. Combining the broad range of the different data (chemical, physical, biological, management), the applied approach evaluated the SMN results in terms of changes in soil due to degradation (land use change, wind erosion) and showed the impact on soil properties. This was possible through using the synergies of the broad range of observed data showing the impact of soil degradation on different indicators and variables. The approach connected process-based models with the monitoring data and validated the models with the SMN data. Additionally, the use of both basic and intensive monitoring data serving different monitoring aspects was demonstrated using modeling and elaborating full nutrient balances. As a last step, future directions and additional relevant measurements were determined for the BDF-SH SMN. Thus, the thesis addressed the research gap of a missing detailed evaluation of a regional German soil monitoring network.

Moreover, the applied methodology of this thesis can, thus, be used for the evaluation of other SMNs, namely regional, national or international. Interpreting the results of this thesis, the value of the BDF-SH SMN is more accessible to international scientific studies and programs and can be used easier. This also applies to the use of process-based models for studies focusing on changes in soil and soil degradation. The thesis also underlined how the broad range of observed data might create combined effects, thus recommending the inclusion of the measured soil properties also for other SMNs on an international scale. Future research might focus on the harmonization and the synergies of the BDF-SH SMN with other SMNs and on a stronger coupling with more process-based models for other forms of soil degradation to provide a reliable base for future long-term soil monitoring.

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## **Eidesstattliche Erklärung**

Hiermit erkläre ich, dass ich die vorliegende Dissertation, abgesehen von der Beratung durch meine Betreuer, nach Inhalt und Form selbstständig verfasst habe und keine weiteren Quellen und Hilfsmittel als die hier angegebenen verwendet habe. Diese Arbeit hat weder ganz noch in Teilen bereits an anderer Stelle einer Prüfungskommission zur Erlangung des Doktorgrades vorgelegen und wurde nicht veröffentlicht oder zur Veröffentlichung eingereicht. Veröffentlicht wurden ausschließlich die drei Fachartikel, jeweils einzeln in den genannten Fachzeitschriften, im Rahmen der vorgelegten kumulativen Dissertation. Ich erkläre, dass die vorliegende Arbeit unter Einhaltung der Regeln zur Sicherung guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft erstellt wurde. Ich erkläre weiterhin, dass mir kein akademischer Grad entzogen wurde.

Kiel, 30.01.2020

(Rainer Nerger)