SOIL FUNCTIONS – TODAY'S SITUATION AND FURTHER DEVELOPMENT UNDER CLIMATE CHANGE

Kirsten Madena, Helge Bormann and Luise Giani

With 3 figures and 4 tables
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Summary: Climate change will have effects on many ecosystems, including the top layer of the earth: the soils. Climate-induced changes in soil properties can lead to changes in soil functions and their importance for soil protection. These possible changes have been evaluated within the German part of the EU Interreg IVb project "Climate Proof Areas" in two pilot regions in the Wesermarsch (Germany). The evaluation of eight different soil sub-functions was carried out using the evaluation method TUSEC-B based on soil information gained from soil maps for present (Status Quo) and climate-adapted soil properties. Four different climate scenarios for 2050 were considered. The evaluation results of the individual soil functions have been summarized to an overall evaluation result using the maximum principle. The evaluation results for the Status Quo show that large areas of the pilot regions are important for soil protection regarding both the individual soil function evaluation and the summarized evaluation. The adaptation of climate-influenced evaluation parameters results in an increase of the importance of protection of the soils for some sub-regions and in a decrease for others, depending on the scenario. The differences in the extent and direction of changing evaluation results mainly depend on changes in soil organic matter content and groundwater level. They are different for the individual soil functions and regarding the overall evaluation result, but show the influence of climate change on soil functions. On the basis of these results, it is recommended to consider climate-induced changes in soil functions within spatial planning processes such as area-wide coastal protection or water management measures (e.g., dike or reservoir construction), to avoid the loss of soils with valuable functions that are worth protecting.

Zusammenfassung: Der Klimawandel wird sich auf viele Ökosysteme, einschließlich des Ökosystems „Boden", auswirken. Diese klimabedingten Änderungen der Bodeneigenschaften können zu Veränderungen in den Funktionen des Bodens führen und dessen Bedeutung für den Bodenschutz verändern. Im Rahmen des EU-Interreg IVb-Projektes „Climate Proof Areas" wurden daher in zwei Pilotregionen in der Wesermarsch (Deutschland) diese möglichen Veränderungen analysiert und bewertet. Die Bewertung von acht verschiedenen Bodenteilfunktionen erfolgte mittels der Bewertungsmethode TUSEC-B für heutige und klimaangepasste Bodeneigenschaften unter der Berücksichtigung vier verschiedener Klimaszenarien (2050). Die auf Karteninformationen basierenden Bewertungen der Teilfunktionen wurden abschließend in einer Gesamtbewertung, basierend auf dem Maximumprinzip, zusammengefasst. Die Ergebnisse der Bewertung für den Status Quo zeigen, dass weite Bereiche der Pilotregionen sowohl hinsichtlich der Einzelfunktionen als auch in Bezug auf die Gesamtbewertung für den Bodenschutz wichtig sind. Die Anpassung der klimabeeinflussten Parameter an die projizierten Klimabedingungen in 2050 resultiert, je nach Szenario, sowohl in einer Erhöhung als auch in einer Abnahme der Schutzwürdigkeit der Böden. Diese Unterschiede in Ausmaß und Richtung der Veränderungen sind insbesondere auf die Änderung des Gehaltes an organischer Substanz und des Grundwasserstandes zurückzuführen. Sie variieren für die Bewertungsergebnisse der Einzelfunktionen und der Gesamtbewertung, zeigen jedoch den Einfluss des Klimawandels auf die Funktionen eines Bodens auf. Basierend auf diesen Ergebnissen ist eine Berücksichtigung klimatisch bedingter Veränderungen der Bodenfunktionen innerhalb von Raumplanungsvorhaben (z.B. flächendeckender Küstenschutz, wasserwirtschaftliche Maßnahmen (u.a. Deich- oder Polderbau)) zu empfehlen. Nur so ist ein zukünftiger Verlust von wertvollen Bodenfunktionen und damit von Böden mit einer hohen Schutzwürdigkeit zu vermeiden.

Keywords: Climatic change, coastal area, soil function evaluation, TUSEC-B, Northern Germany

1 Introduction

As the active layer between atmosphere and lithosphere soils regulate many biological and hydrological processes. Thus, soils fulfill various ecological and social functions, differentiated into natural, utilization, and archive functions. The most obvious function is the production function (e.g., production of crops or raw material). Additionally, soils are the basis of life for animals, plants, and humans providing for essential needs such as water, nutrients and the surface to live on. They regulate

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many processes within the water and nutrient cycle, including the transformation of contaminants. Preserving the natural and cultural history by keeping information on natural impacts like sediment transport by flooding or sand storms and anthropogenic changes, respectively, soils are also important historical archives.

"The capacity (of soil) to function" is the simplest definition for soil quality, as stated by the Soil Science Society of America (SSSA 1995). Improving soil quality and reversing soil degradation are major topics in the context of soil protection and solution approaches have been changing continuously (Carter et al. 1997; Warkentin 1995). Until 1976, when the Food and Agricultural Organization of the United Nations published the "Framework for Land Evaluation" (FAO 1976), soil evaluation focused on agricultural productivity. With the Framework, which was revised in 2007 (FAO 2007), the evaluation process has been widened to include alternative land uses such as forestry and nature conservation to enhance the protection of the environment. On the legal basis, Germany enacted the German Federal Soil Protection Act in 1998 as a basic legal principle for soil function protection and restoration (BBodSchG 1998). With this introduction into national law, increasing attention was paid to the multi-functionality of soils on national and international level (Lehmann and Stahr 2010). Different international institutions started to consider the wide range of functions the soil undertakes within the ecosystems (EC 2002, 2006; Karlen et al. 1997). Additionally, the evaluation of soil functions as a basis for soil protection measures within spatial planning processes became more important and should be implemented in the land use negotiating process in future (Bouma 2001).

During the past years, with a thorough discussion about climate change and its impact on ecosystems, the general interest in assessing the vulnerability of soil development and soil functioning has further increased. Changes in climatic conditions, especially in temperature and precipitation, can change soil properties and finally the soil functions (e.g., EEA 2008; IfB 2008; Rounsevell et al. 1999). For example, higher temperatures, as projected for the future, can lead to increasing soil organic matter decomposition, and hence changes in soil hydraulic and physical properties (Kardol et al. 2010). As a result, the water storage capacity and the productivity of soils might decrease, and the vulnerability and importance of individual soil functions might change. Due to the complexity and interaction of climate-induced changes in the water and heat balance of soils, however, contrary changes in soil functions can occur which are mostly combined with related changes in land use and in the soil microorganism population. Investigations performed in North Germany by Springob et al. (2001) showed that the mean content of organic carbon of different Ap horizons strongly increased with precipitation. Verzandvoort and Kuikman (2009), who discussed the influence of climate change on soils in their report, also described the positive and negative effects on soils and the important role of soils within climate adaptation strategies. To evaluate shifts in soil functions of a site, it is therefore necessary to understand which and how soil properties can change and how these changes can be incorporated into the evaluation process.

Since the start of the discussion on implementing soil protection issues in spatial planning concepts, different evaluation methods for different scales and different focal points have been developed. More than 80 evaluation methods, based on different data bases, planning scales, and selections of evaluated functions, exist in Germany (e.g., PLANUNGSGRUPPE ÖKOLOGIE UND UMWELT GMBH 2003). For spatial planning purposes, an evaluation approach needs to be clearly structured, applicable to different planning levels, and comprehensive regarding the soil functions which can be evaluated. Additionally, an aggregation of evaluation results for individual soil functions is often required to rate their ecological value. In most cases the size of the area as well as the available soil data and information are the factors limiting the choice of methods.

Thus, the aim of the present work is to investigate whether and in which direction a projected climate change can induce changes in soil functions and whether this can be identified by using an appropriate evaluation method. We used the TUSEC (Technique for Soil Evaluation and Categorization for Natural and Anthropogenic Soils) approach (Lehmann et al. 2008) to evaluate the soil functions on the effect of climate change in two water board areas in the administrative district Wesermarsch (Northern Germany). This recently developed evaluation method considers most of the soil functions defined by the BBodSchG (1998) and has a clear evaluation procedure. It was tested for natural and anthropogenic soils at different sites in South Germany, Austria, Italy, Slovenia, and Switzerland (Jenny et al. 2006). TUSEC has been developed for soil evaluation of natural and anthropogenic soils in the temperate zone and comprises two evaluation levels which differ in the required evaluation parameters and the possible evaluation scale (see 3.1). Due to the parameters taken as a basis for the evaluation process it is possible to consider climate-induced changes in soil properties. Based on four different scenarios of climate-induced changes, we changed five evaluation parameters to evaluate the future worthiness of soils in the project area and compared the results with the evaluation results of the present climate situation. We think this procedure will be useful to avoid losing valuable and protectable soils in future and can be used in spatial planning processes, for example, following the discussion and development process within the German part of the EU Interreg IVb project "Climate Proof Areas" (CLIMATE PROOF AREAS 2011), which this study is part of.

2 Study area

The study area is located in the northern part of Germany and comprises the water board areas Butjadingen (north, ~216 km²) and Stadland (south, ~ 113 km²), which belong to the administrative district Wesermarsch (Lower Saxony) (Fig. 1). Dominated by the North Sea, the climate is humid with moderate temperatures (~8 °C, mean annual temperature) and precipitation (~710 mm, mean annual precipitation) (Mühr 2007). The soils of the entire Wesermarsch region are mainly marsh (nearly 75%) and peat (nearly 15%) soils (Severin 2008). Only 0.5% of the district area are sandy soils (LANDKREIS WESERMARSCH 2003). The development of these marsh and peat soils is closely related to the Holocene sea transgression and regression phases. Transgressions led to sedimentation of fine material in shallower and still water areas as well as sedimentation of coarser material close to the shore. Peat growth and the development of fens set in during regressions with concurrent high groundwater levels. Nowadays, the region is cut off from the sea by dikes. The groundwater influence is still present, but regulated by drainage mainly in winter time and by watering during summer. With increasing human activities and improved melioration techniques anthropogenic soils have been developed.

Different hydrological conditions, land management as well as the specific pedogenetic factors and processes led to a wide range of marsh and peat soils in our study area. It is dominated by marsh soils with mainly Gleyic Fluvisols (calcaric) (45.7%), Gleysols (clayic) (25.1%), and Haplic Gleysols (15.8%). About 8.5% of the area is covered with peat soils like Sapric Histosols or Histosols with clayic, organic, or anthropogenic layers (Fig. 1).

Land use in the Wesermarsch region is characterized by agriculture (80% of the area). Especially due to the soil conditions, 90% of the agricultural land is under grassland farming.

Coastal protection and drainage of the main land is vital for this area because of the flat relief with some parts of it being below mean sea level and its location close to the sea. For hundreds of years, the Wesermarsch and many other regions in the German coastal areas have been drained by ditches and pumping stations in the winter time. Due to water scarcity in the summer months the ditches have also been used for watering the arable fields and cattle with surface water from the Weser River. Nowadays, the water management system is negatively influenced by the increasing salt concentration in the irrigation water caused by the deepening of the Weser River (GFL/BIOCONSULT/KÜFOG 2006). Projected higher storm tides and sea level rise may also increase the amount of salt water flowing upstream the river to the tidal gates used for watering (Beckum, Strohausen) (Grabemann et al. 2005). Additionally, changes in climatic conditions such as less precipitation in summer and therefore a higher watering demand, may aggravate the salt water problem and cause follow-up problems which have to be solved by coastal protection and water management.

3 Materials and methods

3.1 TUSEC and the overall evaluation approach

To evaluate the soil functions in our project area, we chose TUSEC (Technique for Soil Evaluation and Categorization for Natural and Anthropogenic Soils), a method which has been developed to evaluate soil functions for soils under temperate climate, comprising TUSEC-A and TUSEC-B (beta-version) (Lehmann et al. 2008). Compared to the A-procedure which is based on detailed pedological characteristics of the area, the B-procedure can be used for an orienting evaluation in larger areas. It is based on secondary data (e.g., pedological, topographical, or historical map information) and can be applied for scales of 1:25,000 and smaller. Because of the ori-

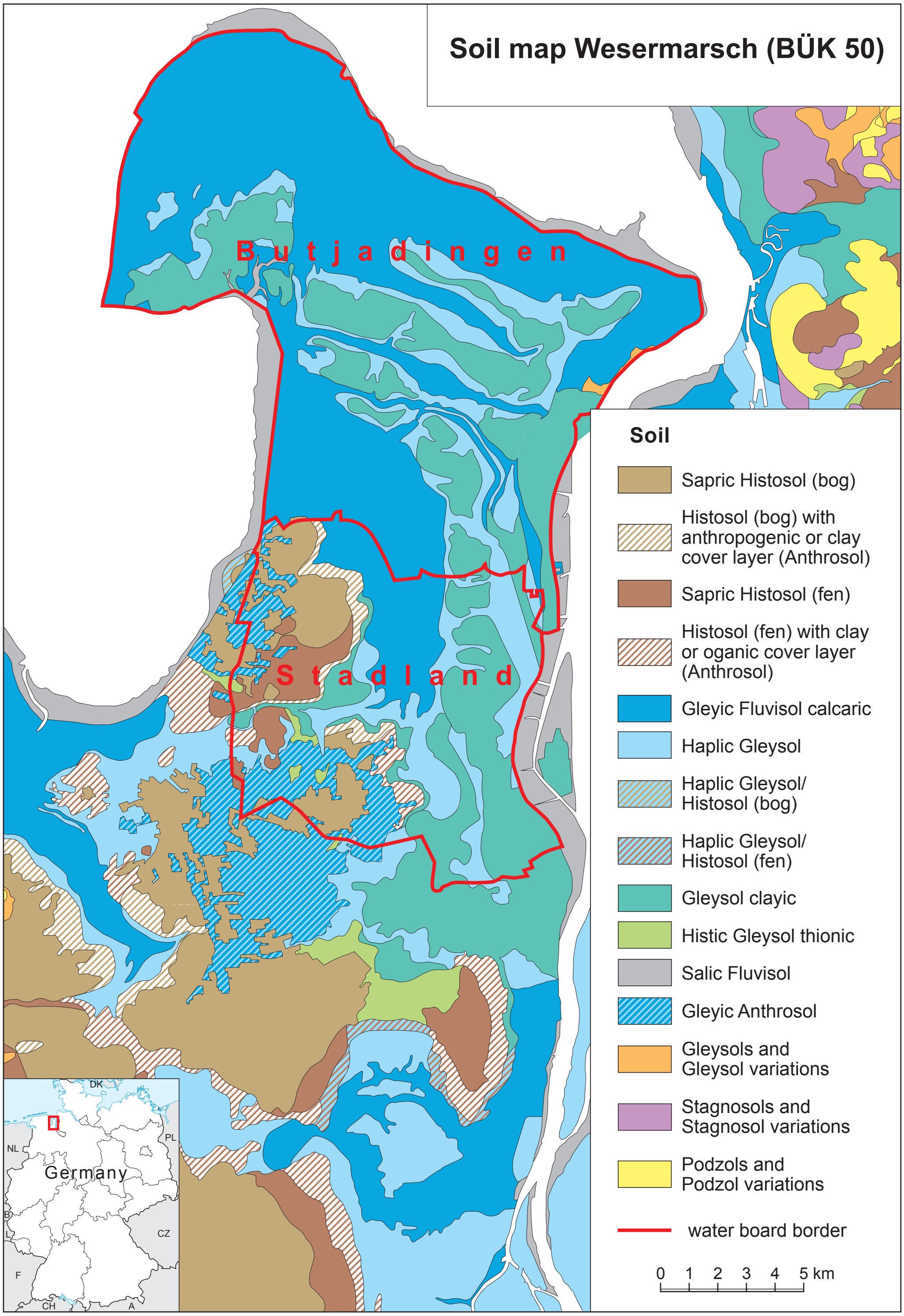

Fig. 1: Location and soils (WRB classification) of the study area (north: Butjadingen; south: Stadland)
Source: based on data of Nds. Bodeninformationssystem NIBIS with permission of LBEG, Hannover; NIBIS® Kartenserver (2010) and TK 25 (© LGN)

enting character the evaluation results should be verified by field data analyses and site inspections later on. The used soil data are mainly values averaged to a depth of one meter. Only the information about the organic matter content is topsoil-related. To evaluate the soil functions in the rural areas Butjadingen and Stadland for the present situation (Status Quo) and for 2050, we used the B-procedure of the TUSEC approach. Table 1 shows the soil functions, defined by the BBodSchG (1998), and sub-functions which were evaluated using the TUSEC-B method. Each sub-function is described by evaluation criteria and parameters, respectively, generated from map information. For example, the importance of the evaluated site for soil protection regarding the habitat and basis of human life is evaluated by the evidence of point or diffuse source contamination by old deposits or

Tab. 1: TUSEC-B (beta-version): soil functions, sub-functions, and the corresponding evaluation criteria and parameters (in italics: supplementation/deviation of manual specifications)

soil function	soil sub-function	evaluation criteria	parameters (manual)	parameters (adapted)
habitat and basis of life	habitat and basis of life for humans	classification of contamination	current and historical land use, soil contamination	potential brownfield sites: old deposit, disused military site
	habitat and basis of life for animals and plants	anthropogenic influence, extreme site conditions	groundwater table, available water capacity (awc) (derived from texture, organic matter content, information about consolidation), current and historical land use, soil conditions (treatment)	*percentage of soil sealing,* anthropogenic soil material, awc (derived from organic matter content, texture (*incl. decomposition degree for peat), bulk density*), *upper* groundwater table
medium for decomposition, balance and restoration of substances (filtering, buffering, substance-converting properties)	filter and buffer for heavy metals	derived parameters	clay content, organic matter content (through texture, soil type), pH	clay content, texture, organic matter content, pH/*carbonate content*
	chemical reactor	derived parameters	organic matter content, thickness of topsoil	organic matter content, thickness of topsoil
part of the ecosystem	part of the water balance	derived parameters	water conductivity (derived from texture, skeletal material (or similar material), anthropogenic source, profile development, consolidation, stratification), awc (see above)	water conductivity (derived from *leachate rate*, bulk density, texture (*incl. decomposition degree for peat*)), awc (see above)
archive function	archive of natural history	rareness (soils with special characteristics, if area ≤ 0,1 % of the investigation area)	fossil soils, bogs, soils from rare material, soils with periglacial characteristics, soils with extreme gleyic characteristics	plots with characteristic soil profiles, permanent investigation sites, *percentage of soil type area of total area (<1%)*, rare soils (here: peat soils, Gleyic Regosols, Histic Gleysols (thionic))
	archive of cultural history	derived parameters	soils with important artefacts, soils with a special land use history	*here: wharfs, dikes (percentage of area of total area)**
production function	food and biomass production	derived parameters	organic matter content, mean annual temperature	organic matter content, mean annual temperature

* Categories: >10% = 1; >5% - <10% = 2; >2,5% - <5% = 3; >0% - 2,5% = 4; 0% = 5

military sites. And-, if-, or- etc. "decision trees" are used to evaluate the sub-function at five evaluation levels, with level 1 representing a very high importance for soil protection and level 5 representing a very low importance for soil protection. Hence, a point-source contaminated site will be classified as "very low important for soil protection" regarding the function as habitat and basis of human life (structure: "if site is not contaminated = 1; if site is contaminated with point-source pollution (restoration not necessary) = 4; if site is contaminated with point-source pollution (restoration necessary) = 5). Notwithstanding the specifications in the manual we adapted some parameters due to the available data base (see 3.2), e.g., adding the leaching rate as one parameter to characterize the water balance function (Tab. 1). More information on the evaluation method and a precise description are given in the manual (Lehmann et al. 2008).

To keep the evaluation structure of the TUSEC approach, also the soil sub-functions without climate-sensitive evaluation parameters were evaluated and integrated into the overall evaluation result.

TUSEC does not provide a guideline for summarizing the individual evaluation results of every soil function into an overall evaluation result, which is often required by spatial planners. To obtain such an overall evaluation result, the maximum principle was applied in this study, meaning that functions which were evaluated with a very high importance for soil protection, dominate the overall result of the evaluated plot. As opposed to an average determination, lower important functions are not considered and therefore, a very high worthiness of protection of the individual evaluation is retained.

To summarize the individual evaluation results (eight soil sub-functions) the following classification was used:

individual evaluation result:	overall evaluation result:
≥ 2 x 1 or 4 x 2	1
≥ 2 x 2	2
1 x 2 or ≥ 2 x 3	3
≥ 2 x 4	4
otherwise	5

with

1 = very high importance for soil protection
2 = high importance for soil protection
3 = medium importance for soil protection
4 = low importance for soil protection
5 = very low importance for soil protection.

3.2 Data "Status Quo"

For the soil function evaluation with TUSEC-B we used available information about soil type, land cover, potential brownfield sites, plots with characteristic, regional soil profiles, and permanent investigation sites gained from special maps (soil information system) provided by the State office for Mining, Energy, and Geology (LBEG) of Lower Saxony (Germany).We used the soil type units of the BÜK 50 (soil overview map 1:50,000) as evaluation units and the data stored in the digital BÜK50 data base. The BÜK 50 is a soil overview map generated from secondary information (geology, topography, land use etc.) and is based on information from representative soil profiles for each map unit. In addition to information on pedology, geology, hydrogeology, and land cover, the soil information system provides derivative maps based on the BÜK 50. Therefore, additional information on leaching rates was available (Tab. 1: adapted parameters).

Information about historical coastal protection constructions, such as dikes and wharfs, was obtained from the Lower Saxony State office for preservation of historical monuments (NLfD). These data are assumed to represent the present situation of soil and site properties, named "Status Quo".

3.3 Climate change scenarios for 2050

Within the evaluation process, the influence of four climate change scenarios on soil functions was analyzed (Tab. 2). The influence of land use alteration on soil properties, as a result of climatic or demographical changes, was not considered because of the rural planning scheme discussed within the "Climate Proof Area" project. It was stated that, from today's point of view, the focus will be on the effort to sustain the characteristic landscape, especially the proportion of agricultural land (Ahlhorn et al. 2011). Therefore, and also because of the land use-independent evaluation procedure, land use changes were not included within the evaluation process.

All scenarios are based on the climate change assumptions determined within the "Climate Proof Area" project for the region Wesermarsch (Bormann et al. 2009). The following changes

Tab. 2: Assumed changes of climate-affected parameters considered within the evaluation process

scenario 2050	temperature [°C]	leachate rate [%]	groundwater level [cm]	organic matter content [level, %]	decomposition [level]
I	+ 1,5	+ 4	+ 5	-1 level (15)	+1 level
II	+ 1,5	+ 4	+ 5	+1 level (15)	–
III	+ 1,5	–	–	+1 level (15)	–
IV	+ 1,5	–	–	-1 level (15)	+1 level

in climate elements were projected based on the emission scenario A1B (IPCC 2000, 2007) and on WETTREG data (Spekat et al. 2007):

temperature:	+ 1 – 1.5 °C
precipitation (winter):	app. + 25%
precipitation (summer):	app. - 15%
evapotranspiration (annual):	app. + 5-7%.

All scenarios assume the same increase in temperature, but partially differ regarding changes in leachate rate, groundwater level, organic matter content, and level of organic matter decomposition (Tab. 2). Scenarios I and II, and scenarios III and IV, respectively, are equal regarding leachate rate and groundwater level. Their main difference is an increase or decrease in organic matter content or decomposition level of organic matter. The organic matter content and the decomposition level are described by short symbols according to the Bodenkundliche Kartieranleitung (AD-HOC-AG BODEN 2005). The organic matter content is divided into eight categories (h0 to h7) and each category refers to a range of mass percentage of organic matter (e.g., h2 is equivalent to 1 – <2 mass-%). The classification of the decomposition level of organic matter is based on the visible plant structure within the turf and comprises five categories from z1 (very low) to z5 (very high) (AD-HOC-AG BODEN 2005).

It is well known that microbial activity increases with increasing temperature, resulting concurrently in decreasing organic matter contents (e.g., Hörmann 1993; IFB 2008; Kardol et al. 2010; Powlsen 2005). To quantify the loss of organic matter we used the information on temperature dependence of soil organic matter decomposition given by Kirschbaum (1995). From the laboratory-based data he deduced a decrease of C_{org} of ~10% at a mean annual temperature of 5 °C and of ~3% at a mean annual temperature of 30 °C upon a temperature increasing by 1 °C. By applying these calculations to our investigation area with a mean annual temperature of approximately 8 °C, the C_{org} content will decrease by approx. 9%, which means a decrease of 15% of the initial soil organic matter (SOM) content. To consider the influence of soil moisture, we additionally assumed an increase in SOM in scenario II due to reduced soil microbial activity caused by higher soil moisture (Springob et al. 2001). Within the evaluation procedure, an increase or decrease in organic matter content and organic matter decomposition by one level each is equivalent to a change by one category (according to the Bodenkundliche Kartieranleitung (AD-HOC-AG BODEN 2005)), which approximately corresponds to a change by 15% of the initial SOM content.

The hypothesized higher leachate rate in 2050 compared to today is based on findings of Osterkamp et al. (2001) who assumed an increase in precipitation by 10% in the coastal Weser region and therefore higher groundwater recharge in this flat area. Simulating the groundwater and soil water balance Hoffmann et al. (2005) calculated an increase in groundwater recharge in this region. Thus, we assumed an increase in leachate rate of 4% (precipitation (+10%) minus evapotranspiration (6%), see above).

The assumption of an increase in groundwater levels is based on projected increasing precipitation and leachate rates. Brammer and Brinkmann (1990) predicted higher groundwater levels in coastal soils due to sea level rise. Schirmer (2006) also assumed a rising groundwater level in the Lower Weser region. Furthermore, Hoffmann et al. (2005) simulated the changes in the groundwater surface distance for two coastal investigation areas in the Lower Weser region which are near or within our study area. They identified a decrease in the groundwater surface distance of 5 cm and 22 cm due to sea level rise and higher groundwater recharge. For the total investigation area (comprising large parts of the region Wesermarsch), they predicted a rising groundwater level. Based on these simulation results and on the assumption that less water might be pumped out of the area, e.g., due to higher pumping costs, we assumed a maximum groundwater level increase of 5 cm until 2050 for scenarios I and II. In scenarios III and IV, we hypothesized that the water management will not change and that the drainage capacity will be still sufficient to maintain the present groundwater level.

4 Results

4.1 Soil function evaluation "Status Quo"

On the basis of today's soil properties most parts of the study area are of very high (50.7%) and high importance (21.2%) for soil protection (Fig. 2). These areas are dominated by Histosols and Gleyic Fluvisols (calcaric) which are widely spread in the region. The lowest importance for soil protection, comprising 1.5% of the area, is represented by two Gleysol (clayic) plots, while the rest of the region (26.6%) is of medium importance.

The overall evaluation result is mainly influenced by the evaluation results of the individual habitat functions (not shown). Nearly the entire region is worth protecting (highly and very highly protectable) regarding its functioning as the basis of human life (96.5%) and as the habitat and basis of life for animals and plants (99.9%). The Gleyic Fluvisols (calcaric) and Salic Fluvisols are very good filter and buffer for heavy metals and therefore highly protectable. Furthermore, the Gleyic Fluvisols (calcaric) are of high importance for soil protection as part of the water balance, because they have a comparatively higher available water capacity and are of high importance for food and biomass production. Especially, the Histosols in the study area are of very high/high importance regarding their function as chemical reactor, but are barely worth protecting regarding their filter and buffer capacity for heavy metals, which also applies to the Haplic Gleysols, Gleysols (clayic), and the Gleyic Anthrosols in the area.

Plots representing Salic Fluvisols, Histic Gleysols (thionic), Histosol (fen), and Gleyic Regosols are archives of natural history and therefore of very high importance for soil protection. Because of the settlement history in the study area, i.e. wharf and dike constructions, and the differently weighted area percentages of these constructions within the evaluation units, the soils are mainly of medium importance for cultural history.

4.2 Soil function evaluation "Status Quo – 2050"

Adapting the evaluation parameters to the assumed climate-induced changes in 2050, the worthiness of protection regarding the overall evaluation result changed differently depending on the applied scenario (Fig. 3, Tab. 3). The smallest changes are ascertained by scenario IV with 77.1% of the area without any differences between the Status Quo and 2050. The remaining scenarios are very similar regarding the proportion of "no changes" (62.6–63.7%). The biggest differences in the importance for soil protection (overall result) are based on scenario II which leads to an enhancement of the soil worthiness in 2050 by two evaluation levels. In general, the changes in the overall evaluation result are mostly in the positive direction. This is true for scenarios II and III showing an increase of the importance of soil protection of 37% and 36.6%, respectively. The evaluation of scenario I results in a more positive development of the soil functions (23.5%), but shows also negative changes (12.7%). Scenario IV is the only scenario which leads primarily to a negative development of the overall evaluation result (21.3%).

The analysis of the individual soil function evaluation results shows a higher increase of the importance for some soil functions as compared to the overall evaluation result (max. plus four evaluation levels).

Most changes in the importance of soil protection are due to changes in soil organic matter. This is shown in scenarios II and III in which the comparatively high proportion of a positive development of the "chemical reactor function" is caused by SOM changes. The same is true for the production function of the evaluated soils. An increase in organic matter content results in a positive change while a decrease leads to a negative development of the soil functioning. The importance of soils as a habitat and basis of life for animals and plants is only slightly influenced by the assumed climatic changes, but is mainly positive for scenarios I and II. This can be explained by the definition of this soil function, which is targeted on the importance of extremely dry and wet locations. Because of the assumed higher groundwater levels, the soil moisture increases and therewith the rareness of the location for plants and

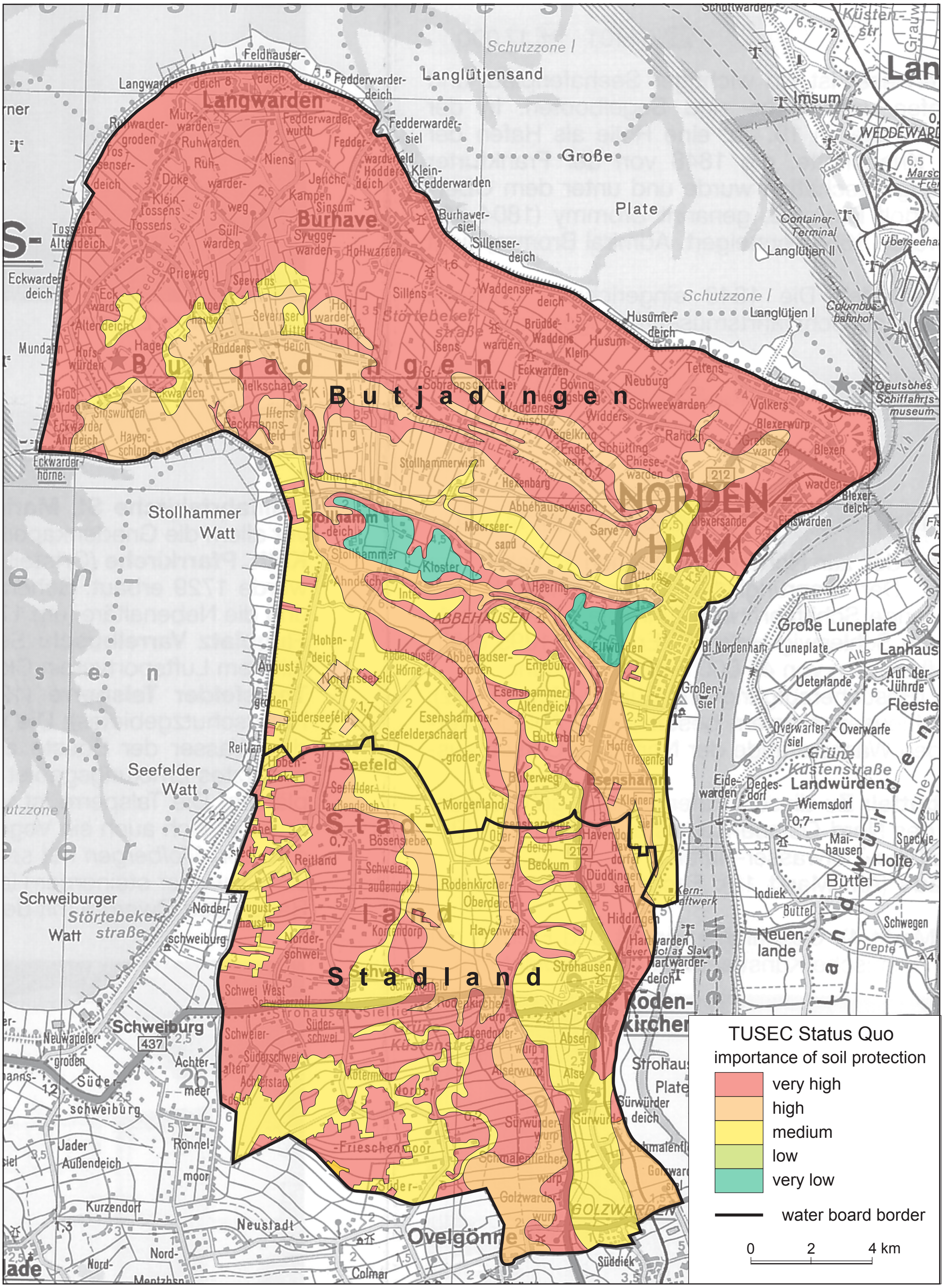

Fig. 2: TUSEC-B: Overall soil function evaluation result for the Status Quo; northern part: Butjadingen; southern part: Stadland
Source: based on data of NLfD (2010) and NIBIS® Kartenserver (LBEG, 2010) and TK 25 (© LGN)

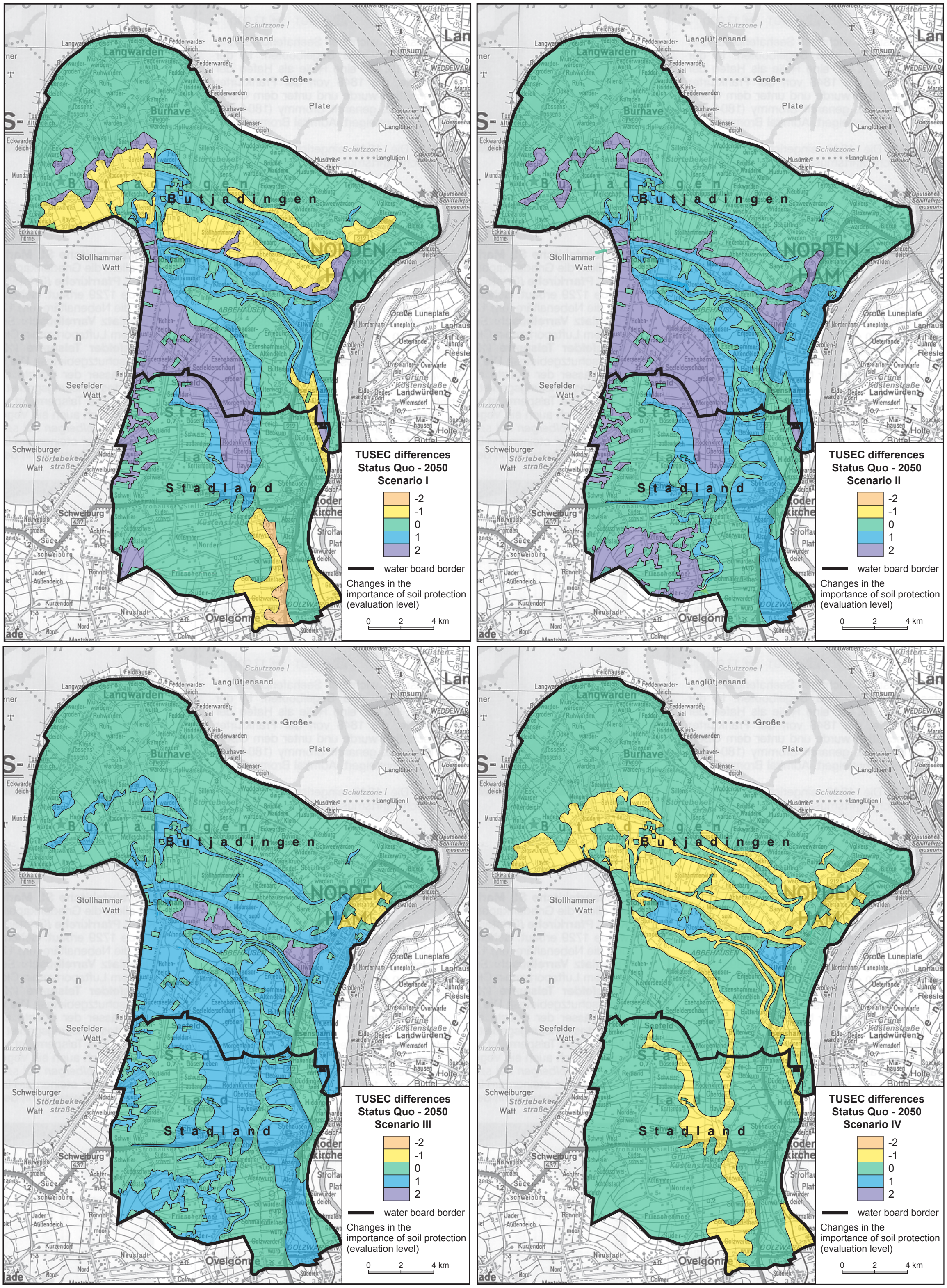

Fig. 3: TUSEC-B: Changes in the importance of soil protection. Overall soil function evaluation result for 2050 – scenarios I - IV; northern part: Butjadingen; southern part: Stadland. Source: based on data of NLfD (2010) and NIBIS® Kartenserver (LBEG, 2010) and TK 25 (© LGN)

Tab. 3: TUSEC-B: Differences between the results of the individual soil function evaluation for the Status Quo and 2050 presented for each scenario (area percentage of evaluation level). No differences between Status Quo and 2050 for LIFE1, ARC1, and ARC2 (not shown)

I II scenario III IV	differences LIFE2		differences STOFIT1		differences STOFIT3		differences STOFIT4		differences PROD1		differences overall result	
proportion -1	0.1	0.1	0.5	0.5	6.6	0.7	0.2	0	36.6	0.6	11.9	0
[%]	0.5	0.5	0.1	0.1	0	0	0	0.2	0.6	36.6	0.9	21.3
proportion -2	0	0	0	0	0	0	0	0	0	0	0.8	0
[%]	0	0	0	0	0	0	0	0	0	0	0	0
proportion 1	52.5	52.5	4.2	0.9	9.8	36.5	0	0.1	0	26.9	10.4	20.0
[%]	0	0	0.9	4.2	34.0	18.3	0.1	0	26.9	0	35.0	1.6
proportion 2	0	0	0	0	0	0.3	0	0	0	0	13.1	17.0
[%]	0	0	0	0.5	8.8	0	0	0	0	0	1.6	0
proportion 3	0	0	0	0	0	0	0	33.5	0	0	0	0
[%]	0	0	0	0	0	0	33.5	0	0	0	0	0
proportion 4	0	0	0	0	0	0	2.0	2.0	0	0	0	0
[%]	0	0	0	0	0	0	2.0	2.0	0	0	0	0
proportion 0	47.4	47.4	95.3	98.6	83.5	62.5	97.8	64.4	63.4	72.6	63.7	63.1
[%]	99.5	99.5	99.1	95.2	57.3	81.7	64.4	97.8	72.6	63.4	62.6	77.1

Notes: LIFE1: habitat and basis of life for humans; LIFE2: habitat and basis of life for animals and plants; STOFIT1: water balance function; STOFIT3: filter & buffer for heavy metals; STOFIT4: chemical reactor; PROD1: production function; ARC1: archive for natural history; ARC2: archive for cultural history

animals. Small, more or less positive changes (plus 1 evaluation level) were identified for the water balance function and the filter and buffer function for heavy metals in 2050.

Due to the evaluation criteria regarding the habitat and basis of human life and both archive functions, which do not comprise climate-induced parameters, there are no changes when comparing the present and the 2050 situations.

To identify soil type-related patterns in the future change of soil quality, we determined the area percentage of the soil types in relation to the differences in the evaluation level (present – 2050). Table 4 summarizes the results for each scenario and gives the area percentage of the soil types regarding the proportion of the evaluation level and the appearance in the area, respectively. For example, only Gleyic Fluvisols (calcaric) show a two-level downgrading in the worthiness of protection. Therefore, this soil type comprises 100% of the evaluation level which represents only 5.18% of the total appearance in the study area.

Considering the soil type-related changes no clear pattern is observable. It is worth mentioning that the worthiness of protection of nearly 99% of the Gleyic Anthrosols areas increases with increasing organic matter content (scenarios II and III). The soil protection value of the Calcic Gleysols in the south-western part of Butjadingen (see Fig. 1 and 3) probably increases with rising groundwater levels (scenarios I and II).

5 Discussion and conclusions

This study on the impact of climate change on soil functions shows that the worthiness of protection of soil functions will be influenced by climate-induced changes in soil properties.

Depending on the assumed future climatic development and the chosen scenario these changes can be positive or negative and vary regarding the extent of change. Although our study is based only on an orientating evaluation method, it enabled us to identify parameters which, alone or in combination, change the future importance of soils for protection.

The most important parameter causing soil function changes appears to be the organic matter content. This is in line with the conclusions of Verzandvoort and Kuikman (2009), who highlighted the key role of organic matter regarding soil properties influenced by climatic changes. Organic

Tab. 4: TUSEC-B: Differences between the overall evaluation results for the Status Quo and 2050 presented for each scenario (area percentage of soil types)

	scenario I			scenario II		
differences [level]	**soil type**	**[%] of evaluation level**	**[%] of appearance in the area**	**soil type**	**[%] of evaluation level**	**[%] of appearance in the area**
-2	Gleyic Fluvisol (calcaric)	100	5.18			
-1	Gleysol (clayic)	100	47.61			
1	Gleyic Fluvisol (calcaric)	81.49	18.57	Gleyic Fluvisol (calcaric)	42.51	18.57
	Gleysol (clayic)	14.90	6.18	Gleysol (clayic)	55.61	44.26
	Haplic Gleysol	3.61	2.38	Haplic Gleysol	1.88	2.38
2	Haplic Gleysol	20.36	16.86	Haplic Gleysol	15.70	16.86
	Gleyic Fluvisol (calcaric)	66.89	19.14	Gleyic Fluvisol (calcaric)	51.58	19.14
	Gleyic Anthrosol	12.75	41.15	Gleyic Anthrosol	23.57	98.66
				Gleysol (clayic)	9.15	6.18
0	Haplic Gleysol	18.72	75.58	Haplic Gleysol	20.22	80.76
	Gleyic Fluvisol (calcaric)	44.65	62.28	Gleyic Fluvisol (calcaric)	45.12	62.28
	Salic Fluvisol	0.34	100	Salic Fluvisol	0.34	100
	Gleysol (clayic)	18.18	46.20	Gleysol (clayic)	19.71	49.56
	Gleyic Anthrosol	3.74	58.85	Gleyic Anthrosol	0.09	1.34
	Sapric Histosol (bog)	6.84	100	Sapric Histosol (bog)	6.91	100
	Sapric Histosol (fen)	3.58	100	Sapric Histosol (fen)	3.62	100
	Histosol (bog) with Salic Fluvisol layer	2.05	100	Histosol (bog) with Salic Fluvisol layer	2.07	100
	Histosol (fen) with Histic Gleysol (thionic) layer	1.07	100	Histosol (fen) with Histic Gleysol (thionic) layer	1.08	100
	Histic Gleysol (thionic)	0.45	100	Histic Gleysol (thionic)	0.46	100
	Gleyic Regosol	0.38	100	Gleyic Regosol	0.38	100

scenario III			scenario IV		
soil type	[%] of evaluation level	[%] of appearance in the area	soil type	[%] of evaluation level	[%] of appearance in the area
Gleyic Fluvisol (calcaric)	100	1.97	Gleyic Fluvisol (calcaric)	44.00	20.54
			Gleysol (clayic)	56.00	47.61
Gleyic Fluvisol (calcaric)	49.25	37.72	Gleysol (clayic)	100	6.18
Gleysol (clayic)	31.72	44.26			
Haplic Gleysol	7.61	16.86			
Gleyic Anthrosol	11.43	98.66			
Gleysol (clayic)	100	6.18			
Haplic Gleysol	20.99	83.14	Haplic Gleysol	20.48	100
Gleyic Fluvisol (calcaric)	44.06	60.32	Gleyic Fluvisol (calcaric)	47.08	79.46
Salic Fluvisol	0.35	100	Salic Fluvisol	0.28	100
Gleysol (clayic)	19.87	49.56	Gleysol (clayic)	15.03	46.20
Gleyic Anthrosol	0.09	1.34	Gleyic Anthrosol	5.25	100
Sapric Histosol (bog)	6.97	100	Sapric Histosol (bog)	5.65	100
Sapric Histosol (fen)	3.65	100	Sapric Histosol (fen)	2.96	100
Histosol (bog) with Salic Fluvisol layer	2.09	100	Histosol (bog) with Salic Fluvisol layer	1.69	100
Histosol (fen) with Histic Gleysol (thionic) layer	1.09	100	Histosol (fen) with Histic Gleysol (thionic) layer	0.88	100
Histic Gleysol (thionic)	0.46	100	Histic Gleysol (thionic)	0.37	100
Gleyic Regosol	0.39	100	Gleyic Regosol	0.31	100

matter is a major factor influencing, for instance, the water storage capacity, the nutrient balance (chemical reactor), and the bonding capacity for harmful substances. The biological, chemical and physical properties of soils are especially influenced by the amount of organic matter (Baldock and Skjemstad 1999). Therefore, also the intensity of changes in the evaluation results depends on the initial amount of organic matter. The climatic impact is smaller on soils with lower organic matter contents. Possible reasons could be (i) an organic matter threshold from which changes are not relevant anymore or (ii) the quality of the information about organic matter content which is only given by classification level and not by exact data. For instance, soils with soil organic matter content reaching the upper limit can stay within the classification level, although the organic matter content decreases by 15%. Another cause can be (iii) the fact that organic soils are not explicitly considered within the TUSEC method, because soil components are generally considered with respect to the mineral part. There is no doubt, however, that climate change will influence the organic matter content of soils (e.g., IFB 2008; Kamp et al. 2008) and possibly the related soil functions, as shown by the result of this study. This knowledge leads to the question of whether soil organic matter will increase or decrease and will result in an improvement or impairment of the soil functions. In our view, this question cannot be answered definitively because of the complex interaction of parameters influencing the soil organic matter content, like temperature, water content, and microbial composition. For example, microbial activity increases with temperature rise, but can also decrease with an increase in soil water content. Therefore, it is necessary to consider the site-specific conditions when estimating the future amount of soil organic matter and the development of soil functions (Kolbe 2008). Additionally, further research on the interaction of influencing parameters is required, which is also claimed by Engel and Müller (2009) in their report on the influence of climate change on soils in Lower Saxony. This important information enables climate-induced changes in organic matter content to be specified on regional and local scales and soil function evaluation results to be concretized.

The second important parameter causing soil function changes seems to be the groundwater level which directly influences the soil moisture and indirectly influences the accumulation or decomposition of organic matter. An increasing groundwater level but constant soil temperature will result in a decreasing microbial activity. This leads to a higher organic matter content and increases, for example, the productivity and water storage capacity of soils to some extent. However, high groundwater levels can also result in decreasing soil productivity due to water logging. Depending on whether the water management or the natural water regimes will change in future in the evaluated area or part of the area, the importance of protection can change. Especially water management changes, whose impact can be more or less predicted, have to be taken into account when discussing climate-induced changes in soil properties and functions. If there are no changes in groundwater regulation and the present groundwater level is kept, water-related changes in soil properties can also be neglected as well as soil movement processes (water erosion) in the flat study area.

In general, our research shows that it is possible to incorporate climate change into the evaluation process of soil functions. The used evaluation method TUSEC-B allows us to evaluate soil functions of larger areas and to see the results in a wider spatial context. It was possible to evaluate the soil functions in our project region which comprises an area of ~329 km². TUSEC-B provides an overview of the general worthiness of protection of the soils in the region and can be used in planning processes. The orienting character of the approach enabled specific areas suitable for planning purposes to be identified, but they need to be verified by field investigations. Also the currentness of data used for the Status Quo evaluation should be revised. We assumed that the basic data reflect the present properties of the soils, but the data have not been updated recently and might not be representative of the Status Quo.

Summarizing the individual evaluation results to an overall result, we applied the maximum principle and defined five classification levels. Using different categories with different weightings would lead to different evaluation results depending on the data base, the spatial planning level as well as on the question of whether individual evaluation criteria are relevant to the problem.

Nevertheless, the implementation of spatial planning measures, which are mostly long-term and area- consuming projects, should take into account that soils which are less worth protecting today can be of higher worthiness in future. For example, the localization of future spatial water management measures, as discussed within the German "Climate Proof Area" project, could be combined with the results of this soil function evaluation by planning water storage constructions or other adapted water management measurements in future less vulnerable and important areas for soil protection. After choosing specific places based on the soil function evaluation, systematic soil type identification is necessary to verify the input data of the evaluation process.

Furthermore, soil function evaluation methods need to be parameterized in more detail to simplify their implementation in spatial planning and to enhance their applicability, which was also mentioned by Lehmann and Stahr (2010). They stated that the concept of soil functions need further adaptation to spatial planning and land use aspects. Additionally, more studies are needed to investigate the future development of soil functions based on different evaluation methods.

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Authors

Dr. Kirsten Madena
WG Soil Science, Institute of Biology
and Environmental Sciences
University of Oldenburg
26111 Oldenburg
Germany
kirsten.madena@uni-oldenburg.de

Prof. Dr. Helge Bormann
Chair of Water Management and
Engineering Hydrology
Department of Civil Engineering
University of Siegen
57068 Siegen
Germany
helge.bormann@uni-siegen.de

Prof. Dr. Luise Giani
WG Soil Science, Institute of Biology
and Environmental Sciences
University of Oldenburg
26111 Oldenburg
Germany
luise.giani@uni-oldenburg.de