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Integrated assessment of cropland soil carbon sensitivity to recent and future climate in the Elbe River basin

JOACHIM POST*, TOBIAS CONRADT, FELICITAS SUCKOW, VALENTINA KRYSANOVA, FRANK WECHSUNG & FRED F. HATTERMANN

Potsdam Institute for Climate Impact Research, RD 2: Climate Impacts and Vulnerabilities, PO Box 60 12 03, D-14412 Potsdam, Germany

joachim.post@dlr.de

Abstract Carbon storage in soils is sensitive to changing climatic conditions, potentially increasing C fluxes from soils to the atmosphere. This study provides an assessment of recent climate variability (1951–2000) and potential future (2001–2055) climate change impacts on soil C storage for croplands in the German part of the Elbe River basin. Results indicate that recently (1991–2000) croplands are a net source of carbon (net annual flux of 10.8 g C m^{-2} $year^{-1}$ to the atmosphere). The recent temperature trend for the years 1951–2000 (+0.8 K in summer and +1.4 K in winter mean temperature) alone have already caused a significant net flux of 1.8 g C m^{-2} $year^{-1}$ to the atmosphere. Future climate change (2001–2055) derived from regionalised meteorological properties driven by the IPCC-SRES A1 scenario results in an increased net C flux of an additional 4 g C m^{-2} $year^{-1}$ in comparison to the reference period (1951–2000). Uncertainties attached to C flux results are estimated with a standard error of 6%. Besides climate-induced alteration of net C fluxes, considerable impacts on groundwater recharge (−45.7%), river flow (−43.2%) and crop yield (−11% to −15% as a basin-wide average for different cereals) were obtained. Recent past and expected temperature changes within the Elbe basin predominantly contribute to the increase of net C fluxes to the atmosphere. However, decreased crop growth (crop yields) and decreased expected water availability counteract even higher net C losses as soil C turnover is reduced through less C input (less crop growth) and drier soil conditions (decrease in water availability). Based on this study, present-day and potential future development of net C fluxes, water components and crop yields were quantified. This allows integrated assessment of different ecosystem services (C storage, water availability and crop yield) under climate change in river basins.

Key words integrated modelling; ecohydrological model; climate impact; soil carbon dynamics; C flux; croplands

Evaluation intégrée de la sensibilité du carbone des sols agricoles au climat récent et futur dans le bassin de l'Elbe

Résumé Le stockage de carbone dans les sols est sensible aux changements de conditions climatiques, qui accroissent potentiellement les flux de carbone des sols vers l'atmosphère. Cette étude fournit une estimation des impacts de la variabilité climatique récente (1951–2000) et du changement climatique futur potentiel (2001–2055) sur le stockage de carbone dans les sols agricoles de la partie allemande du bassin de l'Elbe. Les résultats indiquent que les terres agricoles étaient récemment (1991–2000) une source nette de carbone (flux net annuel de 10.8 g C m^{-2} an^{-1} vers l'atmosphère). La tendance récente pour la température pour les années 1951–2000 (+0.8 K et +1.4 K pour les températures moyennes respectivement estivale et hivernale) a déjà généré à elle seule un flux net significatif de 1.8 g C m^{-2} an^{-1} vers l'atmosphère. Le changement climatique futur (2001–2055) déduit des propriétés météorologiques régionalisées selon le scénario IPCC-SRES A1 conduit à une augmentation du flux net de carbone de 4 g C m^{-2} an^{-1} par rapport à la période de référence (1951–2000). Les incertitudes liées aux résultats de flux de carbone sont estimées avec un écart type de 6%. En plus de l'altération des flux nets de carbone, des impacts considérables du climat sur la recharge hydrogéologique (−45.7%), l'écoulement en rivière (−43.2%) et les rendements culturaux (−11% à −15% pour le bassin, en moyenne pour différentes céréales) ont été obtenus. Les changements récents et attendus en matière de température au sein du bassin de l'Elbe sont la cause principale de l'augmentation des flux nets de carbone vers l'atmosphère. Cependant, la diminution de la croissance végétale (rendements culturaux) et la diminution prévue de la disponibilité en eau ont un effet contraire sur les pertes nettes de carbone en réduisant le renouvellement du carbone du sol, en raison d'apports de carbone moindres (moins de croissance végétale) et de conditions pédologiques plus sèches (diminution de la disponibilité en eau). Sur la base de cette étude, les évolutions contemporaines et futures potentielles des flux nets de carbone, des composantes hydrologiques et des rendements culturaux ont été quantifiées. Cela permet une évaluation intégrée des différents services écosystémiques (stockage de carbone, disponibilité en eau et production agricole) en contexte de changement climatique au niveau de bassins versants.

Mots clefs modélisation intégrée; modèle éco-hydrologique; impact climatique; dynamique du carbone du sol; flux de carbone; terres agricoles

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* *Present address*: German Aerospace Centre, German Remote Sensing Data Center, Department for Environment and Security, Oberpfaffenhofen, D-82234 Wessling, Germany.

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INTRODUCTION

Changes in the soil carbon (C) pool influence the atmospheric C pool and the soil fertility status as the soil C is important for soil aggregation, nutrient availability, water storage capacity and buffering ability (Carter & Stewart, 1996).

High amounts of soil C (approx. 1–2 Pg C year^{-1} during the 1980s, Houghton 1996, 1999) have been lost to the atmosphere due to human intervention (e.g. cultivation of soils, changes in land use and cover), besides the increase in atmospheric CO_2 and other greenhouse gases (GHG) mainly caused by fossil fuel combustion and cement production. Additionally, climate change possibly alters soil C storage by enhancing decomposition and mineralisation and, consequently, increases the C flux from soils to the atmosphere (Kirschbaum, 1995; Bellamy *et al.*, 2005). The losses of soil C not only increase atmospheric C content, but also degrade the soil fertility. This leads to a complex series of interactions between the biosphere, the hydrosphere and the atmosphere, which requires an integrated assessment of the relevant hydrological, vegetation and biogeochemical processes driven by land use, land management and climate (Lal, 2004). Furthermore, the observed significant precipitation trend in the Elbe basin during the period 1950–2000 (Wechsung *et al.*, 2005) indicates a decrease of approx. 46 mm in summer and an increase of approx. 50 mm in winter. The temperature increase of 0.8 K in the summer season is lower than that of 1.4 K in the winter season. The significant increase in temperature, especially in the winter, along with long-term trends in precipitation, is important for plant growth, hydrological properties and soil C and N processes. Quantifying climate-induced changes in soil carbon storage in the recent past, and under possible future climate change scenarios, is therefore of pivotal interest.

Croplands play an important role in this context, as human intervention in these areas is high and heterogeneous; therefore, cropland soil C status has been affected more intensively than that of other ecosystems. According to a European-scale assessment, croplands are currently estimated to act as a source of carbon, representing a net carbon flux of 300 Tg C year^{-1} (1 Tg = 10^9 kg) from land to the atmosphere, whereas other ecosystems are estimated to be C neutral or a C sinks (Janssens *et al.*, 2003).

In this paper, we quantify the recent-past and current state of soil C storage in croplands and net C fluxes from soils to the atmosphere, and provide information on how soil C dynamics might unfold under anticipated climatic changes within a temperate central European region, the German part of the Elbe River basin. The basin is dominated by agricultural land use and is expected to experience considerable climate changes.

Consequently, the following objectives are addressed: quantification of present-day soil C dynamics in croplands, considering a representation of county-level crop share distributions, management schemes and climate properties; quantification of soil C sensitivity due to climate variability in the reference period (1951–2000); and determination of future soil C storage sensitivity under a regionalised climate change scenario for the period 2001–2055.

METHODS

The SWIM-SCN model

The Soil and Water Integrated Model (SWIM, Krysanova *et al.*, 1998) is a continuous-time, semi-distributed river basin model, which integrates hydrological processes, vegetation growth, water erosion, sediment fluxes and nutrient dynamics at the river basin scale (Krysanova *et al.*, 1998, 2000). The spatial aggregation units are sub-basins, which are delineated from digital elevation data. The sub-basins are further disaggregated into so-called hydrotopes, which are defined by uniform combinations of land use and soil type and therefore thought to be hydrologically homogeneous (Krysanova *et al.*, 2000).

The SWIM model is driven by climate, soil properties, land use and land management, and is designed to investigate effects of climate and land-use change on hydrological processes, vegetation growth, and water quantity and quality. Recently, SWIM was extended by a process-based, multi-compartment model of soil organic matter dynamics (coupled Soil Carbon and Nitrogen turnover: SWIM-SCN, Post, 2006; Post *et al*., 2007b). The adopted description is a module of the forest growth model 4C describing soil organic matter dynamics for forest ecosystems (Grote *et al*., 1999; Lasch *et al*., 2002). The model extension fits the level of complexity of other process descriptions in SWIM, and was developed taking into account constraints of data availability and model parameterisation (Post *et al*., 2007b).

The carbon and nitrogen turnover into different pools is implemented as a first-order reaction (Parton *et al*., 1987). The processes are controlled by specific reaction coefficients. The effects of soil temperature and soil water content on decomposition and mineralisation are considered through reduction functions (Kartschall *et al*., 1990). Mineralisation is inhibited if the soil water content decreases to below half the saturated water content within each soil layer. The influence of soil temperature is described by the Van't Hoff rule (Van't Hoff, 1884). Plant-derived soil organic matter from fine and coarse roots is distributed in the soil layers according to plant-specific rooting depth and a root mass allocation scheme (Jackson *et al*., 1996). Crop residues and organic fertilisation are distributed within the average ploughing depth of 30 cm.

A detailed description, and an assessment of land management impacts on soil C dynamics using the extended SWIM-SCN model, can be found in Post (2006) and Post *et al*. (2007b).

The Elbe River basin

The Elbe is one of the largest rivers in Central Europe and drains into the North Sea. The assessment was performed for the German part of the Elbe River basin, which covers an area of 80 256 km^2 (total basin area is approx. 148 000 km^2) from the Czech border to the North Sea. About 52% of the German part is covered by cropland, 29% by forest, 6% by settlements and industry, and 13% by meadows and pasture, lakes, mining pits, and other land-use forms.

Climatically, the Elbe basin marks a transition from an Atlantic to a continental climate. The basin is one of the driest regions in Germany, with mean annual precipitation below 500 mm in the lee of the Harz Mountains (western part of the basin), where the loess plains with high agricultural productivity are located. The long-term mean annual precipitation over the whole basin is 659 mm for the period 1951–2000 (ATV-DVWK, 2000).

Hydrologically, the area can be subdivided into three main subregions: (1) the mountainous area in the south (approx. 20% of the total area); (2) the hilly mountain foreland, predominantly covered by loess soils (approx. 28%); and (3) the undulating northern lowlands (approx. 52% of the total area).

Simulation set-up

Necessary pre-processing steps, calibration and validation of hydrological and crop growth processes are described in Hattermann (2005). These studies were made with the same simulation set-up for the same region to investigate changes in water availability and crop yield under global change impacts in the Elbe River basin.

Spatial input data comprise the European land cover data set CORINE (Dollinger & Strobl, 1996), and the general soil map of the Federal Republic of Germany (BÜK 1000, scale 1:1 000 000, Hartwich *et al*., 1995). The necessary climatic data at a daily time step were obtained from 84 stations located in and surrounding the Elbe basin that contain measurements of all necessary climate information, as well as 285 additional raingauge stations. The data were homogenised to continuous time series from 1951 to 2000, comprising daily air temperatures (minimum, maximum and average), precipitation, global radiation and relative humidity. These data were spatially interpolated by an inverse-distance weighted interpolation using a digital elevation model as additional information (Hattermann *et al*., 2005).

The climate change scenario is based on results of the Hamburg ECHAM4-OPYC3-T42 global circulation model (Röckner *et al*., 1999) driven by the IPCC SRES (Intergovernmental Panel on Climate Change – Special Report on Emission Scenarios) emission scenario A1 (Nakicenovic & Swart, 2000). This scenario gives a rather moderate temperature increase of approx. 1.4 K by 2055.

The resulting climate patterns were regionalised by Gerstengarbe & Werner (2005) using the statistical downscaling model STAR (STAtistisches Regionalmodell, Gerstengarbe *et al*., 1999). The STAR model produced 100 long-term transient time series of the possible future climate (2001–2055), considering observed long-term climate patterns of the meteorological stations in the Elbe River basin by incorporating a conditioned Monte Carlo approach in the downscaling process (Gerstengarbe & Werner, 2005). The 100 realisations cover the possible range of climate change. One realisation representing the most probable scenario for the study area was used for regionalised climate change assessments (Gerstengarbe & Werner, 2005).

Regionalisation of agricultural land use and management is implemented, ensuring a crop-share representation at the county level, by attributing respective six-year crop rotation cycles to the hydrotopes, the smallest simulation units of SWIM. Thus, the simulated crop-share distributions agree with the recent crop-share statistics (1996–1999) of each county in the German part of the Elbe basin (Wechsung *et al*., 2005). This provides a regionalised representation of agricultural land use for the reference period (1951–2000), which is kept stable as the agricultural land use in the scenario period (2001–2055).

Climate change effects alone would induce only small changes in future agricultural land use. A decrease in cropland area of approx. 0.9% could be estimated, with the shares of different crops cultivated in the area remaining relatively stable (Hattermann, 2005).

Fertilisation is parameterised for each crop using regional fertilisation recommendations (MLUR, 2000) for agricultural management. A portion of 70% of harvest by-product remaining on fields is assumed, based on information gained from the literature (Zimmer & Roschke, 2001; Schmidt & Osterburg, 2004; Post *et al*., 2007b).

The model was initialised using data on soil physical properties, and C and N storage derived from soil data of the Federal Republic of Germany (BÜK 1000, scale 1:1 000 000, Hartwich *et al.* ,1995). The C input to soil through plants is driven mainly by climatic, soil nutrient and hydrological conditions. Harvest and fertilisation management data (crop specific) were kept constant throughout time. Agricultural management was parameterised to mirror common practices, but technological changes, such as improved seed quality, higher efficiency of fertilisation and changes in harvest index, were neglected due to there being insufficient data available for parameterisation.

The assessment focuses on soil carbon dynamics, considering the development of the C content in the topsoil (down to the ploughing depth of 30 cm) and the entire soil (i.e. down to the maximum rooting depth, depending on soil type—usually 80–100 cm). Furthermore, the exchange of carbon between the biosphere and the atmosphere (net biome exchange, NBE) is considered, where NBE is the net ecosystem exchange (NEE) corrected by the loss through major episodic disturbances (*L*d):

$$\text{NBE} = \text{NEE} + L\text{d} \tag{1}$$

$$\text{NEE} = R\text{h} - \text{NPP} \tag{2}$$

$$L\text{d} = H - F \tag{3}$$

Equations (2) and (3) give the definitions for NEE and *L*d: the heterotrophic soil respiration (*R*h) reduced by the net primary production (NPP) makes up NEE; and *L*d is determined as the balance of C input from organic fertilisation (*F*) and C removal through harvested crop yields (*H*). Other ecosystem disturbances, such as fire, are not considered. Negative values of NBE denote a net flux of C from the atmosphere to land, i.e. an increase in soil C.

Determination of recent climate change effects on soil C storage

In a first approach, the annual NBE values of 12 hydrotopes, simulated for the recent climate for the period 1951–2000, were analysed. The sample hydrotopes were chosen to represent the most typical agricultural landscapes of the Elbe River basin. The dependency of NBE on soil temperature and time was then modelled and applied to all 11 347 agricultural hydrotopes of this SWIM set-up. Hence, the average carbon loss due to recent climate change could be quantified.

First approach A six-year cycle of crop rotation and fertilisation was applied; their strong effects on NBE were removed by linear factor models and the annual data were divided into six classes according to their position within the cycle. The differences between the mean values of these classes were regarded as entirely caused by the crop rotation. Thus, all data were adjusted by the difference between the class means and a common mean. We referred to this elimination of the crop rotation/fertilisation effect as “decyclisation”, with reference to the term “deseasonalisation” known from economics.

After this preliminary filtering step, the impacts of climate variables on NBE could be investigated. The correlations with time and annual averages of soil temperature, soil water content and climatic water balance were computed and visualised.

Having found significant dependencies on soil temperature and time, partial correlation coefficients were computed, because the three variables were cross-correlated due to the upward temperature trend:

$$r_{a,b|c} = \frac{r_{a,b} - r_{a,c} \cdot r_{b,c}}{\sqrt{\left(1 - r^2_{a,c}\right)\left(1 - r^2_{b,c}\right)}} \tag{4}$$

In the relevant equation (4), $r_{a,b|c}$ denotes the partial correlation between the variables a and b (without the influence of c), and $r_{a,b}$, $r_{a,c}$ and so on are the common correlation coefficients between the indexed variables.

Additionally, the correlations between NBE and time showed a dependency on the mean absolute NBE values, which was then taken into account for all agricultural hydrotopes.

Application to all agricultural hydrotopes The influence of $\overline{\mathrm{NBE}}$, the average NBE level, on NBE change over time, had already been modelled for all agricultural hydrotopes. A third-order polynomial turned out to produce the best fit, and this was then implemented in equation (5), which gives the full regression model for all NBEs:

$$\mathrm{NBE}_{x,y} = \alpha + \beta_0\, S\mathrm{Temp}_{x,y} + \beta_1 y\, \overline{\mathrm{NBE}_x} + \beta_2 y\, \overline{\mathrm{NBE}_x}^{2} + \beta_3 y\, \overline{\mathrm{NBE}_x}^{3} + \varepsilon \tag{5}$$

where $\mathrm{NBE}_{x,y}$, is the net biome product at hydrotope x in year y; α is the intercept; $\beta_{0\ldots3}$ are numeric coefficients; $S\mathrm{Temp}_{x,y}$ is soil temperature at hydrotope x in year y; $\overline{\mathrm{NBE}_x}$ is the average net biome product at hydrotope x; and ε is individual fit error.

For practical reasons, the net biome products, soil temperatures and years were centred around zero as mean value before calculating the regression, thus avoiding the intercept α. The most important output is then $\hat{\beta}_0$, the estimate of the response of NBE on soil temperature.

To estimate the increase in soil temperature caused by climate change, a simple linear fit was applied. Hence, the multiplication of temperature increase and NBE response produced an estimate of the mean shift in annual NBE values.

For a final calculation of soil carbon loss caused by climate change, an integration of the NBE shift over the 50 years was required, as any surplus NBE contributes year by year to the amount of additionally respired carbon.

RESULTS

Model validation and uncertainties related to C dynamics

The SWIM model has been validated for hydrology, vegetation growth, erosion and nitrogen dynamics for the Elbe River basin according to a multi-scale, multi-site and multi-criteria approach (Krysanova *et al.*, 1998, 2007; Krysanova & Becker, 1999; Hattermann *et al.*, 2005). Testing of soil C turnover-related processes (soil water and temperature dynamics, crop growth and yield assessment, soil nitrate dynamics, and long-term soil C trends) using field experiments

Table 1 Comparison of basin-wide averages for water components, crop yield (winter wheat) and net biome exchange (NBE) simulated using SWIM-SCN with observed data. Modelled values derived from Post *et al.*, 2006 and Krysanova *et al.*, 2007.

	Observed (mean 1961–1990)	Simulated (mean 1961–1990)	Scenario period (mean 2046–2055)	Change, simulated reference to scenario period (%)
Precipitation (mm)	687.2 [a]	695.0	616	–11
Actual evapotranspiration (mm)	526.9 [a]	518.0	536	1.0
Direct runoff (mm)	76.9 [a]	89.0	53	–40.4
Groundwater recharge (mm)	94.6 [a]	88.0	47.7	–45.7
Total discharge (mm)	171.5 [a]	177.0	100.5	–43.2
Crop yield (winter wheat) (dt/ha)	64.3 [b]	64.1	55.8	–13
NBE (g C m^{-2} $year^{-1}$)	0.59–25.9 [c]	10.8 [d]	14.0 [e]	29.6

[a] Leibundgut & Kern, 2003.
[b] Agricultural statistics, 1999.
[c] Rinklebe & Makeschin, 2003.
[d] mean (1951–2000).
[e] mean (2001–2055).

has been documented by Post *et al.* (2006, 2007a). The overall modelling efficiency was high for several field sites and management practices (different crop rotation, fertilisation, etc.), documenting the model's ability to represent the aforementioned processes. In terms of long-term soil C dynamics, the modelling results achieved reflect observations, and are comparable to other soil organic matter models tested at the same sites (Smith *et al.*, 1997; Post *et al.*, 2007a). For regional C dynamics, the modelled values were compared to values documented in the literature for the study area.

Modelling of the main water components and crop yield on the basis of basin-wide averages compares well to observations (Table 1, Krysanova *et al.*, 2007). Direct comparison of modelled and observed net C fluxes at the regional scale was not possible due to a lack of observations. Comparison with measurements upscaled to the landscape domain present in the study area produces comparable values and a test for model plausibility (Table 1).

A quantification of input data and parameter uncertainties at the plot and river basin scales was described by Post *et al.* (2006, 2008). Overall uncertainty resulting from all input factors considered (model parameters plus model input data) shows a coefficient of variation ("standard error") between 5.1 and 6.7%, and accounted for a soil carbon content variation of ±0.065 to ±0.3% (0.06–0.15 t C ha^{-1} $year^{-1}$). Parameter-derived uncertainty contributed most to the overall uncertainty. Uncertainties stemming from variations in soil and climate input data are striking (Post *et al.*, 2008).

Characterisation of present-day soil C storage

Soil carbon storage changes in the first 30 cm (topsoil) between 1951 and 2000 show a slight increase of soil C content (Fig. 1). Considering the changes in soil C storage for the whole soil, a decrease is obtained as a basin-scale average. The quantified loss is 509 g m^{-2} soil C. The simulated decrease in soil C storage consequently results in a net C flux from the land to the atmosphere, reflected in positive NBE values (Fig. 1, average annual NBE of 10.8 g C m^{-2} $year^{-1}$).

The spatially-distributed properties of average values for topsoil C storage and NBE in the period 1991–2000 for the Elbe River basin deliver a baseline situation of C storage and land–atmosphere fluxes (shown in Fig. 2).

The highest topsoil C storage (12 000–30 000 g C m^{-2}) is in the loess landscape with fertile soils and in alluvial soils in the lowlands (black, Fig. 2(a)). The lowest values (< 8000 g C m^{-2}) are

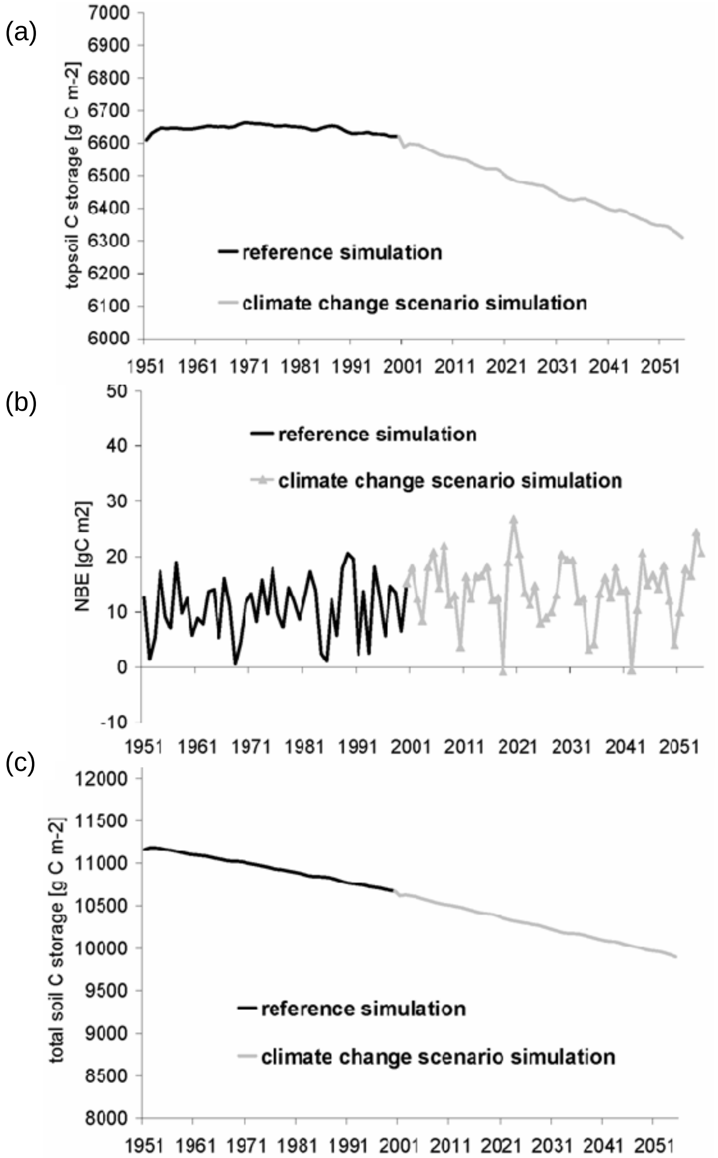

Fig. 1 Basin-scale averages for the reference and climate change scenario periods for: (a) topsoil C storage (g C m^{-2}); (b) total soil C storage (g C m^{-2}); and (c) net biome exchange (g C m^{-2}).

found in the mountain areas and the periglacially-formed part of the lowlands, dominated by sandy soils. Average annual C flux to the atmosphere (NBE) is highest (85–195 g C m^{-2} $year^{-1}$) in the loess landscapes and in alluvial parts of the lowlands (blue areas in Fig. 2(b)). Riparian zones of the Elbe River are associated with positive NBE values. In general, it is visible that most areas are net sources of C with positive NBE values. Only parts of the lowlands (periglacial landscape with sandy soils) and eastern loess areas are detected as C sinks (negative NBE values, Fig. 2(b)).

Recent past (1951–2000) climate impacts on soil C storage

Detection of climate variables as the driving force for soil C change To investigate which climate variables have an impact on NBE, the dominating effect of crop rotation on the soil C dynamics had to be eliminated first. Figure 3 shows this pattern for the sample hydrotope “Leipzig”: Fig. 3(a) and (b) depicts the evolution of soil C and NBE, respectively; these are the decyclised NBE values. The data points are shown as numbers according to their position within the six-year cycle. The dots in Fig. 3(b) and (c) are obtained by subtracting the deviations between the individual means

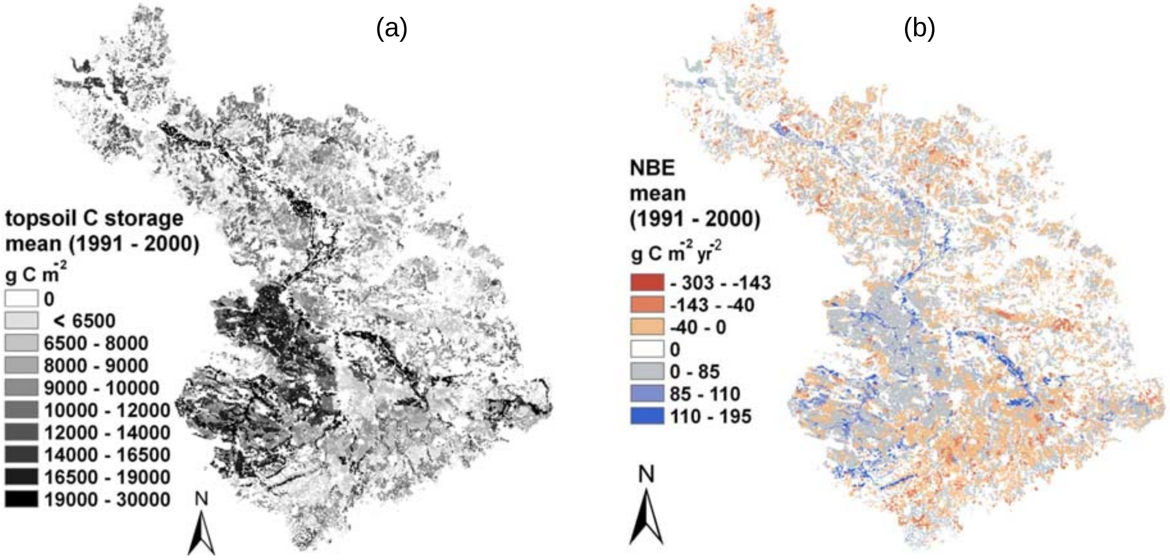

Fig. 2 Map of average (a) topsoil C storage (g C m^{-2}) and (b) NBE (g C m^{-2} year^{-2}) for croplands only in the Elbe basin, for the period 1991–2000, based on reference conditions.

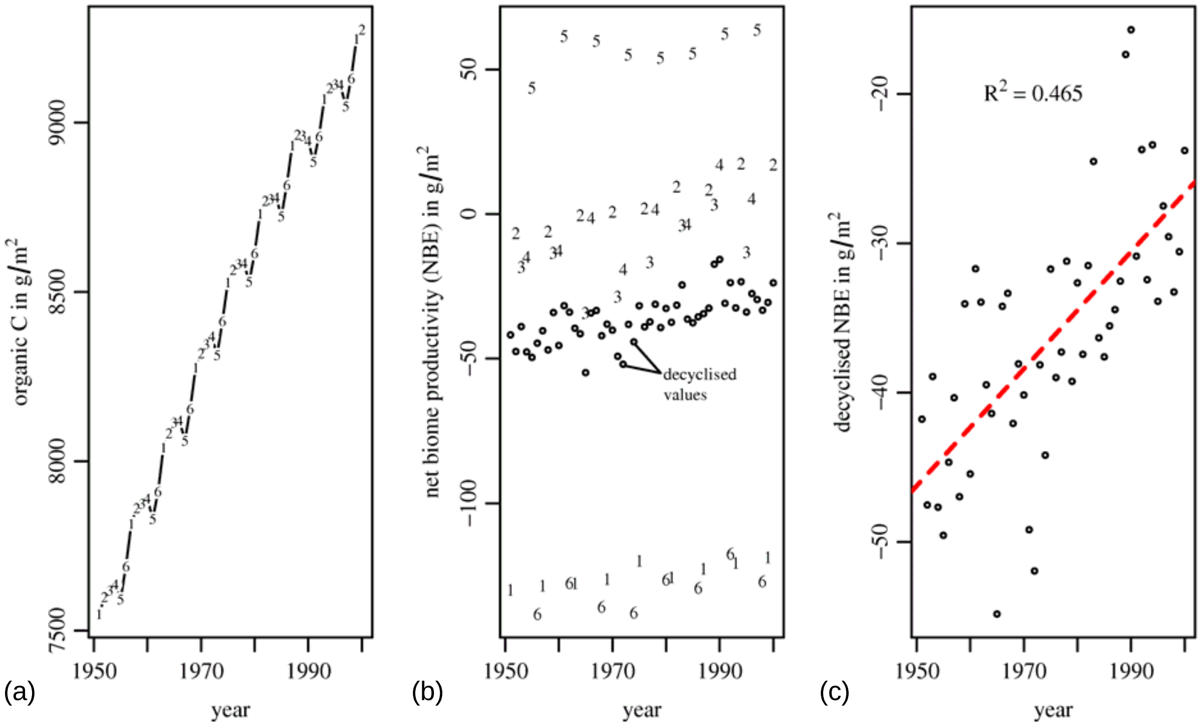

Fig. 3 (a) Soil carbon development for the sample hydrotope Leipzig. (b) Respective NBE development, original and decyclised values. (c) Trend regression for the decyclised NBE values.

of the rotation groups and their entire average from the original NBE values. Figure 3(c) is just a scaled version of (b) showing the regression line of decyclised NBE with a clear upward trend.

In Fig. 4, the annual averages of soil temperature, soil water content and climatic water balance have been plotted against the decyclised NBE values. These, and all other possible variable pairs, including time, are shown in the upper right part, along with the respective correlation values for a single hydrotope. Regarding NBE, the increasing tendency over time can

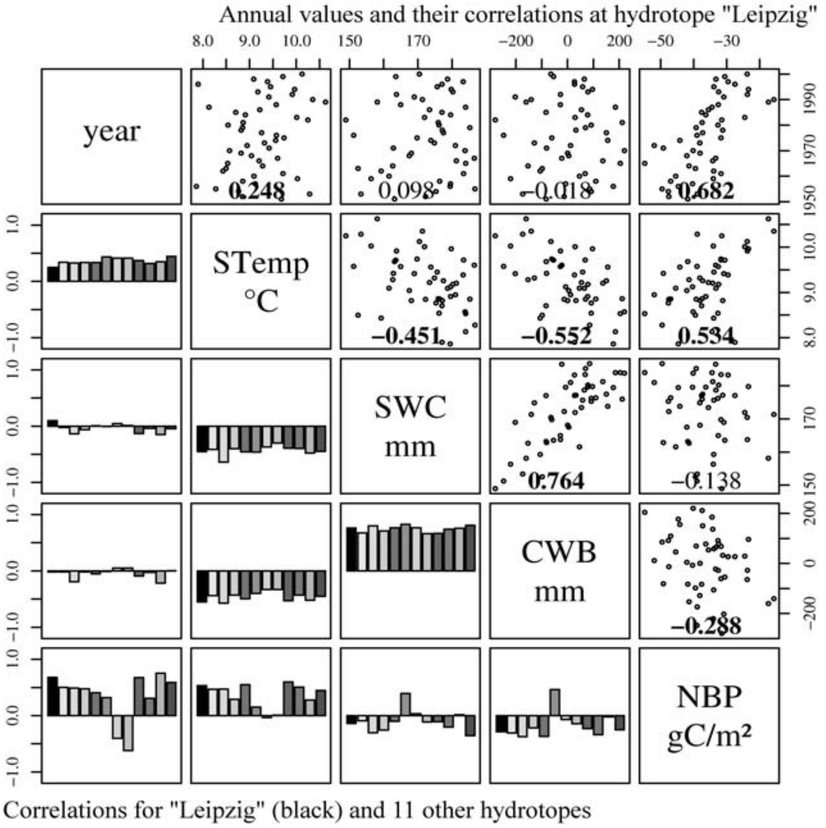

Fig. 4 Upper triangular matrix: Time scatter plots and the annually modelled variables soil temperature (*S*Temp), soil water content (SWC), climatic water balance (CWB), and net biome exchange (NBE) for the hydrotope "Leipzig". The numbers indicate the correlations. Lower triangular matrix: Bar plots of these and 11 respective correlations from other selected hydrotopes

be found again here, as well as a certain positive correlation with soil temperature. The other relations to soil water content and climatic water balance (which are strongly correlated) are negligible.

The lower left part of Fig. 4 summarises the same analysis carried out for 12 different sample hydrotopes. The correlations are shown as bars (see the scales from –1 to +1 on the left-hand side). Clearly, positive correlations between NBE and soil temperature can be revisited in at least 10 out of the 12 cases, while the picture for soil water content and climatic water balance remains unclear: although a majority of cases seems to be negative here, they are less pronounced.

The clear picture given by positive correlations between soil temperature and time in all hydrotopes, and the absence of recognisable time dependencies in soil water content and climatic water balance, delivers a second reason to concentrate on soil temperature effects alone.

A negative time tendency of NBE occurs for just those two hydrotopes shown in Fig. 4 that are characterised by indifferent correlations between NBE and soil temperature. In these cases, the positive temperature effect on NBE is probably superseded by a negative base trend of NBE having other causes.

What governs NBE time trends besides temperature (or other climatic influences) can be seen in Fig. 5(a), where the dependency on its absolute level in the different hydrotopes is shown. The two hydrotopes with decreasing NBE over time are characterised by positive mean NBE values, i.e. a long-term decay of soil C.

Figure 5(b) shows schematically how the soil C pool of any hydrotope tends towards an individual equilibrium, which is far from being reached within our modelling time frame. For instance, a trajectory below the equilibrium indicates a rising C content coupled to NBE values that become less negative (rising over time). The two hydrotopes in question are associated with

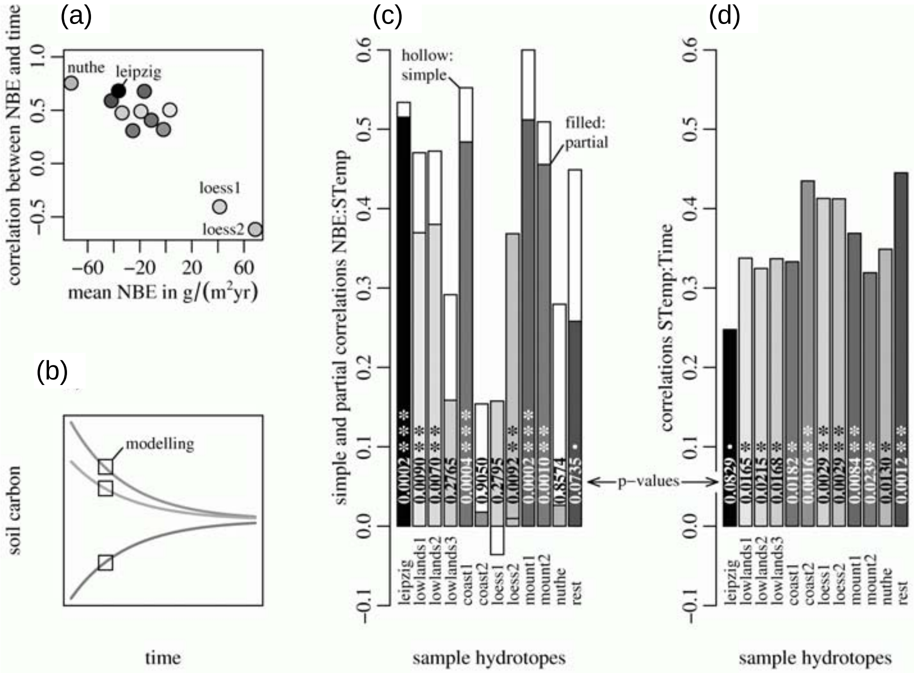

Fig. 5 (a) Dependency of NBE development over time (correlation on *y*-axis) on the mean absolute values of NBE. (b) Schematic visualisation of the background effect: hydrotope-specific, increasing or decreasing NBE on its way to soil carbon equilibrium. (c) As NBE is time dependent *per se*, the proportion of this dependency in the correlation of NBE and soil temperature shown here had to be removed by partitioning. (d) Correlation between soil temperature and time. In (c) and (d) the significance of the correlations is indicated by *p* values and "star codes" written into their bars. In most cases, the one-star level for 95% significance is reached or exceeded, which provides strong evidence for a recent temperature trend influencing NBE dynamics.

trajectories above the equilibrium, while the "Leipzig" hydrotope, with its dynamics shown in Fig. 3, gives an example of the former case. Soils tend towards C equilibrium either for C inputs higher than or equal to soil C losses (soil C saturation), or for C inputs considerably smaller than C losses over long periods (more than 50–100 years). The latter is the lower soil C limit (often referred to as "inert C"), which represents physically and chemically protected C compounds in the soil. This effect is schematically represented in Fig. 5(b). Under the assumed C inputs, soils tend towards an equilibrium C condition over long time frames.

The results of partitioning of the correlation coefficient between NBE and temperature, and the respective values for the soil temperature trends themselves, are shown in Fig. 4(c) and (d). For the NBE dependencies, it can be stated that in seven of the 12 cases the probability for observing real effects is 99% or higher. The same strong finding holds for the soil temperature increases over time: here the 95% level is met in all but one case.

Conclusively, the recent climate has significantly influenced the modelled soil C dynamics through an upward temperature trend. It is quantified in the next section. This has been carried out for the entire quantity of 11 347 agricultural hydrotopes.

Quantification of recent soil C loss driven by climate only The third-order polynomial fit, modelling the influence of the average NBE levels on NBE change over time, yields an R^2 value of 0.9063. The t testing of the polynomial coefficients underpins their high significance, with p values below 2×10^{-16} for each of them.

The fit of the linear model for the pure temperature effect on NBE by equation (5) is $\hat{\beta}_0 = 3.294$, i.e. a temperature increase by 1 K leads to an average additional soil C respiration of nearly 3.3 g m^{-2} $year^{-1}$.

The other coefficients are estimated at $\hat{\beta}_1 = -8.017 \times 10^{-3}$, $\hat{\beta}_2 = 5.784 \times 10^{-6}$, and $\hat{\beta}_3 = 7.176 \times 10^{-3}$, resembling the values obtained for the regression of single NBE values. In this case, R^2 is 0.1317, but now NBE values for each hydrotope and each year have been fitted, while before only their linear trends were estimated. Again, all polynomial coefficients are highly significant, with p values below 2×10^{-16}.

The mean increase in soil temperature was estimated to be 0.022 K year^{-1} by the linear fitting described above. This allows computation of the annual shift in soil C dynamics induced by climate change:

$$3.294 \text{ g C K}^{-1} \text{ m}^{-2} \cdot 0.022 \text{ K year}^{-1} = \frac{\mathrm{dNBE}}{\mathrm{d}t} = 0.0725 \text{ g C m}^{-2} \text{ year}^{-1} \qquad (6)$$

After multiplication by the 50 years of modelling time, we can state that annual carbon respiration increased by approx. 3.6 g C m^{-2} between 1951 and 2000 due to climate change. In the long run though, any climatic impact on NBE would disappear as a result of a new equilibrium being established. Assuming that the equilibrium drift is negligible compared to climate-induced NBE changes, we can estimate the cumulated carbon loss by integrating over the 50 years:

$$\mathrm{C}_{\mathrm{lost}} = \int_0^{50} y \cdot \frac{\mathrm{dNBE}}{\mathrm{d}t} \mathrm{d}y = \frac{1}{2} \cdot 50^2 \cdot 0.0725 \frac{\mathrm{gC}}{\mathrm{m}^2} = 90.6 \frac{\mathrm{gC}}{\mathrm{m}^2} \qquad (7)$$

Anticipated future climate change effects

Keeping land use the same as in the reference period and considering climate change only (most probable realisation) leads to a decreasing soil C content in both the topsoil and the entire soil. Average loss in the scenario period is 278 g C m^{-2} for topsoil and 720 g C m^{-2} for the entire soil. In comparison to the reference condition, climate change leads to a decrease in topsoil C storage (Fig. 1). Average net flux of C to the atmosphere increased from 10.8 g C m^{-2} year^{-1} in the reference period to 14 g C m^{-2} year^{-1} under climate change (Table 2). Due to climate impacts alone, a significant positive trend ($p < 0.001$) in NBE is identified for the period 1951–2055 (Fig. 1).

Table 2 Change in topsoil and total soil C content (end minus start value of simulation), net annual C flux to the atmosphere (NBE) and respective climate-only contribution, for the reference simulation (1951–2000) and the climate change scenario simulation (2001–2055).

	Change in topsoil C content (g C m^{-2})	Change in total soil C content (g C m^{-2})	Net annual flux to atmosphere, NBE (g C m^{-2} year^{-1})
Reference period (1951–2000)	−9	−509	10.8
Climate contribution			1.8
Climate change scenario period (2001–2055)	−278	−720	14.0
Climate contribution			3.2

A comparison of changes in topsoil C storage and NBE for the reference conditions (1991–2000) and climate change only (2046–2055) is given in Fig. 6(a) and (b). The highest loss of topsoil C, at 9577 g C m^{-2}, occurs in the loess area (southwestern part of the Elbe basin) and in the alluvial areas of the lowlands with some gains (maximum value of 3650 g C m^{-2}). Only minor changes are identified in the eastern loess areas, the periglacially formed lowlands and parts of the mountain area (Fig. 6(a)).

Areas with losses in topsoil C storage can also be identified as areas of net annual flux to the atmosphere (sources of C, red areas in Fig. 6(b)). The largest such areas in the Elbe basin were identified as sources of C, with some hotspots in the southern part with a conversion of carbon sinks to carbon sources due to climate change only. Identified C sinks in the basin in general are

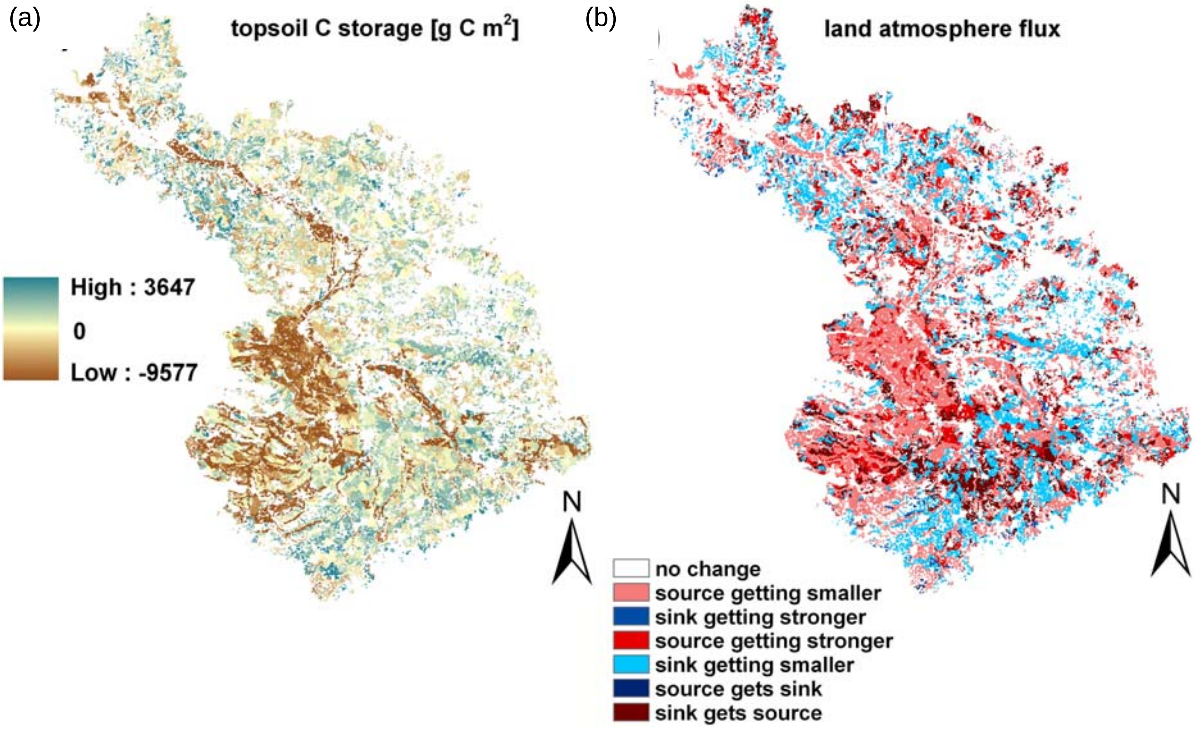

Fig. 6 Difference map for: (a) mean topsoil C storage (g C m^{-2}) and (b) qualitative illustration in changes of net biome exchange (NBE) for climate change only minus reference condition. Please note that averaged values of the periods 1991–2000 for the reference conditions and 2046–2055 for the scenario conditions are used. Topsoil C storage values below zero denote a loss of C under scenario conditions compared to reference conditions.

shrinking, staying as C sinks under climate change only, but nevertheless losing C in comparison to the reference situation (bright blue areas in Fig. 6(b)).

DISCUSSION

Changes in climate (mainly temperature and precipitation) significantly alter soil C storage. This alteration is mainly caused by changes in the turnover properties of soil organic matter in soils (mineralisation and decomposition), but also by changes in the amount and quality of C inputs. Climate directly or indirectly influences these properties.

Changing climate, as already observed and expected to continue in the study area, will lead to an increase in temperature and a decrease in precipitation, except for winter precipitation in the western mountain areas (Harz and Thüringer Wald) which will most likely increase (Gerstengarbe & Werner, 2005). An increase in temperature will speed up the turnover processes of soil organic matter, but changing precipitation patterns (future decrease in precipitation amount for most of the basin) will counteract the temperature effect. Soil moisture properties anticipated for the Elbe basin (decrease in soil water content) will reduce the temperature effect on soil C storage. Additionally, an increase in temperature and atmospheric CO_2 concentration will enhance the NPP. However, considering the same regionalised climate change scenario and fertilisation effect caused by an increase of CO_2 concentration, C3 crop yields (e.g. winter wheat, summer barley) are expected to be reduced by 11–17%, whereas C4 crop yields (e.g. silage maize) will not be significantly affected on average (Hattermann, 2005; Wechsung *et al.*, 2005). Consequently, the amount of soil C added will decrease.

To address the consequences of changes in climate for croplands at the regional scale, a simulation set-up was established to create the characterisation of regionalised climate and agroeconomic properties for the time frame 1951–2055. This allows for enhanced present-day and future soil C assessments under changing climate.

Recent past (1951–2000) climate impacts on soil C storage

Regions contributing most to net annual C flux to the atmosphere for the reference period were identified based on the spatial distribution assessment (Fig. 2). The eastern loess regions and alluvial parts of the lowlands can be identified here. Soils in these regions have the highest soil C contents and show higher sensitivity to climate changes than soils with low organic C. The fertile loess soils, in the areas with the highest NBE values, are dominated by intensive agricultural use. Alluvial soils in the lowland region are affected more by groundwater and can be assigned mainly to riparian zones of the Elbe River and its tributaries. These water-influenced soils have developed a high organic matter content and act as C sources under cultivation. The mountain areas and periglacially formed parts of the lowlands (sandy soils) can most commonly be assigned as C sinks.

The present-day dynamics of soil C storage were quantified. Average annual NBE is 10.8 g C m^{-2} $year^{-1}$ (Table 2). In comparison, mean annual soil C losses based on measurements and then upscaled to the national scale are, e.g. 24 g C m^{-2} $year^{-1}$ for Austria, and 76 g C m^{-2} $year^{-1}$ for Belgium (Janssens *et al.*, 2003). Rinklebe & Makeschin (2003) reported mean annual soil C losses of between 0.59 and 25.9 g C m^{-2} $year^{-1}$ for a loess region in lower Franconia (Germany) based on measured soil C changes for a period of 27 years (see Table 1).

The increase in temperature (+0.8 K in the summer and +1.4 K in the winter) causes an increase in the turnover processes of soil C. As a result, soil C storage for both topsoil and total soils decreased (Fig. 1) due to the temperature change observed in the reference period. Net flux to the atmosphere—attributed to observed temperature increase only—is approx. 1.8 g C m^{-2} $year^{-1}$ (Table 2). For the total cropland area in the German part of the Elbe River basin, climate-induced fluxes amount to an increase in C flux to the atmosphere of approx. 0.07 Mt C $year^{-1}$ (1 Mt = 10^9 kg).

Anticipated future climate change effects

Climate change in the scenario period (2001–2055) leads to an enforcement of decreasing soil C content, especially for the topsoil C storage. The combined increase in mean temperature of 1.4 K until 2055 and CO_2 fertilisation effect on crop growth, with a decrease in precipitation amounts (−15%) for most of the study area, have led to a decrease in crop yields (Hattermann, 2005; Wechsung *et al.*, 2005). This translates accordingly into a decrease in C input to the soil. An expected increase in crop growth due to higher temperatures and CO_2 fertilisation does not occur in the study area (Hattermann, 2005; Wechsung *et al.*, 2005). The main reason for this is the decrease in precipitation and, hence, a change in hydrological properties. Hattermann (2005) investigated changes in water availability in the Elbe basin using the same simulation set-up (see Table 1). Changes in temperature and precipitation led to a slight increase in actual evapotranspiration and a strong decrease (by 40%) in runoff properties, groundwater recharge (decrease by 46%) and water resources (Table 1). Climatic water balance (precipitation minus potential evapotranspiration) is negative and shows a clear decreasing trend for the period 1951–2055, with stronger decreases in the scenario period (2001–2055, −2.7 mm $year^{-1}$). The resulting decrease in soil water storage has an impact on soil organic matter turnover properties (i.e. it reduces decomposition and mineralisation processes), and counteracts the temperature effect on the turnover in soil organic matter. Consequently, the loss of soil C due to the effects of climate changes is less strong than reported in other studies. For example, Bellamy *et al.* (2005) reported large-scale C losses from soils (0–15 cm soil depth) over the past 25 years under all land-use conditions in England and Wales (based on soil measurements). Changes in climatic patterns (increase in temperature and decrease in precipitation) for this moist, temperate region (with mostly wet soils) are seen as the main driver of the strong C losses. Although there is an ongoing debate about the temperature sensitivity of soil C turnover processes (e.g. Giardina & Ryan, 2000; Fang *et al.*, 2005; Knorr *et al.*, 2005), the evidence for this feedback based on laboratory and field experiments, and modelling studies has been provided in the mean time (Bellamy *et al.*, 2005). However, the temperature effect on soil C turnover declines when soil moisture conditions inhibit soil C turnover, as is most probably the case in parts of the Elbe basin. In contrast to the UK, where the temperature effect on soil C turnover dominates, the effect of decreasing soil moisture on soil C turnover dominates in most of the Elbe basin (Jones *et al.*, 2005). Nevertheless, climate change alone causes a significant decline in soil C storage and increase in NBE. Additional C flux due to climate change is 3.2 g C m^{-2} $year^{-1}$, which corresponds to an increase of 30% compared to the reference period, with an additional flux of 0.13 Mt C $year^{-1}$ in the scenario period.

The spatial pattern of change in topsoil C storage and NBE due to climate change, found in this study, leads to the identification of regions with the largest changes. The largest decreases in soil C storage are predominant in the loess and alluvial lowland soils. These include soils with high soil C contents and high water holding capacities. A decrease in expected soil water content does not reduce C turnover compared to soils with low water holding capacities. A further outcome is that soil C losses are proportional to soil C content, which was also observed for soil C losses in England and Wales (Bellamy *et al.*, 2005). Most of the Elbe basin is characterised as a C source, with some regions acting as sinks but becoming smaller under climate change impacts. Soils with low C content, predominant in the periglacially formed lowlands (sandy soils on ground moraines) and the mountain areas, had the smallest soil C decreases. In those soils, the declining soil water due to climate change reduces C turnover significantly, resulting in lower C losses.

CONCLUSIONS

This study provides an assessment of present-day soil C dynamics and an analysis of the effects of plausible regionalised climate change impacts on both soil C storage and annual net C fluxes to the atmosphere for croplands in the German part of the Elbe River basin. The regionalised external driving forces of climate and agro-economy, allow a spatially-distributed assessment to be made of climate change-induced alterations to soil C dynamics beyond water cycle components and crop growth.

Simulated soil C dynamics for the reference period (1951–2000), taking into account local crop-share distributions and observed climate, produce a decrease in soil C storage and a net annual flux of C to the atmosphere of approx. 10.8 g C m^{-2} $year^{-1}$. For the recent climate within the reference period, the dependency of the modelled soil C dynamics on the soil temperature, and the significance of a soil temperature trend (driven by measured data), was shown and quantified.

The climate trend already present in the reference period causes an approximate net loss of C to the atmosphere of 1.8 g C m^{-2} $year^{-1}$ (0.07 Mt C for the Elbe cropland area). Under anticipated future climate change, this effect amounts to about an additional 4 g C m^{-2} $year^{-1}$ (0.16 Mt C for the Elbe cropland area). An increase in temperature (+1.4 K until 2055) results in an increase in soil C turnover, which is inhibited by soil water storage, but nevertheless contributes to net C fluxes from soils to the atmosphere. Because of increasing atmospheric CO_2 contents and increase in temperature, crop growth is stimulated and the growth period increases. Accordingly, vegetation requires considerably more water, which poses the limiting factor resulting in decreased crop yields under climate change conditions compared to the reference period. Hence soil C input derived from crop residuals decreases, and also contributes to, soil C storage losses.

Regionally, areas suffering from the biggest changes were identified based on the scenario assumptions used. Soils with high C contents, which are concentrated in the eastern part of the loess area and in alluvial parts of the lowland areas, deliver the highest decrease in C. For the loess area, intensive agriculture dominates with crop rotation and shares, resulting in decreasing soil C, which is already visible under the reference conditions. In soils influenced by water with high C content in the alluvial regions (riparian zones), climate change (increase in temperature and decrease in precipitation) causes a strong decrease in soil C storage. Soils in the periglacially formed lowlands and in the mountain areas (mainly less fertile soils with sandy to loamy soil texture and low soil C content) show a smaller decrease due to climate change.

Overall, the croplands in the Elbe basin are currently acting as C sources, with an increasing tendency under expected climate change. Additionally, a strong decrease in water resources ,degrading cereal crop yields due to expected climate change, was disclosed using an integrated assessment. In terms of croplands acting as C sources, changes in cultivation (e.g. in crop shares, extensification, bioenergy crops) have the potential to mitigate this effect. For example, with extensification through conversion of 30% of the cropland area into ley, the basin would become an overall C sink without significantly changing the water components (overall C storage of 4 g C m^{-2} $year^{-1}$; Post, 2006). Cultivation of bioenergy crops on 30% of cropland area mitigates C fluxes to the atmosphere and delivers additional fossil fuel substitutes (see Post, 2006). However, the use of fast growing, woody bioenergy plants (e.g. poplar) demands high amounts of water and nutrients and has the potential to amplify a decrease in water resources. Additionally, increased amounts of harvest residuals left on fields contribute considerably to soil C increases (Post, 2006). Afforestation also delivers an increase in soil C and is accountable within the Kyoto protocol. Yet investigations by Wattenbach *et al*. (2007), using the same model and study area (Federal State of Brandenburg, Germany, which is part of the Elbe River basin), show a negative impact on the regional water balance (3.7% increase in mean annual evapotranspiration due to afforestation).

This study showed impacts on ecosystem services (mainly C storage) that could occur through climate change alone. Further investigations are planned to integrate the impacts of land-use change (land-use conversion and changes in cultivation practices) on C storage, the water cycle and vegetation growth.

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