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Large-scale integrated assessment of soil carbon and organic matter-related nitrogen fluxes in Saxony (Germany)

Felix Witing[1,2,] *, Michael Gebel[3], Hans-Joachim Kurzer[4], Holm Friese[5], Uwe Franko[1]

[1.] Helmholtz Centre for Environmental Research (UFZ), Department of Soil Physics, Theodor-Lieser-Straße 4, 06120 Halle/Saale, Germany

[2.] Helmholtz Centre for Environmental Research (UFZ), Department of Computational Landscape Ecology, Permoserstraße 15, 04318 Leipzig, Germany

[3.] Gesellschaft für Angewandte Landschaftsforschung (GALF) bR, Am Ende 14, 01277 Dresden, Germany

[4.] Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie (LfULG), Fachbereich Pflanzliche Erzeugung, Bodenkultur, Waldheimer Straße 219, 01683 Nossen, Germany

[5.] Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie (LfULG), Referat 44 Oberflächenwasser, Wasserrahmenrichtlinie, Zur Wetterwarte 11, 01109 Dresden, Germany

* Corresponding author: felix.witing@ufz.de

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Highlights:

- Soil organic carbon (SOC) & nitrogen dynamics in Saxony were simulated on a 500m grid.
- The CCB model was specifically adapted & validated for large-scale simulations of SOM.
- C input to arable soils increased while C turnover conditions decreased (1998-2014).
- SOC stocks increased by 1.2 ‰ per year, largely driven by conservation tillage.
- Climate variability caused a high annual dynamic in organic matter related nitrogen.

Abstract

Changes in land-use, agricultural management and climate affect the turnover and storage of organic carbon in soils (SOC) as well as the nitrogen mobilization from soil organic matter (SOM), with potential side effects on nitrogen availability and leaching. When addressing the requests for increased carbon storage in soil as well as for the reduction of nitrogen losses, integrated approaches on regional scales are required that take into account the actual changes in agricultural management and climate. This study investigated the arable land (7345 km²) of Saxony (Germany) with regard to the following: (1) the trends of SOC storage and organic matter-related nitrogen fluxes, including their subregional and annual dynamics, (2) changes in the carbon input to arable soils and the turnover of organic matter, and (3) the contribution of different drivers (climate, crop production and fertilization, tillage system) to the simulated SOM changes for the period 1998–2014 on a 500 m grid. The model CANDY carbon balance (CCB) was specifically adapted for large-scale simulations of SOM turnover to link spatial data on soils and climate with regional statistics on agricultural management. This new 'regional mode' of CCB has been validated using data from 391 plots across different European locations. The initial SOC levels for Saxony assumed steady state conditions at the beginning of the simulation period and have been validated using data from 667 monitoring sites. The results showed an increase in the SOC stocks of the arable soils of Saxony of 785 x 10^3 t C (1.24 ‰ annually) during the simulation period. At the same time, the model simulated an average increase in organic nitrogen stored in SOM of approximately 7.5 kg N ha^{-1} a^{-1}, with considerable differences between individual years and subregions. Both the increase in carbon inputs to soil (+8 %) and the reduction of carbon turnover rates (-10 %) had positive effects on SOC storage. While the increased use of conservation tillage was the most important driver for the overall increase in SOM storage in Saxony, climate variability and crop production and fertilization had the largest effect on its annual dynamics.

1 Introduction

Agriculture in Central Europe is currently faced with new challenges and opportunities. New markets for agricultural raw materials (e.g., bioenergy) created a strong incentive to intensify agricultural production (Fischer et al., 2010; Lotze-Campen et al., 2010). At the same time, the demands on agriculture to further minimize the negative effects of land use on the environment (e.g., nitrate leaching and loss of soil carbon) are increasing. Changing climate conditions exert additional pressure and require an adaption of agricultural management (Olesen et al., 2011; Olesen and Bindi, 2002; Reidsma et al., 2010).

Against the backdrop of changes in agricultural management but also with regard to climate change, impacts to the soil organic matter (SOM) balance, carbon to nitrogen (C/N) ratios and nitrogen leaching can be expected (Bindi and Olesen, 2011; Smith et al., 2005). Processes of enrichment and depletion of carbon and nitrogen in SOM significantly influence the preservation of soil fertility and the release of nutrients from the organic pool. They also influence the soil functions related to carbon storage. To address these problems, integrated approaches are necessary that consider organic nitrogen pools as well as organic carbon pools with individual C/N ratios (Gruber and Galloway, 2008).

To avoid a trade-off between further intensification and the growing requirements for resource efficient and sustainable production, it is necessary to improve the understanding on current trends in soil organic carbon (SOC) and nitrogen storage and to evaluate the impacts of agricultural use on larger scales. However, the large-scale spatially distributed quantification of carbon and nitrogen dynamics in soil is especially challenging. Data availability is typically limited with respect to agricultural management and SOM monitoring data, and the results must be evaluated under consideration of the respective conditions of the landscape and its management.

The aim of this study was to 1) quantify the recent changes in SOC storage and organic matter-related nitrogen fluxes in the arable land of Saxony (Germany) and to highlight their subregional and annual dynamics; 2) analyze changes in the carbon input to arable soils and the turnover rates of organic matter; and 3) quantify the impact of different drivers (climate, crop production and fertilization, tillage system) on the observed changes in SOM. The modeling approach was implemented on a 500 m grid using the CCB model (CANDY carbon balance; Franko et al., 2011), specifically adjusted for large-scale problems of SOM turnover.

2 Material & Methods

2.1 Study area

The federal state of Saxony in East Germany is dominated by agricultural land use (52 %). Arable land covers approximately 7345 km² and is intensively used due to its fertile loess soils. Data on soils, climate, land-use and agricultural management have been provided by the 'State Agency for the Environment, Nature Conservation and Geology of Saxony' (LfULG) and GALF bR ('Gesellschaft für Angewandte Landschaftsforschung'). The underlying database has already been used successfully for the quantification of diffuse matter transport in the river catchment areas of Saxony using the model

STOFFBILANZ (Gebel et al., 2016, 2013, 2010; Halbfaß et al., 2009). The STOFFBILANZ database has been transferred into a format suitable for the CCB model used in this study (see section 2.3).

The modeling approach was based on a grid with a cell size of 500 m. Each grid cell was considered homogenous in terms of topography, soil, land use and climate. For this study, only arable land was considered, resulting in 29380 grid cells for the whole area. The parameterization of climatic conditions was based on data from the regional climate information system ReKIS (www.rekis.org). For the period 1998 to 2014, monthly data on a 1 km² raster were taken from the ReKIS climate database and interpolated according to the spatial (500 m) and temporal (annual) resolution requirements of this study.

Climatic conditions in Saxony are temperate but vary substantially between the lowlands (8 °C to 10 °C; 500 to 800 mm precipitation) and low mountain ranges (6 °C to 8 °C; 900 mm to 1200 mm). The average contents of clay, silt and stones in the topsoil were derived from the soil map series of Saxony (LfULG, 2012). Arable land is dominated by silty soils, especially loamy silt (44 %) and sandy silt (25 %). Raster cells containing peat soils have not been considered for modeling.

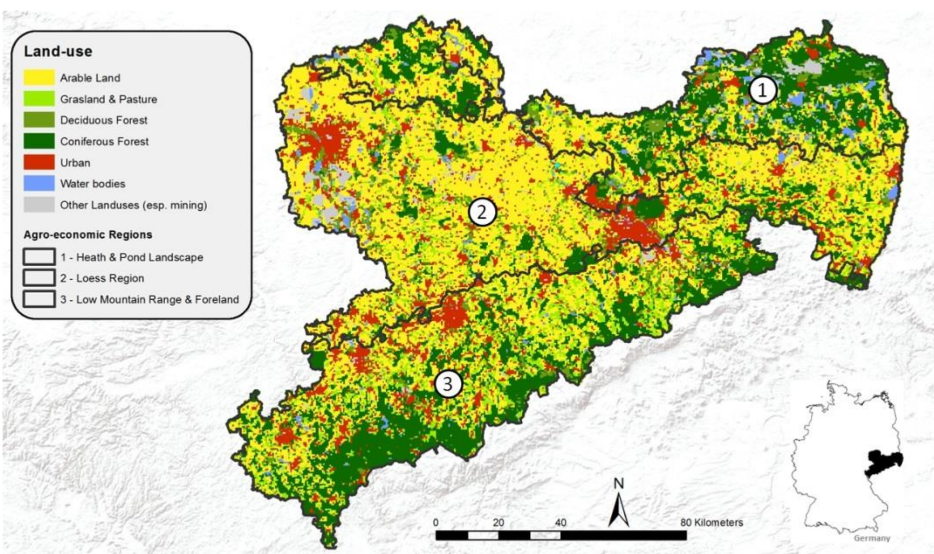

Figure 1: Land-use and agro-economic subregions of the study region Saxony

The study area is subdivided into three ‘agro-economic regions’ according to landscape characteristics and agricultural structure (LfL, 1999): (1) Saxon heath and pond landscape, (2) Saxon loess region, and (3) Saxon low mountain range and foreland (Figure 1). Table 1 summarizes the important properties of these three agricultural regions.

Table 1: Land-use and physiogeographic characterization of the agro-economic regions of Saxony. Average values for the specified periods.

	Heath & Pond Landscape	**Loess Region**	**Low Mountain Range & Foreland**
Arable land [%]	31.9	52.5	28.4
Grassland & pasture [%]	8.1	9.8	16.7
Temperature[1] [°C]	9.6	9.3	7.8
Precipitation[1] [mm]	736	770	961
Clay content[2] [%]	4.4	9.5	13.8
Silt content[2] [%]	22.8	65.3	58.2
Stone content[2] [%]	10.4	7.4	16.2
Conservation tillage 2000/2012 [%]	13.3 / 26.5	14.5 / 34.3	14.9 / 52.1
Catch crops[3] [%]	4.5	4.0	4.6

[1] Period 1990-2014, [2] of agricultural land (topsoil), [3] Period 2000-2012

2.2 Agricultural parameters

Each grid cell with arable land-use holds information on crop harvest areas and yields for 20 different crops (Table 2) as well as information on catch crops, tillage systems and fertilizer applications. The land management data were available for five time slices: 2000, 2005, 2010, 2011 and 2012. Data related to crop cultivation and tillage systems were based on regional statistics at the municipality level and InVeKoS data (Integriertes Verwaltungs- und Kontrollsystem).

In the period under review, cereals were the dominant crops (58 %) in Saxony followed by winter rape (15 %) and maize for silage (9 %). The cultivation of catch crops became more important in the investigated period (2000: 3.0 %, 2012: 6.6 %). Furthermore, the share of conservation tillage increased strongly (2000: 14.4 %, 2012: 37.1 %). Based on expert knowledge of the state agency LfULG, it was assumed that by-products (esp. straw, beet leaves) of relevant crops were removed from 20 % of the arable land.

Table 2: Average crop shares and crop yields in Saxony for the period 2000-2012

	Crop Share [%]	**Yield [t ha^{-1}]**
Winter Wheat	24.5	6.9

Winter Barley	13.5	6.5
Winter Rye & Triticale	10.8	5.8
Spring Cereals	8.5	4.8
Winter Rape	15.4	3.8
Maize for Silage	8.7	45.2
Field Grass	2.7	37.2
Clover Grass	2.6	39.1
Other[1]	13.2	

1 fallow, sugar beet, grain maize, vegetables, legumes, sunflowers, potatoes

The quantities of fertilizers applied are based on an analysis of the fertilization advisory system BEFU (Förster, 2013) for Saxon farmers. It covers the application of organic and mineral nitrogen as well as the N input from atmospheric deposition. For organic fertilization, slurry and manure were considered in the simulation. Information on other organic fertilizers (e.g., biogas digestate, compost) was not available.

2.3 Modeling approach

2.3.1 CCB Model

In this study, the CCB model (Franko et al., 2011) was used to simulate the soil-related carbon and nitrogen dynamics of arable land in Saxony. CCB is based on the model CANDY (Franko et al., 1995) and was developed to answer practice oriented research questions. Due to simplified process modeling, it has fewer requirements regarding data input. It describes the turnover of decomposable carbon in annual time steps for average site conditions depending on crop yields, input rates of fresh organic matter and the initial organic carbon content of the soil. The modeling of turnover is based on first-order kinetics using the Biological Active Time (BAT) as time variable according to the concept in CANDY (Franko and Oelschlägel, 1995). BAT is estimated from site conditions (soil physical parameters of the topsoil, tillage system, annual precipitation and air temperature).

Within CCB, the carbon input to SOM is aggregated to a 'soil carbon reproduction flux' (C_{rep}). It includes all carbon from fresh organic matter (FOM), which is transformed to SOC and considers the quality of the different sources of FOM regarding the formation of new SOC. C_{rep} either originates from the non-harvested biomass of the cultivated crops (crop residues and crop by-products) or from organic amendments. The turnover of organic nitrogen in CCB is controlled by the dynamics and the C/N ratios of the FOM and SOM pools. Outputs of CCB include the annual dynamics of SOC concentration, SOC mineralization and SOC reproduction from FOM as well as soil organic nitrogen dynamics, with particular attention to nitrogen mineralization from FOM and SOM and immobilization in SOM. For a simplified overview of the pools and fluxes of the CCB model, see supplementary material Figure A1.

2.3.2 Model adjustments for large-scale assessments

Several model adjustments have been necessary to use CCB for large-scale studies such as this. In contrast to previous model applications on plot scale, the simulation objects are not homogeneous in space and time (such as agricultural fields) but represent a gridded integration over several management units. In this new 'regional mode', the model is driven by the area average and the proportional coverage of the individual management activities (cropping, tillage etc.) within one spatial modeling unit (e.g. farm, pixel, or municipality). In particular, the ability to use crop share statistics instead of crop rotations can be essential for large-scale modeling approaches. However, the adjustments to run the model with aggregated data also included the handling of crop by-products, application rates of fertilizers and spatial shares of conservation tillage. The adapted procedure of modeling conservation tillage is based on a soil texture-dependent reduction of BAT and has been published by Franko and Spiegel (2016).

Applying CCB to larger scales made it necessary to optimize its data management and computational efficiency. This included the possibility of providing discontinuous management data in the form of time slices (e.g., 2000, 2005, 2010) as well as a framework of parallel computing of one CCB database. All new developments of CCB, which enable the simulation at meso to large scales, have been summarized in a special module ('regional-mode') to enable easy changing between different modeling tasks.

In addition to the technical implementation, it was evaluated whether the modified handling of management data causes systematic errors in the modeled output. Here, it must be considered that the aggregation of management data includes a temporal and a spatial aspect: the temporal aggregation of the crop rotations of one site into crop harvest area relations as well as the spatial aggregation of pools and fluxes of neighboring sites. The CCB validation database (Franko et al., 2011) was used for this analysis, which covered 391 treatments from long-term field experiments at 40 different locations and 4794 measurements of SOC. The original management data included in this database cover yearly information on cultivated crops and yields, handling of by-products, fertilizer applications and irrigation. To analyze the effects of data aggregation, the management variety of all

391 treatments was spatially aggregated to 40 locations homogeneous in soils and climate conditions. The results of the treatment-specific simulations were compared to the simulations using aggregated management data.

2.3.3 Initialization of soil carbon levels of Saxony

For the quantitative assessment of SOC dynamics and related nitrogen fluxes, it was necessary to initialize SOC concentrations for the complete study region. In CCB, long-term stabilized SOC (C_{lts}) must be distinguished from decomposable SOC (C_{dec}). Large-scale monitoring data regarding SOC concentration in agricultural soils in Saxony were not available. It was therefore assumed that the fraction of C_{lts} is typical for individual site conditions. To assess C_{lts}, the SOC parameterization of the STOFFBILANZ model for Saxony was used, which is based on soil type and elevation. The amount of initial C_{dec} was calculated individually for every grid cell. The calculation assumed that the agricultural management and climate of the years 1998-2004 was also applicable for the time period before 1998 and that the initial SOC was in a steady state, which corresponds to this agricultural management and climate. Thus, the initial C_{dec} was determined using the C_{rep} fluxes and BAT values of this time period.

The initialization of SOC levels was evaluated using data from the long-term SOC monitoring network operated by the state agency LfULG. In total SOC measurement data of 667 permanent monitoring plots throughout Saxony have been considered for this analysis, all located on arable land and have been sampled at least three times. To have a common basis for the evaluation, both (i) the grid-based initialization of the CCB model and (ii) the SOC measurements of permanent plots were aggregated based on soil type and agro-economic region.

2.3.4 Model application and sensitivity assessment of different drivers

The soil-related carbon and nitrogen dynamics of the arable land in Saxony were simulated for each of the 29380 grid cells (500 m x 500 m) using the agricultural parameters and initialization of SOC concentration as stated in the previous sections. The simulation was run in yearly time steps, covering the period 1998–2014. Data on agricultural management were used in time slices: the parameterization of the management stayed constant during the simulation until the data of a new time step was available.

A scenario approach was used to assess how the most important drivers - climate, crop cultivation and fertilization, tillage systems – and their development over time individually contributed to the yearly dynamics and overall changes in SOC during the simulation period. Three different model runs were carried out, where each time only one of the three drivers kept the parameterization of the original (reference) scenario, while the other two drivers got a temporally constant parameterization for each grid cell based on their average value in the initialization period (1998-2004) (Table 3).

The results from the individual scenarios allow for a ranking concerning the relative importance of the temporal development of each analyzed driver. As a quantitative measure, the correlation coefficient was calculated between the results of the reference scenario (original dynamics of all drivers) and the individual test scenarios where only one driver was kept in its original dynamic. Furthermore, the net change in SOM storage between 1998 and 2014 was quantified.

Table 3: Sensitivity assessment of the contribution of different drivers to system dynamics (Reference = dataset 1998-2014)

		Analyzed driver		
		Climate	Crop cultivation & fertilization	Tillage system
Dataset used	Climate	Reference	Avg. 98-04	Avg. 98-04
	Crop cultivation & fertilization	Avg. 98-04	Reference	Avg. 98-04
	Tillage system	Avg. 98-04	Avg. 98-04	Reference

3 Results

3.1 Validation of the CCB module for large-scale simulation

The new 'regional-mode' of CCB was successfully validated by comparing 391 treatment-specific simulations (using plot-specific management data) with 40 upscaled simulations ('regional-mode') using management data aggregated to the level of experimental location (see supplementary material Figure A2). The standard simulation of the 391 experimental treatments resulted in very good statistical quality criteria, using 4794 SOC measurements for validation. The root-mean-square error (RSME) was 1.2 g kg^{-1}, the mean absolute error (MAE) was 0.9 g kg^{-1} and the coefficient of determination (r^2) was 0.94. With a percent bias (PBIAS) of 0.3 % and a mean error (ME) of 0.03 g kg^{-1}, systematic errors were negligibly small.

The simulation on the scale of experimental locations ('regional-mode') slightly worsened the absolute quality criteria RMSE (1.7 g kg^{-1}), MAE (1.2 g kg^{-1}) and r^2 (0.9) but still gave acceptable results. As a result of input data aggregation, the heterogeneity in the simulated SOC dynamics between the different experimental plots of a location was lost. Nevertheless, PBIAS (0.2 %) and ME (0.02 g kg^{-1}) slightly improved, and the general trend in the timeline of carbon storage of a location was adequately represented.

3.2 Initialization of SOC concentration for the arable land of Saxony

The average initial SOC concentration of the arable land of Saxony was 15.09 g kg^{-1}, which is in a reasonable range as reported in other studies (Rank et al., 1999). RMSE of the model initialization compared to the respective monitoring data of the 667 permanent plots was 3.3 g kg^{-1} when aggregating the data based on soil type and geographic location (Figure 2). The monitoring data showed a high variability in measured values, but correlated satisfactorily with the steady state initialization (r^2=0.55). There was a tendency to underestimate SOC concentrations in light (sandy) soils while overestimating SOC concentrations in heavier (loamy) soils. Because no management data for the permanent plots were available, the reasons for this pattern could not be analyzed. However, the linear regression equation was very close to the ideal 1:1 line, having a slope of 0.93. Because the SOC initialization was representative of an average management of larger regions, its overall variability was lower than in the individual permanent plots.

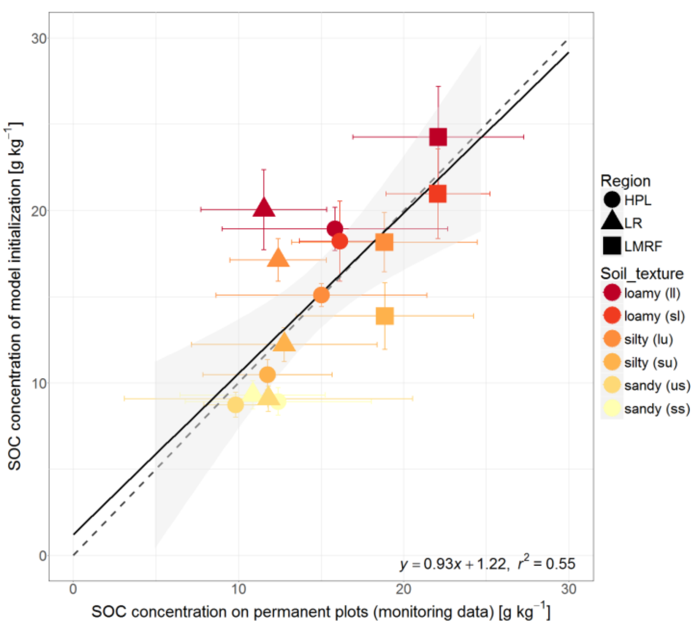

Figure 2: Comparison of the SOC concentration (topsoil, 0 - 30 cm) from the monitoring of permanent plots and the calculated initial values assuming "steady-state" conditions for the year 1998. The measured data of the permanent plots and the initialized model values of the CCB grid cells were aggregated based on soil type and agro-economic region (HPL = Saxon heath and pond landscape, LR =

Saxon loess region, LMRF = Saxon low mountain range and foreland). Soil texture classes (Ad-Hoc-Arbeitsgruppe Boden, 2005): sandy soils (ss = sandy sand, us = silty sand), silty soils (su = sandy silt, lu = loamy silt), loamy soils (sl = sandy loam, ll = loamy loam).

3.3 Trends in regional SOC stocks

During the simulation period, the average SOC storage in the topsoils of Saxon arable land increased from 15.1 g kg^{-1} (1998) to 15.4 g kg^{-1} (2014) and so by approximately 2 %. The total increase in carbon storage of 0.3 g kg^{-1} in topsoils (30 cm) corresponds to approximately 785.3 x 10^{3} t C. Compared to initial SOC levels, the average yearly increase was 1.24 ‰. In 2.9 % of the total simulation area, the gains in SOC were higher than the currently discussed target of 4 ‰ (Minasny et al., 2017). Nevertheless, the individual trend values exhibit considerable heterogeneity and on 14.9 % of the arable land SOC stocks decreased.

When looking at individual regions in Saxony, there have been considerable differences in the average SOC concentration as well as in the trends of carbon storage (Figure 3). In 2014, the arable land of the low mountain ranges had the highest average SOC value (19.7 g kg^{-1}), followed by the loess areas (15.3 g kg^{-1}) and the heath and pond landscape (10.0 g kg^{-1}). With respect to trends of carbon storage, a similar pattern was observed: the low mountain ranges (76.3 kg C ha^{-1} a^{-1}) and the loess areas (69.8 kg C ha^{-1} a^{-1}) stored more than twice as much additional carbon in SOC during the simulation period than the heath and pond landscapes (23.6 kg C ha^{-1} a^{-1}). Relative to the initial carbon content in 1998, the total gains were 2.1 %, 1.8 % and 1.3 %, respectively.

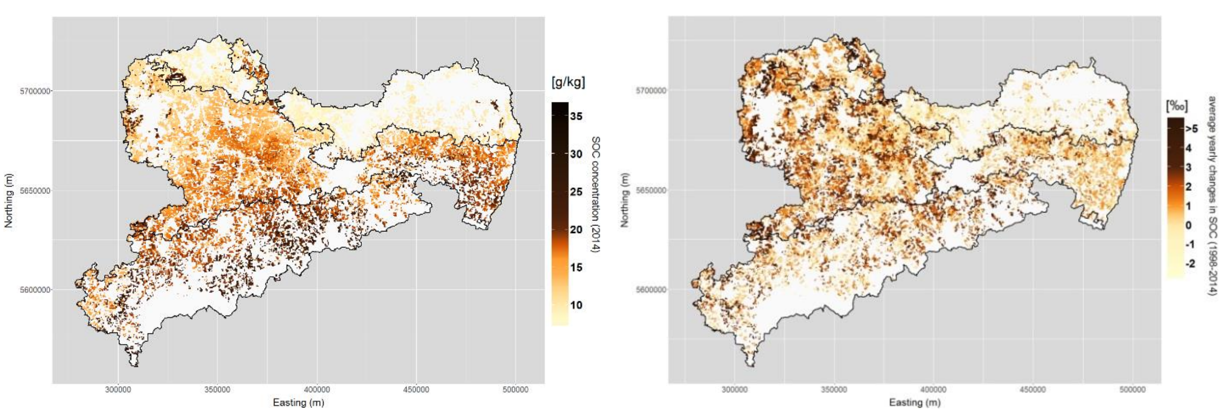

Figure 3: SOC concentration 2014 [g kg^{-1}] (left) and average yearly changes in SOC [‰] for the period 1998– 2014 (right).

3.4 Input and turnover of soil-related carbon

The simulated changes in SOC storage are driven by changes in turnover conditions and carbon input to soil. Within CCB, carbon from FOM that is transformed into SOC is represented by the carbon reproduction flux C_{rep}. Turnover conditions for all carbon pools are aggregated within the model variable BAT. Both model variables changed significantly between the two periods 1998-2004 and 2010-2014. Although showing a high variability between individual sub-regions (Figure 4), the average temporal development of both variables indicated positive effects on SOC storage. For all of Saxony, BAT decreased from 24.4 days (1998-2004) to 22.0 days (2010-2014) and so by approximately 10 %. At the same time, the average C_{rep} flux increased from 1220 kg ha^{-1} a^{-1} to 1314 kg ha^{-1} a^{-1} (+ 8 %).

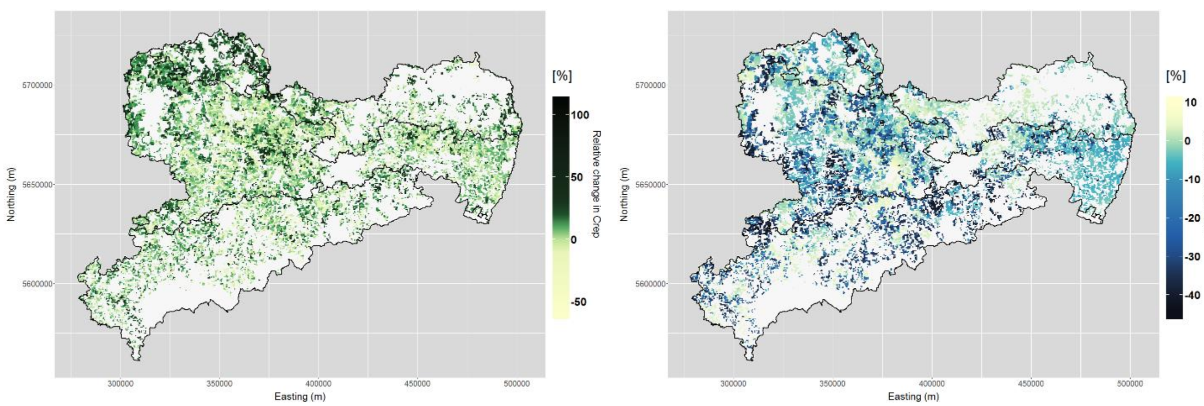

Figure 4: Relative changes in carbon input to SOC (left; expressed as C_{rep}) and SOC turnover conditions (right; expressed as BAT) comparing the average values of the two periods 1998-2004 and 2010-2014. Darker colors represent a positive effect on SOC storage.

Climatic variability had considerable impact on the annual turnover of organic carbon but also to some extent on the C_{rep} flux into soil (see supplementary material Figure A3) due to, e.g., yield variation. Carbon turnover generally benefited from higher temperatures. The effect of precipitation was more heterogeneous. Light (sandy) soils showed higher turnover rates with increasing precipitation, while for heavier (loamy) soils, too much precipitation had inhibitory effects on the turnover of organic matter. Additionally, changes in tillage systems strongly reduced the average turnover of organic carbon (see also section 3.6).

The main sources of FOM changed considerably during the simulation period. In particular, FOM input from winter rape, maize, winter wheat and sugar beet increased, while the contribution of all cereals other than winter wheat declined. These developments were primarily caused by changes in the cultivated area of the individual crops and less by changes in yield. Furthermore, the C_{rep} flux originating from organic amendments increased by 20.2 %.

3.5 Organic matter-related nitrogen fluxes

The model predicted a total increase of organic nitrogen stored in SOM of approximately 93.2 x 10^3 t N during the simulation period, corresponding to an average gain of 7.5 kg N ha^{-1} a^{-1}. When looking at the average annual N cycle in Saxony, 141.7 kg N ha^{-1} a^{-1} was mobilized from SOM due to SOM mineralization, while annual reproduction of SOM (humification of FOM to SOM) stored 149.1 kg N ha^{-1} a^{-1} at the same time. The immobilization of nitrogen due to SOM reproduction increased from 145.5 kg ha^{-1} a^{-1} (1998-2004) to 154.5 kg ha^{-1} a^{-1} (2010-2014). Depending on the C/N ratio of the original carbon source, this N flux into SOM originates in various proportions from the carbon source itself or from the mineral N pool of the soil. On average, 65.2 kg (44 %) of this N flux into SOM originated from FOM, while 83.9 kg N ha^{-1} a^{-1} (56 %) was immobilized from the N_{min} pool during the turnover of FOM to SOM. Crop residues and by-products from winter wheat, winter rape and winter barley contributed the most to the immobilization of N_{min} during the turnover of FOM to SOM (Table 4). The total flux of organic nitrogen from FOM to SOM increased from 61.8 kg ha^{-1} a^{-1} (1998-2004) to 69.4 kg ha^{-1} a^{-1} (2010-2014) (+12 %).

Table 4: Amount of mineral nitrogen immobilized during the turnover of FOM (crop residues and by-products) to SOM (in addition to the N content of the original carbon source) due to the low carbon to nitrogen ratio of SOM compared to most types of FOM.

	1998 [10^3 t N]	2014 [10^3 t N]
Winter Wheat	20.1	18.8
Winter Barley	10.9	9.4
Winter Rye & Triticale	8.3	5.8
Winter Rape	6.1	9.8
Spring Cereals	4.4	5.3
Maize for Silage	2.3	3.5
Field Grass	1.7	2.0
Grain Maize	1.3	3.7
Sugar Beet	0.7	1.0
Other crops[1]	3.2	0.6

[1] Fallow, vegetables, legumes, sunflowers, potatoes, clover grass, catch crops, mustard, pea, soy-bean

The annual dynamics of turnover conditions and FOM input (section 3.4) had large effects on the annual balance of organic nitrogen and related nitrogen fluxes (Figure 5). These dynamics are an important factor for nitrogen leaching and crop fertilization. A high turnover of SOM in 2003 led to a strong mobilization of nitrogen, especially in the loess region. On the other hand, large amounts of nitrogen have been stored in SOM in the years 2005, 2010 and 2013. Due to differences in cultivated crops, the agro-economic regions of Saxony differed substantially in regard to their regional nitrogen balance. The net immobilization was 2.6 kg N ha^{-1} a^{-1} for the heath and pond landscapes, 8.3 kg N ha^{-1} a^{-1} for the loess region and 9.1 kg N ha^{-1} a^{-1} for the low mountain ranges.

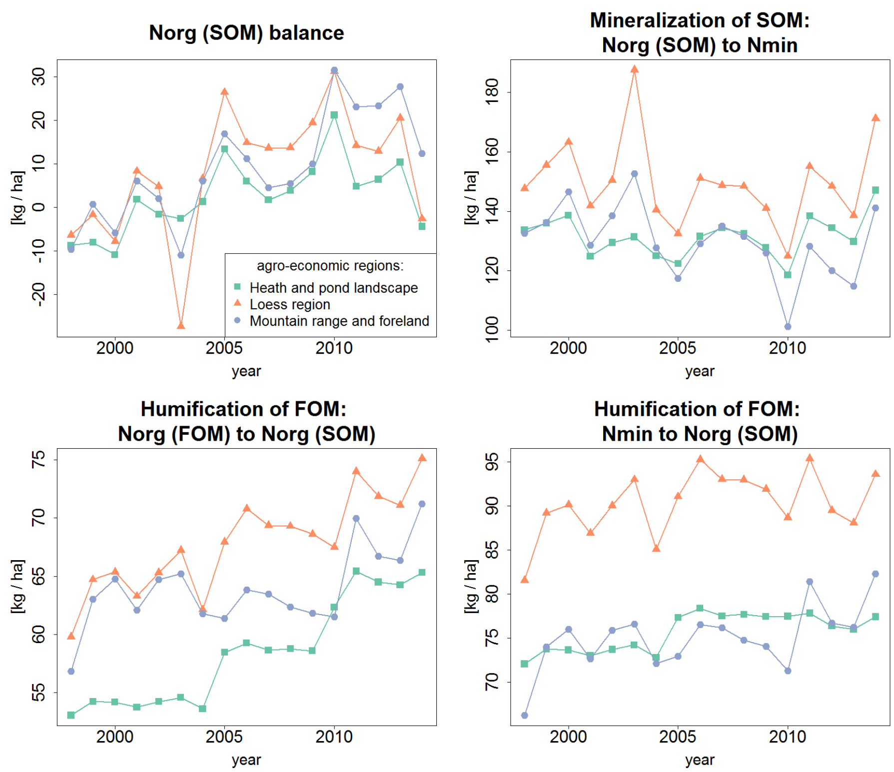

Figure 5: Annual dynamics in the balance of organic nitrogen stored in SOM as well as in the nitrogen fluxes into (humification) and out of the SOM pool (mineralization).

3.6 Contribution of different drivers to changes in SOM

The three main drivers (climate, crop cultivation and fertilization, tillage system) and their changes during the simulation period all had a positive effect on the SOC storage (Figure 6). However, the simulated scenarios demonstrated an unequal contribution of the individual drivers to the net increases in SOC concentration. Compared to the initial SOC concentration, the driver scenarios led to net increases of 0.02 g kg^{-1} (climate), 0.16 g kg^{-1} (crop cultivation and fertilization) and 0.25 g kg^{-1} (tillage system) for the simulation period 1998-2014. The combination of all drivers (reference simulation) increased SOC storage by 0.3 g kg^{-1}, which is only 78 % of the sum of individual effects. The outcomes of the driver analysis, especially the effects of conservation tillage, differed considerably between the individual agro-economic regions. Within the Saxon heath and pond landscape, the trends in conservation tillage and climate led to decreasing SOC levels.

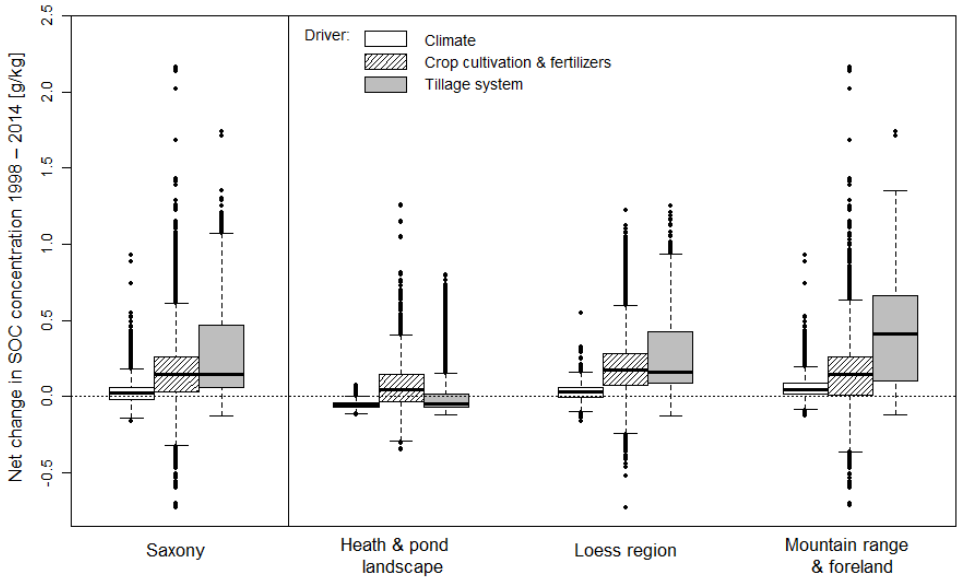

Figure 6: Analyzing the effects of the three main drivers on the net changes in SOC concentration within the simulation period (1998–2014). The changes in SOC concentration between 1998 and 2014 were calculated for every grid cell.

The sensitivity of the drivers was different when considering the Pearson's correlations between reference simulation and individual driver scenarios and thus considering more the annual dynamics in SOM storage. The SOC dynamics of the 'crop cultivation and fertilization' scenario were more similar to those of the reference simulation (r^2 = 0.78) than those of the model runs focusing on tillage system (r^2 = 0.70) or climate (r^2 = 0.58). The annual dynamics in the balance of organic nitrogen stored in SOM revealed a different picture. Here, the dynamics have been considerably stronger than the net changes over the whole simulation period. Climate was identified as a main driver in Saxony (r^2 = 0.65), followed by crop production and fertilization (r^2 = 0.62) and tillage system (r^2 = 0.52). Nevertheless, for every agro-economic region, there was a different key driver behind the annual dynamics in the balance of organic nitrogen (see supplementary material Figure A4).

4 Discussion

4.1 Large-scale simulation of SOM dynamics using CCB

While selected CCB-based indicators have already been used for large-scale analysis of carbon input and turnover conditions in soil (Franko et al., 2015; Witing et al., 2018), this is the first application of

CCB for the large-scale simulation of SOM turnover and storage. The CCB model was extended by a 'regional mode', which has the benefit of using aggregated data on agricultural management that are typically available at lager scales. The application of this methodology was successfully demonstrated for Saxony by quantifying changes in SOC concentration and organic matter-related nitrogen storage on a 500 m grid (29380 cells).

Although the specific model adaptations have been successfully validated, it must be noted that a simulation using regionally aggregated data can only represent the average area-wide balance of that region and averages the management diversity of individual sites within it. With respect to the dataset used for validation, it must be considered that the analyzed experimental sites of one location often have extreme types of fertilization. It can be expected that the different management strategies aggregated within census data are more homogenous.

A proper initialization of SOC pools is a challenging task in SOC modeling (Dimassi et al., 2018; Foereid et al., 2012), especially when the simulated spatial units represent a set of diversely managed agricultural fields. This problem was approached by assuming steady state conditions in SOC storage for the starting period of the simulation. While the validation of this approach was satisfactory, further improvements could be achieved by including the management data of the permanent plots used for validation within the generation of the initial values. Unfortunately, these data were not available for this study. Nevertheless, the approach of steady state initialization has the benefit of highlighting the effects of external drivers on SOM levels during the simulation period.

4.2 Dynamics of SOC and related organic nitrogen stocks in Saxony

For the vast majority of the arable land of Saxony, an increase in SOC concentration during the study period was observed. Although the currently discussed target of 4 ‰ (Minasny et al., 2017) is only achieved in selected locations (2.9 %), the observed average yearly increase of 1.2 ‰ is considerable. The results are in accordance with other studies that observed that SOC stocks in central European regions started to rise from the beginning of the 21st century (Kaczynski et al., 2017). Both the overall decrease in turnover conditions and the overall increase in carbon input to soil led to this positive development in SOC storage.

Considering the 4 ‰ target and the observed trends in Saxony it is important to emphasize their dependency on the continuous presence of casual drivers. If the driver behind positive trends in SOM storage is lost, the stored amounts of C and N will be released again. This is especially critical if gains in

SOM storage are based on changes in agricultural management that are not repeatable. The results indicated that a large part of the increase in SOC storage is due to the increased use of conservation tillage. Despite this, the prevalence of conservation tillage in Saxony might be variable and dependent on the existence of subsidy programs (SMUL, 2017, 2014, 2008). Upcoming subsidy programs should consider not only future carbon storage potentials but also the maintenance of current carbon stocks.

With respect to organic matter-related nitrogen, variations between individual years have been more dominant than the overall trends in storage. Nevertheless, a significant amount of N has been immobilized in SOM. The model results contribute to an integral and spatially distributed understanding of the N and C cycles of arable land. Processes of enrichment and depletion of N in humus significantly influence the preservation of soil fertility but also affect nitrate leaching.

4.3 Effects of drivers, changes in carbon input and turnover conditions

The use of conservation tillage has been shown to be the most important contributor to the overall gains in topsoil SOC concentration. A considerable decrease in overall turnover conditions of organic matter in Saxony was observed, which is largely related to the increase in conservation tillage and the original reason for gains in SOC storage at constant carbon input to soil. The positive effect of conservation tillage on soil carbon storage is widely studied (Alvarez, 2005; Lal and Kimble, 1997; Luo et al., 2010), although there is discussion about the soil depth that has to be considered (Baker et al., 2007).

The indicator C_{rep} aggregates the effect of different carbon sources on SOC storage by considering the quality of the different sources of FOM for the formation of SOC (Franko et al., 2011; Kolbe, 2010). The study revealed considerable gains in C_{rep} fluxes during the simulation period, which were mainly caused by changes in the composition of cultivated crops and in the application of organic amendments and less by changes in the actual yield of individual crops. An important driver for this is the inclusion of biogas production in the agricultural systems of Saxony (Witing et al., 2018).

The effects of climate on the net balance of SOM in the whole simulation period have been minor but became important for its annual dynamics, especially with respect to organic matter-related nitrogen. To give scientifically substantiated recommendations on how to further improve agricultural management in Saxony with respect to SOM storage, it would be important to include long-term climate scenarios in future studies as they effect turnover conditions but also crop yields and therefore the carbon inputs to soil (Davidson and Janssens, 2006; Robertson et al., 2017; Sanderman et al., 2017).

4.4 Conclusion

With the quantification of selected parameters of the soil-related carbon and nitrogen balance on large scales, the CCB model system takes an important step towards an integrated, spatially distributed view on the carbon and nitrogen cycle of arable land. The application of this methodology was successfully demonstrated for Saxony, where we could consider a diverse set of input data thus overcoming a typical limitation for the large-scale simulation of SOM dynamics. Spatial data on soils and climate have been combined with statistical information on agricultural management on various levels. The presented approach has the benefit of reflecting real changes in agriculture and climate. However, due to the resolution of some statistical data sources, the results should not be used for the detailed analysis of individual spots (grid cells).

With respect to the study region of Saxony, considerable amounts of C and N have been stored in SOM of arable soils during the period 1998-2014. However, there have also been significant regional differences, including decreasing SOC levels in 14.9 % of the area. The low mountain ranges and the loess areas stored more than twice as much additional carbon in SOC than the heath and pond landscapes. While the increased use of conservation tillage was the most important driver for the overall increase in SOM storage, climate variability had strong effects on its annual dynamics. Nevertheless, changes in the composition of cultivated crops and in the application rate of organic amendments also had considerable impacts. It is important to emphasize that if the driver behind the positive trend in SOM storage is lost the stored amounts of C and N will be released again. Future subsidy programs should consider not only future carbon storage potentials but also the maintenance of current SOM stores. Otherwise, SOM stores could pose a risk for climate change mitigation and cause nitrate leaching.

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7 Supplementary material

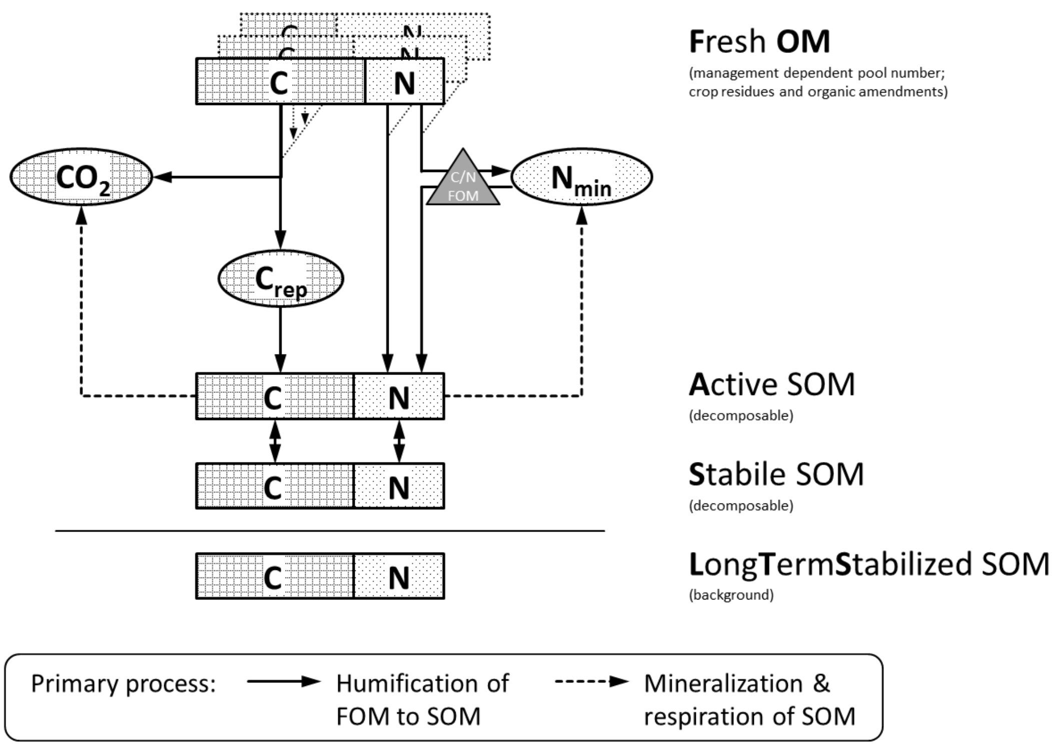

Figure A1: Simplified overview of pools (blocks) and fluxes (arrows) of the CCB model. C_{rep}: carbon reproduction flux from fresh organic matter (FOM) to soil organic matter (SOM). CO_2: release of carbon dioxide. LTS-SOM: long-term stabilized soil organic matter with no turnover during simulation time. Nitrogen fluxes: depending on the C/N ratios of the different FOM and SOM pools additional nitrogen is immobilized from or mobilized into the external pool of mineral nitrogen (N_{min}) during the humification of FOM (modified from (Franko et al., 2011)).

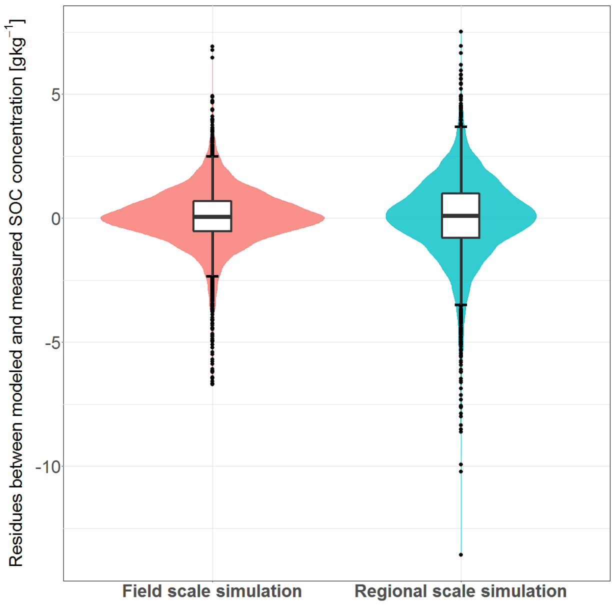

Figure A2: Comparing the residues between simulated (CCB model) and measured SOC concentrations for 4794 measurements of SOC in 40 different locations in Europe. Left: Simulation of SOC dynamics on the scale of experimental treatments. Right: Simulation of SOC dynamics aggregated to the scale of the experimental location – here, the agricultural management of 391 treatments with different management was aggregated to 40 locations homogeneous in soil and climatic conditions.

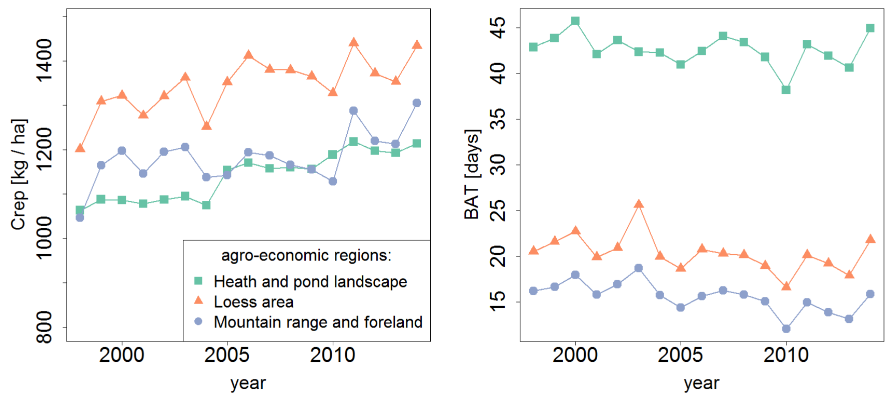

Figure A3: Annual dynamics in carbon input (left; expressed as C_{rep}) and turnover (right; expressed as BAT). C_{rep} aggregates all sources of FOM while considering their quality for the formation of new SOC. BAT aggregates turnover conditions with respect to soil physical parameters, tillage system, annual precipitation and air temperature. During the simulation period, there were several years that had particular effects on regional SOC dynamics. The years 2000, 2007 and 2014 have been outstandingly warm years, while the year 2010 has been a particularly cold one. With regard to precipitation, the year 2003 has to be highlighted as a notably dry year. The years 2002 and 2010 have been the wettest.

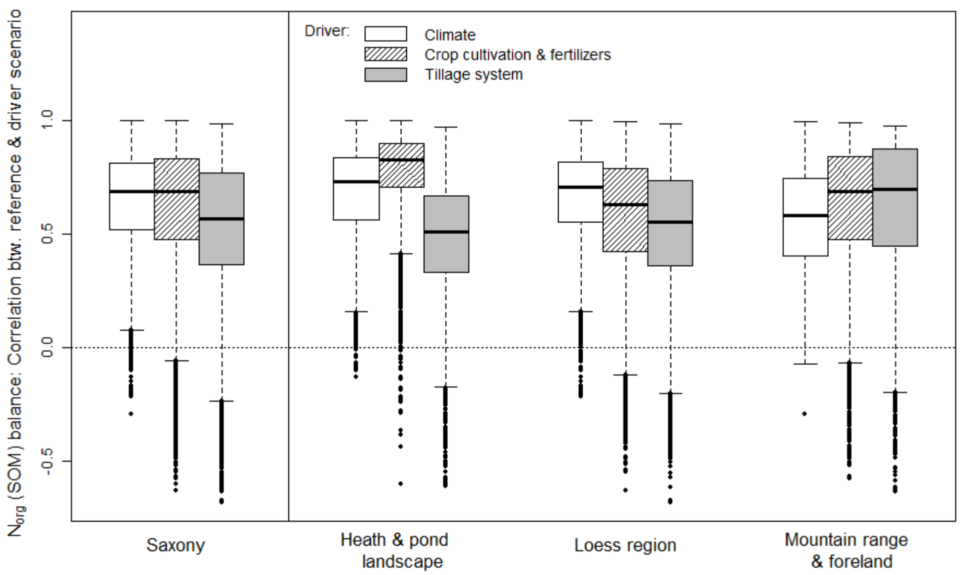

Figure A4: Analyzing the effects of the three main drivers on the annual balance of organic nitrogen stored in SOM. Pearson's correlation between the reference simulation and the model runs focusing on individual drivers was calculated for every grid cell.