Journal of Environmental Management 287 (2021) 112318

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Dynamic soil functions assessment employing land use and climate scenarios at regional scale

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ARTICLE INFO

Keywords:
Dynamic soil functions assessment
Land use scenario
Climate change
Soil organic carbon
Regional case-study
Austria

ABSTRACT

Soils as key component of terrestrial ecosystems are under increasing pressures. As an advance to current static assessments, we present a dynamic soil functions assessment (SFA) to evaluate the current and future state of soils regarding their nutrient storage, water regulation, productivity, habitat and carbon sequestration functions for the case-study region in the Lower Austrian Mostviertel. Carbon response functions simulating the development of regional soil organic carbon (SOC) stocks until 2100 are used to couple established indicator-based SFA methodology with two climate and three land use scenarios, i.e. land sparing (LSP), land sharing (LSH), and balanced land use (LBA). Results reveal a dominant impact of land use scenarios on soil functions compared to the impact from climate scenarios and highlight the close link between SOC development and the quality of investigated soil functions, i.e. soil functionality. The soil habitat and soil carbon sequestration functions on investigated agricultural land are positively affected by maintenance of grassland under LSH (20% of the case-study region), where SOC stocks show a steady and continuous increase. By 2100 however, total regional SOC stocks are higher under LSP compared to LSH or LBA, due to extensive afforestation. The presented approach may improve integrative decision-making in land use planning processes. It bridges superordinate goals of sustainable development, such as climate change mitigation, with land use actions taken at local or regional scales. The dynamic SFA broadens the debate on LSH and LSP and can reduce trade-offs between soil functions through land use planning processes.

1. Introduction

Soils fulfil a variety of societal and environmental functions. They determine the productivity of global land uses, provide habitats, regulate climate, nutrient and water cycles, retain pollutants, and preserve natural and cultural history (Adhikari and Hartemink, 2016; Debeljak et al., 2019; Jónsson and Davíðsdóttir, 2016; Keesstra et al., 2016). Yet, soil functions in terrestrial ecosystems are increasingly under pressure from a rising demand for food, fibre, raw material and human infrastructure as well as from climate change (Kopittke et al., 2019). Globally, about 33% of the land surface is already degraded, mostly because of inadequate land use and land management (FAO & ITPS, 2015; IPCC, 2019b). Land use has bi-directional impacts, i.e. it can promote or impede the provision and quality of soil functions to society and the environment (Huang et al., 2018; Sannigrahi et al., 2018; Smith et al., 2016). Knowledge on such site-specific impacts is needed to improve regionally adjusted land use planning (Cebrián-Piqueras, 2019; Zheng et al., 2019). Evaluating these impacts can inform long-term decision making on alternative land use strategies such as “land sharing” (LSH) and “land sparing” (LSP) (Green et al., 2005). These two concepts, rooted in landscape ecology, enhance the discussion in science and policy making on ensuring sufficient levels of food production, while at the same time securing biodiversity conservation in agricultural landscapes. Yet, previous research has shown that the concepts’ narrow scope on food production and biodiversity falls short in recognizing the effects of land use decisions on a wider range of ecosystem services and their induced impacts on other environmental goals, e.g. carbon storage, pollination, soil or watershed protection (Grau et al., 2013; Ramankutty

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https://doi.org/10.1016/j.jenvman.2021.112318
Received 23 December 2020; Received in revised form 22 February 2021; Accepted 28 February 2021

and Rhemtulla, 2012).

The multifunctional character of soils stands at the core of the soil functions framework, which – closely related to the concepts of soil health (Karlen et al., 2003) and soil quality (Doran et al., 1994) – aims to "place value on the roles soils play in sustaining the wellbeing of humans and of society in general" (Greiner et al., 2017, p. 225). So called Soil Functions Assessments (SFAs) are carried out in scientific and administrative contexts to evaluate soils and their multiple functions by using primary and secondary soil physical, chemical and biological properties to estimate indicators of soil functionality (Ronchi et al., 2019; Vogel et al., 2019). SFAs account for the heterogeneity of soils and their current states in a spatially explicit manner and are considered a valuable tool for land use planning to balance and maintain soil multifunctionality (Haygarth and Ritz, 2009).

Several SFAs have been conducted at local and regional scales (Calzolari et al., 2016; Greiner et al., 2018). For example, SFAs have been standardized in methodological handbooks to support land use planners in Austria (BMLFUW, 2013) and Germany (Ad-Hoc-AG Boden, 2007). SFA methodologies applied in the European context are indicator-based and driven by envisaged objectives and data availability. Addressed target audience and scale of applied assessments are diverse, yet congruence on which soil properties are most essential for the provision of a particular soil function is high among reviewed sources (see supplementary material, section B). Greatest challenges with regard to the comprehensive consideration of soil resources in land use planning are that knowledge is scattered across various scientific disciplines (Vogel et al., 2018, 2019), the rather linear and mono-functional delimitation of reviewed methods (Vereecken et al., 2016) and a prevailing lack to integrate the driving influence of external perturbations, such as land use and climate change, in existing SFA approaches (Bünemann et al., 2018; Vogel et al., 2019). SFAs, which aim to promote sustainable land use, should go beyond assessing the current state of soil by considering future developments. Research efforts to advance currently applied SFA methodology are needed to capture long-term changes of soil functions from altered land use and climate conditions. This seems pressing since land use decisions have long-standing implications, create feedback loops with both soil functions and climate change and are partly irreversible.

We respond to the outlined challenges and the prevailing shortcomings of currently available SFA methodologies by developing a comprehensive dynamic SFA, which captures alterations in a variety of soil functions resulting from changes in key properties of the soil. In particular, we aim to evaluate changes in soil properties represented in soil functions under the land use strategies LSH, LSP, a combination thereof (LBA), and under climate change. As such, dynamic SFAs complement land use assessments on biodiversity and ecosystem services under climate change (Hodgson et al., 2010; Martinez-Harms et al., 2017). They may inform private (e.g. agricultural) land use, land use planning, land use policy decision-making and hence foster the sustainable use of soils and land resources.

A case-study approach was chosen to test the newly developed dynamic SFA in the Austrian Mostviertel region characterized by heterogeneous climate, topographic and soil conditions and considering alternative land use and climate scenarios. The dynamic SFA is used to i) evaluate levels of soil functionality, i.e. nutrient storage, water regulation, productivity, habitat provision and carbon sequestration in a spatially explicit manner, ii) explore how land use and climate scenarios affect the development of soil organic carbon (SOC) stocks and iii) how changes in SOC stocks might alter soil functions in the future.

The article is structured as follows: Section 2 informs about the workflow of the conducted analysis, introduces the Mostviertel study region, the used materials including underlying datasets of soil and land use and scenario data. This is supplemented by details on the chosen methodological approach for the static and dynamic SFA as well as the integrated carbon response functions. Section 3 presents results from the static and the dynamic SFA. Section 4 provides a discussion on potentials and shortcomings of the dynamic SFA and the implications for land use planning as well as the LSP/LSH debate. In section 5, conclusions are drawn.

2. Materials and methods

2.1. Materials

The presented dynamic SFA approach consists of three major steps which are explained in more detail below:

1. Levels of soil functionality are quantified with established static SFA methods for the Mostviertel region and the reference year (2017) considering i) the soil nutrient storage function, ii) the soil water regulation function, iii) the soil productivity function, iv) the soil habitat function, and v) the soil carbon sequestration function. However, the standard static SFA is insensitive to changes in land use and climate. For details see section 2.2.
2. The SFA becomes dynamic by using *carbon response functions* (Poeplau et al., 2011, p. 2415; see section 2.2.2), which allow to anticipate SOC stock change as a response to climate under stable land use as well as under land use change. This is done by integration of regionally specific land use and climate scenario data. The approach acknowledges that SOC is central to understand how levels of soil functionality change over time. The soil functions are reassessed for the year 2100 based on dynamically estimated SOC stocks.
3. Results of the static and dynamic SFAs are compared to prove the value of dynamic SFAs and to derive conclusions on the impacts of climate change and LSH/LSP strategies in a temperate European region.

The proposed methodology is generic with respect to space and time. In this study, it was applied to the Lower Austrian Mostviertel region. High resolution climate scenario data are available for this region. Region-specific land use scenarios on LSH, LSP and LBA resulted from a participatory scenario exercise (see section 2.1.3). The temporal scale includes the reference year 2017 and the future period until 2100. The spatially explicit analysis supports qualitative and quantitative evaluation of temporal and spatial changes in soil functionality.

Data management, such as harmonization and aggregation as well as calculations, has been done using ESRI ArcGIS Software (V10.4.1) and R (V3.6.1; R Core Team, 2017). We rely on the validity of the georeferenced data sources from originally publishing institutions and refrain from accuracy assessments of produced results on soil functionality. A workflow scheme of the applied dynamic SFA methodology is depicted in Fig. 1.

2.1.1. Study-region: The Mostviertel

The Mostviertel region is located in the South-West of the province of Lower Austria (N–S: 48°20′0″N 15°15′0″E – 47°45′0″N 14°55′0″E; W-E: 48°5′0″N 14°30′0″E – 48°10′0″N 15°30′0″E) and covers an area of about 3500 km^2. The North is characterized by a hilly landscape with peaks of around 300–400 m above sea level. A valley stretches along the Danube river in the centre of the region. Elevations are highest in the region's South, mounting up to around 1900 m. Mean annual temperatures range from 5 to 10 °C. Temperatures are rather mild along the Danube river, favouring the cultivation of fruit, wine and vegetables. Alpine regions in the South are generally cooler, rich in snow during

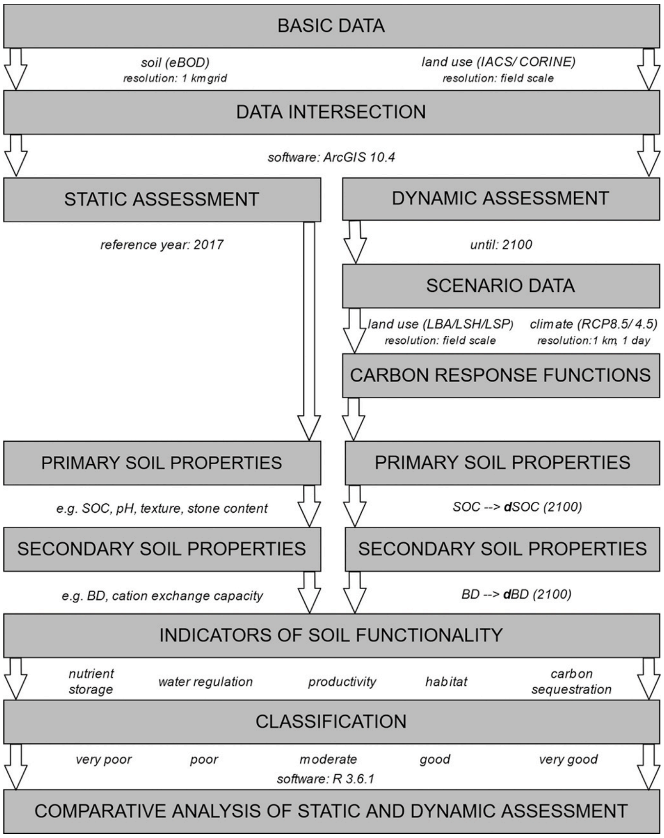

Fig. 1. Method flow chart for the dynamic soil functions assessment. Source: own compilation. (LBA = balanced land use, LSH = land sharing, LSP = land sparing, RCP = representative concentration pathway, SOC = soil organic carbon, BD = bulk density), dSOC/dBD = indicates the simulated change in SOC/BD between 2017 and 2100.

winter and dominated by forests. Mean annual rainfall varies between 700 mm in the North and 1800 mm in the South. Soils in the Mostviertel have been formed under diverse conditions of geology, land use, topography and climate (for details see supplementary material, Fig. A1). Numerous soil types, such as Rendzic Leptosols, Cambisols, Stagnosols, Mollic Fluvisols and Chernozems can be found (Wenzel et al., 2016), which make the region particularly interesting for research on soil functions and their spatial heterogeneity.

2.1.2. Soil and land use data

Horizon-specific soil data for agricultural land (i.e. SOC content, pH-value, texture, bulk density, horizon thickness, stone content, soil depth) were derived from the Austrian soil map (eBOD, Österreichische Bodenkartierung 1:25,000), originally compiled by the Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW). The Austrian soil map is the most comprehensive, freely accessible inventory of cropland and grassland soil data available for Austria at a 1 km grid resolution (Haslmayr et al., 2016). Reliability of eBOD soil data is ensured by combined field sampling and extensive laboratory analyses, extensive expertise of the pedologically trained staff involved in mapping operations and laboratory work, regular plausibility checks, and the centralized database management (UBA, 2001).

Land use data for the reference year of 2017 was derived by combining data from the Integrated Administration and Control System (IACS; European European Union, 2021) and the EU CORINE Land Cover program (CLC, 2012). Land use data are available at the field scale (see supplementary material, Fig. A1b). CORINE Land Cover data are well established, include full spatial coverage but may lack some spatial and categorial accuracy. Therefore, they have been combined with field data from the IACS of the EU Common Agricultural Policy, which has high accuracy from annual monitoring.

Land use data was intersected with soil data using Esri's ArcGIS software to derive the georeferenced basic dataset for the conducted static SFA.

2.1.3. Land use scenarios for the Mostviertel region

A hierarchical multi-scale participatory scenario approach was applied to develop three land use scenarios for the Mostviertel region at the field scale (Karner et al., 2019). The Shared Socio-Economic Pathway "Middle of the Road" (SSP2), which describes social, economic and technological developments that follow historic patterns (O'Neill et al., 2017) guided the definition of the three scenarios emphasizing the land use strategies of land sharing (LSH), land sparing (LSP), and balanced land use (LBA). The strategy of LSH aims for agricultural production and biodiversity conservation on the same land; whereas the LSP strategy calls for spatial division of productive land and land for nature conservation. Under LSP, more intensive farming practices are limited to fertile land to release marginal agricultural land for nature protection or to protect undisturbed land from agricultural expansion (Fischer et al., 2017; Phalan, 2018). LBA represents an intermediate land use, combining elements from the LSH and LSP scenarios. Table 1 summarizes the relative shares of the land uses cropland, grassland, forest and other land as well as their future changes in the respective scenarios for the study region. LBA and LSH differ only slightly with respect to changes in land use, whereas the LSP scenario indicates an increase in forest area and an almost complete abandonment of grassland.

The available land use scenarios represent a point in time. Land use change as proposed by the scenario data is in our study assumed to become effective immediately (2017) and remain stable until 2100, i.e. the scenarios materialize as an abrupt change in land use, ignoring any phases of transition. Observed land use data from the year 2017 were intersected with modelled land use scenario data to reveal the locations of land use change. SOC information provided by the underlying soil dataset for the respective fields or field aggregates in an identified location of change was then used as an input to the integrated carbon response functions (see section 2.2.2) to simulate SOC stocks until 2100.

Table 1
Shares of land uses in 2017 and shares assumed for the LBA, LSH and LSP land use scenarios. Values in brackets indicate changes in land use in the Mostviertel region in comparison to the reference year of 2017 (percentage points). Source: Karner et al. (2019).

Land use	Reference (2017)	LBA	LSH	LSP
Cropland	22% (744 km^2)	21% (−1)	21% (−1)	18% (−4)
Grassland	21% (692 km^2)	18% (−3)	20% (−1)	3% (−18)
Forest	41% (1367 km^2)	43% (+2)	42% (+1)	57% (+16)
Other	16% (556 km^2)	18% (+2)	17% (+1)	22% (+6)

2.1.4. Climate scenarios for the Mostviertel region

Projections of regional temperature are taken from national climate scenarios (ÖKS15; Chimani et al., 2016), which are based on two Representative Concentration Pathways (RCPs; Moss et al., 2010), i.e. RCP8.5 (with radiative forcing through anthropogenic greenhouse gas emissions of 8.5 W m^{-2} in 2100, compared to 1850) representing a scenario, where economic growth and fossil energy remain at the core of global socio-economic development; and RCP4.5 representing a moderate scenario with anthropogenic greenhouse gas emissions falling below today's levels around 2070. The ÖKS climate scenario data are available at a spatial and temporal resolution of 1 km and 1 day. The dataset provides climate projections produced by an ensemble of 13 General Circulation Models (GCM)/Regional Climate Model (RCM) combinations for RCP8.5 and RCP4.5 (see Chimani et al. (2016) for further details). For the presented dynamic SFA, the ICHEC-EC-EARTH/KNMI-RACMO22E (GCM/RCM) model combination was used. The scenarios for the Mostviertel indicate an increase in mean annual temperature of 4 °C under RCP8.5 and of 2 °C under RCP4.5 until 2100, compared to 2017 (see supplementary material, Figure A2). Mean annual precipitation increases by 77 mm in RCP8.5 and 7 mm in RCP4.5 from 2017 until the end of the century (year 2100), with large inter-annual variability.

Daily temperature data were aggregated to monthly means for each 1 km grid cell, which complemented land use and soil data inputs to the carbon response functions.

2.2. Methods

2.2.1. Static soil functions assessment

At first, a literature review was conducted on state of the art SFAs for the European study context (see supplementary material, section B). Mainly, indicator-based assessment methods are used, which enable the spatially explicit evaluation of current levels of soil functionality. They combine primary and secondary soil properties and are derived from look-up tables and pedotransfer functions (PTFs). PTFs are used to estimate secondary soil physical and chemical properties based on primary soil properties (e.g. sand, silt, and clay contents), if original data is missing (Wösten et al., 2001). Derived indicator values are classified qualitatively such that they represent a high or low performance of soil regarding a specific soil function. Plausibility of proposed classification schemes relies on expert judgement (Greiner et al., 2018; Lehmann et al., 2013). The combination with geographic soil information allows for a spatially explicit representation of current soil functionality in a specified region. Major inputs required for static SFAs are soil and land use data (supplementary material, section B).

The static SFA in the case-study region builds on the ensemble of previously reviewed SFA methods. In particular, the literature review informed the choice of indicators and input parameters (which are displayed in Table 2) as well as the classification schemes used to describe the current state of cropland and grassland soils. Furthermore, SFA methods were selected based on their conformity with the research aims of this study and upon whether the data requirements matched data availability for the case-study region. Methods provided by Wiesmeier et al. (2014), Lehmann et al. (2013), Haslmayr (2011) and Oberholzer and Scheid (2007) were developed in several research projects, tested in case-study regions and summarized in administrative guidelines. They matched the defined selection criteria and were adopted for the presented analysis. For some individual soil functions, data requirements for indicator derivation could not be fully met by the primary soil and land use data. If so, missing soil properties were estimated using well established PTFs from the German pedological mapping guideline (Ad-Hoc-AG Boden, 2005).

Derived indicator values were stratified into five ranks of soil functionality ranging from very good to very poor performance following the classification schemes described in the reviewed literature (Greiner et al., 2018; Lehmann et al., 2013). Modifications were made for the soil habitat function and the soil carbon sequestration function. Firstly, the order of assigned ranks was reversed such that level 1 represents very good functionality. This was done to match the classification schemes between the considered soil functions. Secondly, the classification of the carbon sequestration function was based on the internal data structure of derived indicator values through application of the frequently used Equal Interval algorithm for creating map legends in Geographic Information Systems (Esri, 2008). This was necessary because the reviewed literature did not provide a classification scheme. More information on SFA details, classification schemes, and conducted calculations is provided in the supplementary material (Section C).

2.2.2. Dynamic soil functions assessment

Climate and land use change affect several soil properties and related soil functions directly and indirectly (Hamidov et al., 2018). Feedbacks and interactions challenge the identification of suitable entry points to add dynamics to static SFAs.

The conducted literature review on static SFAs (see supplementary

Table 2

Soil functions, indicators and input parameters used for the static soil function assessment. Source: own compilation.

Soil function	Indicators	Input parameters							
		SOC content	pH-value	Texture (sand, silt, clay)	Bulk density	Horizon thickness	Stone content	Soil depth	Land use
Nutrient Storage	Effective cation exchange capacity [mol m^{-2}]	x	x	x	x	x	x		
Water Regulation	Saturated soil hydraulic conductivity [cm/d], Soil water storage capacity [l m^{-2}]	x		x	x	x	x		
Productivity	Soil water storage capacity [l m^{-2}], Air capacity [l m^{-2}], Effective cation exchange capacity [mol m^{-2}], Soil depth [ranks 1–5]	x	x	x	x	x	x	x	
Habitat	Soil microbial biomass [mg kg^{-1}]	x	x	x					x
Carbon Sequestration	Carbon sequestration potential [kg m^{-2}]	x		x	x	x	x		x

Table 3
Carbon response functions integrating soil, land use and climate parameters, used to derive the relative SOC stock change.

Land use change	Carbon response function	Source
Cropland (no change)	$SOC_{t0}+(-0.17-(dMAT*0.05))$	Ciais et al. (2010); Vleeshouwers and Verhagen (2002)
Cropland to grassland	$SOC_{t0}*(1-((-40.98*0.13*clay+0.39*depth-1.05*MAT)*[1-exp(-age/3.35)]))$	Poeplau et al. (2011); Poeplau (2020) in personal correspondence
Cropland to forest	$SOC_{t0}*((38*10^{-3}+92*10^{-3}*MAT)*age)$	Poeplau et al. (2011)
Grassland (no change)	$SOC_{t0}+(0.15-(dMAT*0.05))$	Chang et al. (2015); Vleeshouwers and Verhagen (2002)
Grassland to cropland	$SOC_{t0}*(1+((-40.98*0.13*clay+0.39*depth-1.05*MAT)*[1-exp(-age/3.35)]))$	Poeplau et al. (2011)
Grassland to forest	$SOC_{t0}*((1.31–23*10^{-3}*depth-0.15*MAT+12*10^{-3}*clay)*(age-73*10^{-4}*age^{2}))$	Poeplau et al. (2011)
Forest (no change)	$SOC_{t0}+(0.22-(dMAT*0.05))$	Luyssaert et al. (2010); Vleeshouwers and Verhagen (2002)

Note: depth (0.5*horizon thickness, cm), age (time after land use change, years), MAT (mean annual temperature, °C), clay (clay content, %), dMAT (difference of MAT between that and the previous year, °C), SOC_{t0} (soil organic carbon stock in reference year).

material, section B) reveals that the key soil properties used as input parameters for current assessments are organic matter content, soil texture, bulk density, stone content, soil depth and pH-value. Soil texture, stone content and soil depth have been identified as being rather stable over time and are not prone to changes in climate and land use over decadal time periods (if soil erosion processes are not considered) (Baveye et al., 2016). More relevant for soil functions' dynamics are the organic matter content, bulk density and pH-value. These "manageable soil properties" (Dominati et al., 2010, p. 1863), also known as "functional soil characteristics" (Vogel et al., 2018, p. 86) are sensitive to shifts in climate and land use and are therefore critical for assessing potential impacts of a changing environment on soil functions.

Soil organic matter, and therefore SOC as being one of its major components (see supplementary material, section C.1), is particularly sensitive to climate and land use change (Madena et al., 2012). It responds to aboveground biomass retention or removal, type of organic inputs into the soil, tillage as well as turn-over and temperature-dependent decomposition rates (Garcia et al., 2018; Jungkunst, 2019; Smith, 2012). Furthermore, SOC is represented in each soil function (Masciandaro et al., 2018) and is either a direct or an indirect input for all of the reviewed SFAs. In order to become dynamic, the selected static SFA (see section 2.2.1) is supplemented by a module to simulate the time- and location-specific development of SOC stocks under climate change and changing or stable land use, using the carbon response functions (Table 3) introduced by Poeplau et al. (2011).

The functions are limited to SOC developments in topsoil (i.e. <30 cm), as Poeplau et al. (2011) have not found significant changes in subsoil organic carbon resulting from climate or land use changes.

Relative changes in topsoil organic carbon stocks were simulated on a yearly basis for the case-study region and a period of 83 years, i.e. from the reference year 2017 until 2100. To do so, the carbon response functions were parameterized with spatially explicit SOC stock estimates for the reference year. For SOC stock estimation PTFs are applied to primary soil properties (i.e. SOC content, bulk density, stone content and topsoil depth) as derived from the original soil data.

The carbon response functions of Poeplau et al. (2011) were adapted to meet the needs of the case-study application. Adaptations were based on methodology put forward in the refined guidelines of the Intergovernmental Panel on Climate Change (IPCC) for National Greenhouse Gas Inventories (IPCC, 2019a). For simulating SOC stock change for land use conversions from cropland to grassland, we assume a symmetric development compared to conversions from grassland to cropland by multiplying the original term (grassland to cropland) with −1 (as suggested by Poeplau (2020) in personal correspondence). This is reasonable due to the fact that the original trajectory simulates an increase in SOC stock by 128 ± 23% (cf. Poeplau et al., 2011), which is implausible for SOC sequestration in grasslands of the Mostviertel region. We further replace carbon response functions for land use change by the respective no-change functions, 20 years after the land use change was implemented (i.e. in 2037). The large divergence between a 20-year period assumed by the IPCC (2019a) for SOC stock change induced by land use conversions and a period of up to 200 years for new SOC equilibria to be reached as suggested by Poeplau et al. (2011), have led us to this decision. For results based on Poeplau et al. (2011) and further discussion, we refer to section 4.1 and Fig. D1 in the supplementary material.

The simulated relative changes in SOC stock served for final estimation of SOC stock in 2100 and for reassessing soil functionality, i.e. to come up with the dynamic SFA. The dynamic SFA was applied to cropland and grassland soils. Forest soils were included in the simulation of SOC stock dynamics only. Data from the global soil organic carbon map (V1.5.0; FAO, 2019) with a 1 km grid resolution were implemented in the forest carbon response functions (as data available from eBOD dataset is limited to agricultural land only).

3. Results

3.1. *The current state of soil functions in the Mostviertel region*

The static SFA provides spatially explicit results for the five chosen soil functions for cropland and grassland soils in the Mostviertel region under current land use, climate and soil conditions for the reference year 2017 (Fig. 2). Regarding the nutrient storage function, 93% of cropland and 97% of grassland soils are attributed good to very good functionality. Poorest functionalities are found in soils towards the North of the study region and those formed on the quaternary alluvium in the West of the Mostviertel (cf. supplementary material, Fig. A1a). Levels of soil water regulation do not show a decisive spatial pattern. Distribution of very good to very poor functionalities are rather similar on cropland and grassland soils. Around 70% of both cropland and grassland soils are assigned good or moderate functionality. Twenty percent of grassland soils but only 13% of cropland soils are found in the category "very good". Again, soils located in the far West of the study region are those with the poorest performance. The spatial pattern of soil functionality in terms of productivity is similar to that found for the nutrient storage function.

Around 75% of cropland and 80% of grassland soils are assigned very good productivity levels. Whereas levels of soil functionality in nutrient storage, water regulation and productivity coincide regarding cropland and grassland soils as well as spatial distribution, soil habitat function and carbon sequestration functions show different patterns. Habitat functionality on cropland soils is rather poor, with 20% of them assigned moderate, 45% assigned poor, and 25% assigned very poor functionality. On grassland soils, 14% are assigned very good, 36% good and 30% moderate functionalities, whereas only 6% are attributed poorest

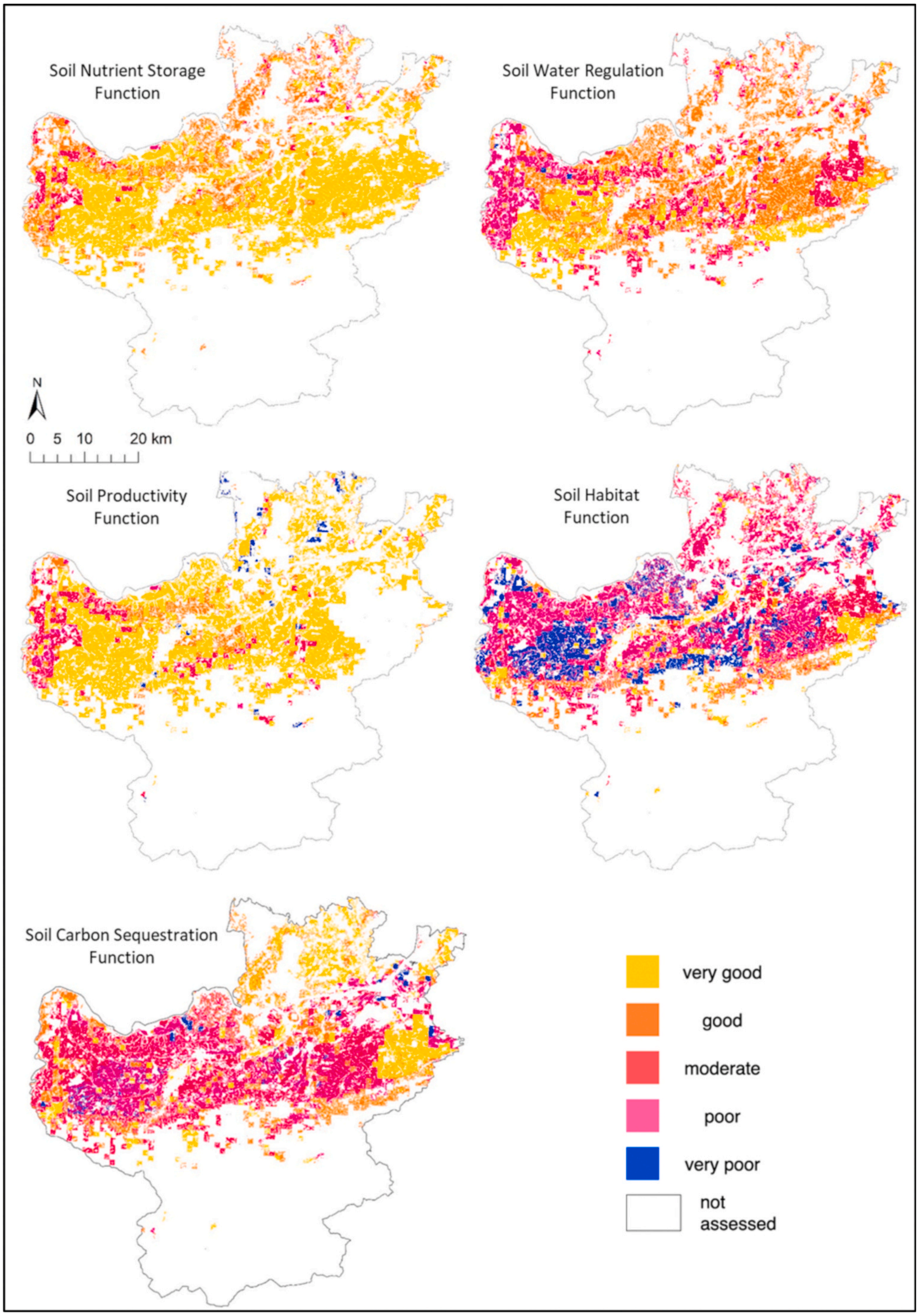

Fig. 2. Estimated levels of soil functionality at the field scale for cropland and grassland soils in the Mostviertel region in 2017. Own compilation, based on SFA results using soil data (eBOD) and land use data (IACS/CORINE).

functionality. The soil carbon sequestration function ranks lowest throughout the region's centre, which indicates currently low carbon saturation. The level of carbon saturation seems to be higher in topsoils under grassland, whereas cropland soils in the central Mostviertel could sequester additional carbon from the atmosphere. Around 70% of cropland soils are assigned moderate to very poor functionality regarding carbon sequestration (compared to 57% of grassland soils). These assigned levels indicate an additional carbon sequestration potential between 4.7 and 9 kg m^{-2}. Further information regarding the current state of soil functions on crop and grassland soils can be found in the supplementary material (Fig. D3).

3.2. Development of soil organic carbon over time

The results of the applied carbon response functions show steadily increasing total regional SOC stocks over the course of the century, i.e. the soils in the Mostviertel region function as a carbon sink under all land use and climate scenarios (Fig. 3a). Yet, differences in the amount of sequestered SOC become apparent among the LBA, LSH and LSP scenarios. Calculated SOC stocks amount to 28.4 Mt in 2017 and increase to 31.8 Mt (RCP4.5) in 2100 under LBA, to 32 Mt (RCP4.5) under LSH, and to 32.2 Mt (RCP4.5) under LSP. Differences in the calculated SOC stock values for the two climate scenarios are small (0.07–0.17 Mt; see Fig. 3a).

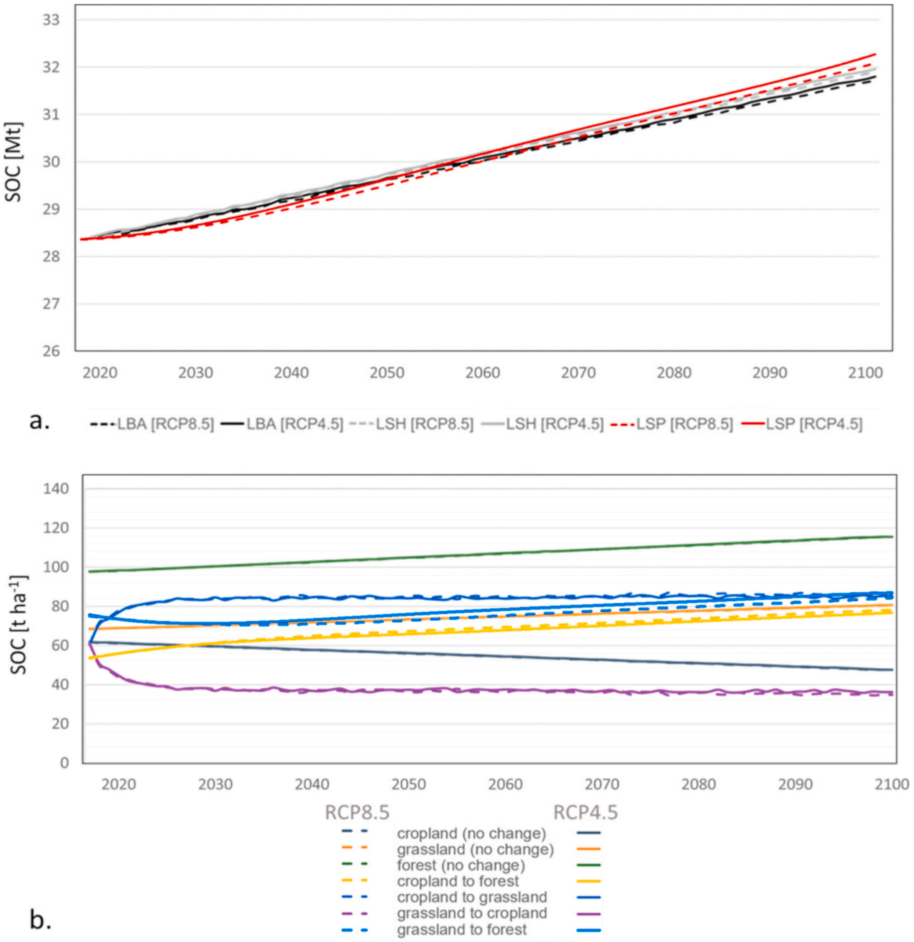

Fig. 3. Carbon dynamics of a. total regional SOC stock and b. mean SOC in topsoil (<30 cm) by land use and climate scenarios (2017–2100). Values for b are aggregates over all three land use scenarios for each land use conversion.

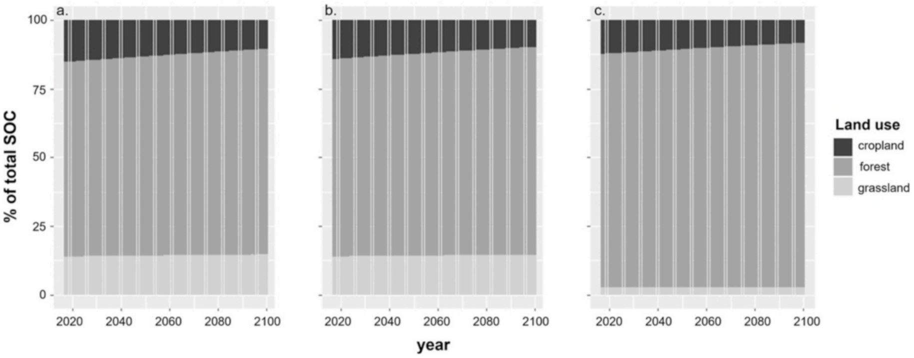

Fig. 4. Relative contribution [%] of land uses to the total regional SOC stock in the Mostviertel region by the land use scenarios a. LBA, b. LSH, c. LSP and the climate scenario RCP4.5 until 2100 (after land use conversion).

According to the calculations, cropland soils in the Mostviertel store around 4.3 Mt SOC (15.3% of total SOC stock) in 2017. SOC stocks in grassland soils amount to 4.5 Mt (15.9% of total SOC stock), and forest soils have SOC stocks of 19.6 Mt (68.8% of total SOC stock). The contribution to SOC stocks considering land use changes is displayed in Fig. 4 until 2100. Changes in contributions modelled until 2100 are very similar between the LBA and LSH scenarios. Cropland soils' contributions are estimated to decrease to 10.6% (LBA) and 9.8% (LSH) in 2100 under RCP4.5, even though total cropland area declines by only 1% in both land use scenarios. The contribution of forest soils increases to ≈75% in LBA and LSH in 2100, whereby LBA and LSH assume that forests cover 43% and 42% of the total area, respectively. Contribution of grassland increases by 1 percentage point (LBA and LSH), even though total grassland area decreases from 21% to 18% of the total area in LBA, and from 21% to 20% in LSH until 2100. Modelled changes in SOC in LSP reduce contributions of croplands in 2100 to 8.4%, of grasslands to 2.8% and increase those of forests to 88.8% in 2100.

Fig. 3b visualizes the development of modelled regional mean SOC stocks in topsoils (<30 cm) of the Mostviertel for the different land use conversions induced by the respective land use scenarios. The calculated mean initial SOC stocks are 63.4 t ha^{-1} in croplands and 69.2 t ha^{-1} in grasslands. The mean SOC stock in forest soils is comparatively high

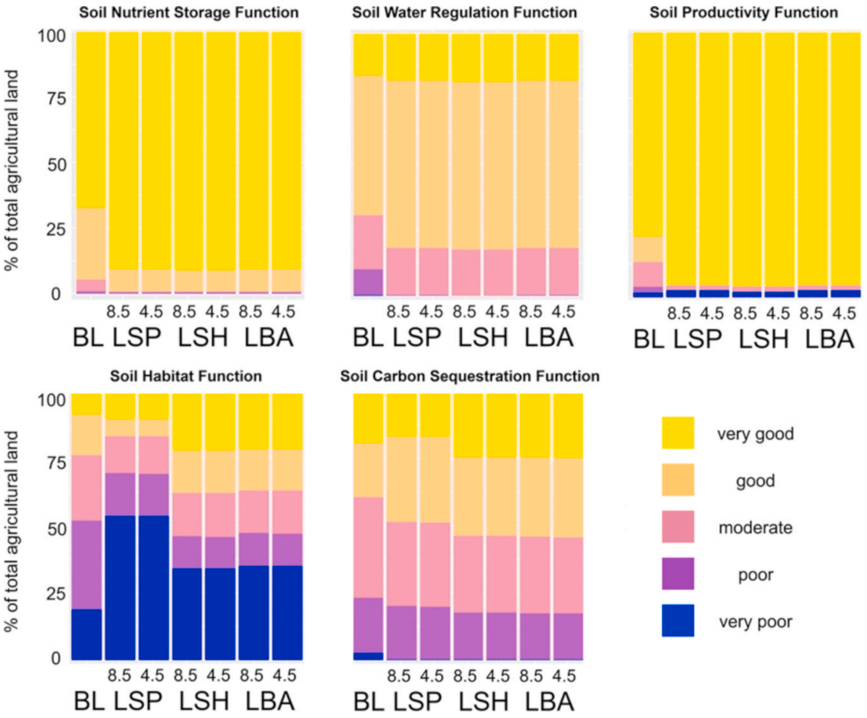

Fig. 5. Levels of soil functionality in the reference year 2017 (BL) and in 2100 by land use (LBA = balanced, LSH = land sharing, LSP = land sparing) and climate scenarios (RCP8.5, RCP4.5).

with roughly 97.6 t ha^{-1}. Conversions from cropland to grassland (grassland to cropland) lead to a rather rapid increase (decrease) of SOC stocks in topsoils during a period of about 10 years until a new equilibrium is reached. Land use conversions from grassland to cropland drive the largest decreases in mean SOC stocks until 2100 by ≈ -25 t ha^{-1}. Except for areas turned into or remaining cropland, all other investigated land use changes result in a slow increase of mean SOC stocks. This increase is largest in soils subject to conversions from cropland to grassland. Note that afforestation on previous grassland leads to an initial decrease of SOC stocks but results in an overall increase until 2100. For conversions from agricultural land use to forest only SOC changes in the mineral soil are considered (forest floor not included). Yet small, climate scenario impacts on SOC stocks are largest on soils turned from grassland to forest resulting from mean annual temperature changes in the calculation. For grassland converted to forest, SOC changes by ≈ 12.4 t ha^{-1} under RCP4.5 and ≈ 9.6 t ha^{-1} under RCP8.5 between 2017 and 2100.

3.3. *Temporal dynamics of soil functions*

The changes in SOC stocks calculated via the carbon response functions indicate the land use and climate change induced impacts on soil functionality in the Mostviertel region. Fig. 5 illustrates changes in levels of soil functionality between 2017 and 2100 by land use (LBA/LSH/LSP) and climate scenario (RCP8.5/RCP4.5). Lighter colours (yellow) symbolize good functionality and darker ones (blue) indicate poor functionality.

Results from this dynamic SFA show that soil functions of nutrient storage, water regulation and productivity can increase their quality over time due to an overall increase of SOC. Yet, they do not show any difference among land use or climate scenario if assessment results are aggregated across agricultural soils (i.e. cropland and grassland soils) in the Mostviertel. Regarding nutrient storage 67% of agricultural soils in the Mostviertel region reach highest ranks (very good), 28% are attributed rank 2 (good), 4% reach rank 3 (moderate), and only 1% is assigned rank 4 (poor), whereas none is attributed lowest (very poor) ranks in the 2017 reference year. Simulated changes in SOC lead to overall improvements of the soils' nutrient storage function until 2100, resulting in 99% of soils in the Mostviertel being attributed good or very good functionality. Also water regulation and productivity functions of soils are estimated to improve until 2100. The share of soils, which reach rank 1 (very good) or 2 (good) in terms of water regulation increases from 69% in 2017 to 82% in 2100. For productivity, only 5% of soils remain with moderate, poor or very poor functionality compared to 14% in 2017.

The combined effects of climate and land use change scenarios result in an increased share of agricultural soils being attributed a very good habitat functionality (between +1.8 and + 13.3 percentage points compared to 2017), as well as an increased share of agricultural soils being attributed very poor habitat functionality (between +15.5 and + 34.9 percentage points compared to 2017). The magnitude of change differs by land use, yet not by climate scenario. A closer look at grassland and cropland soils (see supplementary material, Fig. D3) reveals that especially cropland soils are affected by an increased share of assigned very poor habitat functionality (+37.4 to +38.3 percentage points compared to 2017). By contrast, grassland soils contribute to an increased habitat functionality. The potential of soils to sequester additional amounts of carbon decreases in all scenarios as indicated by a larger share of soils with good and very good functionality (2017: 39.2%; LBA: 53.9% (RCP8.5)/54.2% (RCP4.5); LSH: 53.5% (RCP8.5)/ 53.8% (RCP4.5); LSP: 48.4% (RCP8.5)/48.7% (RCP4.5)). The difference between LSP and the other land use scenarios indicates the stronger depletion of SOC on a larger share of agricultural land in the LSP approach.

Apart from the information on changes in soil functions on the aggregated scale of the Mostviertel region, the assessment provides insights on where those changes occur (see supplementary material, Fig. D2). The spatial heterogeneity of increases and decreases in levels of soil functionality becomes apparent.

4. Discussion

4.1. Impact of land use and climate change on soil organic carbon and soil functions

This study shows the impact of land use and climate change on soil functionality based on simulated developments of SOC in cropland and grassland topsoils in the Mostviertel region. The temporal changes in SOC stocks indicate most rapid accumulation and depletion for land use changes from grassland to cropland and vice versa. This corresponds to findings from Smith (2008), who identifies fastest SOC losses when grassland or forest are converted into cropland, due to limited and labile input of above-ground biomass as well as more intensive soil disturbance in cropland management. Similarly, the model results presented by Skalský et al. (2020) show that land use change towards cropland negatively affects SOC stocks in Slovakia. In our case, the larger cropland area under LSP (compared to LSH and LBA) leads to stronger SOC depletion but is offset by forest soils representing 57% of the regional area and serving as carbon sink. The simulated steady decrease of SOC in Mostviertel cropland soils may change if more details on organic carbon inputs were included in the carbon response functions. For Central-European cropland it has been shown that SOC stocks can be maintained or even increase over long periods of time, depending on type and amount of inputs from plant residues or manure (cf. Skalský et al. (2020). For Austria, previous analyses have shown that organic matter contents in topsoils of cropland were increased by 0.2–0.4% within a period of 15 years, mainly because of widespread implementation of soil conservation measures promoted through the Austrian agri-environmental program (BMLFUW, 2015; Freudenschuβ, 2010).

With regard to grassland, mean SOC stocks in topsoils (Fig. 3b) are estimated to reach 80.6 t ha^{-1} (grassland no-change) and 85.2 t ha^{-1} (cropland to grassland) towards the end of the 21st century. Simulations indicate that mean SOC stocks in Mostviertel grassland soils still outreach those in the mineral topsoil layer in grasslands or croplands converted to forests under the investigated scenarios. Simulated changes of SOC stock for grassland converted to forest reflects an initial short-term decrease of SOC in the topsoil. This concurs well to findings from Anderl et al. (2020) and BMLFUW (2015), which confirm that mineral soils, which are converted from grassland to forest land use, represent a carbon source in Austria. If managed extensively, Austrian grasslands can store significant amounts of SOC, with 104 t ha^{-1} in the upper 30 cm compared to 106 t ha^{-1} in the upper 50 cm of mineral soils in forests (Gerzabek et al., 2005; Weiss, 2000). Based on measured data, Martin et al. (2011), Meersmans et al. (2008) and Wiesmeier et al. (2019) also argue that SOC storage in topsoil increases in the order cropland < forest < grassland in temperate zones. Differences between the presented results and findings in the literature may be explained by study site properties such as soil type, climate conditions, grazing regimes, type of forest, species composition or management (Garcia et al., 2018; Smith et al., 2016). If both, litter overlying the mineral soil, and mineral topsoil organic carbon contents were to be considered, forest SOC would most probably outnumber stocks under grassland usage across all simulated trajectories, as forest soils have been estimated to build the main carbon reservoir in Austria (BMLFUW, 2015).

The diverging trend among SOC development on cropland and grassland, resulting in SOC stock differences of roughly 40 t ha^{-1} in 2100, can be explained by the data used to derive the respective carbon response functions. Poeplau et al. (2020) find a 30% difference in the amount of SOC stored in grassland compared to cropland soils, which reflects assumptions in international guidelines (IPCC, 2019a) and also average conditions in Austria (Haslmayr et al., 2018). The 10% difference between SOC stocks of Mostviertel grassland and cropland soils in the reference year of 2017 resemble data for Lower Austria (cf. Haslmayr et al., 2018). However, compared to findings from other regions (e.g. Poeplau et al. (2020) SOC stock changes may be overestimated for prevalent conditions in the Mostviertel region.

While the impacts of land use change on SOC are evident, projected impacts of rising temperatures until 2100 are negligible and become cumulatively apparent only towards the end of the century (Fig. 3a), where temperature developments in the two considered climate scenarios show the largest spread (see supplementary material, Fig. A2). This concurs to model results on long-term developments of SOC stocks in Slovakia by Barančíková et al. (2014). Their SOC stock simulations considering two climate scenarios show diverging trends only around the year 2080. Regarding the dominance of land use in comparison to climate on the development of SOC found in the Mostviertel region, diverging opinions exist within current literature. While Wiesmeier et al. (2019) and Skalský et al. (2020) conclude that land use is indeed most influential, Rial et al. (2017) find climate to be the main driver of SOC dynamics. For sites in Switzerland, González-Domínguez et al. (2019) find that soil moisture and temperature variables have only a minor influence on SOC dynamics at the regional scale. They however stress physico-chemical soil properties and landform to be key drivers. Diverging conclusions might be the result of different analytical procedures and scales, assumptions on climate change and other regional differences in natural and socio-economic drivers of SOC dynamics (see section 4.4).

The impact of land use and climate change on soil functions is shown for the year 2100, taking into account the simulated SOC development on agricultural land. The relative importance of SOC for individual soil functions becomes obvious. While the performance of soils regarding their nutrient storage, water regulation and productivity functions show a rather uniform reaction, differing impacts of land use scenarios on soil functionality are most visible for the soil habitat and carbon sequestration functions. For example, LSH supports the advantageous characteristics of grassland (compared to cropland) for habitat provision and SOC storage as supported by Smith (2008) and Spurgeon et al. (2013).

4.2. Implications for land use planning

Results of static SFAs typically inform land use planning, such as observed in Austria. However, they may mislead involved stakeholders to believe that soil functionality remains stable over time. By integrating the dynamic feature of projecting SOC over a timespan considered relevant, it becomes clear that future development of soil functionality indeed depends on type, extent, and location of imposed land use decisions. The presented results support conclusions drawn by Robinson et al. (2017) and highlight that land use planning shall consider future dynamics of soil functionality in order to enhance sustainable development.

The integration of dynamic SFAs into land use planning processes seems reasonable to stimulate soil-sensitive decision-making. The approach highlights the multi-dimensional impacts of land use decisions on the soil resource over time. It reinforces that a static, mono-functional consideration of soils in planning processes is short-sighted and may lead stakeholders to disregard the “bigger picture” (Techen and Helming, 2017). The dynamic SFA enables coupling environmental goals set at higher scale, e.g. climate change mitigation, with their implications for actions to be taken at the subordinate scale, e.g. land use planning within regional boundaries and vice versa. For example, if regional authorities in the Mostviertel push to increase regional food production through expansion of cropland on the fertile soils, the results of the dynamic SFA highlight the trade-offs for carbon sequestration. The results show that soils dedicated to crop production lead to SOC decreases and can thus hardly contribute to climate change mitigation. Planning authorities making use of the dynamic SFAs can both qualitatively and quantitatively discuss potential implications of suggested measures. For instance, they can take informed decisions on allocating compensation areas to offset negative environmental effects of actions taken in one place (Caprioli et al., 2021).

The approach further highlights that decisions on land use planning should not be taken by local, regional or superordinate authorities alone, but should involve a large array of actors (González-García et al., 2020) including individual land managers and farmers, who have a significant influence on whether overall long-term environmental goals can be met. The dynamic SFA can enrich multi-level stakeholder discussions on future land use and helps to visualize potential contributions of different land use strategies to climate change mitigation or habitat provision (Techen et al., 2020).

Land use planning should explore possible futures of land use and climate and their impacts in order to stabilize or even enhance soil functionality in a strategic and site-specific manner such that societal and environmental goals can be met (Cebrián-Piqueras, 2019; Cook et al., 2014). The proposed dynamic SFA is a step forward in this direction.

4.3. Lessons learned for LSH and LSP

The LSP scenario has a bi-directional effect regarding the development of SOC from a regional perspective. Firstly, it results in a large increase of forested land, which steadily accumulates SOC in its mineral soil. Secondly, almost all previous grassland areas are lost to forests, which eventually leads to a decrease of SOC stocks in the remaining agricultural area. Insights from the LSH scenario reinforce evidence on the value of grassland for likely increases in soil microbial biomass, as indicated by a larger share of soils attributed good or very good habitat functionality. Coyle et al. (2016) state that large scale conversions from grassland to forest should be prevented due to an induced loss of below ground habitats. This and the fact that landscape diversity will be reduced under LSP, supports Fischer et al. (2012) in their argument that LSP leads to the loss of agrobiodiversity and traditional landscapes, which should be accounted for in land use decisions.

Furthermore, our results support questions of scale regarding the implementation of LSP and LSH in land use planning. Implementing LSP at large regional scales might lead to unfavourable conclusions in the context of sustainability as Hagemann et al. (2020) have stated. The spatially explicit visualization of increases and decreases in levels of soil functionality due to changes in land use (supplementary material, Fig. D2) shows that effects are indeed heterogeneous at the local scale and are highly dependent on underlying biophysical conditions. Moreover, temporal scales of analysis are considered important as well (Phalan (2018), which is confirmed by the assessment of regional SOC stocks in the Mostviertel under LSP and LSH. More specifically, the effect of alternative land use strategies on SOC sequestration differ if short or long periods of time are considered for analysis. The time for SOC sequestration (e.g. maintaining land use vs. conversion; see Fig. 3b) or for saturation effects in SOC stocks to be reached, differs greatly among land uses. Depending on the posed research questions and societal objectives (rapid sequestration or long-term storage and accumulation), different time periods need to be chosen for analysis to provide adequate answers and to draw adequate conclusions in land use planning.

Coupling the LSH and LSP strategies with a range of soil functions additionally supports a wider debate on LSP and LSH beyond aspects of food production and biodiversity. It enables to take other ecosystem services and functions into account and thereby prevent undesirable and otherwise overlooked effects (Grau et al., 2013).

4.4. Methodological considerations and outlook

The main advantage of the carbon response functions applied in this study is their incorporation of land use and climate variables into empirical rules that correspond to the pedotransfer functions generally applied for SFA. However, uncertainties with respect to dynamic SFAs remain. For instance, the applied carbon response functions subsume various management practices within one land use, even though agricultural management has been identified as highly influencing both SOC developments (Garcia et al., 2018) and soil functions dynamics (Hamidov et al., 2018). Furthermore, the applied carbon response functions ignore changing precipitation regimes and humidity conditions. The coupled effects of temperature and precipitation developments drive decomposition rates (cf. Gottschalk et al., 2012) and would most probably lead to more pronounced differences between SOC developments under RCP4.5 and RCP8.5. What adds to the dominant impact of land use drivers on soil functionality over climate variables, is the consideration of mean annual temperature values entering the SFA as a function of individual land use change types. However, Goidts et al. (2009), who explored the driving forces of SOC change by cluster and multiple regression analyses, support our methodological assumptions. They find that SOC change induced by altered climate conditions can have a diverging trend whether on cropland or grassland, meaning that climate impacts on SOC dynamics indeed depend on land use type.

We acknowledge factors controlling SOC dynamics to be scale-dependent and subject to a particular “hierarchy of controls” (Manning et al., 2015, p. 1189). Wiesmeier et al. (2019) find that land use drivers show largest effects on SOC dynamics at the regional scale and that the effect of climate increases with scale. The relative weight of environmental drivers on changes in SOC differs with functional complexity among individual soil properties, i.e. associated spatial heterogeneity and temporal variability (Lehmann et al., 2020). Accordingly, our results need to be interpreted for the specific region and do not claim universal validity. They may hold true for the case-study context only and are a direct function of the data and methodology employed.

Methodological limitations of the presented study might be overcome by the development of locally calibrated SOC response functions or the application of a more sophisticated bio-physical process model. This would increase complexity as well as data requirements but would allow for a more detailed representation of agricultural management and soil processes. It could also advance scientific discussions on the dichotomy of LSP and LSH in intensive and extensive management systems. More complex biophysical SOC-process modelling would further require the incorporation of water availability, soil erosion processes and inputs of above-ground plant biomass to soil, all affecting SOC development in the mineral soil and depending on the regional specificities. There is always a challenge to find a balanced level of abstraction for the representation of natural systems in data, maps, or models, which might impair the accuracy of derived results. Yet, certain simplification and aggregation is necessary with regard to data acquisition, data handling and computational efforts (Papadimitriou, 2020).

The SFA methods and data applied for this study, limit the scope of the assessment to agricultural soils. High resolution forest soil data is currently not available. The inclusion of forest soils in the assessment would require the consideration of an alternative soil data source, and the adjustment of the pedotransfer functions and evaluation schemes for forest soil functions (Greiner et al., 2018).

Baveye et al. (2016), Calzolari et al. (2016) and Greiner et al. (2017) have outlined that SFAs are generally accompanied by a wide range of uncertainties, which stem from certain levels of subjectivity in the selection of indicators of soil functionality and their ranking regarding the fulfilment of a certain soil function. Lacking monitoring or experimental data for the region does not support in-depth validation. However, using harmonized national soil data as well as the application of well-established SFA methods and indicators, and the reliance on calibrated pedotransfer functions for the study context allow to manage these uncertainties.

Finally, the presented approach could be further complemented by analyses on the societal demand for soil functions (Schulte et al., 2019; Staes et al., 2018) imposed by food security, biodiversity conservation, nutrient management, water quality or climate change mitigation at local to global scales. These societal demands shall be considered as dynamic as well and shifts in weights among different soil function can be expected. The dynamic soil functions assessment may improve the ex-ante evaluation and impact assessment of alternative land use strategies under changing climate conditions.

5. Conclusions

Soil function assessments extend the information basis for land use planning from the current focus on productivity to a comprehensive understanding of soil functionality. We propose the dynamic SFA to enrich land use decision making by integrating climate and land use specific projections of SOC, which are of high future relevance. Our analysis shows the dominance of land use compared to climate drivers on SOC developments in the Mostviertel region until the end of the century and how these lead to changes in soil functions. In terms of LSH and LSP, the dynamic SFA suggests that such strategies should be discussed in a broader context including their effects on nutrient storage, water regulation and carbon sequestration beyond agricultural production and biodiversity. While the regional implementation of a LSP strategy leads to higher accumulation of SOC in mineral soils in the Mostviertel and can be considered more valuable for climate change mitigation, LSH supports the provision of below-ground habitats on agricultural land. However, these results are sensitive to the underlying biophysical conditions of where a certain land use is implemented.

Author contribution

Elisabeth Jost: Conceptualization, Methodology, Formal analysis, Writing – original draft, Martin Schönhart: Conceptualization, Methodology, Writing – review & editing, Rastislav Skalský; : Methodology, Writing – review & editing, Juraj Balkovič: Writing – review & editing, Erwin Schmid: Conceptualization, Methodology, Writing – review & editing, Supervision, Hermine Mitter: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Research was kindly supported by the BiodivERsA/FACCE-JPI project “Towards multifunctional agricultural landscapes in Europe (TALE)” funded by the Austrian Science Fund (FWF): I 2046-B25. Additional funding was provided by the “Sustainable nitrogen management under climate change (NitroClim.AT)” project, which is part of the Austrian Climate Research Programme (ACRP). Work of Rastislav Skalský and Juraj Balkovič was funded by the CIRCASA project (774378 – CIRCASA – H2020-SFS-2016-2017/H2020-SFS-2017-1). Open access funding provided by University of Natural Resources and Life Sciences Vienna (BOKU).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112318.

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