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A model-based carbon inventory for Switzerland's mineral agricultural soils using RothC

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Summary

A model-based soil organic carbon (SOC) inventory system for mineral soils with permanent grassland and with cropland in Switzerland has been developed. Since 2019, it has been used for national greenhouse gas (GHG) reporting under the United Nations Framework Convention on Climate Change (UNFCCC). The inventory system also serves as a tool to estimate soil carbon (C) sequestration potential, to explore the sensitivity of SOC to environmental conditions or management and to project future SOC changes. The inventory system is based on the SOC model RothC and incorporates management of the 19 most important crops and six agricultural grassland categories, accounting for residue management, cover crops and manure applications. The RothC model is tested using measured data from eight long-term Swiss experiments and outperforms three other models of similar complexity. An allometric equation, adapted to measurements made in Switzerland, is used to derive the amount of plant C inputs to the soil based on annual yields. Meteorological data are derived from the Swiss meteorological service. The clay content of the soil is roughly estimated based on a soil suitability map. To calculate initial SOC stocks, an approach that relates SOC stocks to clay content, elevation and land use type is used. The sizes of the different C pools in the RothC model are estimated using a pedo-transfer function, which proves to be a good alternative to spin-up estimations (i.e. use of a model simulation until a steady state is reached). Upscaling to the national level is carried out by stratifying the country into 24 regions with similar climatic conditions and agricultural production types. An uncertainty analysis (UA) based on Monte Carlo simulations reveals that the average relative uncertainty of annual SOC stock changes was greater than 100 percent for the years 1990 to 2018, for both cropland and permanent grassland. This is due to uncertainty in the input data as well as the coarse spatial resolution of the simulations. This indicates that on a national scale, mineral agricultural soils in general cannot be considered a statistically significant C sink or source.

Zusammenfassung

Es wurde eine modellgestützte Inventarisierung des Bodenkohlenstoffs (Boden-C) für mineralische Böden von Ackerland und Dauergrünland entwickelt. Dieses Inventarisierungssystem wird seit 2019 für die nationale Berichterstattung zu den Treibhausgasen (THG) im Zusammenhang mit der Klimarahmenkonvention der Vereinten Nationen (UNFCCC) eingesetzt. Es kann auch als Werkzeug zur Abschätzung des Potentials der Boden-C-Sequestrierung, zur Analyse der Abhängigkeit des Boden-C von Umweltbedingungen oder zur Prognose der Boden-C-Entwicklung verwendet werden. Das System beruht auf dem Boden-C-Modell RothC und berücksichtigt Daten zur Bewirtschaftung der wichtigsten 19 Ackerkulturen- und 6 Graslandkategorien. Es werden namentlich Daten zu Ernterückständen, zur Gründüngung und zum Einsatz von Düngern einbezogen. Das Modell wurde mittels Daten aus acht schweizerischen Langzeitversuchen getestet und übertraf drei Modelle ähnlicher Komplexität. Es wird eine mit Messungen in der Schweiz abgestimmte allometrische Funktion verwendet, um auf der Grundlage der gemessenen jährlichen Erträge der wichtigsten Kulturen die C-Einträge in den Boden durch Pflanzen zu bestimmen. Die meteorologischen Daten werden von Meteoschweiz bezogen. Der Tongehalt des Bodens wird anhand einer Bodeneignungskarte grob abgeschätzt. Zur Berechnung der anfänglichen Boden-C-Vorräte werden Tongehalt, Höhenlage und Landnutzungstyp berücksichtigt. Die Grösse der einzelnen C-Pools im Modell RothC wird mithilfe einer Pedotransferfunktion berechnet. Dieser Ansatz hat sich als gute Alternative zur Schätzung durch Spin-up (Simulation bis zum Erreichen eines Gleichgewichtszustandes) erwiesen. Für die Hochrechnung auf die gesamtschweizerische Ebene erfolgt eine Schichtung der gesamten Fläche in 24 Regionen mit ähnlichen klimatischen Bedingungen und Bewirtschaftungsarten. Eine Unsicherheitsanalyse basierend auf Monte-Carlo-Simulationen zeigt, dass die mittlere relative Unsicherheit der jährlichen Änderungen der Boden-C-Vorräte in den Jahren 1990-2018 sowohl für Ackerland als auch Dauergrünland grösser ist als 100 %. Die Unsicherheit lässt sich sowohl auf die Inputdaten als auch auf die grobe räumliche Auflösung der Simulationen zurückführen. Dies deutet darauf hin, dass mineralische landwirtschaftliche Böden im Allgemeinen auf nationaler Ebene keine statistisch signifikante C-Quellen oder C-Senken sind.

Resumé

Nous avons développé un inventaire, basé sur un modèle du carbone organique des sols (COS), pour les sols minéraux situés sous les prairies permanentes et les terres cultivées en Suisse. Il est utilisé depuis 2019 au titre de la Convention-cadre des Nations unies sur les changements climatiques (UNFCCC) dans les rapports nationaux de gaz à effet de serre. Ce système d'inventaire sert également à estimer les potentiels de séquestration du carbone dans le sol, à explorer la sensibilité du COS aux conditions environnementales ou au mangement environnemental et à projeter les futurs changements du COS. L'inventaire repose sur le modèle de carbone du sol RothC et intègre la gestion des 19 cultures les plus importantes et de 6 catégories de prairies agricoles en tenant compte de la gestion des résidus, des cultures de couverture et des applications d'engrais. Le modèle RothC a été testé en utilisant les données mesurées dans le cadre de huit essais longue durée suisses, et a surpassé trois autres modèles de complexité similaire. Une équation allométrique, adaptée aux mesures faites en Suisse, est utilisée pour quantifier l'apport du carbone des plantes dans le sol à partir du rendement annuel des cultures principales. Les données météorologiques proviennent du service météorologique suisse. La teneur en argile du sol est grossièrement estimée à partir de la carte des aptitudes des sols de la Suisse. Pour calculer les stocks initiaux de COS, nous utilisons une approche qui relie les stocks de COS à la teneur en argile, l'altitude et le type d'utilisation des sols. La taille des différents réservoirs de carbone du modèle RothC est estimée en utilisant une fonction de pédo-transfert, qui s'est avérée être une bonne alternative à l'estimation par simulation jusqu'à atteindre un état d'équilibre («spin-up»). Pour les simulations à l'échelle nationale, le pays est divisé en 24 régions homogènes présentant des conditions climatiques similaires et des types de production agricole semblables. Une analyse d'incertitude basée sur des simulations par Monte Carlo révèle cependant que l'incertitude relative moyenne des stocks annuels de COS est supérieure à 100% pour les années 1990-2018, pour les terres cultivées comme pour les prairies permanentes. L'incertitude est due à l'incertitude des données d'entrée ainsi qu'à la résolution spatiale grossière des simulations, ce qui indique qu'à l'échelle nationale, les sols agricoles minéraux en général ne peuvent pas être considérés comme puits ou source de carbone.

Abbreviations

AEI	agri-environmental indicators
AZ	agricultural zones (landwirtschaftliche Zonen / zones agricoles)
C	carbon
CC	combination category
CI	confidence interval
CL	the cropland category of sector 'Land Use, Land-Use Change and Forestry'
ET	evapotranspiration
FOAG	Federal Office for Agriculture (Bundesamt für Landwirtschaft / office fédéral de l'agriculture)
FOEN	Federal Office for the Environment (Bundesamt für Umwelt / office fédéral de l'environnement)
FSO	Federal Statistical Office (Bundesamt für Statistik / office fédéral de la statistique)
FSS	farm structure survey (landwirtschaftliche Strukturerhebung / relevé des structures agricoles)
GHG	greenhouse gas
GL	the permanent grassland category of sector 'Land Use, Land-Use Change and Forestry'
LUS	land use statistics (Arealstatistik Schweiz / statistique Suisse de la superficie)
NFI	national forest inventory (Landesforstinventar / inventaire forestier national Suisse)
OrgAm	organic amendments
PDF	probability distribution function
PPN	precipitation
PTF	pedotransfer function
SFU	Swiss Farmers' Union (Schweizer Bauernverband / union suisse des paysans)
SIS	surface incoming shortwave
SOC	soil organic carbon
SPA	summer pasture area
SSM	soil suitability map (Bodeneignungskarte / aptitudes des sols de la Suisse)
TOC	total organic carbon
TSMD	topsoil moisture deficit
UA	uncertainty analysis
UAA	utilised agricultural area (landwirtschaftliche Nutzfläche / surface agricole utile)
VS	volatile solids

1 Introduction

Carbon and soils

Soils store more than twice the amount of C as the atmosphere and about four times as much as global aboveground vegetation (Batjes 1996; Sanderman et al. 2017). Changes in SOC stocks are therefore relevant for GHG budgets. In mineral soils, SOC losses are associated primarily with CO_2 emissions of soils and SOC gains are related to a removal of CO_2 from the atmosphere. Changes in SOC stocks can result from changes in land use, agricultural management or meteorological conditions and over the longer time-scale, thus also climate change.

Inventory / UNFCCC

As an Annex I party, Switzerland submits an annual GHG inventory calculating emissions and removals of all relevant GHGs at the national scale. As part of this inventory, changes in SOC stocks of agricultural soils are reported within the sector land use, land-use change and forestry. Until 2018, a simple approach was used to estimate changes in SOC stocks, namely a combination of a tier 1 and a tier 2 approach (i.e. method of low to intermediate complexity with few country-specific data/parameters). Since 2019 a tier 3 approach is used. The concept for this approach is described in Köck et al. (2013) and its implementation in the present report.

Particularities of the Swiss agricultural landscape

Swiss agriculture has a number of properties which need to be considered for the modelling of SOC at the country-wide scale. Firstly, Switzerland's topography is very diverse, from flat land in the central plateau and in wide mountain valleys, to hilly and mountainous regions. Agriculture is practiced across this gradient, for example managed grassland occurs between ca. 200 and 3000 m asl. Additionally, the topographic gradients in Switzerland can also be very steep, meaning that associated parameters (e.g. temperature) can vary significantly over small spatial scales. Secondly, agricultural management is also very diverse across the country, in part because the (diverse) landscape affects their management through financial, bio-physical or logistical constraints. Thirdly, individual farming practices are quite complex. For example, the vast majority of arable farms employ rotations (6-year crop rotations are typical, often including 2-3 years of grass-clover ley) and crop diversity is very high (section 2.2.5.1). Furthermore, there is a large range of management intensity of grasslands meaning that inputs to the soil (section 2.2.5.3) are very variable.

1.1 Scope

This project has established a system to model SOC stocks of agricultural mineral soils over permanent grassland (GL) and cropland (CL), for the upper 30 cm of soil. Annual SOC stocks are modelled for the years 1990 to present and from these, annual stock changes are calculated. SOC stock changes are estimated for CL remaining CL and GL remaining GL (see section 2.2.2.1 for a description of CL and GL). No land use changes are being modelled (e.g. CL to GL), because sufficient data to test or validate such simulations are lacking.

SOC stocks and dynamics are site-dependent, influenced by parameters that vary with location, including meteorological conditions and clay content. SOC simulatinos therefore need to be location-specific. Additionally, SOC dynamics are management-dependent as they are affected by, for example, fertilisation by organic amendments, or soil cover, themselves related to different crops and grassland categories. This means the simulation of SOC also has to be crop- / grassland-specific.

The model used in this project (RothC, see section 2.1.5) simulates SOC stocks for a single location (e.g. an experimental site or a field). To simulate SOC stocks at the national scale, these simulations need to be upscaled. In general, upscaling can be done either by using a raster-based approach, or by partitioning the region of interest into discrete surfaces with similar conditions and carrying out simulations for each of these. The spatial quality of data relevant to this project precludes the use of the former and it was decided to use a system of discrete surfaces to model the C stock changes (Köck et al. 2013). Such a method has also been applied by for the simulation of SOC stocks of several other countries (e.g. Denmark, Finland, Japan, Canada).

1.2 Aims

The aim of the project is to set up a model-based inventory of CO_2 sinks and sources for agricultural, mineral topsoils (0 to 30 cm) in Switzerland. Annual SOC stocks and stock changes of soils in the category CL remaining CL (including grass-clover leys) and GL remaining GL should be presented. This system should encompass the period since 1990 and should account for the diversity of Switzerland’s physical landscape and of its agricultural systems. Furthermore, the system should be flexible allowing for improvements and for changes in management to be incorporated. A UA should also be carried out to estimate the uncertainty associated with the system.

2 Methods

2.1 Model evaluation and selection

The first step in the development of a tier 3 model-based inventory is the selection or development of a model for the simulation of SOC stock changes. The model should be chosen with regard to the availability of input data and of computational resources. Based on 13 suitability criteria, four soil C models to be tested were selected by Köck et al. (2013): **RothC**, **Yasso07**, **CCB** and **C-TOOL**. Models were chosen that are applicable to cropland and permanent grassland and have at least annual resolution. Models that additionally simulate vegetation were not included, due to the large number of currently unavailable parameters necessary for this. Furthermore, models that have been widely used and proved to work satisfactorily under similar climatic conditions as in Switzerland were preferred.
The four selected models share several features. All models simulate SOC as different C pools with specific turnover rates. The decomposition of SOC follows first-order kinetics and depends on temperature and in all models except C-TOOL, it also depends on precipitation (PPN) or soil moisture. Only in RothC and CCB does soil texture (i.e. the clay content) have an influence on the turnover of soil C. In addition, whether the soil is bare or covered by plants affects decomposition in RothC. C-TOOL and Yasso07 have no inert C pool (i.e. a pool with a turnover of zero). All models treat C inputs from plant residues differently than inputs from organic amendments (OrgAm). The C of plant residues added to soil is allocated to short and medium turnover pools. The C of manure added is in part directly allocated to a slow turnover C pool. CCB is the only model that distinguishes between different types of OrgAm (different types of manure, slurry, compost, sewage sludge etc.). All models except CCB require annual amounts of plant C that is added to the soil (including roots, stubble, extra-root material from turnover and exudation) as input data. These data are rarely measured and therefore different equations, allometric functions, exist to calculate plant C inputs. Because SOC simulations strongly depend on the selected equation (Keel et al. 2017), six different allometric equations were selected for testing (section 2.1.2).
The performance of the four soil C models and the six allometric equations was evaluated for their potential application in the Swiss GHG inventory, using data from long-term experiments. Simulations for different sites were performed using the default settings of the models and measured input data (yields, clay content, meteorological data). The simulated SOC time series were compared with measured SOC.

2.1.1 The four candidate models

2.1.1.1 RothC

RothC is a widely used soil C model that was developed in the UK for crop systems about thirty years ago by Jenkinson et al. (1990) and was further developed by Coleman et al. (1997). SOC is split into five conceptual fractions: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic matter (HUM), and inert organic matter (IOM). The IOM is resistant to decomposition and remains constant over time. Its size is dependent on the total SOC based on the equation by Falloon et al. (1998), which is the standard method used by RothC if no ^{14}C measurements are available (Coleman and Jenkinson 2008). The other compartments decompose by a first-order process, each with their own characteristic rate. New C from plant residues is always added as DPM or RPM. For agricultural crops and improved grassland (e.g. pastures), C inputs are allocated to these two pools at a fixed ratio (DPM/RPM = 1.44, or 59 % DPM and 41 % RPM). Both DPM and RPM decompose to form CO_2, BIO and HUM. The proportion that goes to CO_2 or BIO/HUM is dependent on the clay content. OrgAm is assumed to be more decomposed than plant material and 2% is presumed to be HUM while DPM and RPM each contribute 49%. Active C pools decline at a pool specific rate. The decomposition is increased by temperature and is decreased if the soil experiences topsoil moisture deficit (TSMD), or is covered by plants. It is also affected by the soil clay content. There is no option in the model to explicitely simulate no tillage. The model uses a monthly time step. To calculate initial SOC stocks and pool distributions ("spin-ups", see section 2.2.7) of long-term experiments we used the original version of the model (Coleman and Jenkinson 2008). For all other simulations, we used the function RothCModel in the R package SoilR (Sierra et al. 2012), modified (by adding rate modifying factors) to be identical to the original version.

2.1.1.2 Yasso07

Yasso07 was developed in Finland for forest ecosystems (Liski et al. 2005) and has since been expanded to simulate SOC dynamics under most of the Earth's climatic conditions (Tuomi et al. 2009; Tuomi et al. 2011a; Tuomi et al. 2011b). It describes litter decomposition and SOC cycling based on the chemical quality of the organic matter (OM) and climatic conditions. C inputs are split into four fractions: water solubles, ethanol solubles, acid hydrolysables, and compounds neither soluble nor hydrolysable. In addition, there is a humus fraction that receives part of the decomposition products from the other four pools. Each compartment decomposes with its own characteristic rate that is affected by air temperature and PPN, by first order kinetics. There is no option in the model to explicitely simulate no tillage. The model uses an annual time step.

2.1.1.3 Candy carbon balance (CCB)

The Candy Carbon Balance (CCB) model is a simplified version of the Candy model, developed in Germany (Franko et al. 2011). Four C fractions are distinguished: fresh organic matter (FOM), active soil organic matter (SOM), stable SOM, and an inert long-term stabilized SOM pool. The turnover of C pools is based on first order kinetics and depends on the biological active time. The latter is calculated as annual value based on air temperature, PPN, and soil texture (clay content). There is no option in the model to explicitely simulate no tillage. The model uses an annual time step. It is the only model tested here that directly uses information on yields (t/ha) and organic matter inputs (t/ha). For all other models, the SOC inputs are calculated independently of the model using allometric equations.

2.1.1.4 C-TOOL

The original C-TOOL model was developed by Petersen et al. (2002) in Denmark. It has meanwhile been improved and expanded to simulate SOC dynamics in the top- (0-25 cm) as well as subsoil (25-100 cm, Taghizadeh-Toosi et al. 2014). In C-TOOL, SOC is represented by three pools: Fresh organic matter (FOM), humified organic matter (HUM) and C in resistant organic matter (ROM). Incoming C from plant residues is added to the soil as FOM. Residues from above ground plant parts are added to the topsoil. Depending on the crop, 70-90% of the belowground C input is allocated to the upper layer (spring crop: 80%, winter crop: 70%, grass: 90%, more than one culture per year: 80%), while the rest is allocated to the lower soil layer. If OrgAm are added, a fraction of C is directly allocated to the HUM pool. All pools have a characteristic turnover rate that is affected by clay content, soil temperature, and the soil C/N ratio. The turnover of SOC is described by first order kinetics. After FOM turnover part of the SOC enters the subsoil, another part undergoes humification, the rate of which is affected by the clay content of the soil. The C/N ratio of the soil is used to partition SOC between HUM and ROM pools. There is no option in the model to explicitely simulate no tillage. The model uses a monthly time step.

2.1.2 Estimation of C inputs to soil

Carbon inputs from plants

Carbon models require information on the amount of annual plant C added to the soil (including roots, stubble, extra-root material from turnover and exudation). For three of the models, plant-based C inputs are calculated using allometric equations, with inputs based on measured yields for main crops and cover crops (t/ha). For CCB, information on yields and organic matter inputs are used directly, precluding the use of an independent allometric equation. Six different allometric equations were tested for this project, referred to as: Bolinder (Bolinder et al. 2007), CCB (Franko et al. 2011), C-TOOL (Taghizadeh-Toosi et al. 2014), ICBM (Andrén et al. 2004), IPCC (IPCC 2006c, method applied to C according to Köck et al. 2013) and Swiss. In addition, tests were performed using the *mean* of the six methods. Most allometric equations derive C inputs as a linear function of yield and have been developed for different crop groups (e.g. cereals) or crops. Typically, the equations include a conversion from fresh matter to dry matter, a conversion to C units (assuming 45 % C, following Bolinder et al. 2007) and a factor that relates the yield to the amount of above and below ground plant material (residues) remaining on the field (e.g. straw, roots, root exudates). The allometric equations are described in more detail in the appendices of Köck et al. (2013) and in Keel et al. (2017). The method Swiss is a modified version of the equation described by Bolinder et al. (2007). The original (Bolinder) equation describes the amount of C input as a crop-specific, linear function of the measured harvest. However, a recent field study carried out in Switzerland showed that belowground C inputs of corn and winter wheat were not dependent on yields but were approximately constant (Hirte et al. 2018). For the Swiss equation, these measured C inputs from roots and rhizodeposition were used, scaled to a depth of 0-30 cm based on the equation by Jackson et al. (1996) as described in Keel et al. (2017): For small grain cereals (barley, oat, rye, spelt, triticale, wheat) the value for winter wheat (0.440 t C ha^{-1} yr^{-1}) was used; values for grain corn were 0.338 t C ha^{-1} yr^{-1} and for silage corn 0.807 t C ha^{-1} yr^{-1}; for broad beans the average values of chickpea, dry pea, lentil, soybeans and peas were used. For peas, parameters were derived from N allocation (Mayer et al. 2003). For the six grassland types considered, as well as for grass-clover ley and fallow in crop rotations, a constant SOC input of 2.51 t C ha^{-1} yr^{-1}, derived from Franko et al. (2011) and scaled to 0-30 depth (see above) was used. This approach, though simplistic, was found to result in good model-data agreement for a Swiss long-term experiment (Keel et al., 2017). Table 1 shows the parameters used in the Swiss equation.

Table 1: Parameters used to estimate plant C inputs to the soil using the equation 'Swiss', which is a modified version of the method described in Bolinder et al. (2007). R is relative C allocation and S the respective fraction that is returned to the soil for four different C pools: crop product (P), straw or stover (S), roots (R) and extra-root material (E). Note that in the case of small grain cereals (BA, OA, RY, SP, TR, WH), grain corn (GC) and silage corn (SC), belowground inputs from roots and rhizodeposition are replaced by constant values (see text). In the cases of grass-clover ley and fallow, a constant C input of 2.51 t C ha-1 yr-1 was assumed (not shown).

Crop§	R_P	R_S	R_R	R_E	S_P	S_S	S_R	S_E	Source
BA	0.335	0.482	0.11	0.073	0	0.15	1	1	Bolinder et al. (2007) parameters for small grain cereals
BB	0.2582	0.4446	0.1474	0.1498	0	1	1	1	Gan et al. (2009), Bolinder et al. (2007), Wichern et al. (2007)
FB	0.626	0.357	0.017	0	0	1	0.1	0	Bolinder et al. (2015)
GC	0.386	0.387	0.138	0.089	0	1	1	1	Bolinder et al. (2007), S_S set to 1 according to Swiss practice*
OA	0.335	0.482	0.11	0.073	0	0.15	1	1	See BA
PE	0.263	0.4	0.041	0.296	0	1	1	1	Mayer et al. (2003)
PO	0.739	0.236	0.025	0	0.08	1	0.1	0	Bolinder et al. (2015), S Values according to Swiss practice
RA	0.132	0.528	0.206	0.134	0	1	1	1	Gan et al. (2009)
RY	0.335	0.482	0.11	0.073	0	0.15	1	1	See BA
SB	0.626	0.357	0.017	0	0	1	0.1	0	See FB
SC	0.772	0	0.138	0.09	0.05	0	1	1	Bolinder et al. (2007)
SF	0.304	0.455	0.146	0.095	0	1	1	1	Parameters for SO
SO	0.304	0.455	0.146	0.095	0	1	1	1	Bolinder et al. (2007), S_S set to 1 according to Swiss practice*
SP	0.335	0.482	0.11	0.073	0	0.15	1	1	See BA
TR	0.335	0.482	0.11	0.073	0	0.15	1	1	See BA
VE	0.626	0.357	0.017	0	0	1	0.1	0	See SB
WH	0.335	0.482	0.11	0.073	0	0.15	1	1	See BA

* based on information derived from the agri-environmental indicators monitored as part of the Agricultural Monitoring programme (section 2.2.5.4).
§ BA, barley; BB, broad bean; FB, fodder beet; GC, grain corn; OA, oat; PE, pea; PO, potato; RA, rape seed; RY, rye; SB, sugar beet; SC, silage corn; SF, sunflower; SO, soybean; SP, spelt; TR, triticale; VE, vegetables; WH, wheat

2.1.3 Simulation of long-term trials

To test the models and allometric equations, data from eight Swiss long-term experiments for which SOC stocks were measured at least twice (Table 2) were used. Data from sites Watt and p29C were used to verify the chosen model (2.1.5), whereas data from the other six sites were used for the initial testing (2.1.4). At each site, a number of different experimental treatments (up to 24) exist, listed in Appendix A. From each treatment, annual yields were available. C inputs from OrgAm (e.g. manure, slurry, compost) were either measured or calculated based on the assumption that manure contains 162 kg t^{-1} organic matter (Richner and Sinaj 2017) with a C content of 45 %. For slurry an organic matter content of 67 kg m^{-3} (for undiluted slurry), C content of 45 % and dilution of 1:1 with water were assumed. Measured clay content of the soil and meteorological data were used for the simulations. The simulated SOC time series were compared against measured SOC stocks.

The following combinations of models and allometric equations were tested (Figure 1):

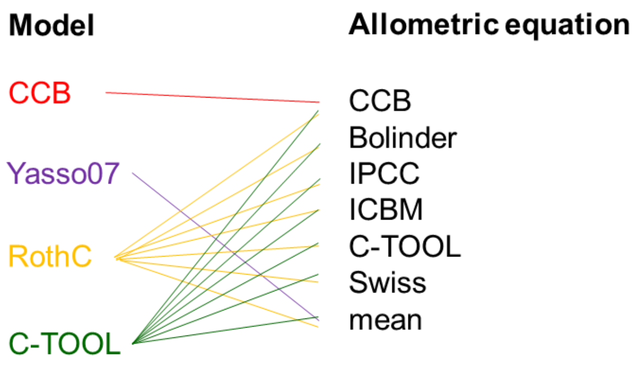

Figure 1: Combinations of models and allometric equations tested.

2.1.3.1 Description of long-term experiments

The Swiss long-term experiments used for testing are described briefly in the following section. More information can be found in Table 2, Appendix A and in the cited references. A summary of the SOC stock changes is given in Keel et al. (2019).
The **Zurich Organic Fertilizer Experiment** (ZOFE) compares twelve different fertilisation treatments (organic and mineral fertilisers and their combination) applied to an 8-year crop rotation including ley, winter wheat, grain corn, and potato (Oberholzer et al. 2014). Prior to the experiment, the field was a natural grassland under low intensity management (Walther et al. 2001). The **DOK experiment** in Therwil (D: biodynamic, O: bioorganic, K: conventional) compares management systems that differ mainly regarding the type and intensity of fertilisation and the methods of plant protection (Mäder et al. 2002; Fließbach et al. 2007). The treatments were applied to plots with identical crop rotations (rotations repeated three times, but started in different years, subplots A, B, C). For model testing only data of the intensive treatments of subplots A for the years 1979-2005 were used (Leifeld et al. 2009). For model verification, all subplots of the conventional treatment at low fertilization intensity were used. Experiment **p24A** in Changins tests 24 different combinations of organic and mineral fertilisers that are applied at different rates to a 6-year crop rotation with winter wheat, grain corn, rapeseed and summer barley (Maltas et al. 2018). A second experiment, **p29C**, was set up in Changins to compare different soil management practices. The 4-year crop rotation is composed of winter wheat, winter rapeseed and grain corn. The plots receive mineral fertiliser according to Swiss guidelines. Until 2006 wheat straw was exported, while corn and rapeseed residues were chopped and left on the field. In the year 2000, cover crops were sown before grain corn. Because soil texture and SOC stocks vary strongly at this site, the experimental field is split in two parts. The experiment **Hausweid** was set up to test different tillage treatments with a high loosening intensity (moldboard plough or chisel) compared to shallow and no-tillage (Anken et al., 2004; Hermle et al., 2008). The 4-year crop rotation comprised winter wheat, winter rapeseed and silage corn. In **Watt** an experiment was set up on a hay meadow, where all plots were cut 3 times per year. This represents a relatively low cutting frequency given the potential productivity (Liebisch et al. 2013). The plots received different amounts of mineral fertiliser. The experiment in **Oensingen** compares two meadows under different management intensities (Ammann et al. 2007). The intensive field was typically cut four times per year and received mineral and organic fertiliser, whereas the extensive field received no fertiliser and was cut three times per year. Prior to the experiment, the site was under ley-arable rotation management. The experiment **Balsthal** is a hay meadow that receives different mineral fertiliser treatments and is cut either twice or thrice a year, representing a relatively low (2x) to intermediate (3x) mowing frequency for the potential productivity of the site, respectively (Thomet and Koch 1993).

Table 2: Long-term experiments on CL and GL sites; MAT = mean annual temperature, MAP = mean annual precipitation; the sites Hausweid and p29C are used for model verification (section 2.1.5).

Name of experiment	Land use	Elevation (m asl.)	MAT (°C)	MAP (mm)	Clay content (%)	Start and end (if not on-going) of experiment
ZOFE	CL	420	9	1040	14	1949-
DOK	CL	300	9.7	791	16	1978-
p24A	CL	430	10.3	1009	14	1976-
Watt	GL	500	9.5	1055	22	1992-2014
Oensingen	GL	450	9.5	1100	43	2001-2011
Balsthal	GL	930	5	1200	16	1972-
Hausweid	CL	540	8.3	1180	17	1987-2009
p29C	CL	430	10.3	1009	25/48	1969-

2.1.4 Comparison of simulations

The results of the different simulations were compared using Taylor diagrams (Taylor 2001). With this approach several aspects of model performance (correlation, root mean square difference, standard deviation) are summarized in a single diagram allowing different simulations to be compared (coloured letters in Figure 2 to Figure 7). Simulations that agree well with observations will lie nearest the black symbol marked on the x-axis (pattern of measured SOC stocks) and have a similar standard deviation, a minimal RMS difference, and a maximal correlation coefficient. All diagrams show results for simulated SOC stocks.

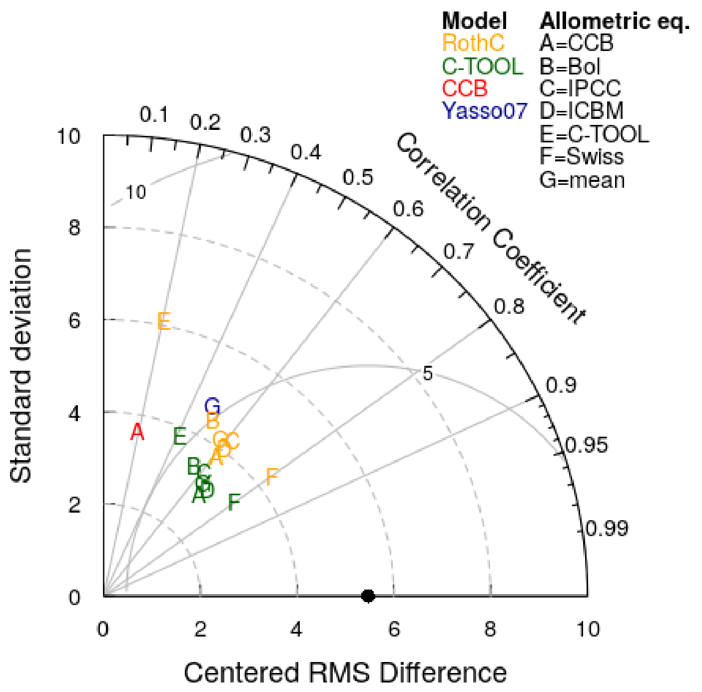

Figure 2: Taylor diagram for the long-term experiment ZOFE where letter colour refers to the model used and letter indicates which allometric equation was used; black dot (= observed statistic) and each single letter refer to the average statistics across all treatments in the experiment. The distance from the origin (bottom left-hand corner) represents the standard deviation; the centered RMS difference between the simulation and measured SOC stocks is proportional to their distance apart (in the same units as the standard deviation, with scale indicated by curved grey lines).

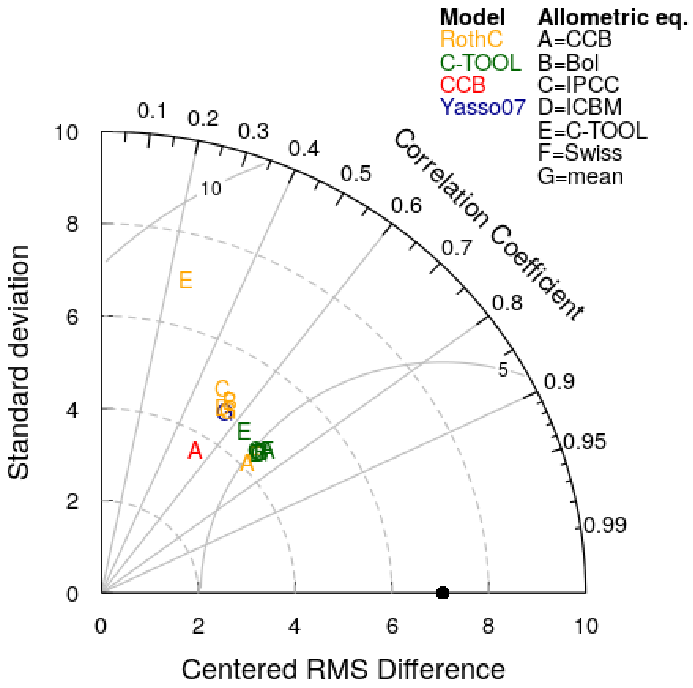

Figure 3: Taylor diagram for the long-term experiment DOK; the meaning of letters and colours is as given above.

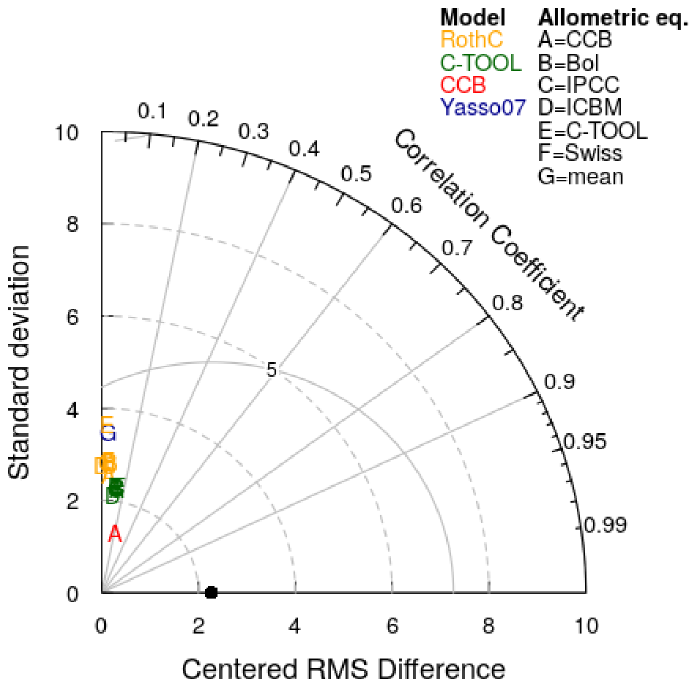

Figure 4: Taylor diagram for the long-term experiment p24A; the meaning of letters and colours is as given above.

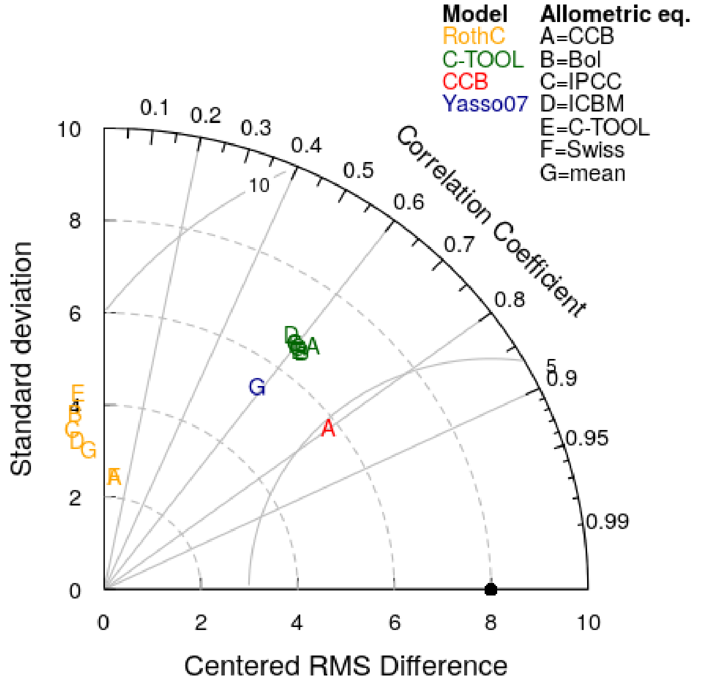

Figure 5: Taylor diagram for the long-term experiment Watt; the meaning of letters and colours is as given above; letters left of the diagram area indicate a negative correlation of simulated and measured stocks.

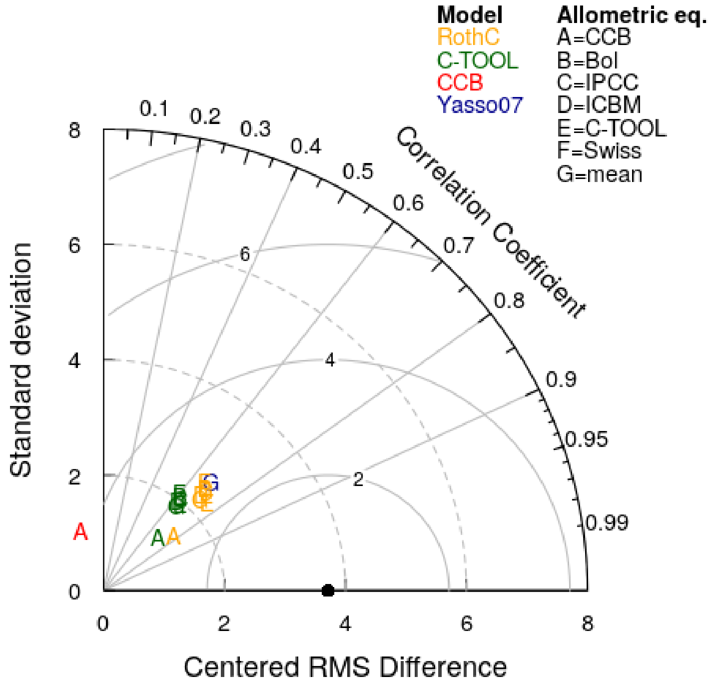

Figure 6: Taylor diagram for the long-term experiment Oensingen; the meaning of letters and colours is as given above.

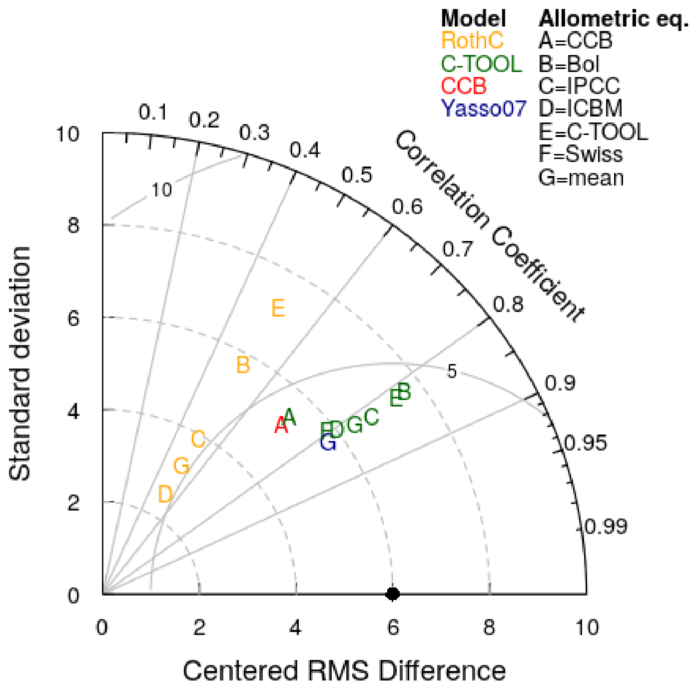

Figure 7: Taylor diagram for the long-term experiment Balsthal; the meaning of letters and colours is as given above.

Based on the results and the results of the Taylor diagrams, RothC and CCB were the best models and CCB and Swiss the best allometric equations. Simulations with C-TOOL were only best for site DOK (Figure 3). Because the model CCB (for technical reasons) can only be run in combination with its own allometric equation (Figure 1), three possible model-allometric combinations remain for the final tests (RothC-Swiss, RothC-CCB, CCB-CCB). While results in Taylor diagrams were analyzed for all treatments per site combined, the following additional tests were carried out for single treatments including those most representative for Switzerland. The criterion for the goodness of fit was the SOC change rate. Results of all tests are given in Appendix B and a selection of results in Figure 8 to Figure 14.

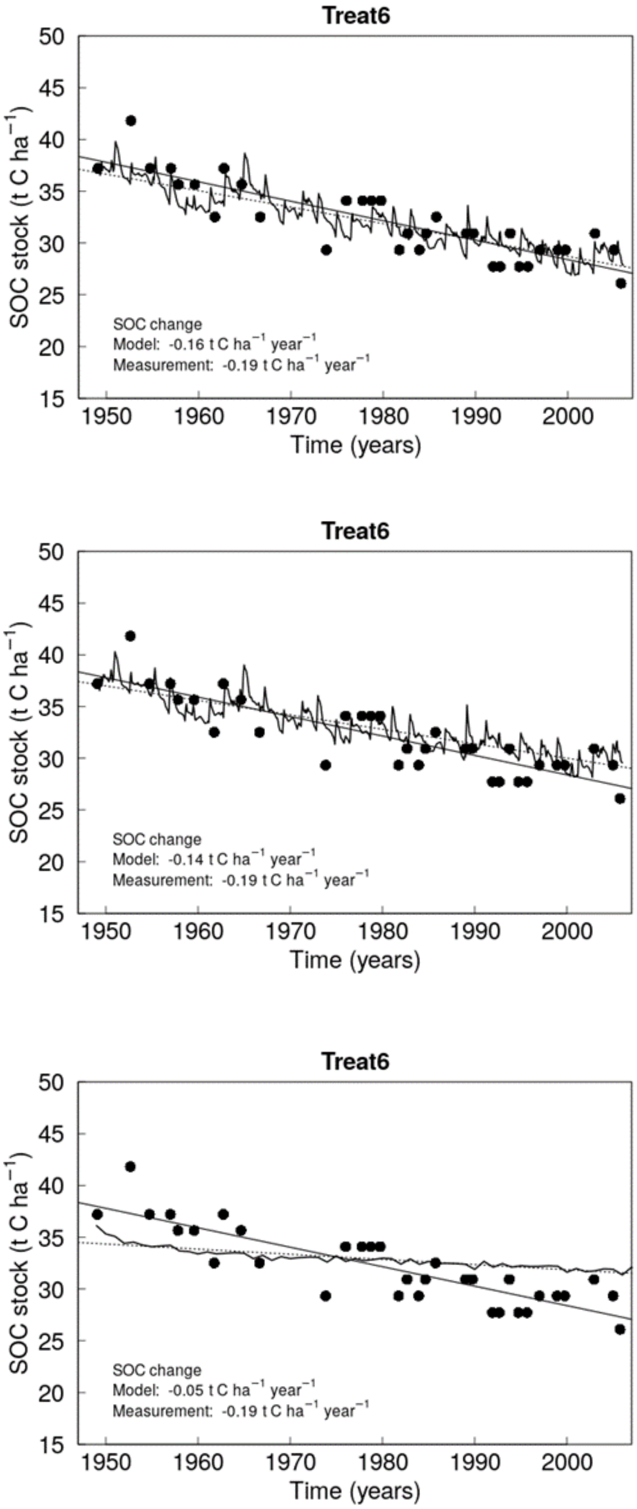

Figure 8: Simulations for the long-term cropland experiment ZOFE (FYM + PK fertiliser, 90, 60, 300 kg NPK ha-1 yr-1 on average); the uppermost panel shows the simulation with RothC-Swiss, the middle panel shows the simulation with RothC-CCB and the lowest panel CCB-CCB; uneven lines = simulations, symbols = measured values, straight solid lines = linear functions of measured values, straight dotted lines = linear functions of simulated values.

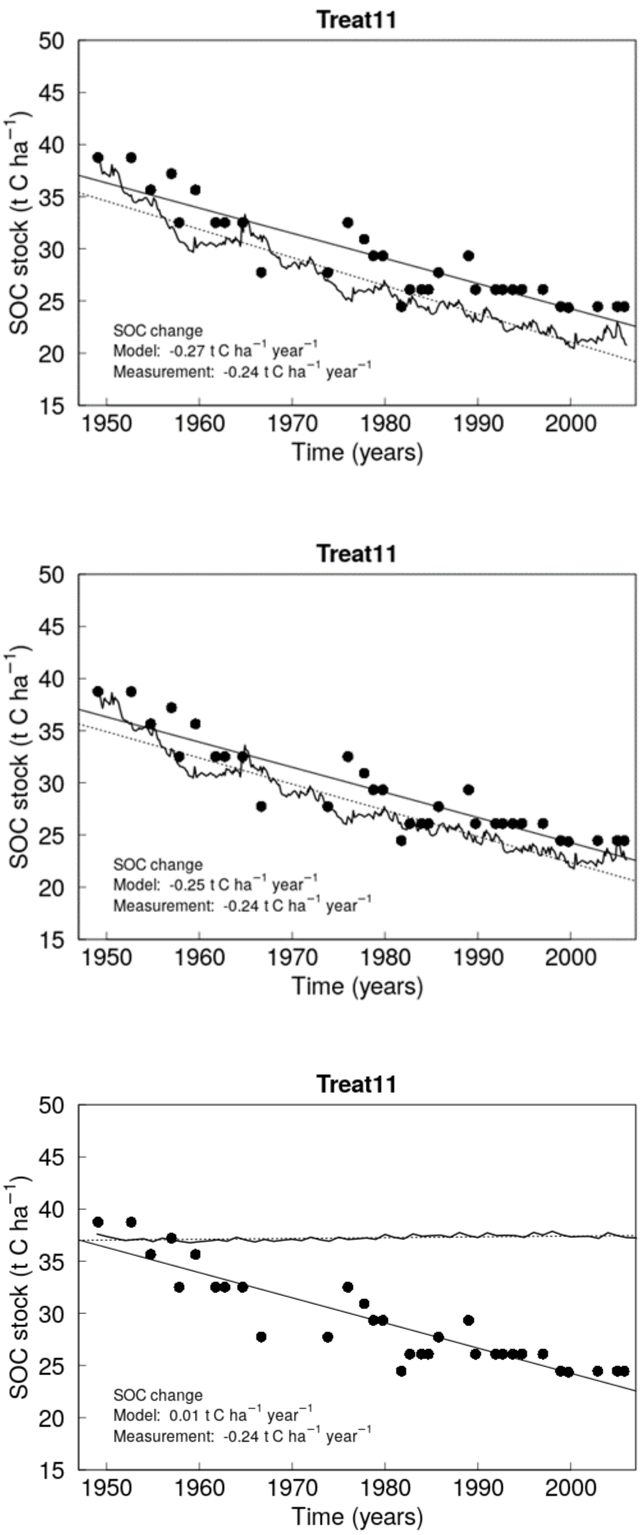

Figure 9: Simulations for the long-term cropland experiment ZOFE (treatment N2P2K2, 140, 40, 65 kg NPK ha^{-1} yr^{-1} on average); the uppermost panel shows the simulation with RothC-Swiss, the middle panel shows the simulation with RothC-CCB and the lowest panel CCB-CCB; uneven lines = simulations, symbols = measured values, straight solid lines = linear functions of measured values, straight dotted lines = linear functions of simulated values.

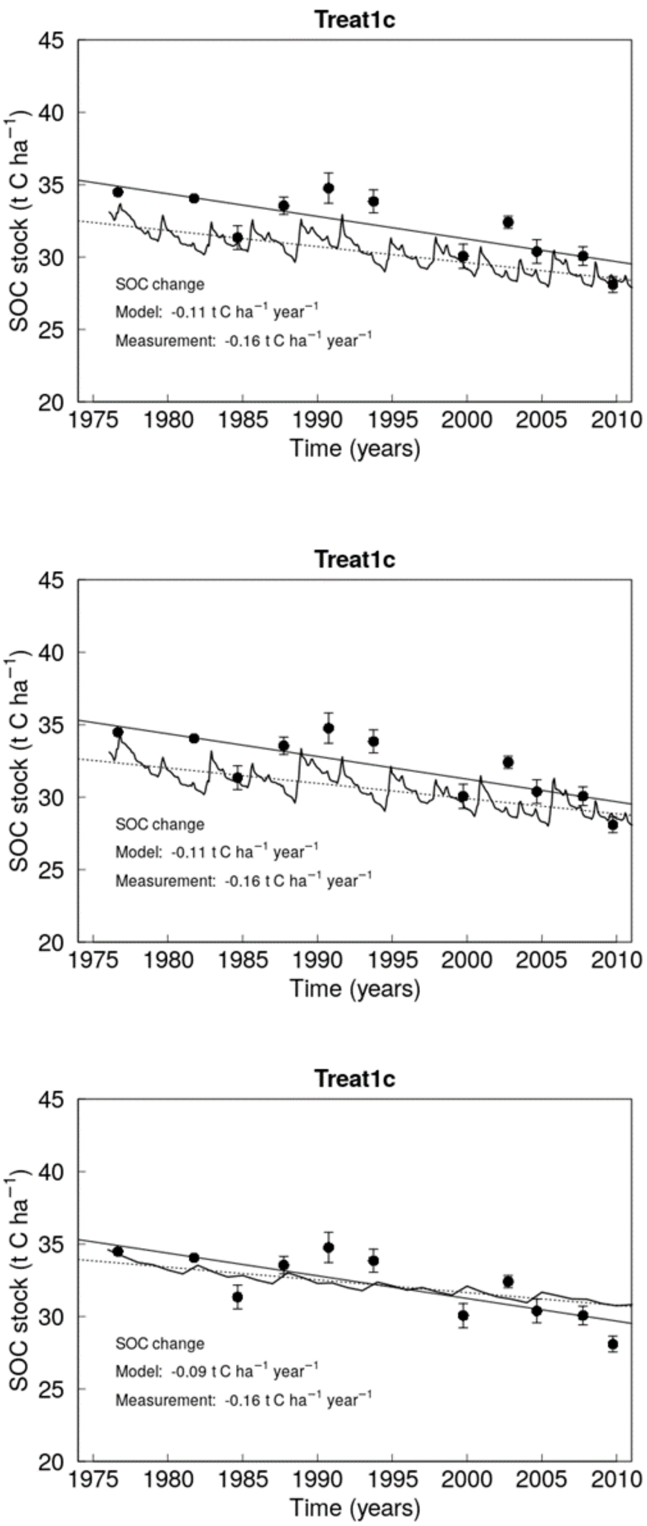

Figure 10: Simulations for the long-term cropland experiment p24A with mineral fertilizer (Treatment C-70; 110, 30, 100 kg NPK ha^{-1} yr^{-1} on average); the uppermost panel shows the simulation with RothC-Swiss, the middle panel shows the simulation with RothC-CCB and the lowest panel CCB-CCB; uneven lines = simulations, symbols = measured values (error bars = measurement of different replicates), straight solid lines = linear functions of measured values, straight dotted lines = linear functions of simulated values.

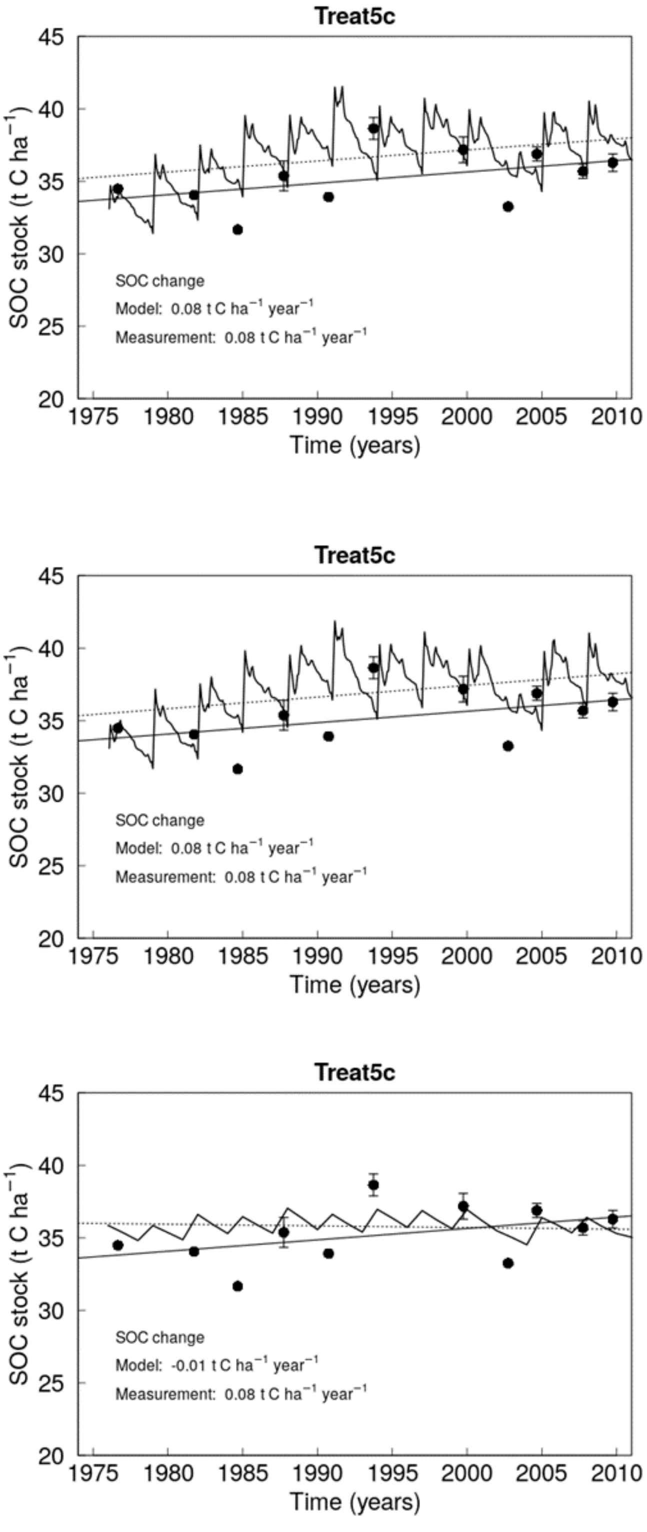

Figure 11: Simulations for the long-term cropland experiment p24A (treatment FYM70-70 with mineral fertiliser and farmyard manure, 465, 135, 555 kg NPK ha^{-1} yr^{-1} on average); the uppermost panel shows the simulation with RothC-Swiss, the middle panel shows the simulation with RothC-CCB and the lowest panel CCB-CCB; uneven lines = simulations, symbols = measured values (error bars = measurement of different replicates), straight solid lines = linear functions of measured values, straight dotted lines = linear functions of simulated values.

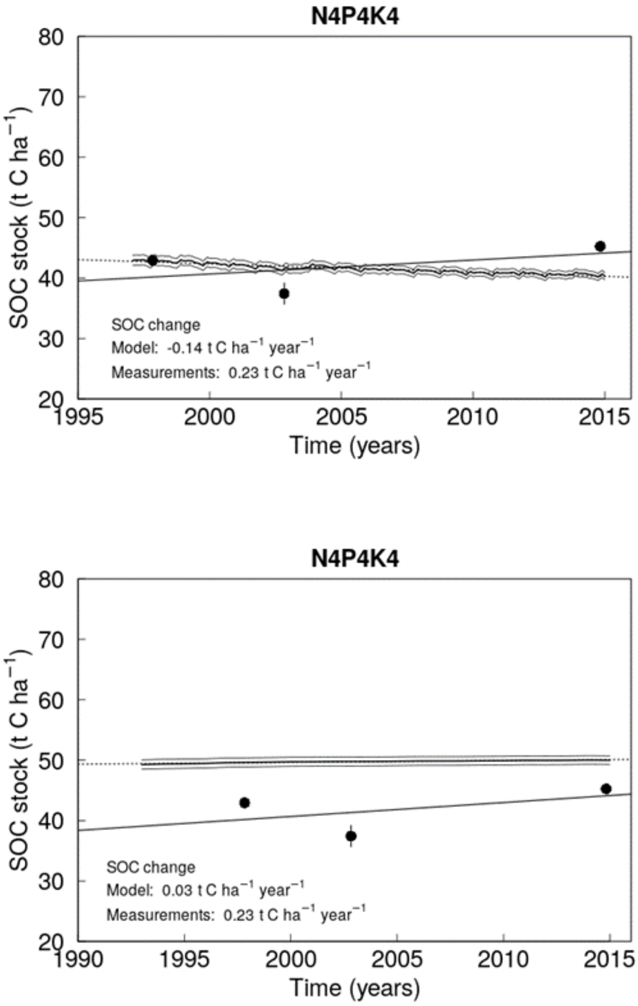

Figure 12: Simulations for the long-term grassland experiment Watt (treatment with mineral fertiliser, 60, 25, 110 kg NPK ha^{-1} yr^{-1} on average and 3 cuts per year); the upper panel shows the simulation with RothC-Swiss (for grasslands RothC-CCB is identical), the lower panel CCB-CCB; uneven lines = simulation of different plots (mean ± standard error), symbols = measured values (error bars = measurement of different plots), straight solid lines = linear functions of measured values, straight dotted lines = linear functions of simulated values.

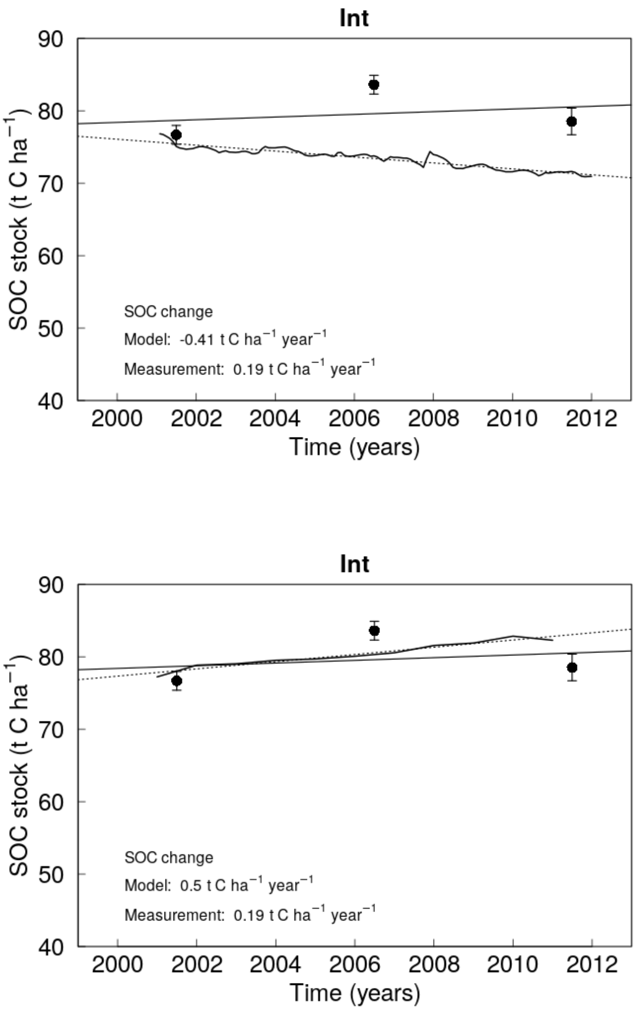

Figure 13: Simulations for the long-term grassland experiment Oensingen (treatment INT with mineral and organic fertiliser, 195, 60, 560 kg NPK ha^{-1} yr^{-1} on average); the upper panel shows the simulation with RothC-Swiss (for grasslands RothC-CCB is identical), the lower panel CCB-CCB; uneven lines = simulations, symbols = measured values (error bars = measurement of different samples), straight solid lines = linear functions of measured values, straight dotted lines = linear functions of simulated values.

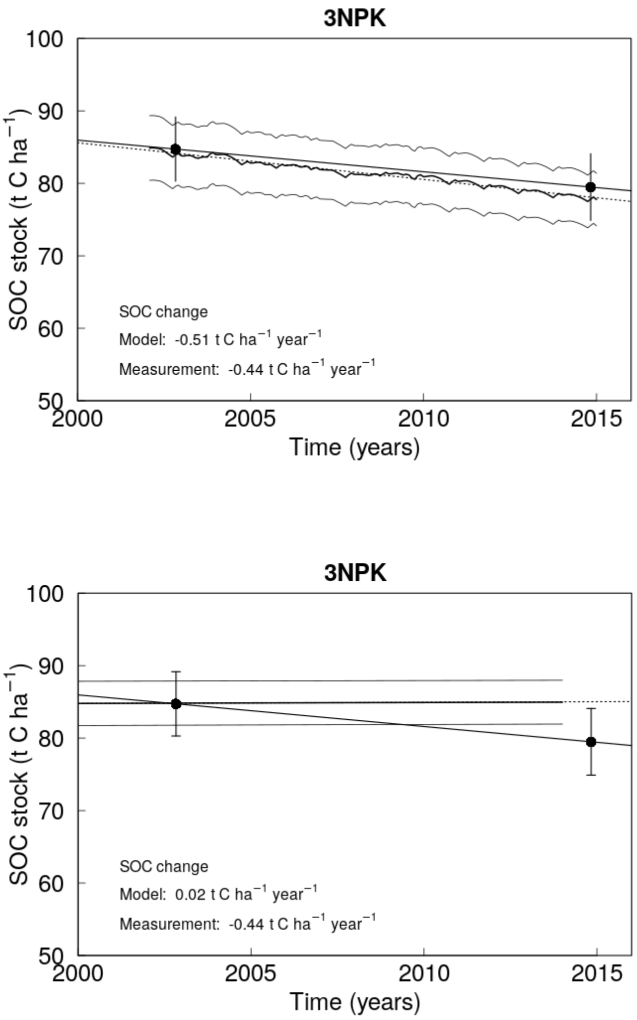

Figure 14: Simulations for the long-term grassland experiment Balsthal (treatment with NPK fertiliser three grass cuts, 75, 35, 200 kg NPK ha^{-1} yr^{-1} on average); the upper panel shows the simulation with RothC-Swiss, and the lower panel CCB-CCB; uneven lines = simulations of different plots (mean ± standard error), symbols = measured values (error bars = measurement of different plots), straight solid lines = linear functions of measured values, straight dotted lines = linear functions of simulated values.

In general, the simulations with the model RothC agreed better with measured SOC trends compared to simulations with the model CCB, both in terms of the direction of SOC trends as well as the magnitude of the trend (i.e. the slope, Figure 8 to Figure 14). One exception was site Oensingen (Figure 13), for which the trend with RothC was negative, while the trend through the measured data is positive. However, the uncertainty of the latter trend is large as it is only based on three measurements. For permanent grasslands we generally have very few long-term experiments and they are of rather short duration. Whether the allometric equation Swiss or CCB was used in combination with RothC made little difference. Equation Swiss, based on Bolinder et al. (2007), has the advantage that missing parameters can be found more easily (e.g. Wiesmeier et al. 2014) and different types of residue management can be tested. Model verification was therefore carried out using RothC alongside the Swiss allometric equation.

2.1.5 Model verification

As a final step of the model selection process, RothC in conjunction with the Swiss allometric equation were used to simulate SOC time series of additional long-term experiments (or single treatments thereof) that had not been used for model evaluation or selection. The results of a selection of these are shown in Figure 15, Figure 16 and Table 3. For permanent GL, very few long-term experiments exist in Switzerland and all available data were used for model evaluation and selection, leaving no data for verification. For cropland, although some sites show high variability in the measured data that is not be captured by the model, good agreement between modelled and measured SOC trends was found overall. **It was therefore decided to use the model RothC and the allometric equation Swiss to simulate SOC of mineral agricultural soils for the national GHG inventory.**

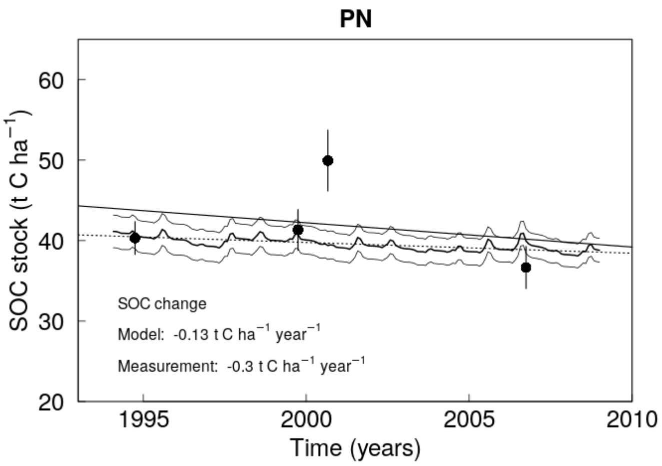

Figure 15: Simulation for conventional tillage treatment at the long-term experiment Hausweid (NPK fertiliser, 130, 35, 135 kg ha^{-1} yr^{-1}); uneven lines = simulation of different plots (mean ± standard error), symbols = measured values (error bars = measurement of different plots), straight solid line = linear function of measured values, straight dotted line = linear function of simulated values.

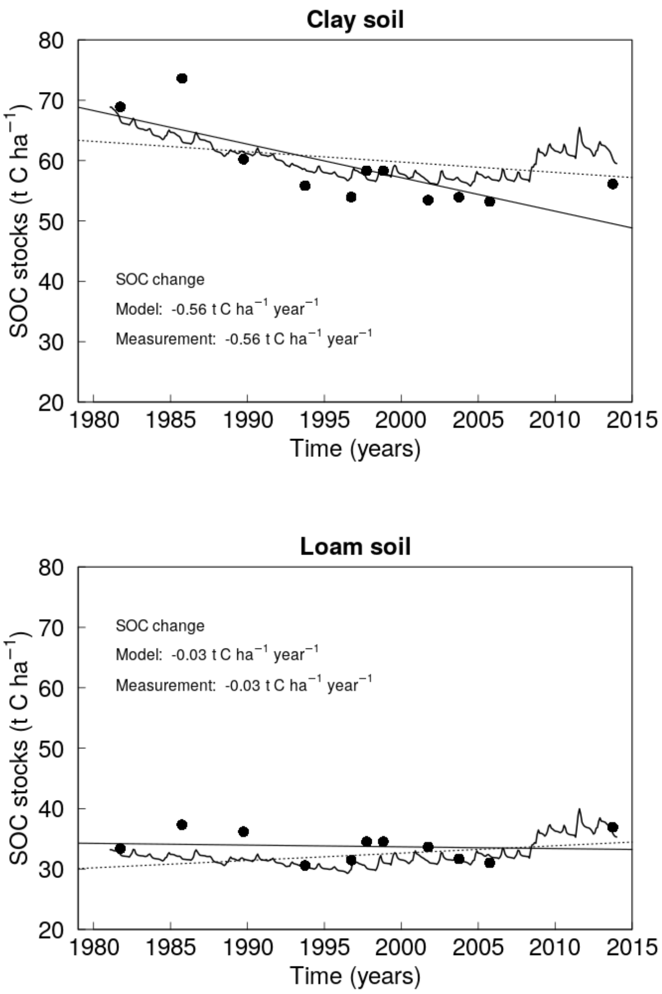

Figure 16: Simulation for conventional tillage treatment at the long-term experiment p29C (NPK fertiliser, 135, 30, 125 kg ha^{-1} yr^{-1}) with different soil types; uneven lines = simulation, symbols = measured values, straight solid lines = linear functions of measured values, straight dotted lines = linear functions of simulated values.

Table 3: Correlation coefficients between the measured and simulated SOC stocks for conventional fertilization treatment (K1) of twelve different plots of long-term experiment DOK.

Plot number	Pearson's correlation coeffficient
19	0.29
21	0.69
23	0.43
31	0.67
33	0.77
35	0.60
61	0.63
63	0.56
65	0.56
73	0.48
75	0.48
77	0.66

2.2 Input data and calculations

2.2.1 Stratification

The upscaling from the point simulation to the national scale was carried out using a system of regions, or 'strata' (singular 'stratum'), which should be – for variables important for SOC dynamics – relatively homogeneous. The following considerations were made during the development of these strata. Firstly, the boundaries of strata had to include spatial boundaries relevant to agricultural practice or to input data. For example, year-round farming occurs only in particular agricultural zones, meaning these zones need to form part of the strata. Likewise, the boundaries of soil texture classes were to be incorporated as information on clay content (derived from soil texture) is used directly by RothC. Secondly, a large number of strata would represent the high regional variation in the landscape well, however the low spatial resolution of many data sets precludes using many small strata as this would incur false precision of results. Lastly, regional upscaling using strata still incurs small-scale variation within strata, for example temperature gradients resulting from topographic variation within strata. These cannot be excluded, but resulting problems can be minimised, as described in individual sections below (e.g. 2.2.3.2).

2.2.1.1 Data sources

Two spatial data sets were used to create the strata.

Firstly, the agricultural zones (AZs) from the Federal Office for Agriculture (FOAG), namely the summer pasture, mountain, hill and valley zones (Figure 17 and Table 4)[1]. These AZs were used to create the strata for two reasons. Firstly, they are defined in legislation[2] meaning any future policy changes concerning SOC could be spatially restricted according to where the relevant farming practices occur. For example, generally, summer pastures are restricted to the 'summer pastures' zone and other forms of agriculture are restricted to the three other zones. Secondly, the AZs account for some variation in management throughout the country, because they were defined based on variables that influence management practices (e.g. accessibility, prevalence of steep slopes).

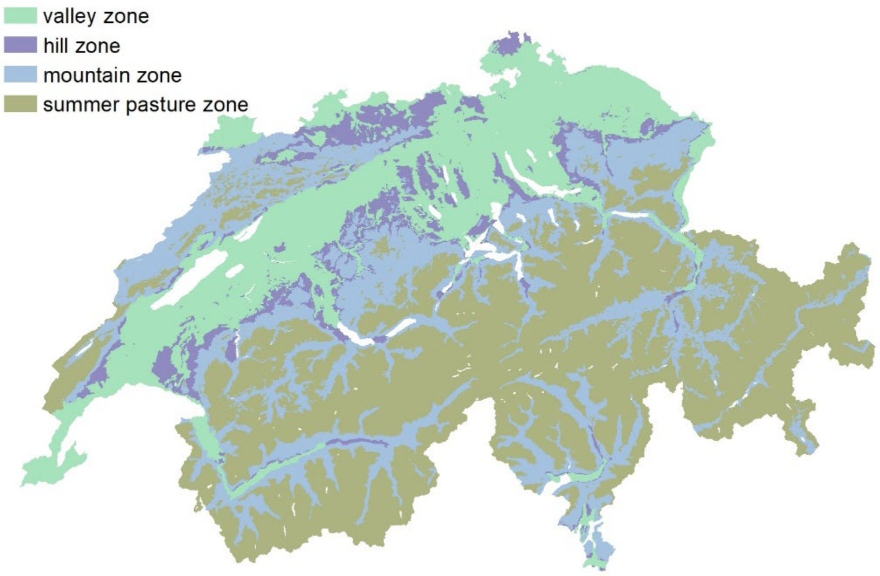

Figure 17: The four AZs used in this project; AZ boundaries © FOAG.

Table 4: The four AZs used to construct the strata.

Agricultural Zone (AZ)	A code
valley zone / Talgebiet / région de plaine	A1
hill zone / Hügelregion / région de collines	A2
mountain zone / Bergregion / région de montagne	A3
summer pasture zone / Sömmerungsgebiet / région d'estivage	A4

[1] See also documentation: https://www.blw.admin.ch/blw/de/home/instrumente/grundlagen-und-querschnittsthemen/landwirtschaftliche-zonen.html; in German, French and Italian.
[2] Legislation: Verordnung über den landwirtschaftlichen Produktionskataster und die Ausscheidung von Zonen (Landwirtschaftliche Zonen-Verordnung); SR 912.1: https://www.admin.ch/opc/de/classified-compilation/19983417/index.html; in German, French and Italian.

The second data set used to create the strata is the production regions from the national forest inventory (NFI)[3], obtained from the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). The five production regions are: Jura, central plateau, Pre-Alps, Alps, southern Alps. Köck et al. (2013) recommended the use of these regions for this project because they are already used in the reporting of GHG gases (FOEN 2019), making the resulting stratification system (of GL and CL) compatible with that of other land use types. Additionally, stratification based on these regions would reflect climatic differences between the northern and southern sides of the Alps, as well as between the Jura region and other parts of Switzerland north of the Alps.
The variation of temperature and PPN within the Alps production region is very high. An important cause of this is the drier eastern high Alps of Graubünden and western high Alps of Wallis in comparison to the wetter central Alps. The Alps production region was therefore split into 'wetter' and 'drier' regions for this project, according to the climate regions published by MeteoSwiss (Schüepp and Gensler 1980). Mean monthly PPN for grassland locations in the 'wetter' Alps for the period 1981 to 2011 was 146 mm and in the 'drier' Alps, 106 mm. The resulting six production regions are shown in Table 5 and Figure 18.

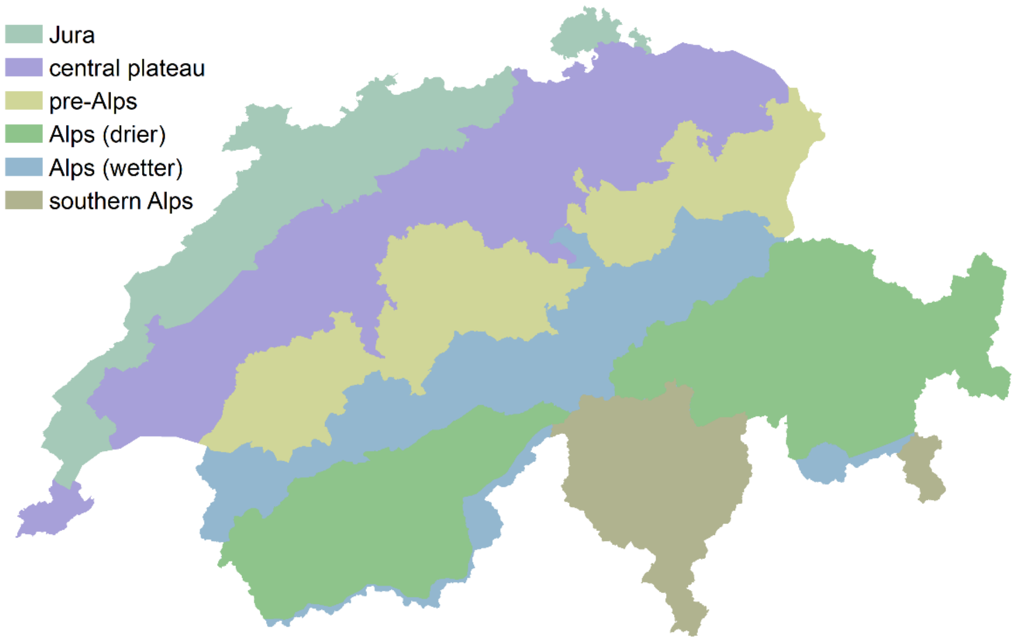

Figure 18: The six NFI production regions used to construct the strata, as adapted for this project (see main text); NFI production regions: Schweizerisches Landesforstinventar © 2012 Eidg. Forschungsanstalt WSL, CH-8903 Birmensdorf; 'drier' and 'wetter' Alps boundaries deduced from the Climate Regions of Switzerland © MeteoSwiss.

3 https://www.lfi.ch/index-en.php

Table 5: The six NFI production regions used to construct the strata, as adapted for this project.

Production region	F code
Jura	F1
central plateau	F2
pre-alps	F3
Alps (drier)	F4_C
Alps (wetter)	F4_W
southern Alps	F5

2.2.1.2 Assembling the strata

The AZs and the NFI production regions were combined by overlapping their boundaries in a GIS system. Where CL and GL points (from the LUS, see section 2.2.2) lay outside the boundaries of these two sets, the extents of the data sets were increased manually to accommodate them. The resulting 24 strata are shown in Figure 19.

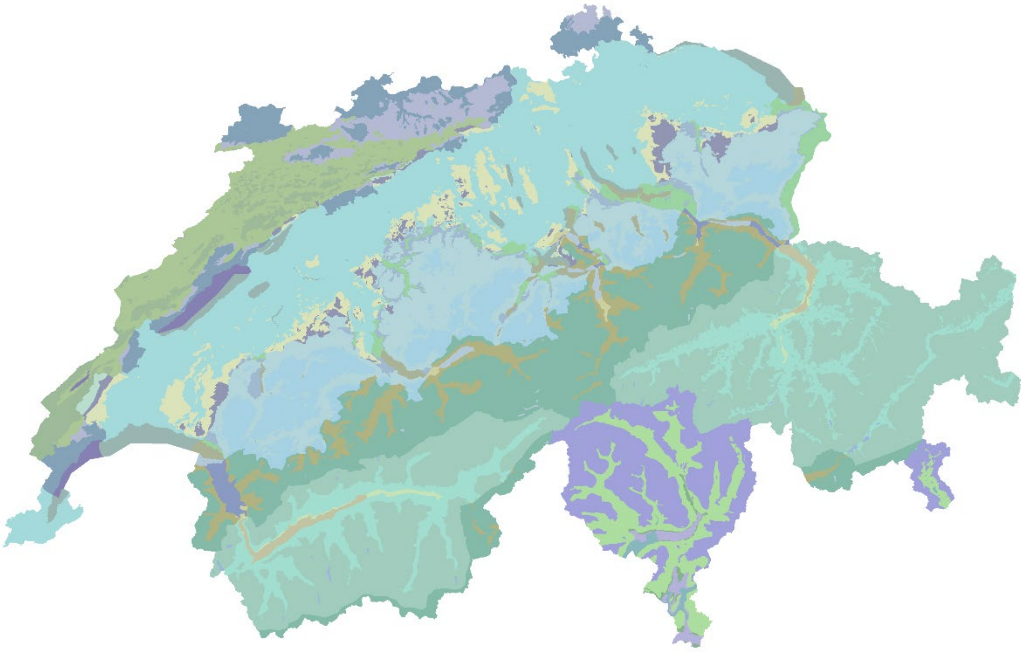

Figure 19: The 24 strata obtained from a union of the AZs and NFI regions.

The 24 strata were coded by concatenating the 'A codes' and 'F codes' of the two input data sets (Table 4 and Table 5). Data used for the SOC modelling (with the exception of clay content, see section 2.2.4) were obtained for each of these 24 strata; their relative surface area was then used to upscale the SOC simulations to the national scale (section 2.2.8.1).

2.2.2 Land use statistics

The location of CL and GL across the country is based on the land use statistics (LUS), generated by and available from the Swiss Federal Statistical Office (FSO). The LUS is a 100 m x 100 m grid of points covering the surface of the country, for which land use (46 categories) and land cover (27 categories) are defined. These categories are defined based on aerial photographs from Swisstopo, interpreted with the aid of additional material such as topographic maps, information on zoning, and nature conservation areas[4]. These categories are further grouped into a nomenclature system, described in the next section.

[4] https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/erhebungen/area.html; in French and German.

The aerial photographs of the LUS were taken during the time periods 1979-85, 1992-1997 and 2004-2009. For this project, it was assumed information from the LUS data sets represents the mid-point of these three time periods i.e. the years 1982, 1994 and 2006.

2.2.2.1 Nomenclature system: 18 combination categories

For GHG reporting in Switzerland the land use and land cover classifications from the LUS are combined into 18 "combination categories" (CCs, tables 6-2 and 6-6 in FOEN 2019). This nomenclature system is used throughout this project and the categories covered in this project are cropland (CL, CC21) and permanent grassland (GL, CC31). The CL category includes arable land in agricultural areas as well as leys. The category GL includes grass and herb vegetation in agricultural areas, with the exception of leys. It covers ca. 65 % of grassland in agricultural and non-productive areas in Switzerland and includes summer pastures. The other grassland categories (35 % of grassland in agricultural and non-productive areas) in the CC nomenclature system are shrub vegetation (CC32); vineyards, low-stem orchards, tree nurseries (CC33); copses (CC34); orchards (CC35); stony grassland (CC36); and unproductive grassland (CC37). These were excluded from this project because we lack the necessary information on their management and data from long-term experiments to parameterise and validate simulations of SOC changes in their soils Köck et al. (2013).

The LUS data set is a 1 ha raster grid. In the CC nomenclature system, CL is represented by 406,394 points and GL by 931,223 points (survey 2004-2009).

2.2.2.2 Thinning the GL and CL data

The CC data were used in this project to define the location of CL and GL. They were also used to extract information from various raster data sets (for example, as in section 2.2.3.2). In order to reduce computational time for the latter task, the points were thinned using the "Delete Identical" tool in ArcGIS, which deletes identical points within a given radius. The data set was reduced in size to ca. $^{1}/_{5}$ for CL and to ca. $^{1}/_{4}$ for GL.

2.2.3 Climate information

RothC requires data on the monthly mean temperature and evapotranspiration (ET), and monthly summed PPN.

2.2.3.1 Data sources

Gridded data of daily PPN sums and mean daily temperature were obtained from MeteoSwiss[5], covering all years since 1990. The grids have a spatial resolution of 1.25 minutes (= 0.02°), corresponding in Switzerland to ca. 2.3 km in the E-W direction and ca. 1.6 km in the N-S direction. The grid data sets are based on a set of non-regular climate stations, using models considering geo-topographic factors to derive the finer-scaled resolution (MeteoSwiss 2011). Temperature values correspond to temperature at 2 m above ground level, for 10-minute interval measurements. Between 86 and 91 climate stations deliver data for this data set. Valley bottoms and mountains are relatively well-represented by climate stations, but slopes less so (MeteoSwiss 2017).

PPN values correspond to rainfall and snowfall water equivalent, recorded from 420 to 520 rain-gauge stations across the country. Though coverage across the country is good, the network is also biased towards areas of lower elevation, with areas above 1200 m asl under-represented (MeteoSwiss 2013).

Data from 1990 to present were extracted for use in this this project. From the daily data, monthly average temperature values and monthly PPN sums were calculated.

Monthly ET was calculated using the Priestley-Taylor (ETPT) method (Priestley and Taylor 1972), estimating reference ET. This method was shown to estimate potential ET of a test site in the Swiss central plateau well (Calanca et al. 2011). The input data sets required for the calculation are gridded daily data of average temperature (see above) and surface incoming shortwave (SIS) radiation (MJ/m^2). The SIS data for 2004 onwards were obtained from MeteoSwiss (unpublished data set, obtained upon request); the SIS data for 1990 to 2003 were obtained from the satellite application facility on climate monitoring (Posselt et al. 2012). The latter data set (resolution 0.03°) was resampled to match the resolution of the gridded data from MeteoSwiss (0.02°), as described in Holzkämper et al. (2015). For a few individual months since 2011, ET could not be estimated due to too many missing data values in

[5] https://www.meteoswiss.admin.ch/home/climate/swiss-climate-in-detail/raeumliche-klimaanalysen.html; in English, German, French and Italian.

the SIS data. The ET values for these months were gap-filled using the average ET values of the respective months from all other years.

2.2.3.2 Applying information to the strata

RothC requires, for each stratum (for CL and GL each), a monthly temperature, PPN and ET value. A weighted average mean was used to obtain these values for each stratum (Figure 20), utilising the distribution of CL and GL points (from the CC data set, section 2.2.2.1) as weighting. A weighting was used because cropland and grassland is typically not evenly or randomly distributed within strata; in more hilly or mountainous regions especially, cropland and grassland tends to occur in flatter regions, often the areas of lower elevation. Ignoring this distribution would introduce a bias into the calculation of, for example, mean temperature, which would be (typically) underestimated.

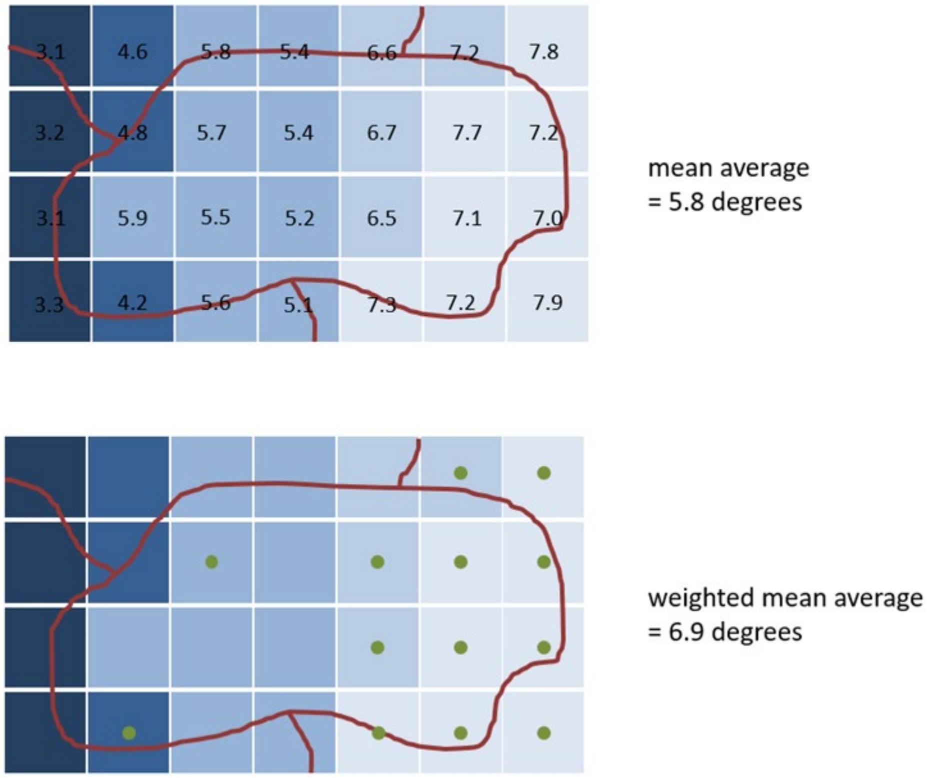

Figure 20: Assigning climate parameter values to a given stratum (example): In the upper panel the mean temperature (numbers given in squares) is calculated for the stratum (red outline); in the lower panel a weighted-average is used, incorporating the distribution of the CL points (green dots). In this example these are clustered towards the right-hand side of the panel where higher temperatures occur, meaning the mean average would give a biased value (too low); the weighted average results in a higher, more appropriate value.

2.2.4 Soil texture information

RothC requires information about clay content (%). There is a lack of detailed soil information about Swiss soils in general (Keller et al. 2018). Clay content was derived from the Swiss soil suitability map (SSM).

2.2.4.1 Soil suitability map

The SSM (Häberli 1980) was produced with the aim of classifying surfaces by their suitability for agriculture and forestry. A digital vector version of this 1:200 000 map was obtained from the FSO (2000). The map does not portray clay content. Soil porosity (portrayed in the SSM) was therefore used to derive soil texture, (Table 6) and clay content was assigned to each soil texture class following Carsel and Parrish (1988). For the texture class 'other' (mostly rocky areas, water bodies, glaciers and urban areas, containing <5 % CL and GL points), no information was given in the SSM. This class was assigned a weighted average clay content of the other soil texture classes (17 %). The twelve classes were aggregated to ten classes (hereafter, 'clay classes', Table 6, Figure 21). For upscaling, the clay class containing mires and raised bog peat (0 % clay) was weighted zero (section 2.2.8) as these surfaces represent organic soils, not considered in this project.

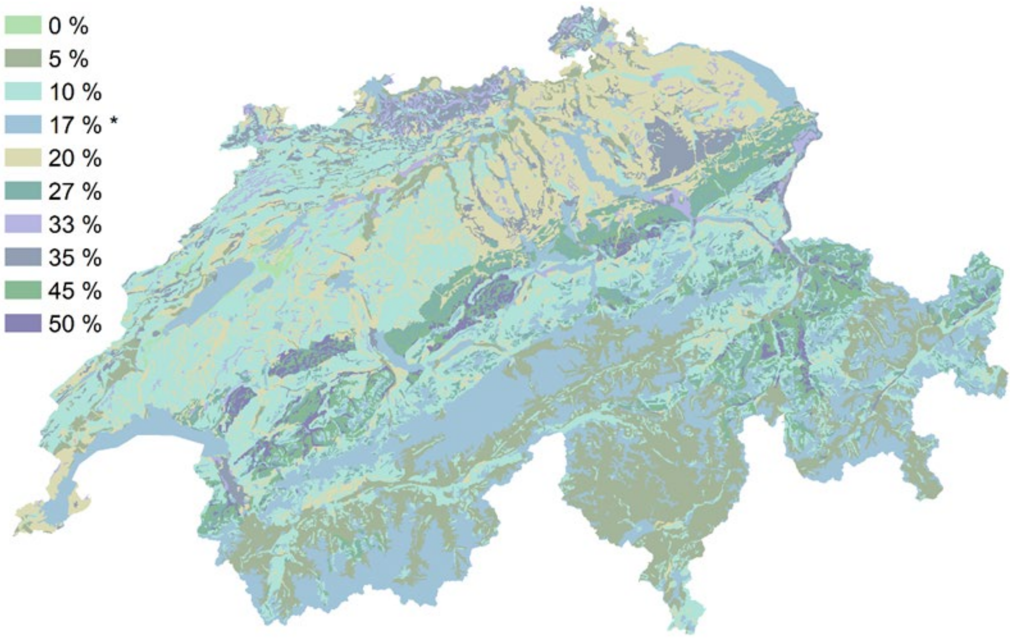

*Figure 21: The ten clay classes as used in this project according to clay content (%), derived from the SSM; * = no information on soil porosity given in the SSM therefore a weighted average clay content was assigned (see text for details).*

Table 6: Soil texture classes derived from the SSM, with corresponding clay content (%).

Soil texture class	Clay %	Clay class
Clay loam	35	S8
Loam	20	S5
Loamy sand	10	S4
Mire	0*	S1
Sand	5	S3
Sandy clay	45	S9
Sandy clay loam	27	S6
Silty clay	50	S10
Silty clay loam	33	S7
Sandy loam	10	S4
Raised bog peat	0*	S1
Other	17*	S2

* = derived values (see text)

2.2.5 Agricultural information

A summary of the agricultural information necessary for the modelling of SOC with RothC is indicated in Table 7.

Table 7: Summary of agricultural information required for the modelling of SOC stocks (overleaf) in this project; numbers in brackets refer to section in this report where more detailed information is given.

Parameter name	**Description**	**Time scale**	**Spatial scale**	**Directly available?**	**Could be derived?**
What grows where?					
crop / grassland type (2.2.5.1)	extent (%) of each crop / grassland category	annual	per stratum	CL: yes GL: partially	GL: also based on unpublished data giving surface of more detailed grassland types (FSO)
cover crops (2.2.5.4)	occurrence of cover crops	annual	per stratum	no	related to main crop, based on recommendations for crop rotations
Plant C inputs					
yield of main crops (2.2.5.2)	the yield (volume per surface area) for each crop	annual	national (per crop)	CL: yes GL: not used	-
by-products	relationship between yield and by-products	not applicable (per crop)	national (per crop)	see 2.1.2	-
straw removal	% of straw removed, per crop	not applicable (per crop)	national (per crop)	see 2.1.2	-
yield of cover crops (2.2.5.4)	the harvest (volume per surface area)	annual	national (per crop)	yes, approximation	-
Soil cover					
soil cover	whether or not a surface is covered with a crop	monthly	national (per crop)	no	using sowing and harvesting dates, and information on cover crop occurrence (above)
sowing date (2.2.5.5)	sowing date, per crop	annual	national (per crop)	yes	-
harvest date (2.2.5.5)	harvest date, per crop	annual	national (per crop)	yes	-
Organic amendments					
OrgAm-C application (2.2.5.3)	amount of OrgAm-C each crop / grassland category receives	monthly	CL: national; GL: per stratum	no	estimated using an OrgAm-model: A function of how much OrgAm is produced, how much farmers apply to different crop groups or to grassland, and the nutrient requirements of individual crop / grassland category
OrgAm-C application, timing	month in which OrgAm is applied	monthly	CL: national; GL: per stratum	no	based on recommended fertilisation dates, sowing and harvesting dates

2.2.5.1 Surfaces (crop and grassland categories)

In this project SOC is being modelled for CL remaining CL and GL remaining GL, since 1990. The cultivation of different crops and grassland categories influences SOC and a variety of these was therefore considered in this project.

Information sources

Data regarding the extent and location of crops and grassland categories each year were based on data from the farm structure survey (FSS)[6], an annual survey forming the basis of subsidies for farmers, carried out by the FSO. This survey is restricted to farmland in the valley, hill and mountain zones (i.e. farmland managed year-round), or the so-called 'utilised agricultural area' (UAA, translated from "landwirtschaftliche Nutzfläche")[7]. The survey covers 98 % of farms in the country and the data are considered to be of very high quality. The spatial resolution of this data set is the municipalities, referring to that municipality in which the farmer is resident. Municipality-level data were obtained by contacting the FSO directly. Data are available for the years 1990, and 1996 to present.

Over 30 (non-woody) **crops** are listed in the FSS. The most abundant 19 crops, including leys, comprising over 99 % of arable land were chosen for this project, as described in Köck et al. (2013). They are listed in Table 9 and their surface shown in Figure 22. Linear interpolation, using data from 1990 and 1996, was used to gap-fill for years 1991 to 1995, with the exception of sunflowers which were assumed to be absent in agriculture until 1994, in accordance with their inclusion in the yield statistics of the Swiss Farmers' Union (SFU, see section 2.2.5.2) from that year onwards.

Six **grassland** types are listed in the FSS. Four of these (extensively-managed meadows, less-intensively managed meadows, pastures and 'other' permanent grassland, the latter comprising of grasslands not eligible for biodiversity-related subsides, mostly mid-intensive and intensively-managed meadows and hereafter referred to as 'intensively-managed meadows') were considered for this project, and together with summer pastures (see below) they comprise over 99 % of agricultural permanent grassland in Switzerland. The other two grassland types (straw meadows, and hay meadows mown annually and in the summer pasture area, SPA) cover a very small surface and were not considered further. Linear interpolation, using data from 1990 and 1996, was used to gap-fill for years 1991 to 1995. The grassland type 'pastures' was sub-divided for this project to 'extensively-managed pastures' and 'intensively-managed pastures'. This was carried out using an unpublished data set obtained from the FSO, which lists the extents of detailed grassland categories at municipal level. Surface information on extensive pastures were available from 1999 onwards. To calculate the area of extensively- and intensively-managed pastures prior to 1999, the mean ratio of these pasture types for the period 1999 to 2003 (which is the same to within +/-5 %) was used.

Information on the extent of the **summer pastures** is not gathered systematically in Switzerland. Summer pastures cover a larger area than the extent of 'permanent grassland' (CC31) located in the SPA, because the CC31 category excludes stony and shrubby grassland (included in other CCs) although some of these are grazed; the location of the CC31 points can therefore not be used to estimate the location of summer pastures. An unpublished estimate of the summer pasture surface was therefore obtained from the FSO; this estimate is also used in the Agriculture sector of Switzerland's GHG inventory. The estimate is a function of the total agricultural surface from the LUS (section 2.2.2) i.e. including farmland in the valley, hill, mountain *and* summer pasture region, minus the UAA (from the FSS, see start of this section). The resulting estimate – used for this project – is an annual time series of farmland in Switzerland *outside* of the UAA, assumed to be summer pastures. The estimate possibly over-estimates the summer pastures however, as the total agricultural surface (from the LUS) includes also hobby farmers whose land is excluded from the UAA of the FSS. Indeed, Herzog et al. (2003) estimated the summer pasture area to be 465,500 ha, based on the 1992-1997 LUS (section 2.2.2); this is 8.6 % lower than the mean estimate for the same time period from the FSO.

The estimated surface area of the six grassland categories used in this project is given in Figure 23 and a summary of the information used to derive extents is given in Table 8.

The relative contributions of grassland and cropland to Swiss agricultural surface is shown in Figure 24. A summary of all crops and grassland categories considered in this project is shown in Table 9.

[6] https://www.bfs.admin.ch/bfs/en/home/statistics/agriculture-forestry/surveys/stru.assetdetail.6993.html; in English, German, French and Italian.

[7] An exception to this are the mown 'meadows in the summer pasture area' to provide fodder for year-round farms (Verordnung über landwirtschaftliche Begriffe und die Anerkennung von Betriebsformen [Landwirtschaftliche Begriffsverordnung, LBV]; SR 910.91). In terms of surface area, these meadows are unimportant (<0.1 % of agricultural grassland surface) and were not considered further.

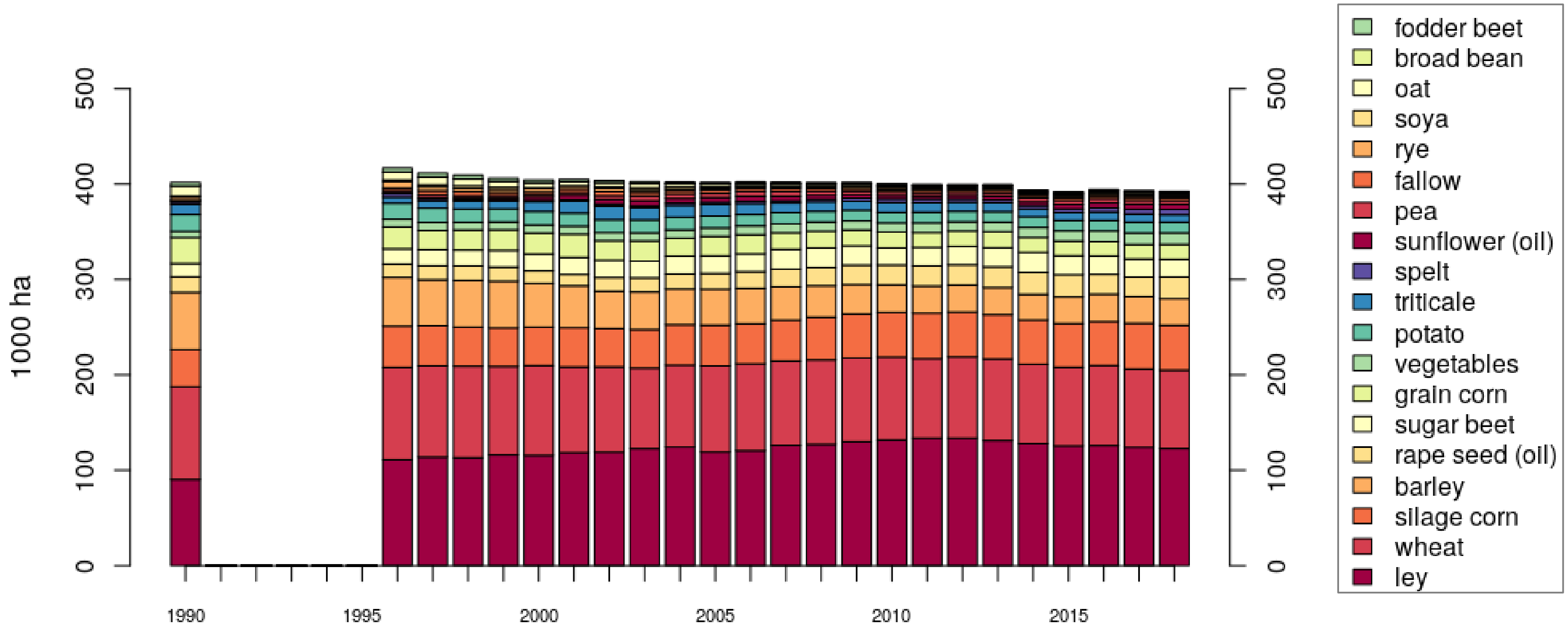

Figure 22: Extent of the most common 19 crops in Switzerland (1990-2018); values for years for which data were unavailable (1991-1995) were gap-filled using data from 1990 and 1996.

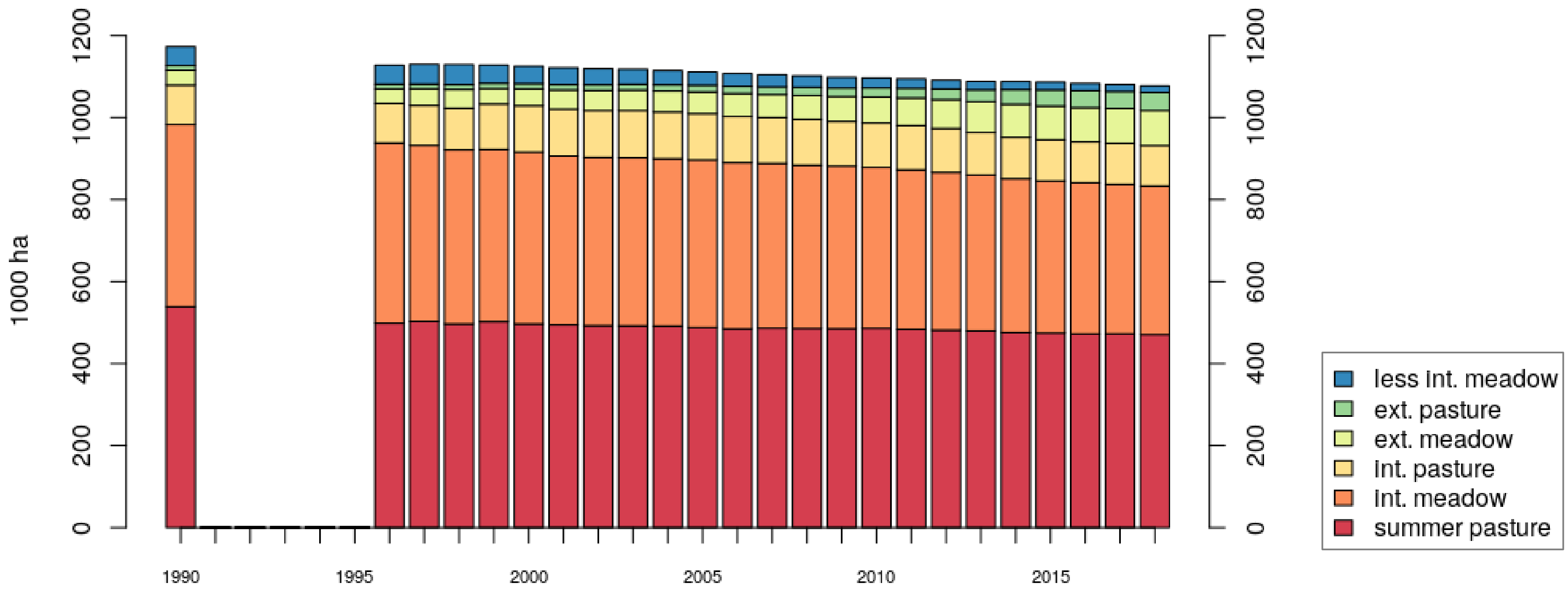

Figure 23: Extent of the six most common agricultural grassland categories in Switzerland(1990-2018) as used in this project; values for years for which data were unavailable (1991-1995) were gap-filled using data from 1990 and 1996.

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Table 8: Summary of the six grassland categories considered for the SOC modelling.

Grassland type	Information on surface obtained from:
extensively-managed meadow	FSS
extensively-managed pasture	FSS ('pasture') and information from FSO on the extent of more detailed grassland categories
intensively-managed meadow	FSS, 'other permanent grassland'
intensively-managed pasture	FSS ('pasture') and information from FSO on the extent of more detailed grassland categories
less-intensively managed meadow	FSS
summer pasture	an estimate derived from the total agricultural surface according to the LUS, and the agricultural surface from the FSS; estimate obtained from FSO (see main text)

The approximate extent of cropland (including leys), year-round managed grassland and summer pasture in Switzerland (for 2017) is given in Figure 24.

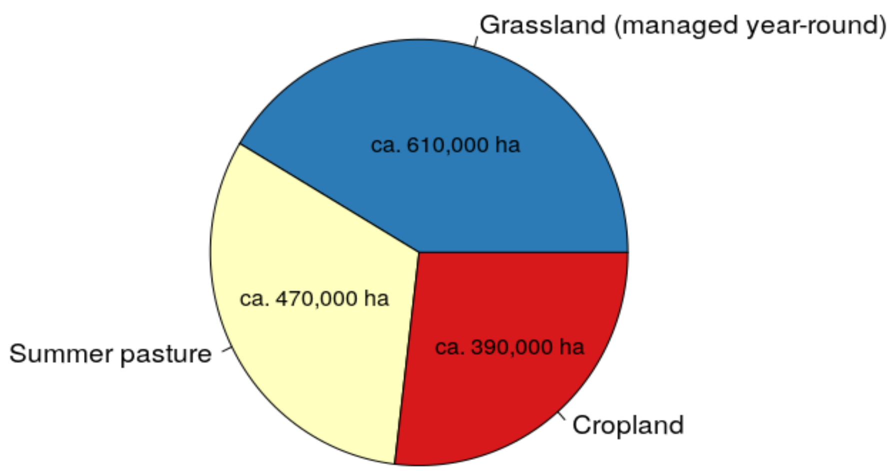


Figure 24: Approximate extent of cropland and grassland in Switzerland.

Table 9: The 19 crops and six grassland categories considered in the project to simulate stocks under cropland (CL) or grassland (GL).

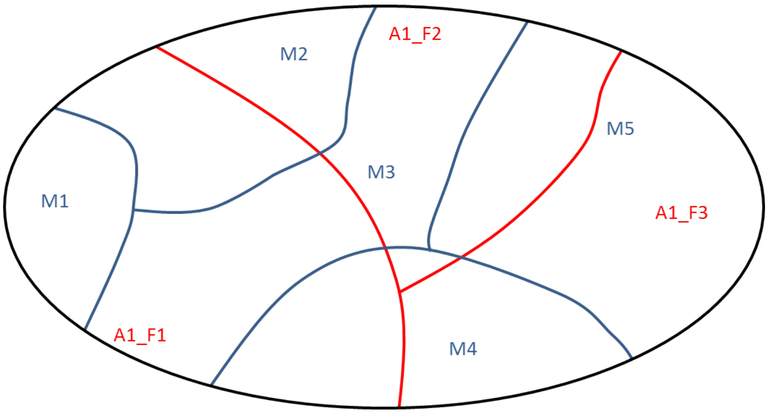
Crop / grassland category	**Code**	**CL / GL**
barley (*Hordeum vulgare* L.)	BA	CL
broad bean (*Vicia faba* L.)	BB	CL
extensive meadow	EM	GL
extensive pasture	EP	GL
fallow	FA	CL
fodder beet (*Beta vulgaris* L.)	FB	CL
grain corn (*Zea mays* L.)	GC	CL
grass-clover ley (main species: *Poa pratensis* L., *Lolium perenne* L., *Festuca pratensis* Huds., *Dactylis glomerata* L., *Trifolium repens* L. and *Trifolium pratense* L.)	GM	CL
intensive meadow	IM	GL
intensive pasture	IP	GL
less intensive meadow	LM	GL
oat (*Avena sativa* L.)	OA	CL
pea (*Pisum sativum* L.)	PE	CL
potato (*Solanum tuberosum* L.)	PO	CL
rape seed (cooking oil) (*Brassica napus* L.)	RA	CL
rye (*Secale cereale* L.)	RY	CL
sugar beet (*Beta vulgaris* L.)	SB	CL
silage corn (*Zea mays* L.)	SC	CL
sun flower (cooking oil) (*Helianthus annuus* L.)	SF	CL
soybean (*Glycine max* (L.) Merr.)	SO	CL
spelt (*Triticum spelta* L.)	SP	CL
summer pasture	SU	GL
triticale (× *Triticosecale* Wittm. ex A. Camus.)	TR	CL
vegetables	VE	CL
wheat (*Triticum aestivum* L.)	WH	CL

Applying data to strata

The spatial resolution of the crop and grassland surface data is the municipality or national scale (summer pastures). The spatial resolution of the upscaling in this project is the strata. Because the strata boundaries do not coincide with municipality boundaries, crop and grassland surfaces had to be assigned to the individual strata. In accordance with legislation[8], all crops and grassland from the UAA (i.e. excluding the summer pastures) were assumed to occur in the (18) strata of the valley, hill and mountain zones (section 2.2.1.1.), whereas summer pastures were assumed to occur in the (six) strata of the summer pasture region (AZ4, section 2.2.1.1.).

For crops and grassland from the UAA, surfaces were assigned to the strata using matrix multiplication (Figure 25): the proportion of each municipality's CL (CC21, for the different crops) or GL (CC31, for the different grassland categories) occurring in each stratum was multiplied by the extent of each crop or grassland category, respectively, in that municipality. The sum of these values across all municipalities gives the extent of each crop or grassland category in each stratum.

The surface of summer pastures was distributed to each of the (six) strata in the summer pasture region proportional to the distribution of CC31 points in these strata. Lacking nationwide information on spatial occurrence, this represents a best estimate.



	M1	M2	M3	M4	M5
A1_F1	1	0.6	0.65	0.42	0
A1_F2	0	0.4	0.45	0.05	0.34
A1_F3	0	0	0	0.43	0.56
sum	1	1	1	1	1

×

	PO	WH
M1	10	3
M2	5	4
M3	8	0
M4	1	7
M5	5	7

➡

	PO	WH
A1_F1	17.9	8.7
A1_F2	7.4	4.3
A1_F3	3.8	8.0

Figure 25: Assigning crop and grassland surfaces to strata using matrix multiplication (example): Municipalities M1 to M5 occur in three strata (A1_F1, A1_F2 and A1_F3) as shown in upper panel (blue lines = municipal boundaries, red lines = strata boundaries), with the proportion of each municipality's surface in each stratum as given in left-hand matrix; M1 to M5 contain potatoes (PO) and wheat (WH), with extent (ha) as given in middle matrix; matrix multiplication is used to obtain the extent (ha) of PO and WH in each stratum, as given in the right-hand matrix.

[8] Legislation: Verordnung über landwirtschaftliche Begriffe und die Anerkennung von Betriebsformen (Landwirtschaftliche Begriffsverordnung, LBV); SR 910.91: https://www.admin.ch/opc/de/classified-compilation/19983381/index.html; in German, French and Italian.

2.2.5.2 Yields of main crops

For the calculation of C inputs from crops (section 2.1.2) annual yield estimates are necessary. For the main crops these were obtained from the SFU, who publish an annual report of agricultural statistics and estimates ("Statistische Erhebungen und Schätzungen über Landwirtschaft und Ernährung", now "Agristat")[9]. The yield statistics are based on the crop harvest divided by its cultivation surface. Information was available for the 19 crops in this project from 1990 to present (except for sunflowers, first yield data: 1994). For wheat and barley weighted averages of the winter- and summer- varieties were taken (using as weightings the extent of winter- and summer- wheat and barley, also available in the Agristat reports) to calculate single wheat and barley yields.
For GL, a constant rate of plant C input was assumed (see section 2.1.2), thus no yield data were necessary.

2.2.5.3 Organic amendments

Organic amendments (hereafter referred to as 'OrgAm', including slurry, poultry manure, solid manure and fresh manure, as well as inputs derived from anaerobic digestion) are a source of C inputs into soils. For RothC the monthly addition of OrgAm-C (per ha) is required, for each stratum, crop and grassland category. As this information is not available for Switzerland, an OrgAm-model was developed as part of this project to derive this information. A number of assumptions were made: Firstly, assuming no OrgAm is imported or exported (but see section 4.3), the amount of OrgAm-C available for agriculture is a function of how much is produced by livestock in a given year. Secondly, different types of OrgAm (e.g. liquid slurry, stacked manure) are preferentially used by farmers for different crops groups or grassland categories. Thirdly, different crops and grassland categories require different amounts of OrgAm. Fourthly, OrgAm requirements of grassland vary also with elevation, meaning the location of the different grassland types is important. Fifthly, different OrgAm types lose C at different rates during storage. Lastly, the summer pasturing of animals effectively moves a considerable amount of OrgAm-C from the year-round pastures up to the SPA, which also needs to be considered in the calculations.

Data sources

Livestock population data were obtained from the data sets used for the Agriculture sector of Switzerland's GHG inventory (FOEN 2019), available in the Agristat reports from the SFU (see section 2.2.5.2). A time series for the period 1990 to present was achieved through a revision and harmonisation of the available data as described in Bretscher and Kupper (2012).
Excretion rates of volatile solids (VS, organic matter) from livestock categories were obtained from values calculated for the Agriculture sector of Switzerland's GHG inventory (FOEN 2019). For cattle, buffalo, camels, horses and deer the VS excretion rates are calculated using equation 10.24 of IPCC (2006b), as a function of gross energy intake (GE), feed digestibility and energy density, ash content of manure and urinary energy (proportion of GE intake). Details are given in (FOEN 2019, pages 296-297 and 279-285). For sheep, swine, goats, mules and asses, poultry and rabbits, the VS excretion rates are taken from IPCC (2006b, tables 10A-7, 10A-8, 10A-9). With the exception of mature dairy cattle, whose milk production (and thus GE intake) has increased over the time period, the VS excretion rates remain constant through time[10].
The **C content of VS** was assumed to be 55 %, in accordance with USDA (2008).
Information relating to various aspects of **OrgAm management** were obtained from the Swiss ammonium model project[11], AGRAMMON (Kupper et al. 2013; Kupper et al. 2018). Within the AGRAMMON project, a farm survey is carried out periodically (2002, 2007, 2010 and 2015), in which farmers provide information on farming practices. Additionally, expert judgement has been used to provide information for 1990 and 1995. The farms chosen for the survey are representative of three different geographic regions of Switzerland and of different AZs (in the valleys, hills and mountains); 3.8 %, 7.2 %, 6.9 % and 14.9 % of livestock units (German: Grossvieheinheit, French: unité de gros bétail) in the country were covered by the four farm surveys, respectively.
The **type of OrgAm** that is produced is determined by animal housing and the manure management system, as described in Richner and Sinaj (2017). Information regarding the proportion of animals (within each livestock category) housed with different manure management systems was obtained from the farm survey from the

[9] https://www.sbv-usp.ch/de/medien/publikationen/statistische-erhebungen-und-schaetzungen-ses/; in German and French.
[10] Annual fluctuations exist in other livestock categories, linked to either changes in proportions of livestock sub-groups or changing age structure over time; these are however small and do not form a trend over time.
[11] https://agrammon.ch

AGRAMMON project. For each of the (six) years represented (see paragraph above), the proportion of livestock being held in systems producing liquid slurry, solid manure and liquid slurry together, deep litter or poultry waste (for poultry only) was calculated. The amount of 'fresh manure' was determined based on the time animals spend out at pasture.

Information regarding the **spreading of different OrgAm types** onto broad crops groups or grassland was also obtained from the AGRAMMON project, again based on expert judgement or results from the farm surveys for different years (as above). For each of the (six) years represented, the proportion of slurry, solid manure and poultry waste spread onto a) small-grain cereals, b) corn, c) grassland or d) 'other' crops is given.

Information regarding **which 'other' crops receive OrgAm** was obtained from Flisch et al. (2009) and Aeby et al. (1995): rape seed, potatoes, sugar beet and fodder beet. Crops other than these, cereals or corn, were assumed to receive no OrgAm.

Anaerobic digestion of OrgAm has increased in the last decade in Switzerland. It represents a removal of OrgAm from agriculture, but also a source of C to agriculture, in the form of digestate, which comprises the remains of the original OrgAm as well as the co-substrate (from non-agricultural sources). Net C removal from farms (accounting for both these flows) is estimated annually for the Agriculture sector of Switzerland's GHG inventory for the period since 1990 (FOEN 2019, chapter 5.3.2.2.3), utilising also information on the amount of the liquid and solid digestates re-introduced to farms (from Kupper et al. 2018). These estimates were used in this project.

The annual movement of livestock to the **SPA** represents a considerable movement of fresh manure within the country. Data regarding the number of different livestock units *moving up* to the summer pastures (1999 onwards) were obtained directly from the FOAG. Data regarding the number of different livestock units *being received* by summer pasture farms (2004 onwards) were also obtained directly from the FOAG. Averages of values since 1999 or 2004 were used to populate the years prior to 1999 or 2004, respectively. The spatial resolution of both data sets is the municipality, and the movement of livestock for the most important livestock categories only (bovids, equids, sheep and goats, and swine) were considered.

Information on the **duration of summer pasturing** was obtained from the Agristat reports from the SFU (see section 2.2.5.2). The average duration of the summer pasturing from 1975 to 2006, 89 days, was used in this project.

Information on annual **straw production**, which forms a large component of some OrgAm types, was obtained from the annual reports of agricultural statistics and estimates from the Agristat reports from the SFU (see section 2.2.5.2). Data are available for the period 1990 to 2006. A linear extrapolation (using values 1990 to 2006) was used to obtain straw production since 2007.

Information on the **rate of C lost during storage** (as a % of the OrgAm-C at the beginning of the storage term) was obtained from published studies where the *in situ* loss of OrgAm-C during storage had been investigated; studies in the temperate zone only were considered. In total, three studies representing 9 data points (slurry), three studies representing 22 data points (stacked manure), three studies representing 7 data points (deep litter), two studies representing 4 data points (poultry waste) and one study representing a single data point (fresh manure) were used (Table 10).

Table 10: Studies used to estimate OrgAm-C loss during storage as well as the % loss of OrgAm-C loss calculated for each OrgAm type (for description of calculation see 'step 6' below).

Liquid slurry**, 13 % loss**	Deep litter**, 24 % loss**
Møller et al. (2004)	Sommer and Dahl (1999)
Wood et al. (2012)	Sommer (2001)
Patni and Jui (1987)	Hao et al. (2004)
Stacked manure, 23 % loss	**Poultry waste, 18 % loss**
Tiquia et al. (2002)	Penn et al. (2011)
Chadwick (2005)	Warren et al. (2008)
Larney et al. (2008)	**Fresh manure, 28 % loss**
	Penttilä et al. (2013)

Information on the **relative nutrient requirements** of individual crops and grassland categories was obtained from the fertiliser guidelines (Richner and Sinaj 2017), using nitrogen (N) requirements, typical yields, and typical livestock unit capacity as proxies for crops, meadows and pastures, respectively. For crops, a set of single nutrient requirements is provided for the whole country. Relative nutrient requirements were thus calculated for this project, irrespective of stratum. On the contrary, for grassland, nutrient requirements are given for different elevation classes and these were accounted for in the OrgAm model: The yields / livestock units of the elevation class ≤ 500 m were assigned to the valley zone, those of the class 700 m to the hill zone, and those of the classes 900 m and 1,100 m to the mountain zone (elevation classes as given in Richner and Sinaj 2017). It is assumed summer pastures receive manure only from those animals grazing there. The mean yields of 'mid-intensive meadows' and 'intensive meadows' (categories from Richner and Sinaj 2017) were used applied to the 'intensive meadows' grassland category of this project (section 2.2.5.1). Yields of 'less-intensive meadows' and 'extensive meadows' were assigned to the grassland categories less-intensive- and extensive meadows, respectively. The mean livestock unit capacity of intensively-managed, mid-intensively managed and less-intensively managed pastures were assigned to the 'intensive pastures' category (section 2.2.5.1) and the livestock unit capacity of 'extensively-managed pastures' was assigned to that category. For meadows and pastures, additional legislative limits to fertilisation were also accounted for, as shown in Table 11.
Information on the **fertilisation of individual crops and grassland categories** with different OrgAm types, as well as **typical dates for fertilisation** (used to deduce typical **duration of OrgAm storage**) was obtained from Flisch et al. (2009), Flückiger et al. (2008), Sägesser and Weber (1992) and Aeby et al. (1995).

Table 11: Summary of fertiliser regime of the six grassland categories.

Grassland category	Fertiliser limits
extensively-managed meadow	No fertilisation, in accordance with legislation[12]
extensively-managed pasture	No OrgAm (except that from grazing animals), in accordance with legislation[12]
intensively-managed meadow	Relative nutrient requirements an average of those for 'intensively-' and 'mid-intensively' managed meadows; requirements differ by strata, according to elevation as given in Richner and Sinaj (2017); grazing assumed in Autumn
intensively-managed pasture	Typical (relative) livestock unit capacity average of that for 'intensively-', 'mid- intensively', and 'less-intensively' managed pastures; livestock unit capacity differs by strata, according to elevation as given in Richner and Sinaj (2017)
less-intensively managed meadow	Relative nutrient requirements differ by strata, according to elevation as given in Richner and Sinaj (2017); fertilisation limited to stacked manure and deep litter, and to equivalent of 30kg N ha^{-1} yr^{-1} once a year in accordance with legislation[12]; grazing assumed in Autumn
summer pasture	No OrgAm (except that from grazing animals) assumed, roughly in accordance with legislation[12]

Calculations (the OrgAm-model)
All calculations pertaining to CL and GL, other than the summer pastures, were carried out for strata in valley, hill and mountain zones; calculations pertaining to summer pastures were carried out for strata in the summer pasture zone (AZ4). The OrgAm-model estimates the annual OrgAm-C application rate (t C ha^{-1}) for each crop or grassland category and for each stratum. Figure 26 shows the outline of this model and the circled numbers in that figure refer to the 'steps' in the descriptions below.
The OrgAm-model calculates the amount of OrgAm-C available in the country, based on herd sizes and excretion rates, accounting for losses due to storage, (net) losses due to aerobic digestion for energy, and straw production. The movement of OrgAm out of the year-round agricultural zones to the summer pastures is accounted for. The

[12] Verordnung über die Direktzahlungen an die Landwirtschaft (Direktzahlungsverordnung, DZV); SR 910.13: https://www.admin.ch/opc/de/classified-compilation/20130216/index.html; in German, French and Italian.

resulting amount of OrgAm-C available thus changes annually. This pool of OrgAm-C is then ‘applied’ to different crops and grasslands (in different strata) according to: which OrgAm types tend to be applied onto which crop groups / grassland category, which crops typically receive OrgAm at all, the nutrient requirements of individual crops / grassland categories (the latter also according to elevation), and – for summer pastures – the distribution of summer grazers.

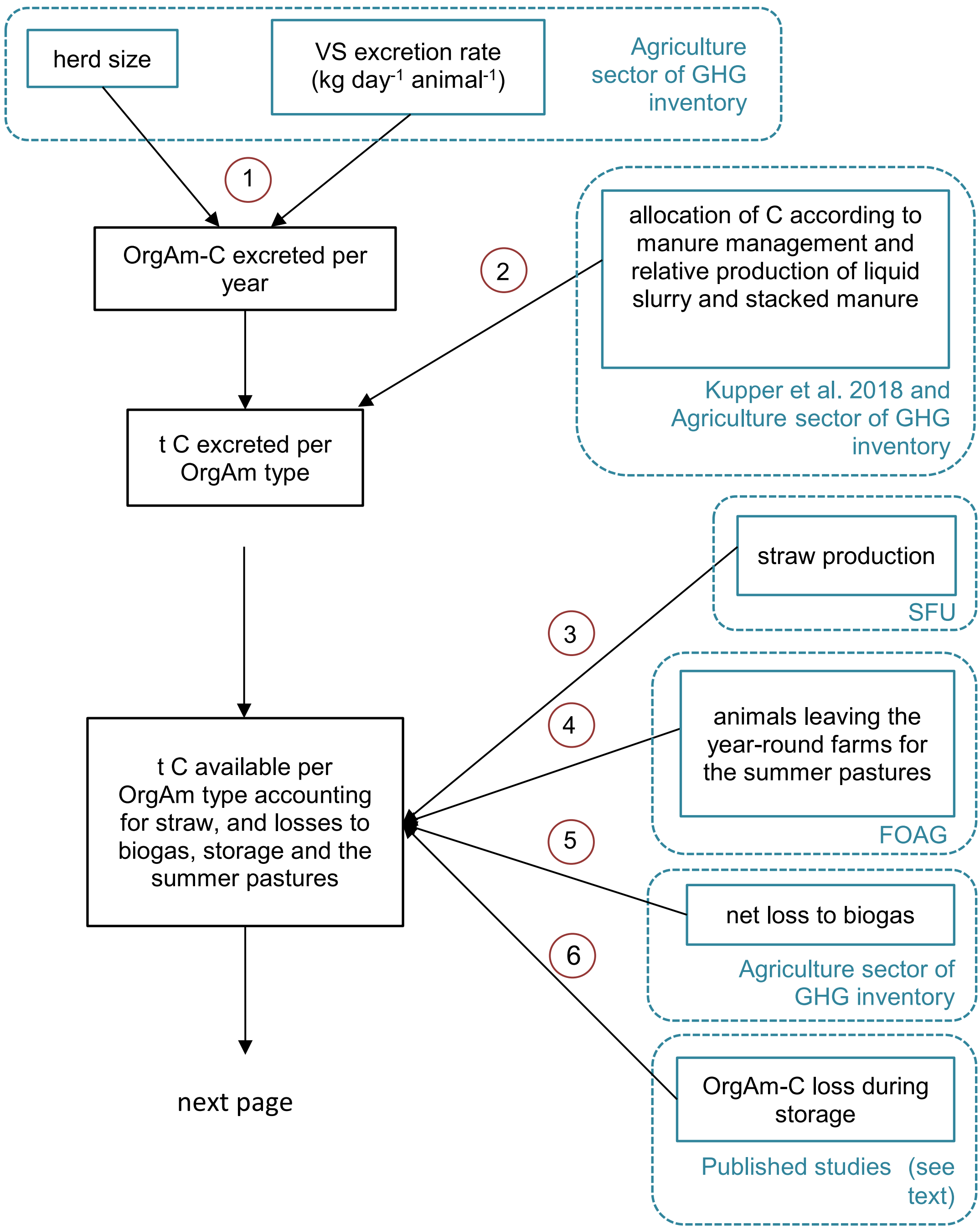
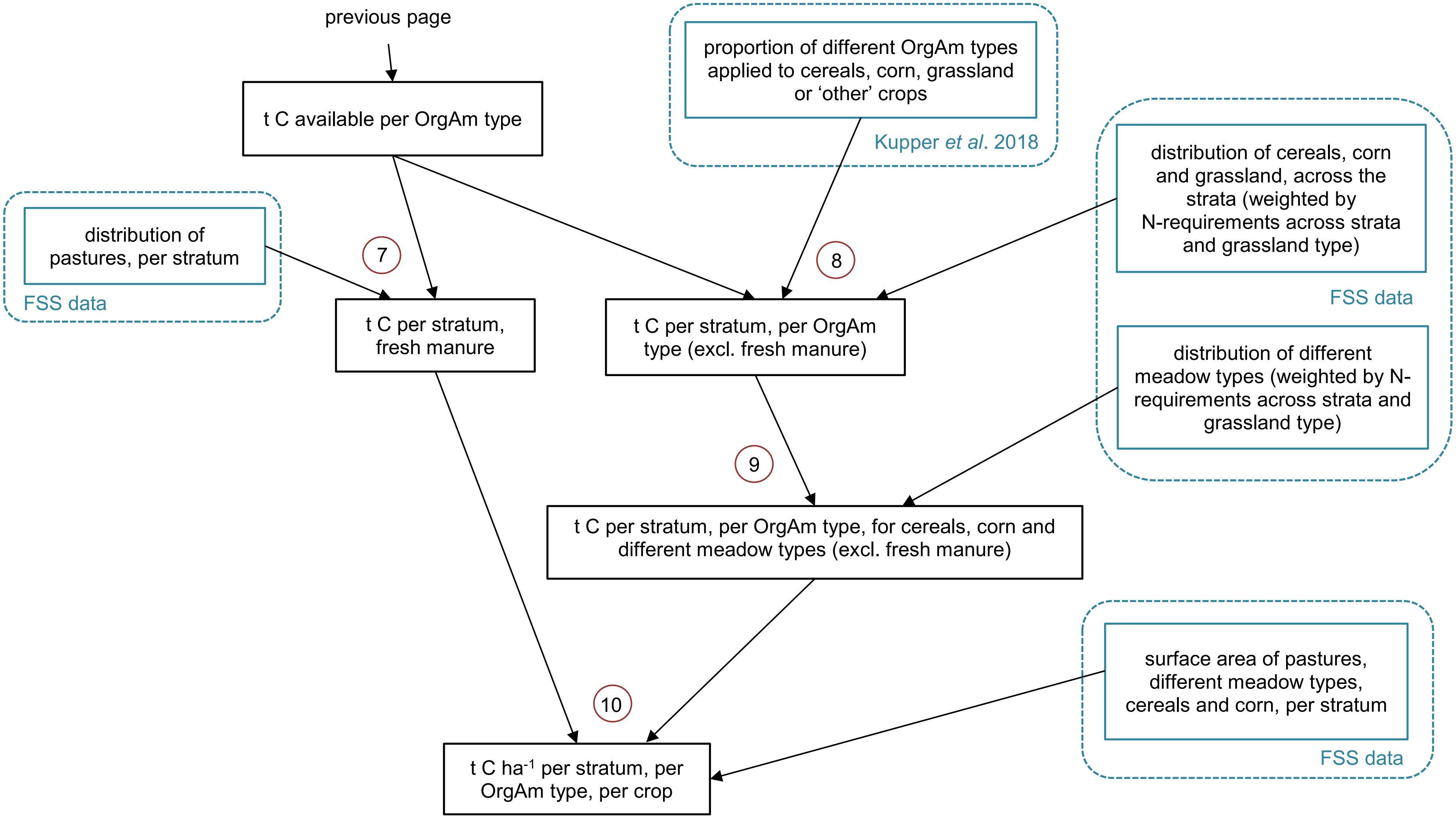


Figure 26: Overview of OrgAm-model to calculate annual OrgAm application rates (t C ha^{-1} yr^{-1}) per crop or grassland category and per stratum; blue boxes depict data sets obtained for this project (data source given in blue text); black boxes depict data sets derived in this project; digits in circles are 'steps', referred to in the main text; unless otherwise stated all calculations were carried out per year, for the period 1990 to present. Figure continues on next page.


previous page
t C available per OrgAm type
proportion of different OrgAm types applied to cereals, corn, grassland or 'other' crops
Kupper et al. 2018
distribution of cereals, corn and grassland, across the strata (weighted by N-requirements across strata and grassland type)
FSS data
distribution of pastures, per stratum
FSS data
7
t C per stratum, fresh manure
8
t C per stratum, per OrgAm type (excl. fresh manure)
distribution of different meadow types (weighted by N-requirements across strata and grassland type)
9
t C per stratum, per OrgAm type, for cereals, corn and different meadow types (excl. fresh manure)
surface area of pastures, different meadow types, cereals and corn, per stratum
FSS data
10
t C ha-1 per stratum, per OrgAm type, per crop

Step 1: Livestock population and VS excretion rates were multiplied to obtain an annual amount of C excreted from different livestock categories, assuming 55 % C content of VS. Calculation from Agriculture sector of Switzerland’s GHG inventory.
Step 2: Information on manure management (= animal housing) of different livestock categories was combined with the total OrgAm-C excreted to calculate the annual OrgAm-C excreted, *per OrgAm type*. The manure management system ‘cattle housing producing stacked manure’ also produces liquid slurry. OrgAm-C was thus allocated to both liquid slurry and stacked manure, using information on the typical VS concentrations of these two OrgAm types, as well as the typical volumes of slurry and stacked manure produced for each animal housing type (tie-stall or loose housing), both according to Richner and Sinaj (2017). Calculation from Agriculture sector of Switzerland’s GHG inventory.
Step 3: Straw-derived C was added to the deep litter ‘pool’ of the available OrgAm-C.
Step 4: Information on the number of livestock units leaving the UAA for the summer pastures was combined with their VS excretion rates (of the different livestock categories) and the duration of summer grazing to estimate the amount of OrgAm-C moving up to the SPA each year. This was deducted from the (total) amount of OrgAm-C available for the valley, hill and mountain zones.
Step 5: The (net) amount of OrgAm-C lost to anaerobic OrgAm digestion (calculation from the Agriculture sector of Switzerland’s GHG inventory) was deducted from the OrgAm-C pool of the valley, hill and mountain zones.
Step 6: The OrgAm-C lost due to storage was deducted from both OrgAm-C pools (the pool available for the valley, hill and mountain zones and the summer pasture pool). For each of stacked manure, slurry and deep litter, the % of C lost during storage from published experiments (see ‘data sources’) was modelled as a function of (log-transformed) storage time, resulting in a statistical model for each OrgAm type. The two coefficient estimates – the intercept and the log(time) coefficient – from each model were used to calculate a OrgAm-C loss (%) for each OrgAm type, assuming a OrgAm storage duration of 1.5 months (corresponding to four OrgAm applications per year). For poultry waste, all four data points from the published studies resulted from ca. 60 days storage and therefore the mean of these was used. For fresh manure, no data were found on the C loss from fresh manure remaining on the field. Penttilä et al. (2013) showed that after ca. 50 days the CO_2 fluxes from field patches with cowpats converge to those of field patches without cowpats. The same logarithmic equation derived for stacked manure storage was therefore used for fresh manure, setting the storage time to 50 days, yielding a C loss of 28 %.
Steps 1 to 6 yielded a national OrgAm-C pool available for agriculture (Figure 27), including summer pastures, taking into account loss due to storage and biogas, and inputs through straw. Steps 7 to 11 (7 to 10 the valley, hill and mountain zones; step 11, SPA) describe how this was distributed across the crops and grassland categories, and across strata.
Step 7: It was assumed that fresh manure falls on pastures. It is however common for farmers to graze animals on meadows for a short period in the autumn. Accordingly, a proportion of fresh OrgAm was deducted from pastures and allocated to meadows (except extensively-managed meadows). The proportion (25 %) was calculated iteratively, so that the quotient C-input / C-output of intensive pastures was ca. 0.28. This value is based on an average of six years of C budget calculations for meadows in Switzerland (Ammann et al. 2007; Ammann et al. 2009) and indicates the productivity of a grassland that can be expected for a given input (in terms of C).
The remaining fresh manure was allocated to intensive and extensive pastures in each stratum, with pastures in lower elevation strata receiving more fresh manure than those in higher strata (based on relative yields, from Richner and Sinaj 2017), and with intensive pastures receiving 3.3 times more OrgAm-C than extensive pastures (based on their relative livestock unit capacities, from Richner and Sinaj 2017).
Step 8: OrgAm-C from slurry, stacked manure, deep litter and poultry waste were allocated to the four categories corn, small-grain cereals, ‘other’ farmland, and grassland, according to information from farmer surveys.
Step 9: The OrgAm-C allocated to each of the four broad categories (step 8) was allocated to individual crops or grassland categories. For the category grassland, OrgAm-C was allocated to leys, intensively- and less-intensively managed meadows (the latter received only deep litter and stacked manure) in different strata, according to the relative yields of these different grassland types at different elevation. For corn, small-grain cereals and ‘other’ farmland, the OrgAm-C of each group was allocated to the relevant individual crops (‘other’ farmland → rape seed, potatoes, sugar beet and fodder beet) according to their relative nutrient requirements.

Step 10: The quantity of OrgAm-C allocated to each crop or grassland category, in each stratum, was divided by the surface of that crop or grassland category in that stratum (section 2.2.5.1), resulting in an annual estimate of OrgAm-C (t C ha^{-1}) per crop / grassland category.
Step 11: (not shown in Figure 26): The OrgAm-C allocated to SU was shared between the (six) strata in the summer pasture region, proportional to the number of livestock units each municipality receives for summer pasturing, accounting for the proportion of each municipality's GL (CC31 points) in each of the summer pasture region strata (analogous to the calculation in 2.2.5.1, sub-section "Applying the data to strata"). The quantity of OrgAm-C allocated to each stratum was divided by the GL surface (CC31 points) in each stratum, resulting in an annual estimate of OrgAm-C (t C ha^{-1}).

OrgAm model results
The amount of OrgAm-C received by crops and grasslands is shown in Figure 28 (crops), Figure 29 (grassland in strata in A1 zone) and Figure 30 (grassland in strata in A3 zone, or A4 zone for summer pastures). Crops not shown were assumed not to receive OrgAm (using information from Aeby et al. 1995; Flisch et al. 2009). Changes in the amount of OrgAm-C received by the different crops or grassland over time (Figure 28 to Figure 30) are due to both changes in OrgAm-C production (largely due to change in herd sizes), changes in the types of OrgAm that are produced, and changes in the proportion of OrgAm that farmers spread over different crop groups / grassland (e.g. cereals received a greater proportion of OrgAm in recent years). The trends of OrgAm-C received by potatoes, rape seed, fodder beets and sugar beets are almost parallel; these crops comprise the 'other' crops that – together – receive a certain proportion of OrgAm according to the farmer surveys.

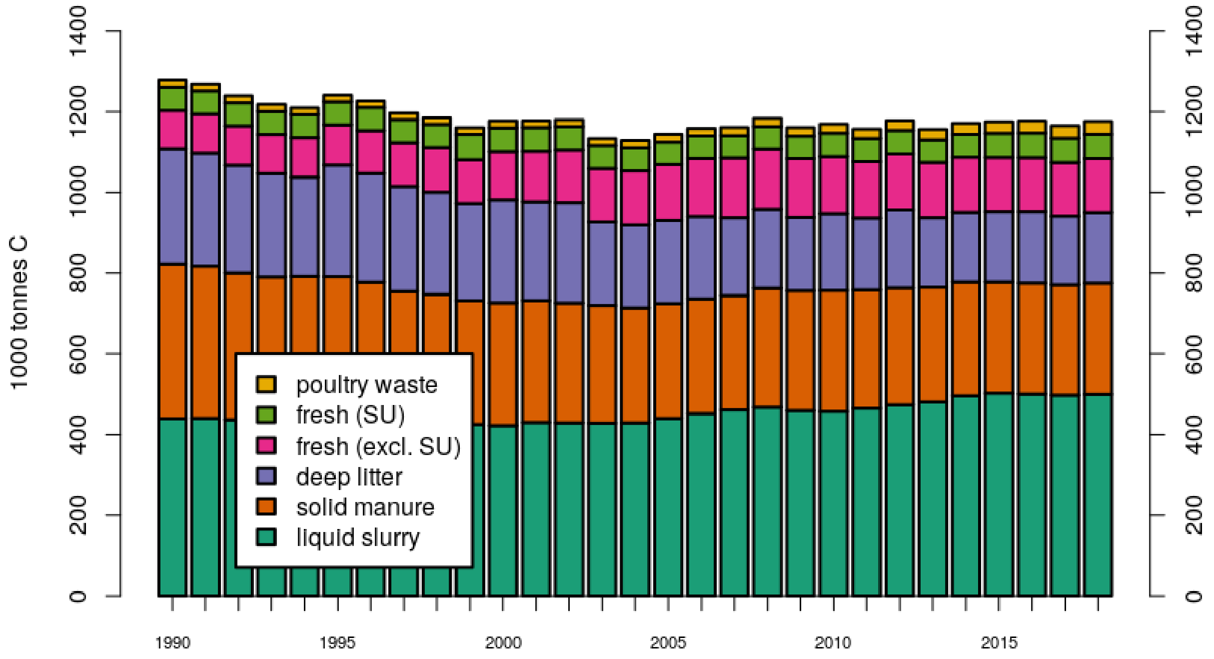


Figure 27: Total OrgAm-C availability (1990-2018) as calculated by the OrgAm model, as a function of that produced, incorporating losses and inputs from anaerobic digestion, losses due to storage, and inputs from straw; SU = summer pastures.

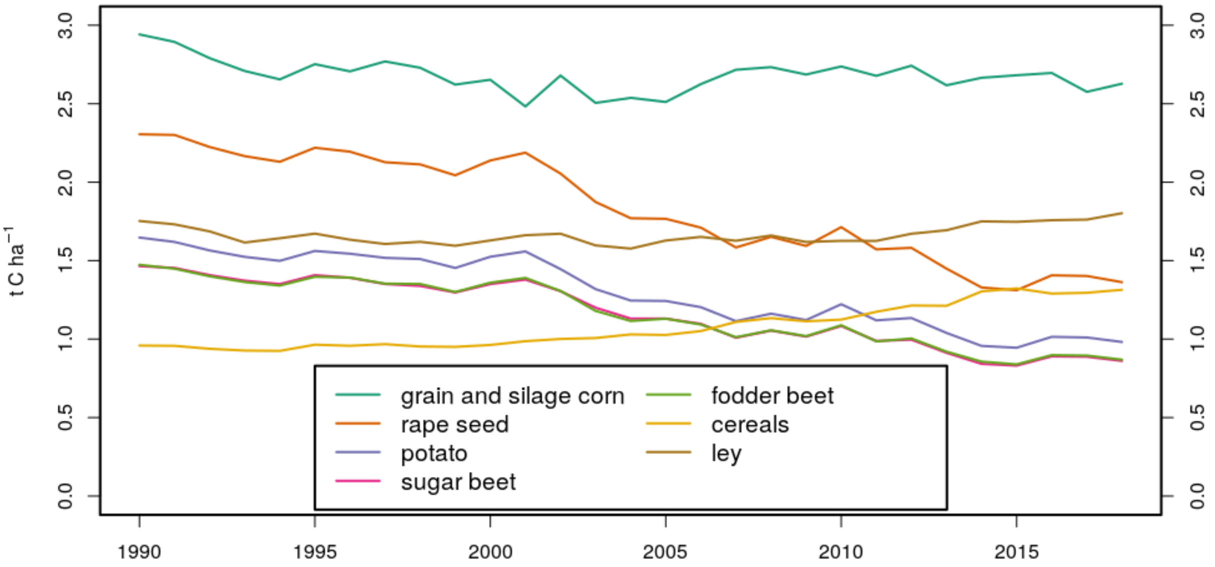


Figure 28: OrgAm-C application to crops (1990 to 2018) as calculated by the OrgAm-model; crops not listed assumed not to receive OrgAm.

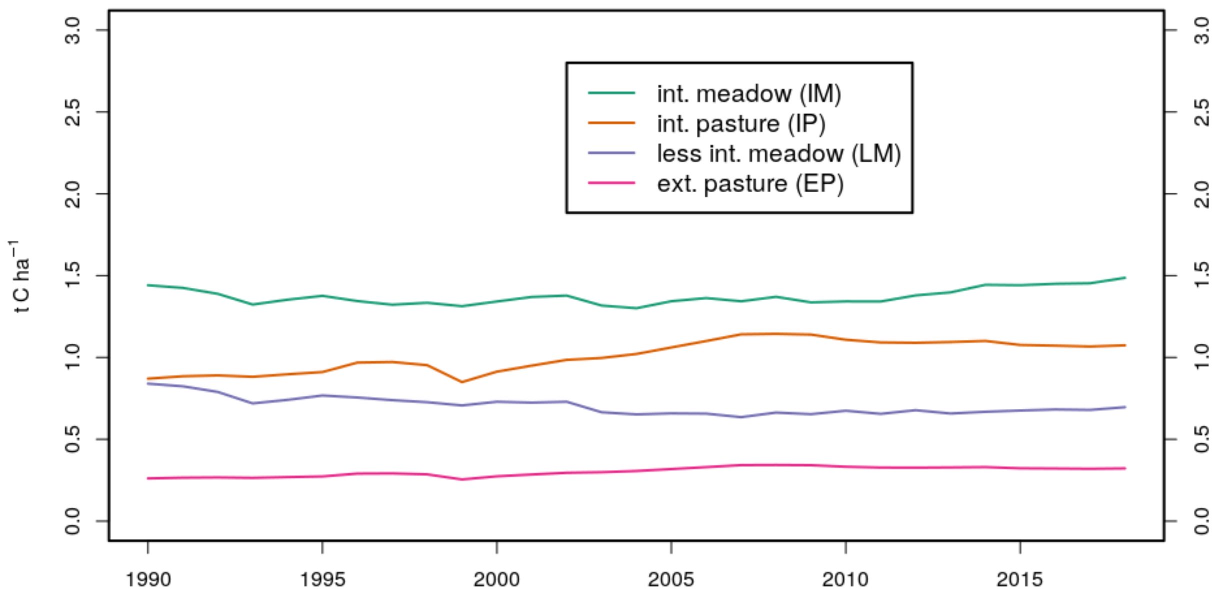


Figure 29: OrgAm-C application to lowland grassland (strata in AZ1, 1990 to 2018) as calculated by the OrgAm-model; extensively-managed meadows assumed not to receive OrgAm, and summer pastures do not occur in AZ1.

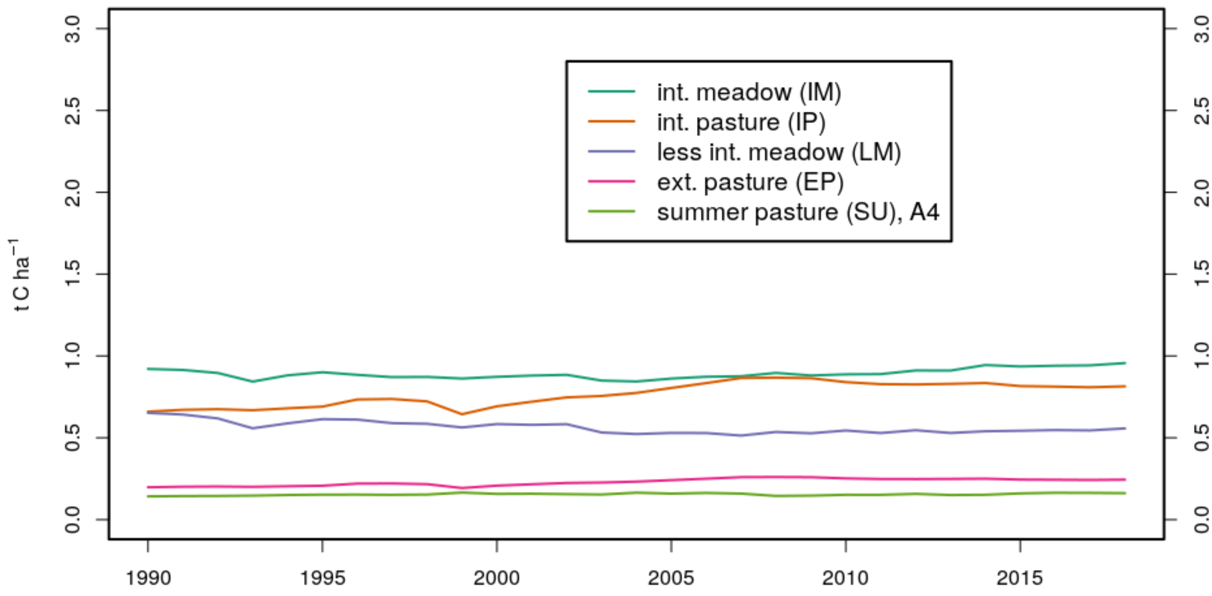


Figure 30: OrgAm-C application to upland grassland (strata in AZ3, except for summer pasture in AZ4, 1990 to 2018) as calculated by the OrgAm-model; extensively-managed meadows assumed not to receive OrgAm.

Control and verification of OrgAm-model

The OrgAm-model was checked in several ways. Firstly, the national OrgAm-C availability was compared to the (national) OrgAm-N application as calculated for the Agriculture sector of the GHG inventory. A conversion from OrgAm-C to OrgAm-N was necessary to do this, calculated using the C:N ratios of different OrgAm types from different animals. OrgAm-C availability relies on i) OrgAm production, ii) that lost to anaerobic digestion, iii) losses of OrgAm-C due to storage and iv) C inputs from straw. Because the former two of these are also calculated for the Agriculture sector of the GHG inventory (Figure 26), this validation effectively checks only losses of OrgAm-C due to storage and inputs from straw. The deviation of OrgAm-N for 2017 between the two estimates is 12.5 %; that is, more N is available according to the OrgAm-model than according to the Agriculture sector. This indicates that either straw inputs into the OrgAm-model are over-estimated and / or that the OrgAm-C losses due to storage are under-estimated. It must be noted however, that the accuracy of this comparison relies on the use of C:N ratios per OrgAm type and per animal category (to convert OrgAm-C to OrgAm-N), and it is possible inaccuracies were introduced in this conversion.

A second check was carried out using the fertilisation guidelines (Richner and Sinaj 2017), where N-recommendations are given for individual crops and grassland categories (the latter across various elevations). These per-crop N-recommendations were compared to the (per crop) OrgAm-N application, calculated using the OrgAm-model and the conversion of OrgAm-C to OrgAm-N, as mentioned above. Because the fertilisation guidelines are used in the OrgAm-model, this verification is not fully independent. However, the fertiliser guidelines i) determine only the *relative* application of OrgAm-C between the crops / grassland categories (not the actual amounts) and ii) do this only partially, as the relative application of OrgAm-C is also determined by the proportion of OrgAm that is spread onto different crops / grassland, as reported by farmers. We therefore consider it a credible validation The validation is however unidirectional: It only checks that the OrgAm-model does not result in crops / grassland being *over*-fertilised. This is because 'under-fertilisation' – i.e. much lower OrgAm application than recommended by the fertiliser guidelines – could be compensated with mineral fertiliser, which is not considered in the OrgAm model. For 2017, N application according to the OrgAm-model was lower than requirements according to the guidelines for all crops (23 to 70 % lower), pastures (81 to 96 % lower) and meadows (34 to 74 % lower), indicating no over-fertilisation.

2.2.5.4 Cover crops

For the purpose of this report, cover crops are those crops planted in between main crops in the rotation, i.e. including catch crops, green manure, green fodder but excluding grass-clover leys. The use of cover crops in Switzerland is quite widespread, in part because they have been promoted as a form of soil protection in legislation[12] since 1998. Their relevance to the SOC modelling is that they represent a plant C input and this can be substantial if they remain on the field as a green manure. The information required for this project is their occurrence in combination with each main crop, their yield, as well as information on whether they are harvested or remain on the field.

Estimating the extent of cover crops

The use of cover crops is not systematically monitored at the national scale in Switzerland. For this project, their use was deduced using the guidelines for crop rotations (Vullioud 2005). There, recommendations are given for each 'pre-crop' and 'main crop' combination, including i) whether or not that combination is suitable, and ii) whether or not a cover crop is recommended for that combination. The probability of a crop being preceded by a cover crop was calculated for the 19 (main) crops considered in this project, as follows: From the crop rotation guidelines (Vullioud 2005), crop combinations considered 'ok', 'good' or 'very good' were considered, only. In a first step, for each main crop, the total area (in ha, in 2014, using data from the FSS, section 2.2.5.1) of preceding crops resulting in a crop combination *requiring a catch crop* was calculated. In a second step, for each main crop, the total area of preceding crops resulting in a crop combination *requiring no catch crop* was summed. For each (main) crop, the first summed value was divided by the second summed value, resulting in the probability of that main crop being preceded by a catch crop. This probability thus takes into account the recommendation of cover crops for each crop combination, as well as the relative occurrence of each crop combination. The results are shown in Table 12 and were used for this project.

These probabilities were validated using data from a further data set, the agri-environmental indicators (AEI). The AEI monitoring forms part of the Agricultural Monitoring Programme[13], as mandated by the FOAG. The AEI data set contains detailed field-specific information on farming practices from ca. 250 to 300 farms, since 2009 (data from 2009 to 2015 were used for this project). The farms join the AEI network on a voluntary basis, for a small financial compensation. The farming practices recorded include the sowing of cover crops and whether these remain on the field or are harvested. The field-specific AEI data were used to list the number of cases where a main crop was preceded by a cover crop *or not*. Cover crop use for barley, fodder beet, grain corn, pea, potato, rape seed, rye, sugar beet, silage corn, sunflower, spelt, triticale and wheat and could be evaluated. It was shown that with the exception of fodder beet, AEI farmers plant cover crops as much as or more frequently than was calculated using the crop rotation guidelines (Table 12). This validation showed that i) best-practice recommendations are generally being followed by AEI farmers, and ii) the AEI farmers use cover crops slightly more than the recommendations state. Given the voluntary nature of the AEI participation however, it is possible that AEI farmers are particularly progressive, working even beyond best practices (i.e. using cover crops more than necessary). This validation was thus unidirectional and we consider the apparent over-use of cover crops by AEI farmers – in comparison with our calculations based on the crop rotation recommendations – unproblematic.
The information deduced from Vullioud (2005) assumes that farmers use cover crops where this is necessary in the rotation and therefore relates especially to the situation *since* 1998 (since then farmers have been required to carry out such measures in order to obtain subsides). No information has been found regarding the use of cover crops prior to 1998. Due to lack of other information, the use of cover crops in association with different main crops (as estimated above) was assumed to apply to the whole time period (1990 to present). It is possible that this assumption leads to an over-estimate of their use prior to 1998 but we have no information to say otherwise or by how much.
The date of first C input to soil from cover crops was set 3 months after the harvest date of the main crop, except for crops harvested in October, where the first C input was set to December. Dates for harvest of cover crops was 4 months after first C inputs.

Green manures vs. green fodder
Cover crops can be grown to be harvested, as a green fodder, or to remain on the field as a green manure. Distinguishing between these is important for SOC modelling because in the former, most above-ground biomass is removed from the field whereas in the latter, it remains. Information from the AEI monitoring programme (see above for details) was used to determine the proportion of cover crops typically harvested or left on the field. For the period 2009 to 2015, between 45 and 57 % (mean = 50 %) of catch crops were grown as green fodder. This proportion (50 %) was incorporated into the calculation of plant C inputs (as below) for the whole time series.

Cover crop C inputs
Cover crop yields are not systematically surveyed. We used the reference cover crop yield from the fertiliser guidelines (Richner and Sinaj 2017) as a proxy (green fodder 2.5 t dry matter ha^{-1}, green manure 3.5 t dry matter ha^{-1}).
Because continuous crops rather than rotations are simulated in this project (section 2.2.6), cover crop yields could not be incorporated directly into the SOC modelling. They were therefore incorporated as part of the main crop yield as follows: The cover crop yields were converted to plant C inputs using the Swiss allometric equation (section 2.1.2), assuming either all yield remains on the soil (green manures) or applying the parameters for rape seed (green fodder). These plant C inputs (green manure and green fodder) were averaged, assuming that half of cover crops grown are green manures and half are green fodder (see above), resulting in a potential C input of 0.863 t C ha^{-1} yr^{-1}. For each main crop, the total cover crop plant C input was multiplied by the probability of that main crop being preceded by a cover crop (Table 12), resulting in a maximum C input of 0.44 t C ha^{-1} yr^{-1}. This was added to the soil in five monthly portions of equal size preceding the main crop's plant C inputs.

2.2.5.5 Crop- / grassland-specific parameters

Additional agricultural parameters necessary for SOC modelling with RothC include: sowing and harvesting dates, the month when soil is covered for the first time and the months during which soil is covered (Table 9). These parameters were obtained or derived from Appendix 7a in Nemecek et al. (2005), from Richner and Sinaj (2017),

[13] www.agrarmonitoring.ch

and from Aeby et al. (1995). The distribution of plant C inputs throughout the season was obtained from Gottschalk et al. (2012). Drymatter fractions were obtained from Richner and Sinaj (2017) and the Agristat publications of the SFU.

Table 12: Parameters related to management for main crops and cover crops used for modelling: Month when crop is sown, harvested, when it first covers the soil, when the first input of C occurs, the dry matter fraction, whether a cover crop is assumed, the fraction of cover crops used (see main text for details), the date when cover crop first covers the soil and is harvested; numbers in square brackets are the corresponding values calculated from the AEI data (see main text, not used in simulation); $_s$ = summer crop; $_w$ = winter crop; --- = not applicable.

Crop*	Category	sowing	harvest	First cover	First C input	Dry matter fraction	Cover Crop	Fraction Cover Crop	First C input Cover Crop	Harvest Cover Crop
BA	CL_w	Sep	Jul	Oct	May	0.85	no	0 [0.14]	---	---
BB	CL_s	Feb	Aug	Apr	May	0.85	yes	0.38	Nov	Mar
EM	GL	---	---	---	---	0.2	no	0	---	---
EP	GL	---	---	---	---	0.2	no	0	---	---
FA	CL_s	---	---	---	---	0.2	no	0	---	---
FB	CL_s	Mar	Oct	May	Jun	0.22	yes	0.51 [0.43]	Dec	Apr
GC	CL_s	May	Oct	Jun	Jul	0.85	yes	0.4 [0.67]	Dec	Apr
GM	CL_s	---	---	---	---	0.2	no	0	---	---
IM	GL	---	---	---	---	0.2	no	0	---	---
IP	GL	---	---	---	---	0.2	no	0	---	---
LM	GL	---	---	---	---	0.2	no	0	---	---
OA	CL_s	Feb	Aug	Apr	May	0.85	yes	0.42	Nov	Mar
PE	CL_s	Mar	Jul	Apr	May	0.85	yes	0.41 [0.62]	Oct	Feb
PO	CL_s	Apr	Sep	Jun	Jul	0.22	yes	0.4 [0.60]	Dec	Apr
RA	CL_w	Aug	Jul	Oct	May	0.9	no	0 [0.03]	---	---
RY	CL_w	Oct	Aug	Nov	May	0.85	no	0 [0.19]	---	---
SB	CL_s	Mar	Oct	May	Jun	0.22	yes	0.51 [0.72]	Dec	Apr
SC	CL_s	May	Sep	Jun	Jul	0.32	yes	0.4 [0.62]	Dec	Apr
SF	CL_s	Apr	Sep	Jun	Jul	0.85	yes	0.38 [0.64]	Dec	Apr

SO	CL_s	May	Sep	Jun	Jul	0.85	yes	0.42	Dec	Apr
SP	CL_w	Oct	Aug	Nov	May	0.85	no	0 [0.10]	---	---
SU	GL	---	---	---	---	0.2	no	0	---	---
TR	CL_w	Oct	Aug	Nov	May	0.85	no	0 [0.12]	---	---
VE	CL_s	May	Oct	Jun	Jul	0.145	no	0	---	---
WH	CL_w	Oct	Aug	Nov	May	0.85	no	0 [0.07]	---	---

*BA, barley; BB, broad bean; EM, extensive meadow; EP, extensive pasture; FA, fallow; FB, fodder beet; GC, grain corn; GM, grass-clover ley; IM, intensive meadow; IP, intensive pasture; LM, less intensive pasture; OA, oat; PE, pea, PO, potato, RA, rape seed; RY, rye; SB, sugar beet; SC, silage corn; SF, sunflower; SO, soybean; SP, spelt; SU, summer pasture; TR, triticale; VE, vegetables, WH, wheat

2.2.6 Simulating crop rotations

Crops in Switzerland are mostly farmed on a rotation basis, meaning a field will be used to grow a different main crop each year. Indeed, a suitable crop rotation forms a prerequisite for farms to receive subsidies, with the aim of reducing crop pests and diseases, soil erosion and compaction, and leaching of pesticides and fertilisers[12, art. 16]. Given the monthly resolution of RothC, the best option – conceptually – to simulate SOC stock changes would be to simulate individual rotations for the period 1990 to present. This approach is however difficult because representing the potentially large range of crop rotations possible in Switzerland would mean carrying out (for each stratum / clay class combinations) a large number of simulations. This is due to i) there being a large number of important crops in Switzerland (section 2.2.5.1), and ii) there not being a small number of typical crop rotations for which SOC stocks could be modelled. Additionally, simulating crop rotations is technically difficult. A second option might be to simulate SOC stocks for leys, as well as for two dummy crops that represent winter and summer crops. A third option might be to simulate SOC stocks for individual crops and leys, as if they were farmed repeatedly on a given field for the whole time period. Conceptually not ideal, the latter two options are technically easier and thus more realistic to realise in the time frame of this project. A comparison of these three options was therefore carried out to test whether or not the latter two options can successfully model SOC stock changes of crop rotations. Note that this issue affects CL only.

2.2.6.1 Methods

The three options outlined above were compared with RothC: Firstly, simulating crop rotations; secondly, simulating two dummy crops (a winter and a summer crop) and leys; thirdly, simulating continuous crops. All simulations were carried out using the climate conditions (1981 to 2014) for stratum A1_F2 (in the valley region on the central plateau, which has the largest proportion of CL in general), assuming 17 % clay content (weighted average of clay classes). For a given crop, its yield was identical for each year, using the mean yield from 1981 to 2014 (or 1990 to 2014 where this was not available). For a given crop, the OrgAm-C application was also identical throughout, using the OrgAm-C application rate from 2014.

A 30-year crop rotation was created, comprising eleven crops (including leys). The crops occur in the rotation at roughly the same frequency as they are grown in Switzerland, and the rotation follows crop rotation guidelines from Vullioud (2005). This rotation was repeated 29 times, each time with a one year lag (e.g. in rotation 1, winter wheat (WH) occurs in 1990, in rotation 2 WH occurs in 1991, in rotation 3, in 1993 etc.), resulting in 30 rotations, each containing the same eleven crops.

For the first option, each of the 30 rotations was simulated once. For the second option, two dummy crops were created. The summer dummy crop had the average annual yield, average OrgAm-C application and typical other management characteristics (e.g. sowing date) of all the summer crops in the 30-year rotation. The winter dummy was created in a similar manner, but using characteristics typical of winter crops. SOC stocks of soils under each of the dummy crops and the leys (simulated as continuous grassland) were simulated once, resulting in three simulations in total. For the third option, SOC stocks for each of the eleven crops used in the first option were simulated once, using crop yields and OrgAm-C application identical to those used for the simulation of the crop rotations. All options had the same C inputs across the 30 years.

The annual SOC stocks of the simulations were compared as follows: For the rotations, the mean results from the 30 rotations were used directly, yielding a single SOC stock value per year. For the second option, the SOC stocks from the leys and from the two dummy crops were averaged, the results weighted according to the occurrence of leys, winter- and summer-crops in the rotation (leys: 8 / 30, summer crops: 10 / 30, winter crops: 12 / 30). For each year, a single value (SOC stock) was thus obtained. For option three, the SOC stocks from the eleven crops were also averaged, weighting the SOC stocks of each crop according to the occurrence of each crop in the rotation. This again yielded a single SOC stock value per year.

2.2.6.2 Results

The 30 crop rotations yielded annual variability of average 5 t C ha^{-1} since 1985 (the first four years were excluded as the deviation here is small due to identical C stocks at the beginning of the simulations) or just over 10 % of the C stocks (Figure 31), which represents that due to different crops. Simulating dummy winter and summer crops and calculating a weighted average of these (taking leys into account) resulted in an over-estimate of average SOC stocks of the 30 rotations after 25 years (since 1985), by on average 2.12 % (Figure 32). Simulating continuous or repeated crops and calculating a weighted-average of these results in a smaller over-estimate of average SOC stocks of the 30 rotations (again since 1985) of on average 1.01 % (Figure 33).

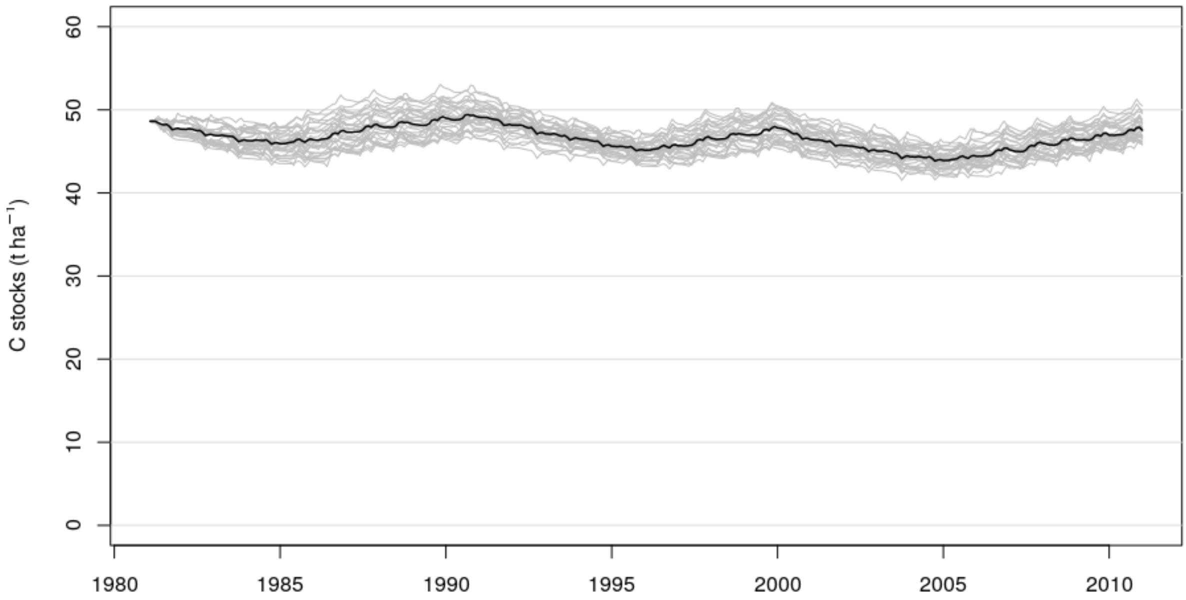


Figure 31: The modelled SOC stocks of 30 rotations (option one, see main text for details) for 1981-2010; grey = the individual crop rotations; black = average across the 30 rotations.

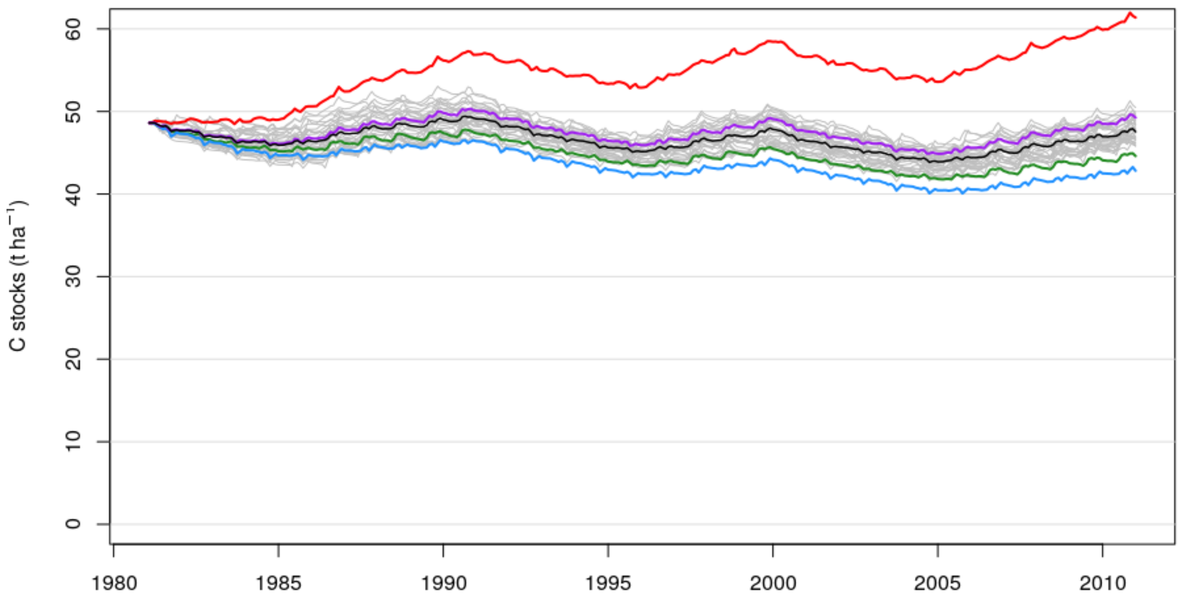


Figure 32: The modelled SOC stocks of dummy crops representing generic summer- and winter-crops (option two, see main text for details) for 1981-2010; grey = the individual 30 crop rotations; black = average across the 30 rotations (grey and black as in Figure 31); red = leys; green = dummy summer crop; blue = dummy winter crop; purple = weighted average of dummy crops and leys.

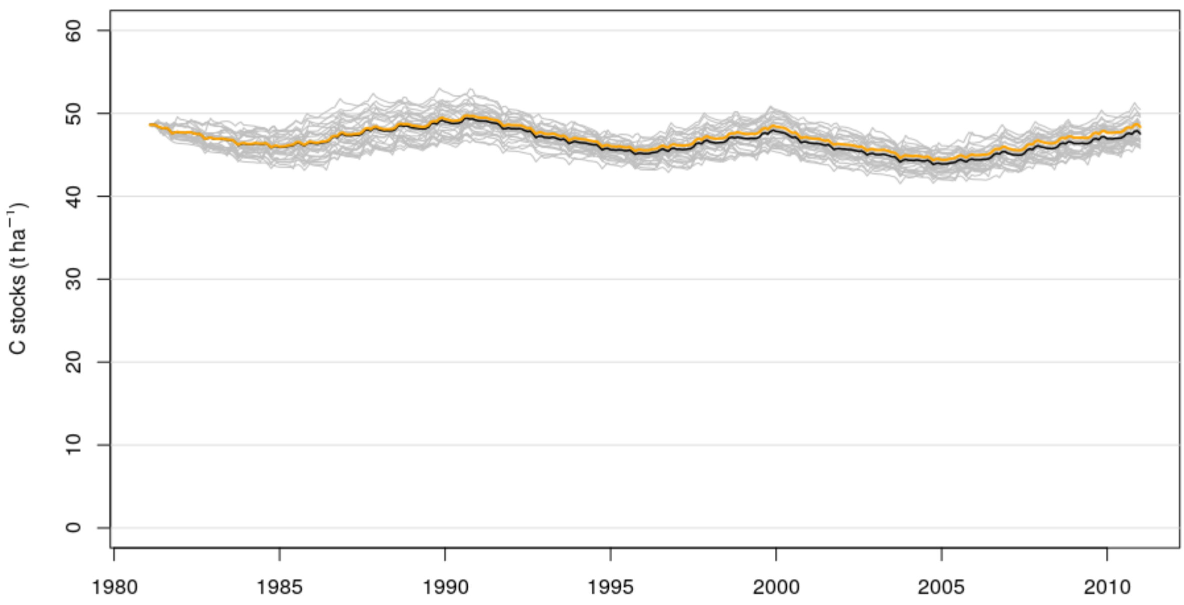


Figure 33: The modelled SOC stocks of continuous crops (option three, see main text for details) for 1981-2010; grey = the individual 30 crop rotations; black = average across the 30 rotations (grey and black as in Figure 31); orange = weighted average of the eleven crops modelled as continuous crops.

2.2.6.3 Implications

The use of either the dummy summer and winter crops, or the modelling of continuous crops both result in a small over-estimate of the C stocks of crop rotations. Simulating continuous crops is however preferred as the over-estimation is smaller (ca. 1 % versus ca. 2 %). It must be remembered that modelling SOC stocks using continuous crops is a compromise: conceptually it is not ideal, however i) its implementation in this project is more realistic; ii) the over-estimation of C stocks is small and because it is relatively stable through time, it should not strongly influence SOC stock change estimates; and iii) it avoids the introduction of variation due to different crop rotations (Figure 31).

2.2.6.4 Application of continuous crops in modelling

Based on the outcome of the test described in the above section, it was decided to simulate continuous crops. Thus, each crop was modelled separately, for each stratum and clay class combination. Weighted averages of these simulations were then calculated, using the relative frequency of each crop (allowed to vary each year) and clay class (constant across years) in each stratum. Leys were modelled as continuous grassland.

2.2.7 Initial SOC and pool distribution

For simulations of SOC time series with RothC, the initial SOC stock and size of the different SOC pools need to be determined. The most common approach is to run a so-called spin-up for the period before the actual simulation starts. This is a long simulation (10'000 years is recommended) with pre-defined (and usually inter-annually constant) C inputs and climate data that is run until SOC stocks reach an equilibrium. This approach was used for long-term experiments, as management information prior to the start of the experiment was available (section 2.1.3). This approach is however computationally intensive and we lack the necessary information for each stratum. An alternative approach was therefore tested, in which the SOC stock is derived from a function that relates SOC to environmental parameters, and in which the distribution of SOC pools is determined by a pedo-transfer function. Based on these initial conditions, simulations were run for the years 1975 to 1990, so called 'historic simulations', to incorporate actual management practice before 1990.

2.2.7.1 Calculating SOC stocks

The RothC simulations require initial SOC stock values. There is no data set covering the whole country containing this information and SOC stocks were therefore estimated using methods outlined in Leifeld et al. (2003) and Leifeld

et al. (2005), using the parameters clay content, elevation, stone content and depth. This approach was already used to calculate SOC stocks by Switzerland for previous GHG, but it was improved by using the location of CC21 and CC31 points directly to locate CL and GL, respectively. In the previous calculation, a different nomenclature system of the LUS from the FSO (the Arealstatistik 1997 system) was used to infer the location of CL and GL. This could however only be done approximately, firstly because CL and GL in the year-around farming area are not separated in the 1997 FSO nomenclature system, and secondly because the GL category of the CC nomenclature system contains some summer grazing grasslands but not all, and it is unclear which correspond to the different relevant categories of the 1997 FSO nomenclature system.
The stocks calculated here are considered an initial estimate, which should be superseded by more precise and accurate estimates in the future[14].

Input data
Elevation data were obtained from a digital elevation model (spatial resolution 200 m, accuracy in Z dimension 1.5 m [central plateau and Jura] to 3 m [mountainous regions]). **Clay content** was obtained as described in section 2.2.4. **Soil depth** and **stone content** were obtained from the SSM (Häberli 1980). Measured values of clay content, elevation, SOC content (%) or bulk density from soil samples were used to parameterise statistical models relating elevation and clay content to SOC content (%), or to provide typical SOC and bulk density estimates, as described below. These measured values were the same used to estimate SOC stocks in Leifeld et al. (2003) and Leifeld et al. (2005).

Calculation of SOC stocks
Following equations from Leifeld et al. (2005), SOC stocks were calculated as:

$$\mathrm{SOC}_{d1-d2}\ (\mathrm{t\ ha^{-1}}) = \%SOC \times (1 - fs) \times d \times \rho\mathrm{d} \qquad \text{Eqn. 1}$$

where SOC_{d1-d2} is the SOC stock between depths $_{d1}$ and $_{d2}$, $\%SOC$ is the SOC content (%), calculated as detailed below, fs is stone content (proportion, derived from the SSM, Häberli 1980), d is the difference between $_{d2}$ and $_{d1}$ in cm, and ρd is the bulk density of the fine earth, calculated as:

$$\rho\mathrm{d}\ (\mathrm{t\ m^{-3}}) = 1.49 \times \%SOC^{-0.29} \qquad \text{Eqn. 2}$$

Calculation of SOC stocks in shallow soils (0 to 20 cm)
The SSM identifies shallow soils as 10 to 30 cm deep. These occur mostly at high elevation in the Alps and (to a lesser extent) in the Jura. We assumed that the median depth of these soils is 20 cm. Both GL and CL occur on this soil, the latter less so. Data from 290 (GL) and 253 (CL) soil samples of the upper 20 cm of soil were available (Leifeld et al. 2005) to parameterise models describing SOC content (%) as a function of elevation (GL only) and clay (CL and GL), following Leifeld et al. (2003). For GL SOC content was estimated as:

$$\%\mathrm{SOC} = \mathrm{elevation\ (m)} \times f1 + \mathrm{clay\ (\%)} \times f2 + c \qquad \text{Eqn. 3}$$

where $f1$ = 0.00238 (CI: +/- 0.000216), $f2$ = 0.0392 (CI: +/- 0.0098) and c = 0.38 (CI: +/- 0.39). For CL SOC content was estimated as:

$$\%\mathrm{SOC} = \mathrm{clay\ (\%)} \times f1 + c \qquad \text{Eqn. 4}$$

where $f1$ = 0.0445 (CI: +/- 0.0078) and c = 1.02 (CI: +/- 0.2200). SOC stocks were calculated using equations 1 ($_{d1}$ = 0, $_{d2}$ = 20 cm) and 2.

Calculation of SOC stocks in other soils (0 to 30 cm)
All other soils were considered to be deeper than 30 cm. Both CL and GL occur on these soil. The SOC stock in the upper 20 cm was calculated as described above, and was added to an additional SOC stock for the 20 to 30 cm

[14] Two Federal Office for the Environment (FOEN)-financed projects: Nationwide digital mapping of C stocks in soils for Switzerland's GHG inventory ("Landesweite digitale Kartierung von Kohlenstoffvorräten in Böden für das Treibhausgasinventar Schweiz "); Technical and methodological basis for the digital mapping of soil properties ("Technische und methodische Grundlagen für die digitale Kartierung von Bodeneigenschaften").

layer ("subsoil"), calculated as follows: Following from Leifeld et al. (2005), values of median %SOC and median bulk density from 124 (CL, %SOC), 41 (CL, bulk density), 116 (GL, %SOC) and 19 (GL, bulk density) soil samples from 20 to 30 cm were applied to equation 1 ($_{d1}$ = 20 cm, $_{d2}$ = 30 cm).

Applying SOC information to the strata

The initial SOC stock estimates were calculated for each grid cell of a 200 m × 200 m raster. In order to obtain SOC stock estimates for the 240 strata (combination of 24 strata / 10 clay classes), an approach similar to that used for the meteorological data (section 2.2.3.2) was taken: The initial SOC stocks raster was overlain with the CL and with the GL points (from the CC data set, section 2.2.2.1) and the SOC stock for each CL or GL point was extracted. For each stratum / clay class combination, the mean SOC stock of the CL points and of the GL points occurring within that stratum were calculated. This resulted in two sets of initial SOC stocks for each strata / clay class combination: one relevant for the simulation of SOC in CL soils and one for GL soils.

2.2.7.2 Estimating initial SOC pools

Based on the total initial SOC stocks, the sizes of the five conceptual SOC pools used by the model RothC (section 2.1.1.1) were calculated. For the inert organic matter (IOM) pool, the equation by Falloon et al. (1998) was applied, which is the standard method used by RothC if no ^{14}C measurements are available (Coleman and Jenkinson 2008). It is a rough approximation of IOM based on total organic C (t C ha^{-1}) for surface soils.

$$IOM = 0.049 \times TOC^{1.139} \ (t\ ha^{-1}) \qquad \text{Eqn. 5}$$

Weihermüller et al. (2013) proposed simple pedotransfer functions (PTFs) to calculate the size of the active pools (resistant plant material [RPM], microbial biomass [BIO], humified organic matter [HUM]). The equations also depend on total organic C (TOC) as independent variable and in addition on the clay content in % mass.

$$RPM = (0.1847 \times TOC + 0.1555) \times (clay + 1.2750)^{-0.1158} \qquad \text{Eqn. 6}$$

$$HUM = (0.7148 \times TOC + 0.5069) \times (clay + 0.3421)^{0.0184} \qquad \text{Eqn. 7}$$

$$BIO = (0.0140 \times TOC + 0.0075) \times (clay + 8.8473)^{0.0567} \qquad \text{Eqn. 8}$$

The decomposable plant material pool (DPM) is very small (0.2-1 % of TOC for the long-term experiments) and turns over rapidly. It was therefore assumed to be zero at the start of a simulation.

To validate equations 6, 7 and 8, the size of the three active pools calculated with PTFs were compared with pools calculated by a 10,000 year spin up. This could not be done for the IOM pool, as both approaches use the same equation. The nearly perfect correlation for the most important active pool HUM (Figure 34) suggests that the PTFs by Weihermüller et al. (2013) offer a good and efficient alternative to the estimation with a spin up. This is supported by the good correlations for the much smaller BIO and RPM pools.

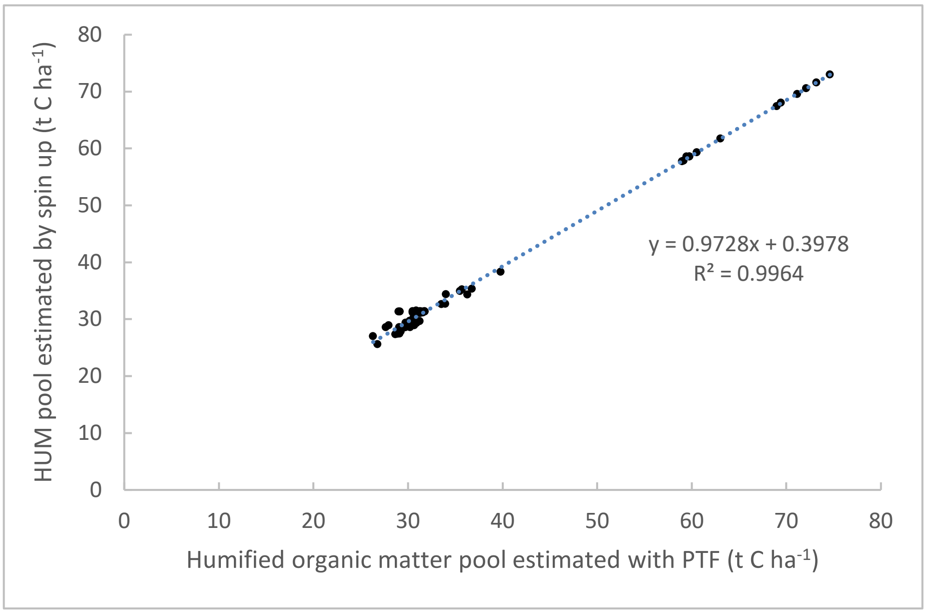


Figure 34: The size of HUM pools for five experimental sites (Balsthal, DOK, Hausweid, Oensingen, ZOFE) estimated with the PTFs from Weihermüller (see main text) or by spin up; each symbol represents a plot.

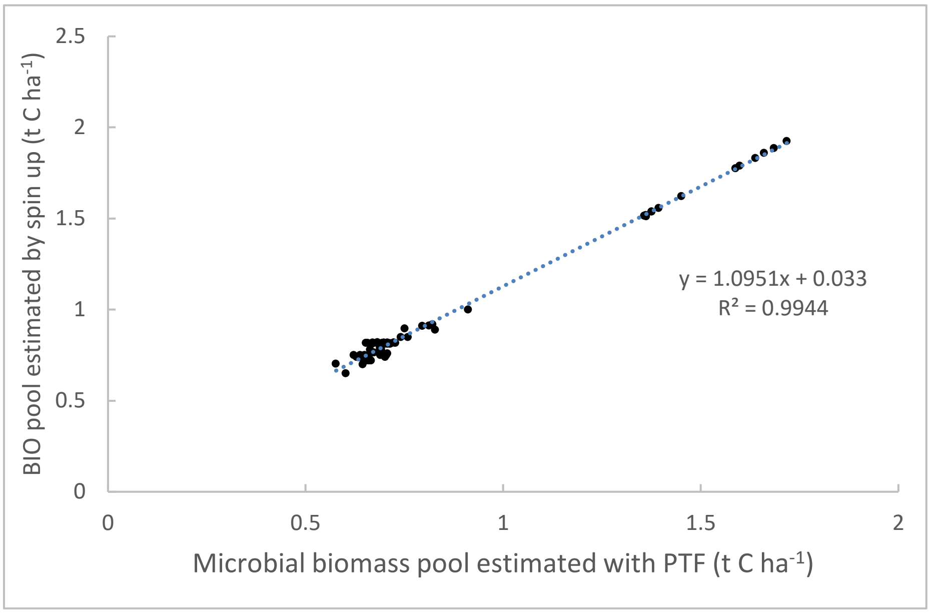


Figure 35: The size of BIO pools for five experimental sites (Balsthal, DOK, Hausweid, Oensingen, ZOFE) estimated with the PTFs from Weihermüller (see main text) or by spin up; each symbol represents a plot.

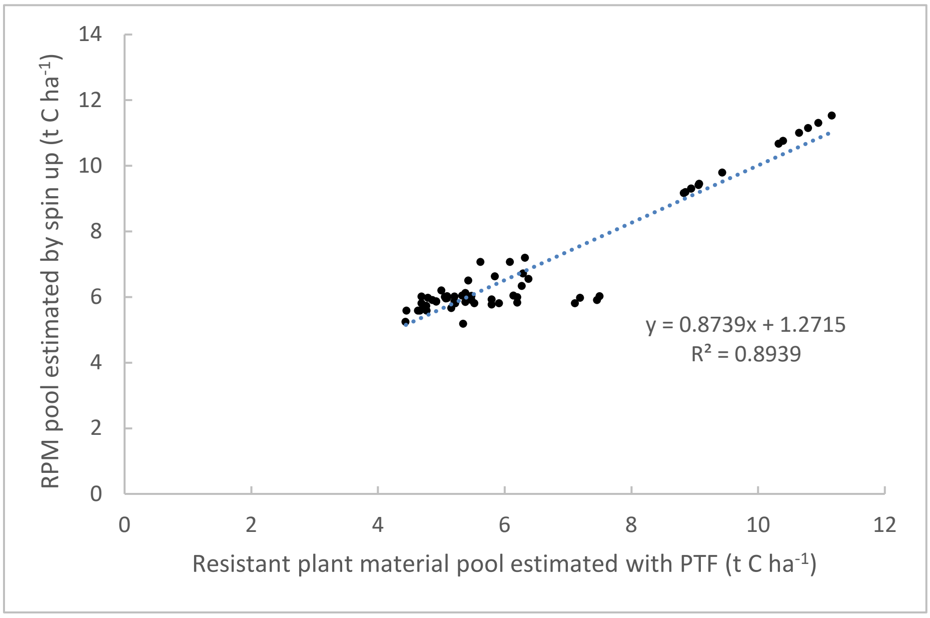


Figure 36: The size of RPM pools for five experimental sites (Balsthal, DOK, Hausweid, Oensingen, ZOFE) estimated with the PTFs from Weihermüller (see main text) or by spin up; each symbol represents a plot.

2.2.7.3 Historic simulations 1975-1990

The method used to calculate initial SOC stocks and SOC pools depends only on environmental parameters. To include also management-related effects on SOC stocks for 1990, so-called historic simulations were run for the years 1975-1990. The initial SOC stocks and the pool distribution were calculated for each stratum, as described above, for 1975.

Historical data

Historical input data for RothC are described in the following sections; for all other input parameters not mentioned here, the 1990 value was applied to the time period 1975-1990.

Climate data were available as gridded data (section 2.2.3.1) from MeteoSwiss for temperature and PPN. For the calculation of ET, SIS radiation data were available from 1983 onwards. For the years prior to 1983, monthly values were calculated as the mean value for the corresponding month, for the period 1983-2014.

Information on **yields** prior to 1990 were obtained from various sources. For sugar beet, rape seed (oil) and silage corn, annual data from 1975 were available from the Agristat reports from the SFU. For potatoes and small-grain cereals, 4-year average yields were available from the FSO 'historical data' database[15], containing national statistics for years prior to 1990; interpolation was used to estimate yields for the (3-year) periods in between. For all other crops, yield information was obtained from the Agristat reports from the SFU as far back in time as possible; yields for prior years were calculated by extrapolation, based on available yield data until 2015.

The OrgAm-model implemented for the main analysis (section 2.2.5.3) was also used to estimate historical **OrgAm application**. Information on historical herd sizes was obtained from SFU (years 1975, 1980, 1985) for all main animal categories except poultry, which was obtained from Klossner et al. (2014) for the years 1973, 1978, 1983, 1988. For all animal categories, interpolation was used to estimate herd sizes between years for which data were available. For most animal categories, information on sub-categories was lacking (e.g. horses < 3 years old or horses > 3 years old). Ratios between sub-categories for the year 1990 were applied to the preceding years in order to calculate herd sizes for sub-categories. Information on straw production for the years 1975 to 1990 was available from the Agristat reports from the SFU. The average amount of OrgAm-C moving to the mountains for summer pasture for the years 1996 to 2014 was applied to all years 1975 to 1990. Information on the **distribution of crops / grassland** categories

[15] https://www.bfs.admin.ch/bfs/de/home/dienstleistungen/historische-daten.html; in German and French.

throughout the strata (used to calculate OrgAm-C application rates) was obtained from the FSO for the years 1975, 1980, 1985; interpolation was used to obtain values for years in between.

For the most important cropland stratum A1_F2 and the dominant crops or grassland categories, neither the total SOC pools nor the single pools changed much over time (Figure 37). The results for the most important grassland categories and strata were very similar (Figure 38). Together these suggest that the C pools were close to an equilibrium state in 1975, supporting the validity of the initialised SOC stocks (2.2.7.1) and C pools (2.2.7.2).

The 1990 SOC stocks and C pools simulated in these historic simulations were used as initial values (year: 1990) for the simulation of SOC stocks 1990 to present.

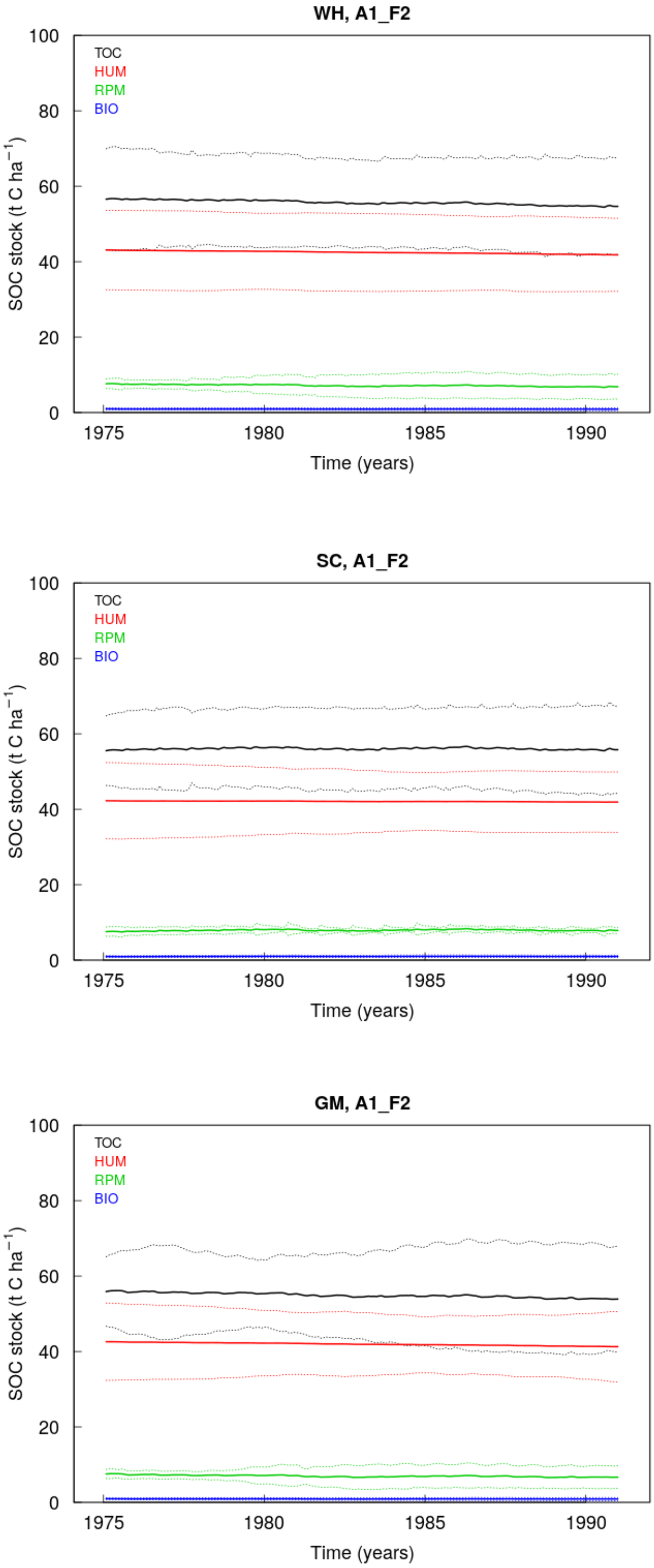


Figure 37: Historic simulations of TOC stocks (CL) for stratum A1_F2 (central plateau) and the three conceptual C pools HUM, RPM, BIO of RothC for wheat (WH), silage corn (SC) and grass-clover ley (GM) averaged over ten different clay classes (± standard deviation shown as dotted lines).

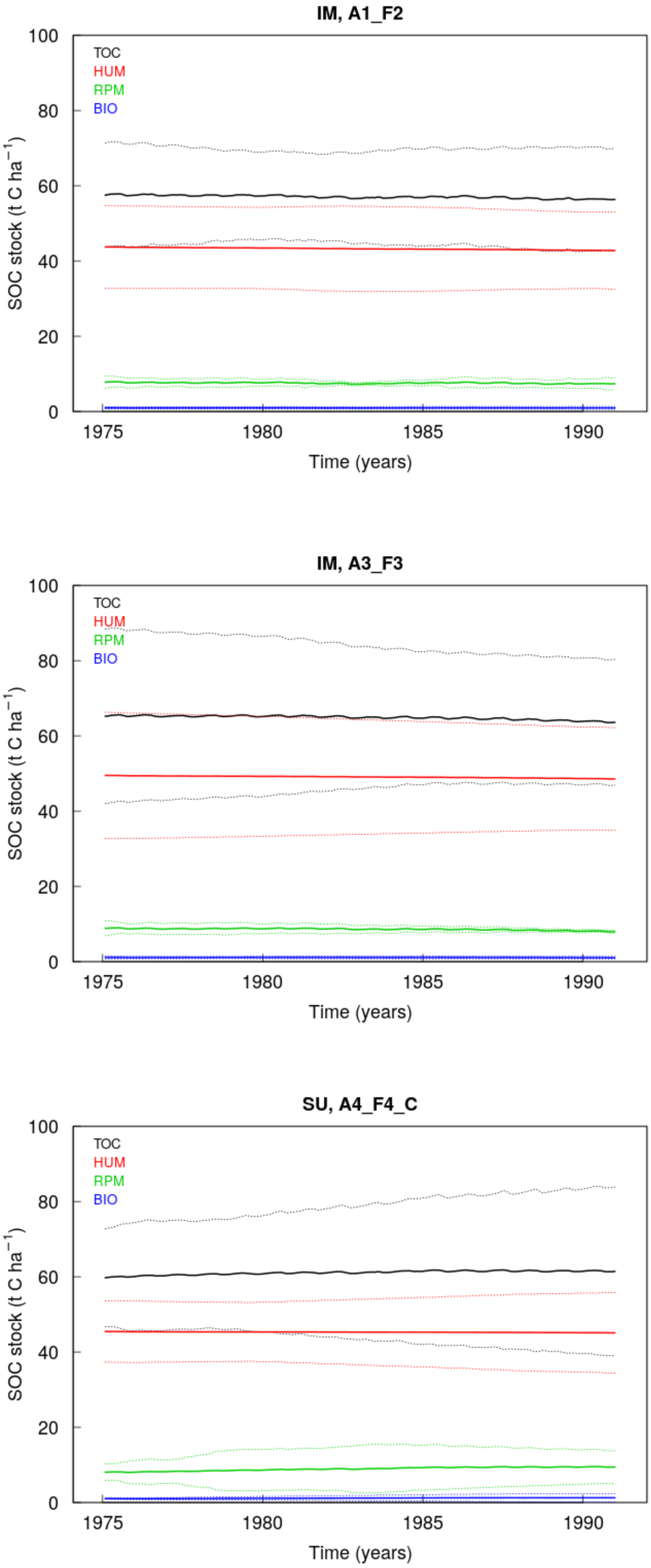


Figure 38: Historic simulations of TOC stocks (GL) for the most important grassland strata and the three conceptual C pools HUM, RPM, BIO of RothC for intensive meadows (IM) and summer pastures (SU) averaged over ten different clay classes (± standard deviation shown as dotted lines).

2.2.8 Upscaling

The RothC simulations are point simulations, modelling SOC stocks for a given soil type managed under a given main crop or grassland category (per year). SOC stock changes however need to be estimated at the national level, encompassing the (high) diversity of crops and grassland categories in the country. This is described in this section.

2.2.8.1 From field scale to strata

A system of strata were used to scale simulations to the national level (section 2.2.1). To account for the farming of crops in rotations, SOC stocks were simulated for individual crops and simulation results of each crop were weighted according to the crop frequency in each stratum (per year, section 2.2.6).

For CL, SOC stocks were simulated for 1990-present for 4,560 different combinations of crop types, strata and clay classes (19 crops × 24 strata × 10 clay classes). For GL, 1,440 simulations were carried out (6 grassland categories × 24 strata × 10 clay classes). Each simulation represents a SOC time series for particular climatic conditions for a specific crop/grassland and clay class. To calculate the overall SOC stocks and SOC changes for each stratum, each of the 190 cropland (or 60 grassland) simulations were weighted by, firstly, their 'crop area fraction' and, secondly, their 'clay area fraction' (Figure 39). This resulted in a SOC time series for each stratum for CL and for GL. The crop area fraction is, each year, the relative abundance of each crop (or grassland category) in each stratum, derived as described in section 2.2.5.1 ("Applying the data to strata"). The crop area fractions for 2017 for CL and GL are shown in Table 13 and Table 14. The clay area fraction is the fraction of each stratum that overlaps with each clay class, calculated as an overlay of the 24 strata and the 10 clay classes (section 2.2.4.1) in a GIS. This matrix (Table 15) does not change each year. The 0 % clay class (assumed to be organic soils, section 2.2.4.1) was given a weighting of zero, as this project considers mineral soils only.

In Switzerland, CL is concentrated in the central plateau: the stratum overlapping most closely with this region (A1_F2) contains 63 % of CL (Table 16) and is dominated by wheat, silage corn and grass-clover ley (WH, SC, GM, Table 13). GL is however distributed much more evenly through the landscape: The most important four strata (A1_F2 and A3_F3 in the year-round farming area, A4_F4_C and A4_F4_W in the summer pastures region) together contain only 53 % of GL (Table 16).

2.2.9 Calculating stock changes

Carbon stock changes were calculated as the difference between mean annual stocks (January to December) of consecutive years.

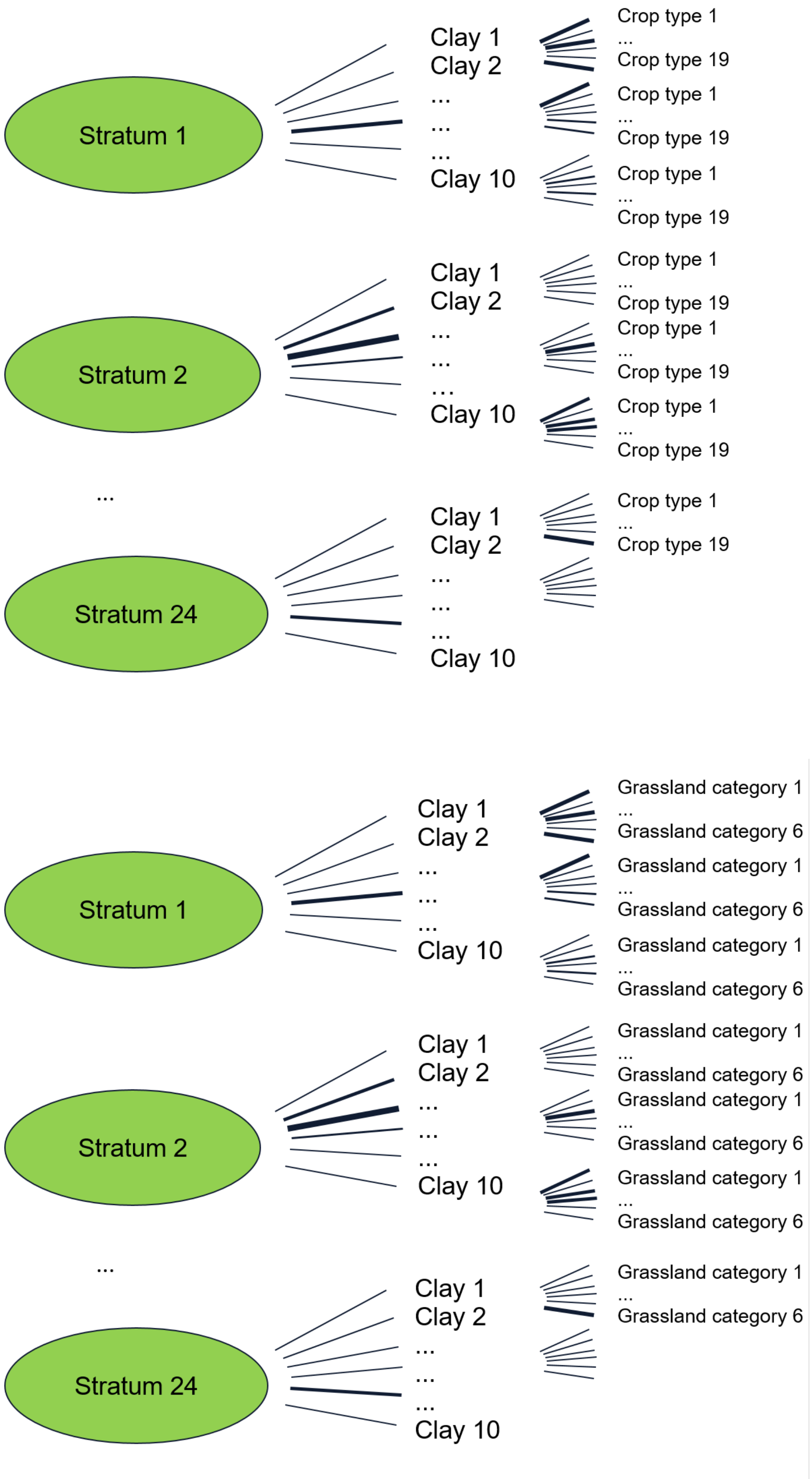
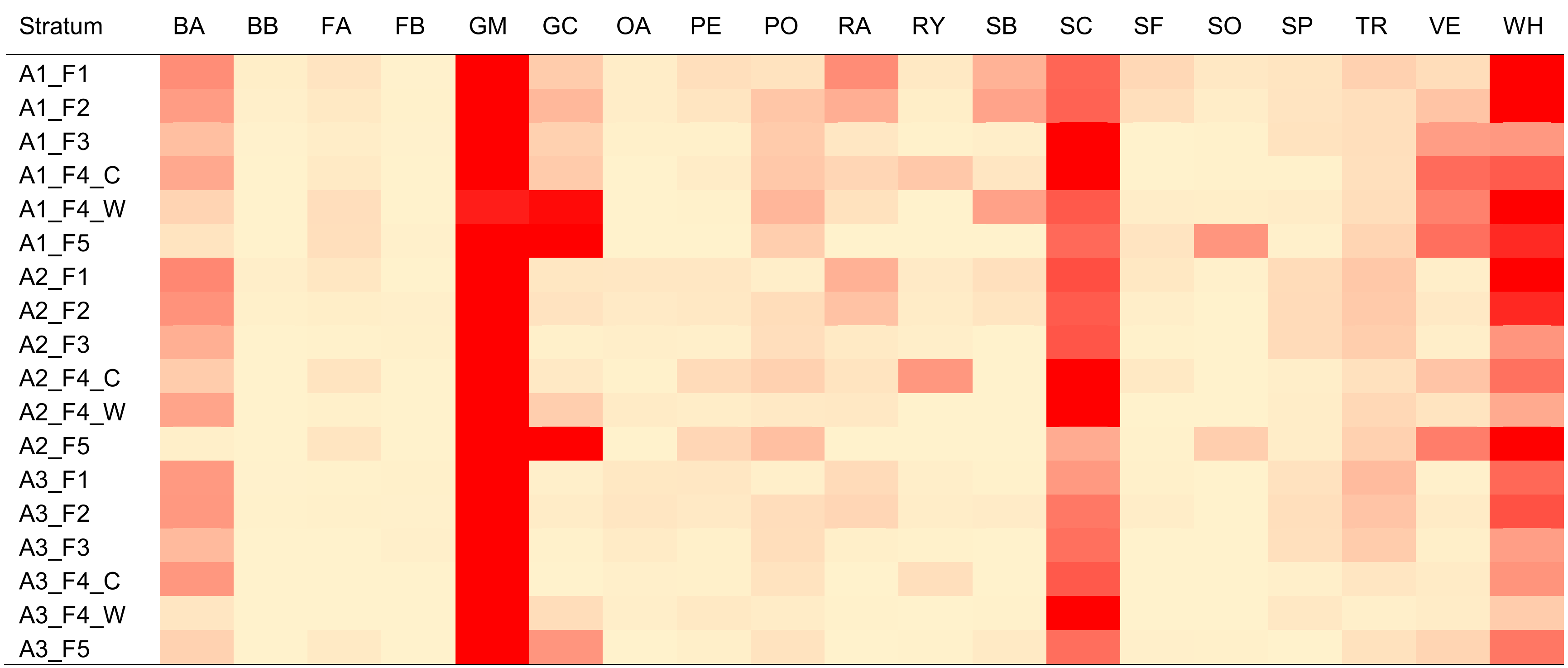


Figure 39: Calculating SOC stocks for individual strata for CL (above) and GL (below); stocks of strata calculated as weighted averages across simulations for all possible clay and crop / grassland combinations.

Table 13: Fraction of each stratum covered by each crop in the year 2017; the fractions change annually thus no data are given; crops that cover 20% or more of a stratum area are highlighted in bright red, decreasing colour intensity indicates decreased crop coverage (lightest colour = 0.5% or less); CL not considered to occur at high elevation (A4) strata; crop names in footnote.



Crop names: BA, barley; BB, broad bean; FA, fallow; FB, fodder beet; GM, grass-clover ley; GC, grain corn; OA, oat; PE, pea; PO, potato; RA, rape seed; RY, rye; SB, sugar beet; SC, silage corn; SF, sunflower; SO, soybean; SP, spelt; TR, triticale; VE, vegetables; WH, wheat

Table 14: Fraction of each stratum covered by each grassland category in the year 2017; the fractions change annually thus no data are given; grassland categories that cover 20% or more of a stratum area are highlighted in bright red, decreasing colour intensity indicates decreased crop coverage (lightest colour = 0.5% or less); summer pastures considered to occur only in high elevation (A4) strata.

Stratum	EM	EP	IM	IP	LM	SU
A1_F1						
A1_F2						
A1_F3						
A1_F4_C						
A1_F4_W						
A1_F5						
A2_F1						
A2_F2						
A2_F3						
A2_F4_C						
A2_F4_W						
A2_F5						
A3_F1						
A3_F2						
A3_F3						
A3_F4_C						
A3_F4_W						
A3_F5						
A4_F1						
A4_F2						
A4_F3						
A4_F4_C						
A4_F4_W						
A4_F5						

Grassland types: EM, extensively-managed meadows; EP, extensively-managed pastures; IM, intensively-managed meadows; IP, intensively-managed pastures; LM, less intensively-managed meadows; SU, summer pastures

Table 15: Relative frequency of the clay classes in each stratum; colour intensity indicates relative frequency of stratum / clay class combination.

Stratum	Clay class									
	0%	5%	10%	17%	20%	27%	33%	35%	45%	50%
A1_F1	0.01	0.14	0.20	0.12	0.29	0	0.07	0.17	0	0
A1_F2	0.02	0.07	0.29	0.08	0.45	0	0.04	0.04	0	0
A1_F3	0	0.01	0.10	0.15	0.30	0.04	0.17	0.22	0.01	0
A1_F4_C	0	0.52	0.14	0.15	0.01	0	0.02	0.15	0.01	0
A1_F4_W	0.02	0.04	0.11	0.11	0.06	0.01	0.15	0.47	0.02	0
A1_F5	0.01	0.26	0.33	0.25	0.15	0	0	0	0	0
A2_F1	0	0.05	0.24	0.01	0.16	0	0.18	0.38	0	0
A2_F2	0	0.02	0.41	0.02	0.45	0.04	0.03	0.03	0.01	0
A2_F3	0	0.02	0.36	0.04	0.41	0.08	0.01	0.05	0.01	0.01
A2_F4_C	0.01	0.58	0.21	0.07	0.07	0.01	0.01	0.04	0.01	0
A2_F4_W	0	0.10	0.14	0.21	0.23	0.12	0.01	0.11	0.08	0
A2_F5	0	0.52	0.32	0.12	0.04	0	0	0	0	0
A3_F1	0.02	0.08	0.59	0.01	0.12	0	0.03	0.14	0	0
A3_F2	0	0.05	0.38	0.01	0.21	0.06	0.01	0.27	0.01	0
A3_F3	0	0.01	0.31	0.01	0.23	0.21	0.01	0.06	0.09	0.07
A3_F4_C	0	0.30	0.35	0.03	0.07	0.09	0	0.01	0.09	0.06
A3_F4_W	0	0.13	0.42	0.04	0.14	0.12	0	0.01	0.08	0.05
A3_F5	0	0.79	0.17	0.02	0.01	0.01	0	0	0.01	0
A4_F1	0	0.05	0.76	0	0.08	0	0.03	0.08	0	0
A4_F2	0	0.07	0.67	0	0.05	0.05	0	0.14	0.02	0
A4_F3	0	0	0.42	0.07	0.05	0.17	0	0.01	0.14	0.13
A4_F4_C	0	0.25	0.19	0.43	0	0.06	0	0	0.06	0
A4_F4_W	0	0.11	0.27	0.46	0.02	0.07	0	0.01	0.05	0.01
A4_F5	0	0.62	0.10	0.26	0	0.02	0	0	0.01	0

Table 16: Fraction of CL and of GL in each stratum for 2017; colour intensity indicates relative frequency of stratum / land use combination.

Stratum	CL	GL
A1_F1	0.12	0.02
A1_F2	0.63	0.11
A1_F3	0.03	0.02
A1_F4_C	0.01	0
A1_F4_W	0.01	0
A1_F5	0	0
A2_F1	0.04	0.02
A2_F2	0.08	0.04
A2_F3	0.02	0.02
A2_F4_C	0	0
A2_F4_W	0	0
A2_F5	0	0
A3_F1	0.03	0.07
A3_F2	0.01	0.02
A3_F3	0.02	0.16
A3_F4_C	0	0.07
A3_F4_W	0	0.04
A3_F5	0	0.01
A4_F1	0	0.03
A4_F2	0	0
A4_F3	0	0.09
A4_F4_C	0	0.16
A4_F4_W	0	0.10
A4_F5	0	0.02

3 Uncertainty analysis

An initial UA was carried out to calculate uncertainty in the annual (year to year) SOC change for years between 1990 and 2017, using a Monte Carlo (MC) approach: For a sub-sample of crop/grassland-clay-strata combinations, RothC simulations were run repeatedly, with the input values of meteorological parameters, plant C inputs, OrgAm-C inputs and the relative extent of SU (as a proportion of all grassland) varying for each iteration.

3.1 Scope and considerations

This inital UA has three main aims. Firstly, to estimate the magnitude of error associated with the calculated annual SOC changes. Secondly, to provide a basis for a future sensitivity analysis (to help decide where to concentrate efforts to improve the data basis in the future). Lastly, to serve as the basis for a future comprehensive UA.
This UA is not comprehensive, for several reasons. Firstly, only error in the dynamic input parameters was assessed; there was no uncertainty in model parameters considered, nor was uncertainty in the initial SOC content or clay content of the soil. The variation in the latter seems however to be well-represented in our simulations, as the relative importance of different clay content classes used in this project is very similar to the distribution of clay content from 719 cropland and 168 grassland sites from across the country (Rehbein et al. 2017). Secondly, the input parameters were assumed to be either 0 % or 100 % correlated, e.g. the variation between herd size and temperature could be either 0% or 100 % correlated. Lastly, the UA was carried out for only the most important crop or grassland / strata / clay content combinations (Table 17), covering in total ca. 49 % of the crop surface, 36 % of year-round grassland and 40 % of summer pastures.

Table 17: The crop or grassland / clay / strata combinations considered in the UA.

Land use	Strata*	Clay class (based on clay content)	No. of crop or grassland types§	No. of combinations	% of CL or GL surface represented
CL	A1_F2	10 and 20 % clay	10 out of 20 (BA, GC, GM, PO, RA, SB, SC, TR, VE, WH)	20	ca. 49
GL (year-round)	A1_F2, A3_F3 and A3_F1	10 and 20 % clay	5 out of 5 (EM, EP, IM, IP, LM)	30	ca. 36
GL (summer pasture)	A4_F4_C and A4_F4_W	5, 10 and 27 % clay	1 out of 1 (SU)	6	ca. 40

* see section 2.2.1 for meanings

§ BA, barley; GC, grain corn; GM, grass-clover ley; PO, potato; RA, rape seed; SB, sugar beet; SC, silo corn; TR, triticale; VE, vegetable; WH, wheat; EM, extensive meadows; EP, extensive pastures; IM, intensive meadows; IP, intensive pastures; LM, less-intensive meadows; SU, summer pastures

3.2 Approach

A 'multiple' MC approach was used to assess uncertainty in annual SOC stock changes. An MC approach was used in accordance to the IPCC guidelines (IPCC 2006a) because it was assumed that the uncertainties might be large, distributed in a non-Gaussian way and because the algorithms are sometimes complex. A 'multiple' approach was used, meaning that instead of a single MC analysis (i.e. comprising the RothC simulations), three MC analyses were used (Figure 40): The first analysis estimated the uncertainty associated with OrgAm-C loss during storage. The second analysis estimated the uncertainty associated with OrgAm-C application, using the output of the first MC analysis as one of several input parameters. The third (main) MC analysis estimated the uncertainty of annual SOC stocks based on RothC simulations, using the output of the second MC analysis as one of several input parameters.

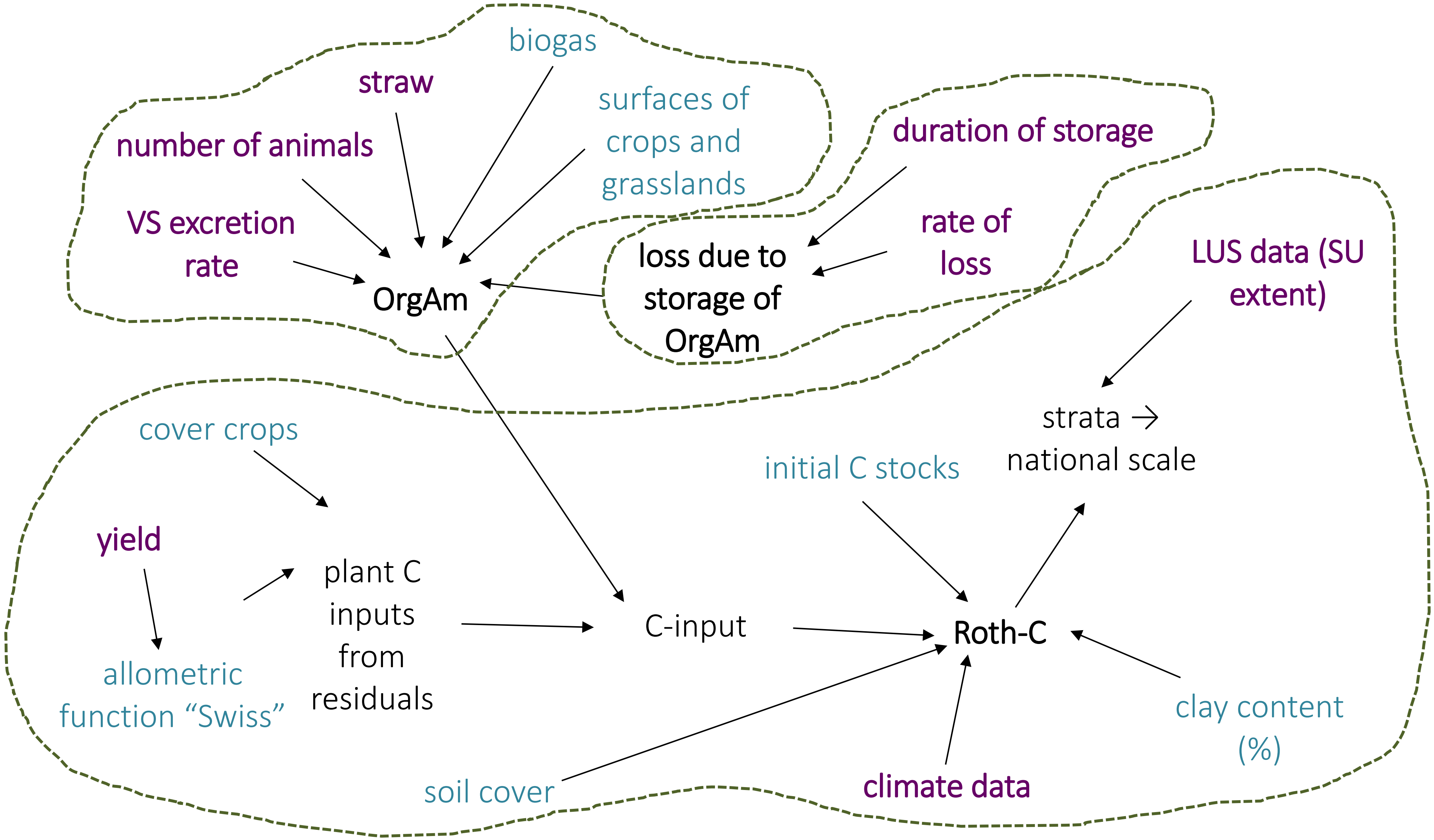


Figure 40: Overview of the UA indicating the three MC analyses (defined by green dotted lines), as well as those variables for which uncertainty was (purple, bold type) or was not (pale blue) considered.

3.3 Data sources

Variation in the following input parameters was considered: climate (PPN, temperature and ET), plant C inputs (the magnitude of variation based on that of plant yields), the amount of OrgAm-C inputs (as a function of variation in VS production rate, herd size, straw production and OrgAm-C loss due to OrgAm storage) and the proportion of the GL surface that is SU.

The input parameters for which uncertainty was considered are described in the following sub-sections. For each input parameter the following points were addressed: Firstly a probability distribution function (PDF) was parameterised to describe the variation. The type of PDF was assigned either according to available information, also using knowledge of how the variation might arise. The PDFs were parameterised where possible using available data, or using expert knowledge. Secondly, it was assessed whether or not there is a trend in the variation over the time period 1990 to 2017, using either data itself or considering how the data were collected. Thirdly, the type of variation that should be represented was considered. This could be measurement error or variation relating to imprecision in the system (due to e.g. the use of large surfaces [the strata] for up-scaling; the use of *annual* herd size data; the use of a *single* rate of OrgAm-C loss due to storage). Where several sources of variation could be identified for a given parameter, the largest one was accounted for. Fourthly, whether the variation between variables is correlated with one another or not.

3.3.1 Meteorological data

The data sets used in this project are gridded data, based on networks of meteorological stations (temperature and PPN, both published) or satellite information (SIS, for calculation of ET). Details for the three data sets used in this project were obtained from the documentation of MeteoSwiss Grid-Data Products (MeteoSwiss 2013; MeteoSwiss 2017; MeteoSwiss 2018). For **temperature**, the meteorological station data are considered high quality and have been measured consistently since ca. 1990, using observations from ca. 90 long-term station series. **PPN** is measured from a high-resolution rain-gauge network of MeteoSwiss, using observations from ca. 430 to 520 (since mid-1970s) stations. There is however systematic under-estimation in rain gauge measurements associated with windier conditions during snowfall, resulting in under-estimation of winter PPN of 4 to 35 to 35 % (lowlands to pre-Alps to Alps, respectively). We however did not attempt to include this uncertainty in this preliminary UA: In RothC, PPN is only relevant for calculating TSMD (section 2.1.1.1), which occurs during periods of low PPN and high ET. The greatest under-estimation of PPN occurs under conditions where TSMD is *least* likely to occur, i.e. in winter / early spring and at high elevation, meaning that it should have a minimal effect on TSMD calculation and therefore SOC dynamics. The calculation of **ET** is based on SIS information. This data set is considered high-resolution grid with validated accuracy. In summary, we considered the meteorological information to be either of medium or high quality or (for PPN) only low quality in situations less relevant to the simulations, therefore we did *not* consider this source of uncertainty in the UA.

For this project, a much larger source of variation stems from the fact that the strata – representing large areas – are assigned single (monthly) values (section 2.2.3.2) for temperature, for PPN and for ET. Although the strata were created with the aim of being as homogenous as possible, they are nonetheless large and cover sometimes large topographic gradients. This source of variation is covered in the UA.

The variation of the three meteorological parameters across the strata was estimated by obtaining the point estimates of temperature, PPN and SIS for each CL and each GL point (from the LUS, section 2.2.2.1), for each of the following strata: A1_F1, A1_F2 and A2_F2 (CL), A1_F2 and A3_F3 (year-round GL) and A4_F4_C and A4_F4_W (summer pastures), for the years 1990, 2000 and 2010. The standard deviation (SD) and coefficient of variance (CV, in %) of the distribution of each meteorological variable, per stratum and per land use type, was inspected.

The magnitude of variation across the CL strata, across the year-round GL strata and across the summer pasture strata is different, therefore PDFs were established for each land use type. The variation was assumed to have a truncated normal distribution. Variation was similar between the three years investigated and there was no temporal trend found i.e. variation within strata has not changed systematically over the period. Per land use type, variation was also similar between the strata investigated. Therefore, a constant error term over time and across strata was assumed for each of the three parameters: ET and PPN, using CV; temperature, using SD (Table 18). The SD rather than the CV was used to define the variation for temperature, because the near-zero temperatures in the winter led to extremely high CV values, although variation in the winter months is – in absolute terms – similar to that in the summer months. It was assumed that relative error between the years is 100 % correlated. For temperature and PPN this assumption is reasonable, as the meteorological networks have remained stable since 1990, and datasets have been homogenised where station relocations or changes have occurred (for temperature). For ET this assumption is met for the period 1990 to 2003 and the period 2004 to present. Correlations between variables were low (-50 to +50 %) and the variables were considered uncorrelated in the UA.

Table 18: Meteorological parameter uncertainty as implemented in the UA.

	CL	GL	SU	Error unit
Temperature	1.36	1.72	2.93	SD (°C)
PPN	26.0	24.0	24.0	CV (%)
ET	8.3	7.3	7.3	CV (%)

3.3.2 Plant C inputs

The plant C inputs are derived from an allometric equation that incorporates yields and the relative C allocation to main and by-products, roots and extra-root material (section 2.1.2). For this initial UA, variation in the crop yields was incorporated in the MC analysis. Variation in crop yields across the country is expected to be one of the major sources of uncertainty in plant C inputs in general, because regions for which yield estimates exist – individual cantons – cover large topographic and climatic gradients across the country.

The PDFs for plant C inputs were assumed to be normal. The variation in the PDFs was estimated by considering variation in plant yields for 13 crops in the main 10 to 14 crop-producing cantons, for the years 1991, 1995, 2000, 2005, 2010 and 2015 (data from the Agristat reports of the SFU). For each year and crop, the CV (%) of yields across the cantons was calculated. The results for the ten crops considered in the UA and for GL are shown in Table 19. With the exception of summer crops in 2015 – a dry and hot summer – and of silage corn, yield variation was stable for each crop across the years considered. Furthermore, there was no trend in the CV across time i.e. the magnitude of variation across the cantons has not changed systematically for this time period. Although reported yield is determined partly by external variables, this stability of variation through time also reflects the fact that the estimate of yields has remained constant through time (SFU pers. comm.). The stability in yield variation meant a single error estimate for each crop for the whole period could be applied, i.e. the error was 100 % correlated through time. Variation in plant C inputs of the different crops were not assumed to be correlated to one another.

Table 19: Plant C input uncertainty as implemented in the UA.

	Code	CV (%)	Comment
CL	BA	6.6	
	GM	8.3	No data, mean CV of other crops*
	GC	7.2	
	PO	11.1	
	RA	7.1	
	SB	10.8	
	SC	20.1	
	TR	8.4	
	VE	8.3	No data, mean CV of other crops*
	WH	6.0	
GL	All grasslands	8.3	No data, mean CV of crops*

* the mean value includes crops not listed in table.

3.3.3 Organic amendments

Uncertainty in several input parameters of OrgAm calculation was considered: Herd size, VS excretion rate, straw production and OrgAm-C loss during storage (the latter a function of storage time and the rate of OrgAm-C loss). Variation in these factors was combined using an MC analysis and the resulting variation (CV [%]) was used to parameterise the OrgAm-C variation in the main MC analysis (Figure 40).

3.3.3.1 Herd size

For herd sizes, Bretscher and Leifeld (2008) describe an uncertainty range of ± 6 % for cattle and ± 6.5 % for other animals (2.5 % and 97.5 % percentiles). This uncertainty includes that due to annual counts as well as that due to seasonal variation. These values (also used in the Agriculture sector of Switzerland's GHG inventory) were adopted here, assuming a normal distribution of error. Following Bretscher and Leifeld (2008), it was assumed that variation is 100 % correlated through time.

3.3.3.2 Volatile solids

For VS excretion rates, Bretscher and Leifeld (2008) describe an uncertainty range of -16.0 to +12.0 % (2.5 % and 97.5 % percentiles). These values (also used in the Agriculture sector of Switzerland's GHG inventory) were adopted here, assuming a normal distribution of error. Following Bretscher and Leifeld (2008) it was assumed that variation was 100 % correlated through time.

3.3.3.3 C loss during storage

The uncertainty of OrgAm-C loss during storage for each OrgAm type was estimated using an MC analysis, considering i) uncertainty in storage duration and ii) the uncertainty of the OrgAm-C loss rate.

The variation in the duration of OrgAm storage (Table 20) was estimated using guidelines for the timing of crop fertilisation and of OrgAm storage (Sägesser and Weber 1992; Aeby et al. 1995; Flisch et al. 2009; Kupper et al. 2013), assuming OrgAm is produced at a constant rate throughout the year. The variation in the rate of OrgAm-C loss was estimated as follows: Estimates of OrgAm-C loss during storage (as a % of the OrgAm-C at the beginning of the storage term) were obtained from published studies (section 2.2.5.3). For each OrgAm type except fresh manure, OrgAm-C loss values from all relevant studies were combined and a statistical model fitted to describe OrgAm-C loss as a function of the (log-transformed) duration of OrgAm storage. As part of the statistical model, uncertainty of the estimates of the two parameters, the intercept and the multiplier, is estimated (given as standard error). These two estimates of uncertainty were used to parameterise the respective two PDFs (for each OrgAm type), assuming a normal distribution of variation.

For each OrgAm type, an MC analysis (5,000 iterations) was used to produce a distribution of OrgAm-C losses from which values were then randomly picked during the main OrgAm-C MC analysis (Figure 40 and section 3.3.3.5). Per OrgAm type, a single rate of OrgAm-C loss was calculated for the whole period 1990 to 2017. This assumes that there has been no systematic change in both the duration of OrgAm storage or the manner in which OrgAm is stored over the period 1990 to 2017. It is possible that this is not the case due to manure management changes in the last decades, including for example the use of covers on slurry tanks, but this was not investigated further.

Table 20: OrgAm-C storage duration uncertainty as implemented in the UA, including details of PDFs for each OrgAm type.

OrgAm type	storage time, PDF shape	storage time (months), PDF parameters	CV (%) OrgAm-C loss
deep litter	trapezoid	min = 0, max = 4, mode 1 = 0.5, mode 2 = 3	45
stacked manure	trapezoid	min = 0, max = 4, mode 1 = 0.5, mode 2 = 3	42
liquid slurry	log normal	meanlog = 1, sdlog = 0.65	71
poultry waste	trapezoid	min = 0, max = 4, mode 1 = 1, mode 2 = 3	46
fresh manure*	no PDF	50 days	26

* no uncertainty was estimated here; Penttilä et al. (2013) indicate that emissions from fresh manure are negligible after 50 days.

3.3.3.4 Straw production

Straw production was assumed to have an uncertainty of 5 % (95 % confidence interval [CI], with error following a normal distribution). This value corresponds to the lowest variation of any of the cereals (spelt, not considered in the UA and thus not shown in Table 19). It was assumed that error between the years is 100 % correlated, as the estimation of yields has remained constant through time (SFU pers. comm.).

3.3.3.5 Calculation of OrgAm variation

An MC analysis (5,000 iterations) was used to combine the error associated with animal numbers, VS excretion rates, OrgAm-storage loss and straw production. It was assumed that the variation in OrgAm-C applied to different crops or grassland was correlated, reflecting a situation where, for example, if animal numbers were particularly high one year, this would affect the OrgAm-C application to all crops or grassland.
The results were used to obtain of OrgAm-C additions for each crop or grassland category (Table 21), which was subsequently fed into the main MC analysis of OrgAm-C (Figure 40).

Table 21 OrgAm-C input uncertainty as implemented in the UA

	Code	CV (%)	Comment
CL	BA	8.8	
	GM	6.9	
	GC	10.9	
	PO	11.0	
	RA	11.0	
	SB	11.0	
	SC	11.0	
	TR	8.8	
	VE	-	assumed not to receive OrgAm
	WH	8.8	
GL	EM	-	assumed not to receive OrgAm
	LM	12.1	
	IM	6.9	
	EP	9.8	
	IP	9.8	
	SU	10.1	

3.3.4 Surface of summer pastures

The calculation of SOC stock changes for GL combines SOC stock changes from the year-round farming regions and summer pastures. To do this, the results of each are (weighted-)averaged, using their relative surface area as a weighting; the uncertainty in the surface of summer pastures therefore needs to be considered. In this project, the estimate of the summer pasture surface is based on the Swiss LUS and the FSS (see section 2.2.5.1). A separate estimate of the summer pasture surface – not used in this project –, incorporating all potentially relevant grassland points from the LUS (nomenclature system from 2004[16]) that occur within the summer pasture region (AZ4), yielded a surface estimate which is ca. 8 % lower. This discrepancy was used to parameterise a normally distributed PDF, incorporated into the main MC analysis of SOC stocks of GL soils.

3.4 The main Monte Carlo analysis

The main MC analysis, which estimated C stocks as calculated by RothC, incorporated variation in climate, plant C inputs, the amount of OrgAm-C inputs and the proportion of GL that is summer pasture (Figure 40). Ten thousand iterations were run. Inspection of the 95 % confidence interval (CI) limits of the MC analyses for two crops and one

[16] https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/nomenklaturen/arealstatistik/noas2004.html including all "alpine meadows" and "alpine pastures" categories.

grassland category suggests that this was sufficient, as – in accordance with the IPCC guidelines (IPCC 2006a) – the CI had stabilised to within ±1 % by 4,000 to 8,000 replicates (depending on the crop / grassland category).
RothC provides monthly SOC stocks as an output. Annual SOC stock changes were calculated as the mean SOC stock for one year, minus the mean SOC stock of the preceding year. It was assumed that error was correlated between adjacent years (see descriptions of individual parameters in section 3.3), therefore SOC changes were calculated using annual SOC stocks of the same iteration (see Figure 47). The 2.5th and 97.5th percentile values of the final MC distributions of 10,000 iterations, for CL and for GL, were used to quantify the uncertainty SOC change (a 95 % CI), as described in McMurray et al. (2017).

3.5 UA Results and discussion

SOC changes were calculated as the change between the years 1990 to 2017 (Figure 41 to Figure 44) and between adjacent years (Figure 46 and Figure 45, selected years shown). Figure 41 to Figure 45 show also the point estimate of SOC stock changes (as obtained from the main analysis), illustrating that the MC analysis was able to re-construct SOC stock changes well.
Across the whole period (1990 to 2017), the uncertainty distributions of annual SOC stock changes for both CL and GL all had negative 2.5 percentiles and (with the exception of two years for CL) had positive 97.5 % percentiles, i.e. the 95 % CIs of both CL and GL annual SOC changes almost always include zero change.
The uncertainty estimates used in Switzerland's GHG inventory for CL and for GL are based on an average of the year-to-year uncertainty (period 1995 to 2017), rather than individual year-to-year uncertainty, for the following reason. For CL, the distribution of uncertainty around the SOC stock change for a few year-to-year comparisons was bimodal (e.g. Figure 45, 2016 to 2017). It is unclear why this is the case: It is related to years where there was a summer drought, and it is possible that the derivation of TSMD or the resulting SOC decomposition rate change within RothC is over-sensitive to drought conditions. To avoid potentially artifactual high uncertainty for individual annual SOC stock changes (that would result from these bimodal distributions), it was decided to use the median of the year-to-year uncertainty to represent the SOC stock change uncertainty in the GHG inventory. For the CL strata tested, the average 2.5th percentile of annual SOC stock changes (1995 to 2017) was -0.179 and the average 97.5th percentile was 0.286 t C ha^{-1}. For the GL strata tested, the corresponding values were -0.142 and 0.364 t C ha^{-1}. Thus, the average 95 % CIs for annual SOC stock changes in CL and GL include zero change.
It is likely that the uncertainty of SOC stock changes has been under-estimated in this initial UA, for two reasons. Firstly, uncertainty from some input variables as well as from SOC decomposition rates within RothC, was not considered. One important input variable is the initial SOC stock. Uncertainty within this parameter was omitted from this UA because information on uncertainty was not available for this project, and because an improved estimate of initial SOC stocks for Switzerland is anticipated within the next years as part of an on-going project[14]; it is recommended that the error associated with the new estimate is incorporated in an UA when this becomes available. Secondly, we assumed that the error between years was 100 % correlated. As mentioned in sections 3.3.1 to 3.3.3, for the majority of input parameters considered it is reasonable to assume they are somewhat correlated (and certainly preferable to assuming error is 0 % correlated between years). Additionally, measured annual SOC stock changes in Switzerland from a recent study of eight long-term cropland experiments range from -0.07 to 0.28 t C ha^{-1} (Keel et al. 2019), values within the range of uncertainty estimated here, suggesting that this approach is suitable (compare with values in Figure 47). However, it can be expected that for most variables, this assumption probably does not hold *completely*, and allowing error to be uncorrelated across time increases uncertainty in SOC stock changes considerably. This is demonstrated in Figure 47: If the error is assumed to be 100 % correlated through time, the SOC stock change is calculated as the difference between SOC stocks of two given years as estimated *by the same* MC iteration. If the error is assumed to be uncorrelated, the annual SOC stock change is calculated as the difference between SOC stocks of two given years as estimated by *two randomly picked* MC iterations. Assuming the latter leads to estimates of uncertainty that are more than an order of magnitude greater (Figure 47).
In short, for various reasons it is possible that we have under-estimated the uncertainty of SOC stock changes. However, the key message resulting from the UA remains the same: For those strata, clay classes and crops or grassland categories tested, the 95 % CIs for annual SOC stock changes in CL and in GL contain zero change. Assuming the strata, clay classes and crops tested are representative of all agricultural activity, this means that **agricultural mineral soils in Switzerland cannot be considered a statistically significant SOC sink or source**.

The information obtained from the UA was applied to the main results of this project by applying the absolute average uncertainty (median of 95 % CI limits, period 1995 to 2017) of annual SOC change to the simulated annual CL and GL SOC changes.

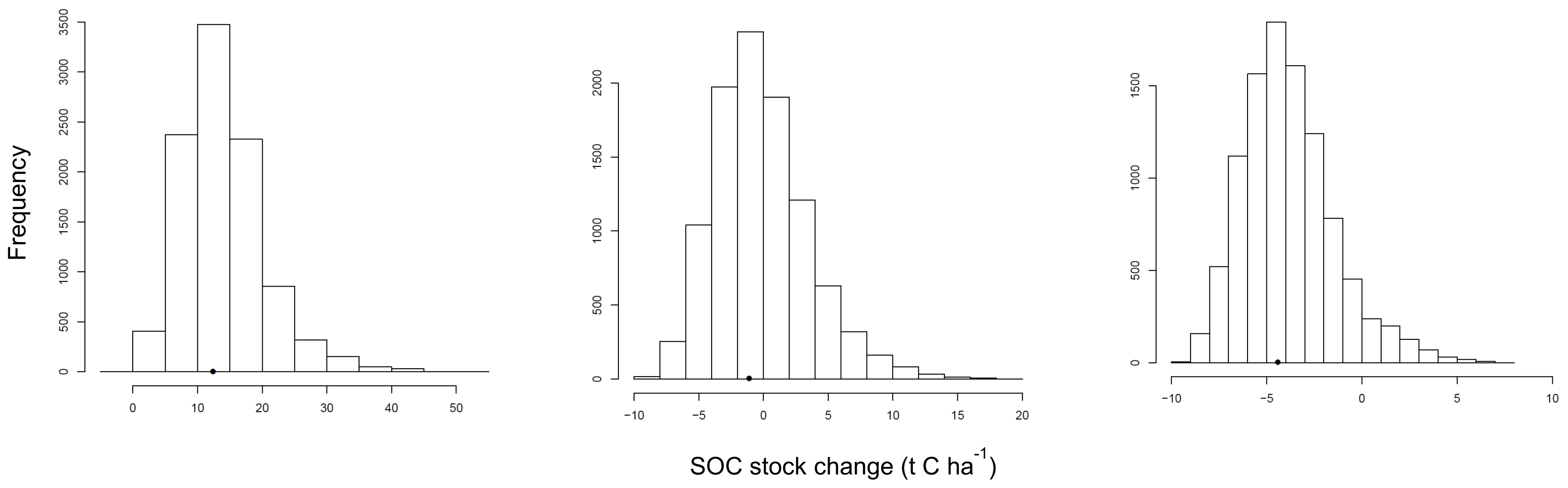


Figure 41: Uncertainty in SOC stock changes (1990 to 2017) of three CL soils as calculated by UA (histogram of results from 10,000 iterations) for the main crop stratum A1_F2, assuming a clay soil content of 10 %; left-hand graph = rape seed, middle graph = silage corn; right-hand graph = wheat; black dot at base of graph = SOC stock changes from main simulation.

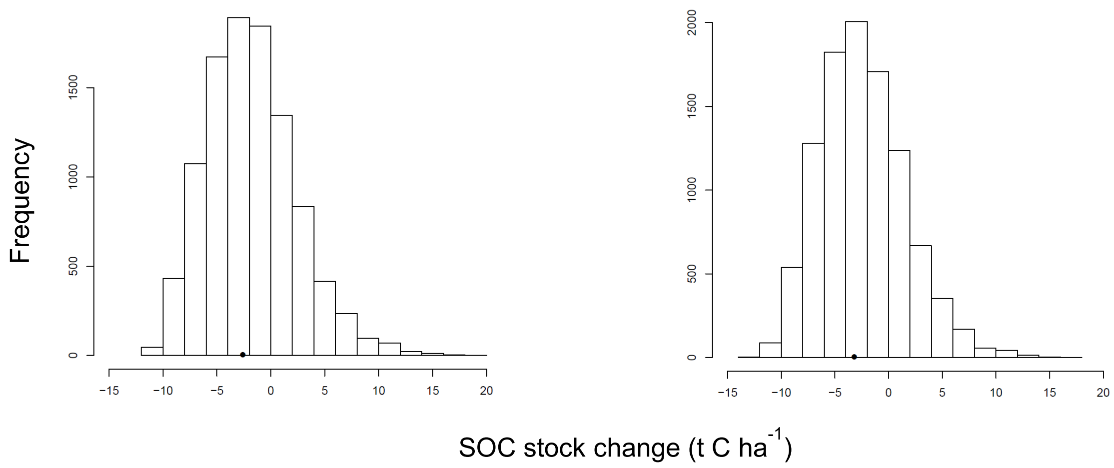


Figure 42: Uncertainty in SOC stock changes (1990 to 2017) of two lowland GL soils as calculated by UA (histogram of results from 10,000 iterations) for the stratum A1_F2, assuming a clay soil content of 10 %; left-hand graph = intensive meadows, right-hand graph = intensive pastures; black dot at base of graph = SOC stock changes from main simulation.

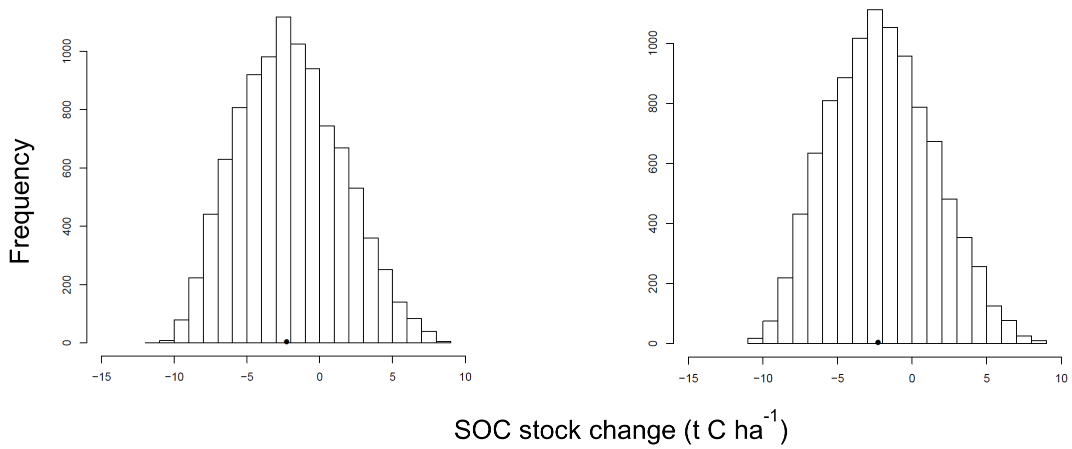


Figure 43: Uncertainty in SOC stock changes (1990 to 2017) of two mountain zone GL soils as calculated by UA (histogram of results from 10,000 iterations) for the stratum A3_F3, assuming a clay soil content of 10 %; left-hand graph = intensive meadows, right-hand graph = intensive pastures; black dot at base of graph = SOC stock changes from main simulation.

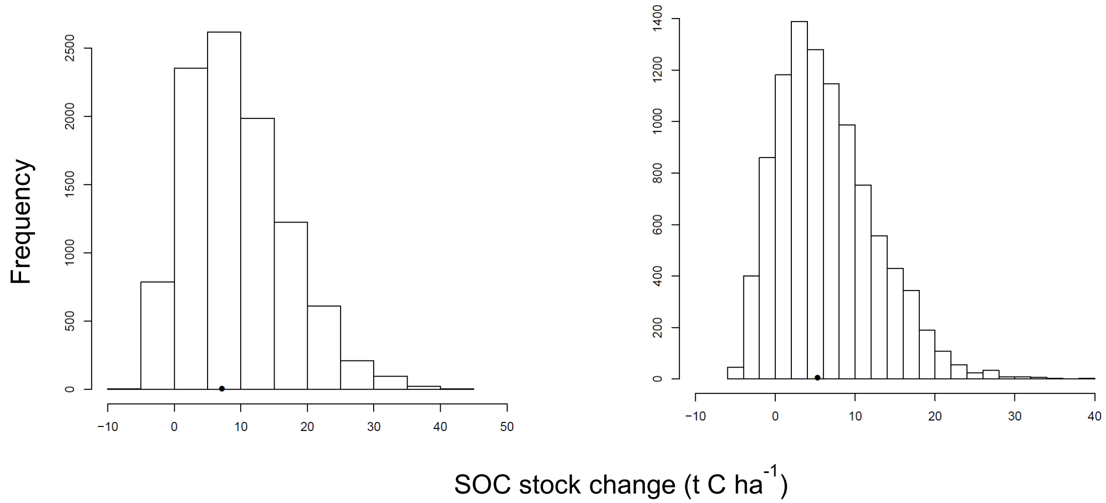


Figure 44: Uncertainty in SOC stock changes (1990 to 2017) of two summer pasture soils as calculated by UA (histogram of results from 10,000 iterations) for the strata A4_F4_C (left-hand graph) and A4_F4_W (right-hand graph), assuming a clay soil content of 5 %; black dot at base of graph = SOC stock changes from main simulation.

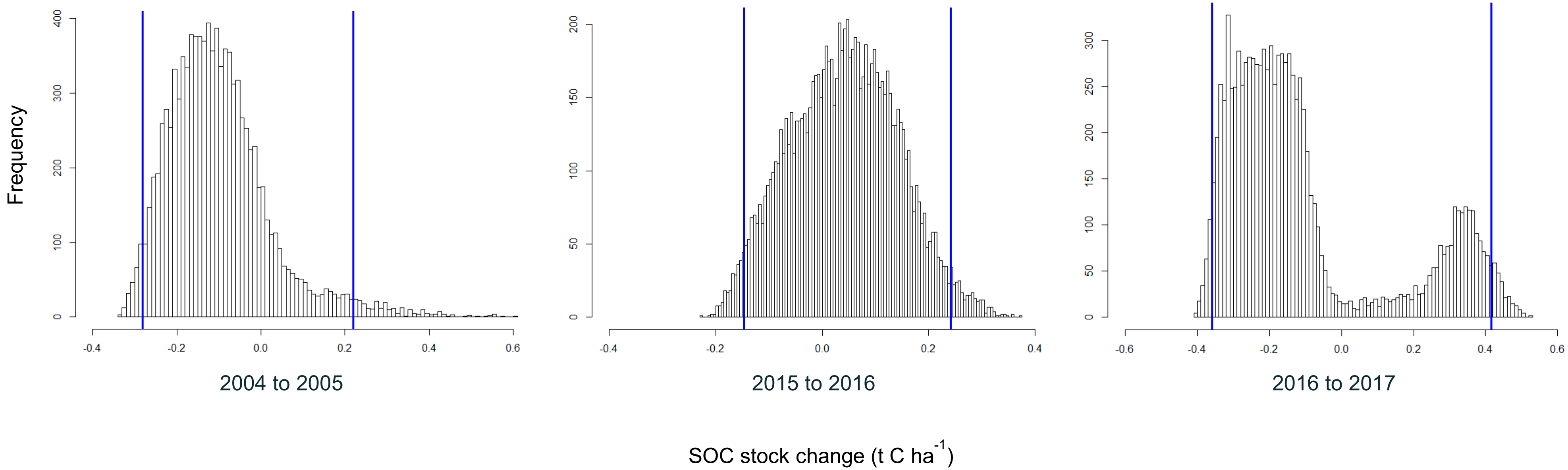


Figure 45: Uncertainty in annual SOC changes for CL, as calculated by UA (histogram of results from 10,000 iterations) for selected years; results are a weighted-average of results from individual crops, selected strata and clay content types, as described in main text; blue lines (2.5th and 97.5th percentiles) represent the 95 % CI boundaries.

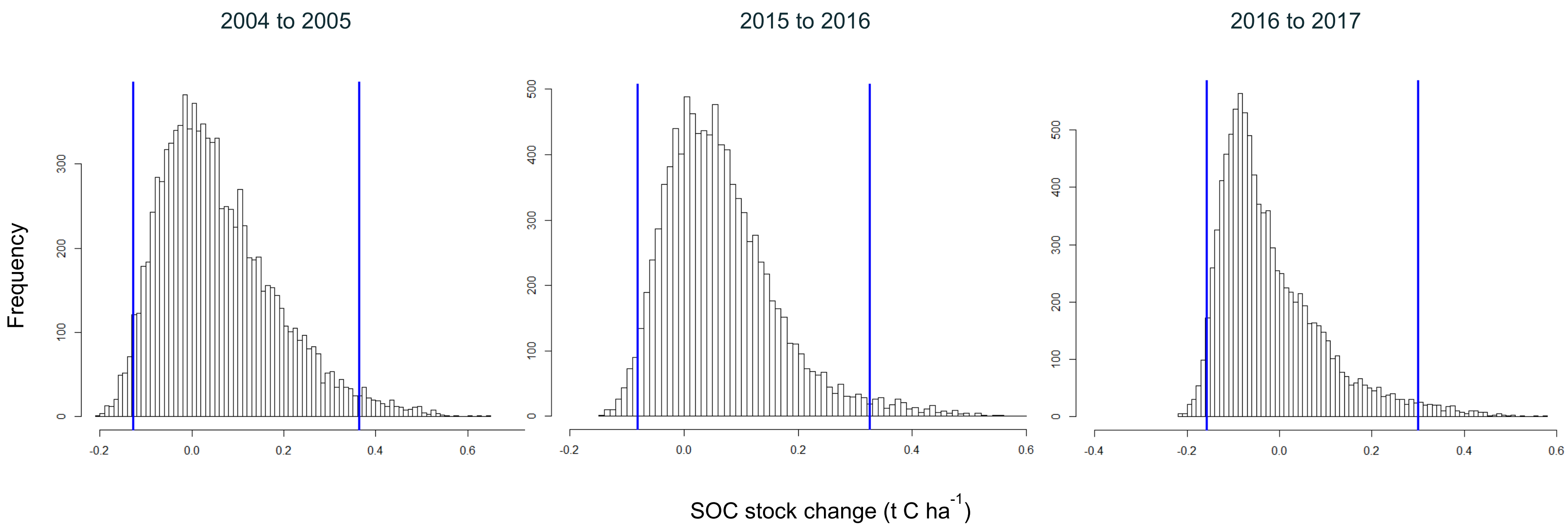


Figure 46: Uncertainty in annual SOC changes for GL, as calculated by UA (histogram of results from 10,000 iterations) for selected years; results a weighted-average of results from individual grassland categories, selected strata and clay content types, as described in main text; blue lines (2.5th and 97.5th percentiles) represent the 95 % CI boundaries.

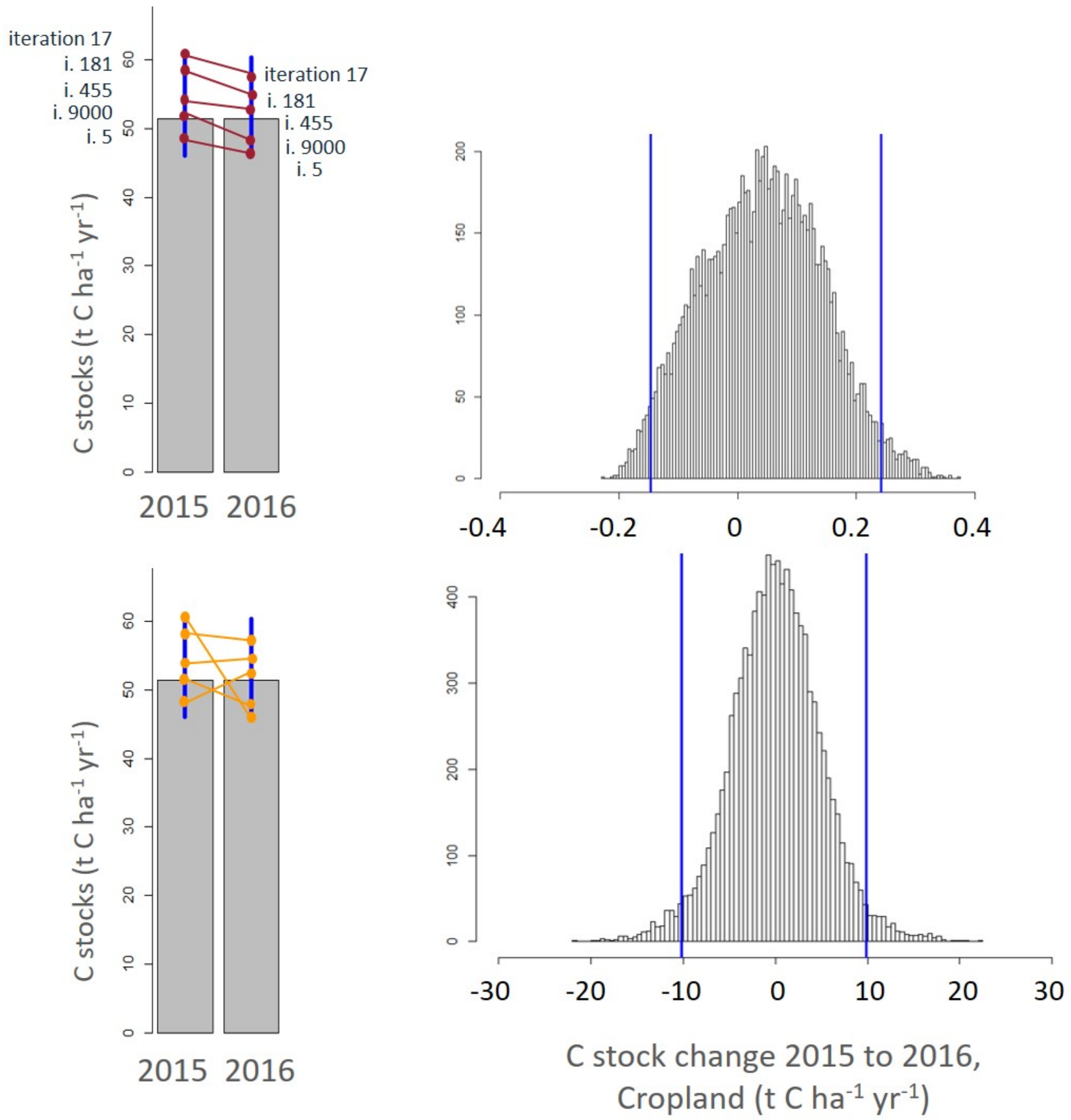


Figure 47: Uncertainty in annual SOC changes with error correlated or uncorrelated through time (figure overleaf); upper graphs = error assumed to be 100 % correlated, meaning 2016 and 2015 SOC stocks of the same iteration are used to calculate stock change (red lines in bar-chart), with histogram showing the corresponding distribution of SOC stock change uncertainty; lower graphs = error assumed to be 0 % correlated through time meaning randomly picked iterations are chosen for the calculation of annual stock change (yellow lines in bar-chart), with histogram showing the corresponding distribution of SOC stock change uncertainty.

4 Results and discussion

A model-based national-scale SOC inventory system has been developed, allowing the calculation of annual topsoil SOC stocks (0-30 cm) and stock changes of mineral soils under CL and GL for Switzerland. The country was stratified into 24 regions characterised by similar agricultural management and climate. Within these strata, ten different clay classes and 25 crop / grassland categories were accounted for, reflecting much of the diversity of the Swiss agricultural landscape.

The system is dynamic and captures inter-annual variability in SOC changes due to both meteorological changes and changes relating to agricultural management. The system has been designed in a flexible way, allowing for both continuous improvements and the representation of future changes in management. Additionally, the inventory system can also serve as a tool to test the effect of altering individual parameters. This allows investigation in two avenues. Firstly by means of a sensitivity analysis, it allows the investigation of which parameters are most important in determining SOC change. This, in turn, can inform where the biggest levers are regarding increasing SOC stocks in soils (within the mechanistic boundaries of RothC) or where future research needs to be directed to reduce uncertainty in the simulations. Secondly, it allows the SOC sequestration potential of measures to be investigated, given local pedoclimatic and management conditions. As SOC cannot be easily measured/monitored over large spatial scales, model-based inventories are useful alternatives to quantify SOC stocks and are key elements for measurement/monitoring, reporting and verification platforms (Smith et al. 2020).

RothC was chosen as the best performing model out of a group of candidate models. It is however (as were all of the models in this group, Köck et al. 2013) a relatively simple model, in that its decomposition rates work with first-order kinetics, and many influencing factors are not considered, including irrigation, no-till or pH dependency of decomposition rates. Some of these limitations are discussed in detail in Köck et al. (2013) and we re-iterate from that publication that using such a 'simple' model is necessary when SOC stocks are being simulated for such a long time period and – especially – large spatial scale, especially for a system in which management and the landscape are so diverse. Likewise, it was a pre-condition that the input parameters necessary for the chosen model needed to either be available, or feasibly derivable, at the national scale for the whole time-period.

Much more complex models exist (e.g. Riley et al. 2014; Wieder et al. 2014) with the main difference that they explicitly account for microbial dynamics. However, for national scale simulation in general, it is unrealistic to use these as appropriate input data are not available. Reflecting this, the few other countries that employ a model-based (tier 3) approach to simulate SOC dynamics, use models of similar complexity to RothC (e.g. Australia, Sweden, Canada, Denmark). Recently, Sulman et al. (2018) compared five different soil C models, one of which resembles RothC (DAYCENT) in that SOC cycling and storage are represented by first-order kinetics. The other four models were more complex and explicitly simulate microbial activity and soil mineral interactions. Simulations for warming and litter addition experiments were compared to observations from field experiments. Overall, there was a wide spread between models and simulations, and results for DAYCENT were (with one exception) within this spread of variation, supporting the use of a simple model.

Finally, other aspects of the model system – other than the SOC model – that have been developed are also simple. For example, the sowing and harvesting dates of crops are independent of weather conditions and elevation. Crop yields are also independent of elevation. Although it would be feasible to implement such dynamic parameters, the required information at the national scale is lacking.

Compared to a measurement-based SOC inventory, using a model offers the possibility to test scenarios where (m)any input parameters may vary. This allows us to assess potential effects on SOC in response to changes in, for example, rates of organic fertilisation, crop residue retention, or the frequency of cover crops. Changes in tillage intensity or irrigation however, cannot be tested with RothC.

In the next sections, we discuss the simulated SOC stocks and changes, comparing the results with other studies from Switzerland and other countries, in so far as this is possible.

The uncertainty associated with the annual SOC changes was estimated using an initial UA, based on an MC analysis (section 3). Based on the results of this UA, **it is concluded that agricultural mineral topsoils in Switzerland are on average neither a statistically significant C sink nor source**.

4.1 Cropland

4.1.1 Initial SOC stocks

Under CL, initial SOC stocks (year 1990) for the 24 strata range between 36.0 t C ha^{-1} and 59.9 t C ha^{-1} (data not shown) and mean stocks per AZ are given in Table 22. This range lies within the range of measurements by the Swiss national soil monitoring for the years 1990-1994 (Gubler et al. 2019, 32.9-111.5 t C ha^{-1}, extrapolated from 0-20 cm to 0-30 cm assuming the same C concentration and bulk density). The range of SOC stocks also includes the mean SOC stock reported for cropland topsoils (0-30 cm) in the Belgian Wallonian region (55 t C ha^{-1}, Chartin et al. 2017) but not the mean reported in Germany's recent soil inventory (61 t ha^{-1}, Jacobs et al. 2018). The lower mean SOC stock calculated for Switzerland (50 t C ha^{-1}) might be explained by the higher stone content of cropland soils in Switzerland; circa 40 % of CL soils here have more than 10 % stones (diameter >2 mm), compared to only 20 % of the CL sampling sites in Germany.
In CL soils, there is no clear increase of SOC content (%) with increasing elevation (equation 4, section 2.2.7.1), as is the case for grassland soils.

Table 22: SOC stocks for CL soils in 1990 (0-30 cm depth) aggregated by AZ, as estimated in this project (section 2.2.7.1). CL does not occur in AZ4.

	AZ1	AZ2	AZ3
Proportion of CL in each AZ (2018, %)	78	14	8
SOC estimate (t C ha^{-1})	50.1	51.5	47.7

4.1.2 SOC stock changes

Regional-scale changes in SOC stocks in CL soils (1990 – 2018) are shown in Figure 48 and national-level changes in Figure 49. Across this period, annual SOC change rates for the whole country range from -0.40 to +0.55 t C ha^{-1} yr^{-1}, with an average of 0.034 t C ha^{-1} yr^{-1} (range: -1.46 to +2.01 t CO_2 equivalents; mean: 0.126 t CO_2 equivalents). Taking into account the large uncertainty associated with the SOC stock change estimates (section 3.5), annual SOC changes are for most years not statistically significantly positive or negative.
Positive as well as negative SOC trends were obtained for single strata. This is in agreement with measurements at the 30 national soil monitoring sites (Gubler et al. 2019 and Figure 50). Within the most important stratum A1_F2, annual SOC changes vary between -0.50 and +0.65 t C ha^{-1} across the time period, in agreement with the changes extrapolated from Gubler et al. (2019, -0.58 to +0.54 t C ha^{-1} yr^{-1} based on reported changes of -12 to 11 %).

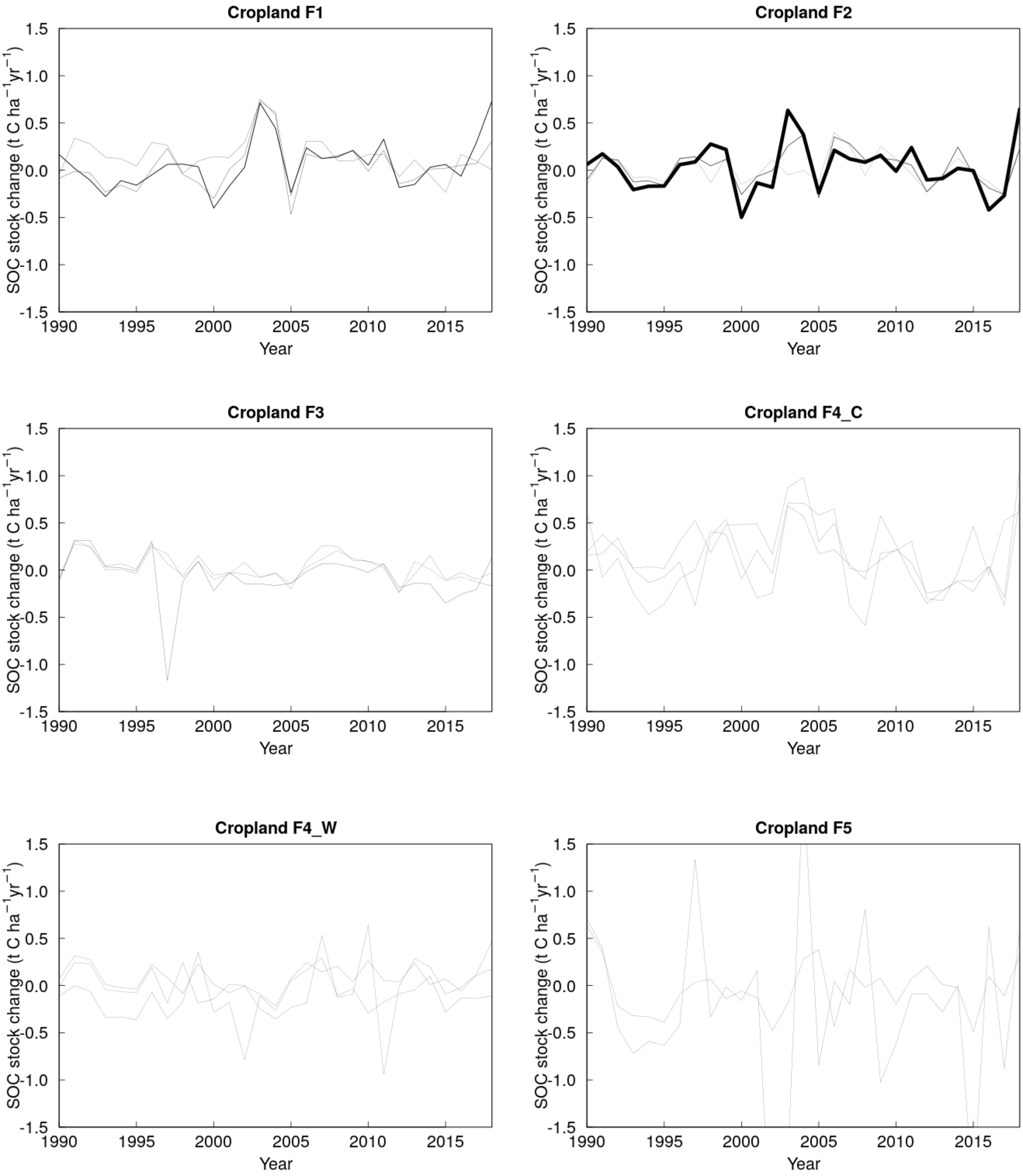


Figure 48: Annual SOC stock changes (0-30 cm) for CL for six production regions (section 2.2.1.1); the line thickness is proportional to the relative surface of each stratum.

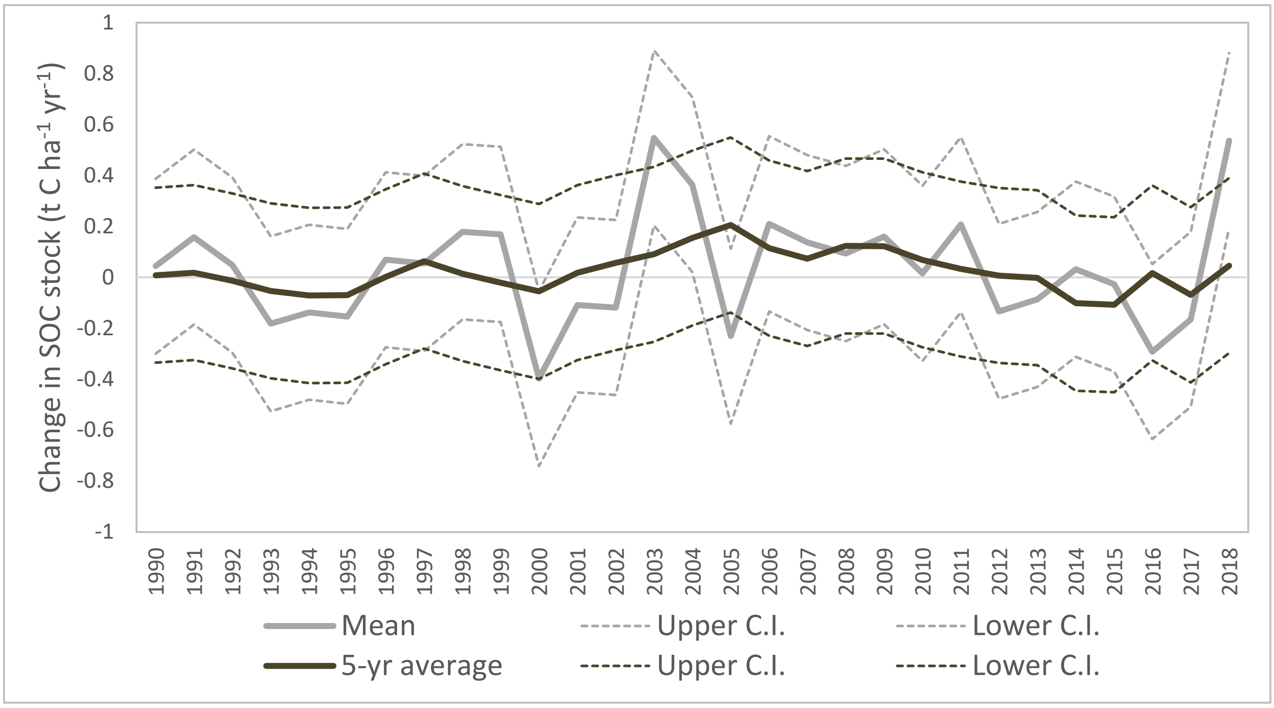


Figure 49: Annual national SOC stock changes for CL soils (0-30 cm) showing annual (grey) and 5-yr average (green) values, calculated using a weighted average across all strata; dashed lines show the upper and lower CIs, using absolute values derived from UA.

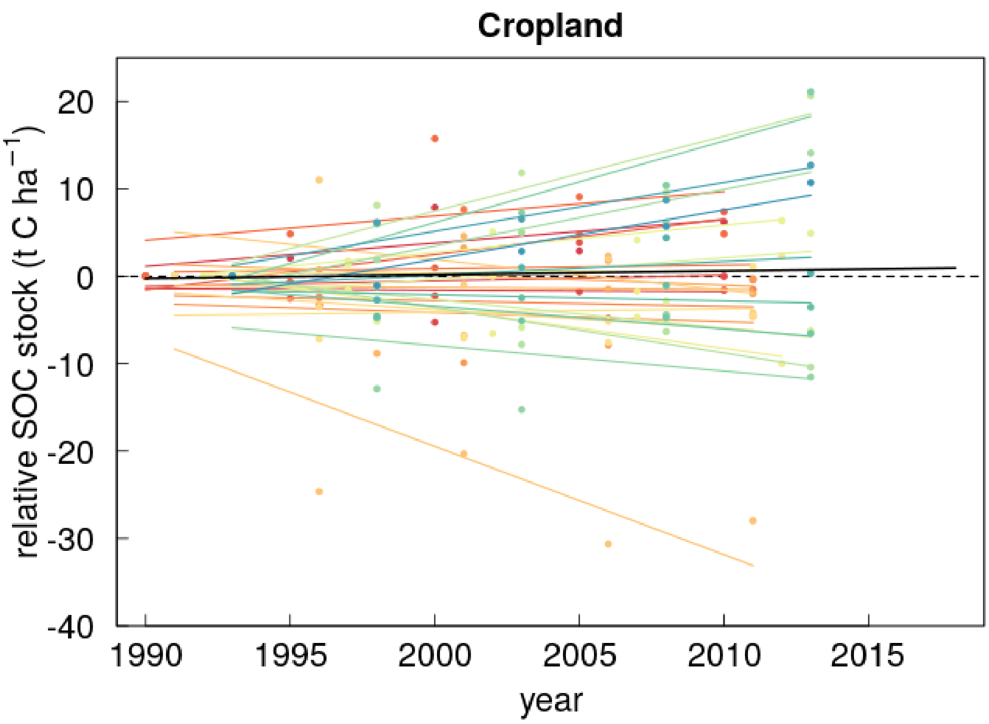


Figure 50: Comparison of simulated and measured SOC stocks for CL using stocks of first measurement of each time series as the baseline (for simulated stocks, the 1990 stocks form the baseline); solid black line shows linear fit of simulated stocks across all strata; dots show measured stocks from NABO soil monitoring sites and coloured lines, the linear fit of each monitoring site; dotted line is line of zero change.

For one very small stratum (A2_F5) some annual SOC changes seem unrealistically high (-3.0 to +2.2 t C ha^{-1} yr^{-1} Figure 48). This variability is probably related to the very high and variable summer PPN of this stratum. This stratum contributes only 0.07 % to the total CL area meaning these changes have little effect on the overall results.

The positive peaks simulated for 2003 and 2018 (i.e. soil was a SOC sink, Figure 49) are probably due to the dry and hot summers of those years. These caused unusually long periods of accumulated TSMD as calculated by RothC, which strongly reduces SOC decomposition rates in the model, leading to an accumulation of SOC. There is however considerable uncertainty in the relationship between soil moisture and soil respiration in general, and the equation in RothC relating TSMD to soil respiration might be more sensitive to dryness than in equations of other models (Falloon et al. 1998). Validating the response of the model under such extreme conditions is generally difficult, as SOC stocks are usually not measured at such high temporal resolution. This is because changes can usually only be detected after several years, due to the large background SOC stocks, inherent spatial and temporal variability and slow soil C increases. At an experimental site in Zurich, measured SOC stocks also show that soils were a sink in the year 2003, but not exceptionally so (Figure 51). Additionally, this comparison is hampered by the timing of sampling: Soil C content was measured in winter time, whereas simulation results represent an annual average. On cropland this is critical as C content can show strong seasonal variation (Leinweber et al. 1994). No further SOC measurements in Switzerland for these summers could be found. What is well known though, is that soil respiration rates do decrease during drought, indicating that decomposition might be slowed down (Canarini et al. 2017). This could lead to an accumulation of C in line with our findings. Other years with prolonged TSMD are 1998 and 2011 (and to a lesser extent 2009); these years also show greater positive SOC stock changes. A comparison with Eddy covariance measurements would be useful to validate this anomaly, but this requires that the study in question calculates a C budget (i.e. accounting for manure imports and harvest exports), allowing SOC dynamics to be inferred. For Switzerland, Emmel et al. (2018) is the only such study we know of, but the year 2003 is not included.

In general, it is difficult to compare results from this project directly with those of long-term experiments or of single (or few-) field site experiments, for three reasons. Firstly, our results relate to SOC changes over a very large spatial scale, meaning that they reflect management changes occurring at both smaller and larger spatial scales. In contrast, experiments or monitoring at specific sites are unable to reflect changes occurring at the larger spatial scale. One example of a management change detectable especially at the large scale is the increased planting of crops that generally lead to increase, rather than decrease SOC stocks (e.g. rape seed, ley), over the last decades: These crops have increased in proportion from 38 % of the total CL surface in 1990, to 47 % in 2017. This increase is probably important for the SOC stock changes across country, but would be barely reflected (if at all) in a study of a few field sites. The second reason why a direct comparison between our CL simulations and long-term experiments is difficult is because we do not simulate real crop rotations, but approximate them by weighting results from continuous crops (see section 2.2.6). Lastly, we know that in several experimental sites the SOC stocks are affected by former land use conversions (Hermle et al. 2008; Oberholzer et al. 2014) and this can be successfully simulated by RothC (section 2.1.3). At the regional scale, however, our setup cannot account for land use changes. Therefore the results of specific sites that are strongly affected by a land-use change cannot be directly compared to our simulations.

The only study we know of that reports SOC changes at the national scale for Switzerland is Stumpf et al. (2018). Combining spectral imagery, a large soil database and a random forest classifier approach, the authors show no significant changes in topsoil C content for CL categories including ley in the rotation. However, they find small (non-significant) losses in SOC of -0.23 and -0.35 g kg^{-1} (i.e., a relative change of between -0.93 and -1.52 %) between the two periods 1995-1999 and 2011-2015. If we convert our stock changes to changes in % for the same years (difference between 1995-1999 and 2011-2015) for AZ1 and AZ2 we get small relative increases of 1.9 % and 2.2 % respectively. However, our results agree with those of Stumpf et al. (2018) overall, in that changes in SOC in this project were also not statistically significant. A direct comparison is between the two studies is however difficult, because the authors report C content (g kg^{-1}) whereas this project calculates C stocks (and thus accounts for any changes in bulk density). Furthermore, CL categories used in Stumpf et al. (2018) are not directly comparable to the categories used here.

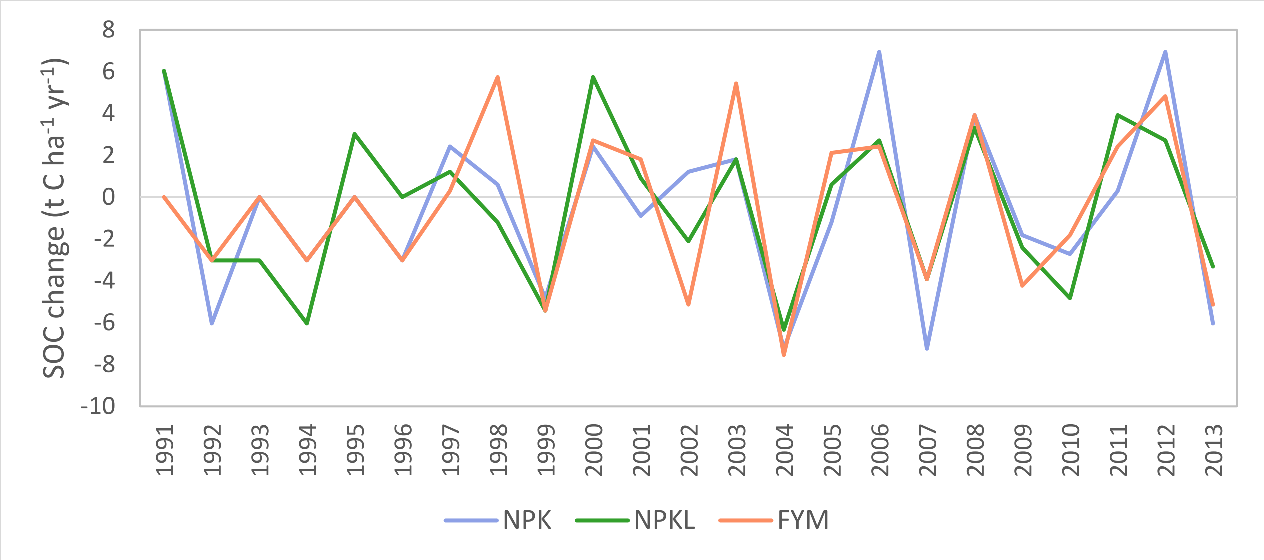


Figure 51: Annual SOC stock changes at an experimental site in Zurich; derived from annual measurements of SOC contents (usually performed in November or December) and a single measurement of bulk density in the upper 0-20 cm of the soil profile. The experiment, "Demo87", tests the effect of different fertilisation treatments: NPK fertiliser (120, 35, 220 kg N, P, K ha^{-1} yr^{-1} on average), NPK plus liming (NPKL), FYM (50 t ha^{-1} yr^{-1}). For more details, see Keel et al. 2019. In the year 2003, soils were a sink for CO_2, but of similar size as in other years.

Comparison to other countries

For CL, the annual variability of stock changes at the national scale is slightly larger than for other countries that apply a comparable approach, i.e. a similar or same model, simulating regions (SD for the period 1990 to 2017 are: Switzerland, 0.197 t C ha^{-1}; Japan, 0.183 t C ha^{-1}; Sweden, 0.180 t C ha^{-1}). Sweden uses a very similar approach (model of similar complexity, simulations for regions). The SD for Switzerland is reduced to 0.17 t C ha^{-1} if the exceptional year 2003 is omitted.

4.1.3 Current SOC stocks

The total topsoil SOC stock under cropland for the year 2017 amounts to 20.02 million t C (lower and upper 95 % CI based on the UA of SOC stock changes: 17.6 and 23.5 million t C). This was calculated based on simulated SOC stocks, applying area-weighting of crops, clay classes and strata, as described in section 2.2.8.

4.2 Grassland

4.2.1 Initial SOC stocks

Under GL, initial SOC stocks (year 1990) for 240 single strata-clay combinations range between 19.7 t C ha^{-1} and 120.2 t C ha^{-1} (data not shown) and mean stocks per AZ are given in Table 23. These stocks are lower than the measured SOC stocks from the national soil monitoring (at 24 sites) for the years 1991-1994 (range: 92.6-213.6 t C ha^{-1}; mean and SD: 123.0 ± 23.4 t C ha^{-1}; measurements of C content and bulk density were made for 0-20 cm and extrapolated to stocks for 0-30 cm, A. Gubler unpublished data). The reason for this discrepancy is unclear. It might be related to the fact that monitoring sites were not selected randomly and tend to be located at sites with rather high SOC stocks that are at least 20 cm deep, whereas values presented in this project include GL surfaces in shallower soils. The sites were originally chosen to monitor pollutants and care was taken to include different land use categories, to account for differences in climatic conditions and soil characteristics; thus, there are monitoring sites within the three dominant strata and within those the GL categories with the largest areal extent are present. The range of SOC stocks calculated in this project includes the mean value obtained for topsoils (0-30 cm) in Germany's agricultural soil inventory (88 t C ha^{-1}, Jacobs et al. 2018) and in southern Belgium (94 t C ha^{-1}, Chartin et al. 2017). The overall mean SOC stock obtained for Switzerland (63.7 t C ha^{-1}) is however lower than these other findings. A possible explanation for the lower SOC stocks might be the high abundance of shallow or stony soils in Switzerland, both typically related to mountainous topography.

Table 23: SOC stocks for GL soils in 1990 (0-30 cm depth) as well as SOC concentration (%), aggregated by AZ, both as estimated in this project (section 2.2.7.1).

	AZ1	AZ2	AZ3	AZ4
proportion of GL in each AZ (for 2018, %)	10	5	23	61
SOC estimate (t C ha^{-1})	60.5	64.0	65.3	66.4
SOC concentration (%)	2.4	2.7	3.7	5.5

In Swiss grasslands, SOC content increases with elevation (Leifeld et al. 2005). The SOC stocks do not increase as much as expected from the calculated SOC concentration (Table 23). This is probably due to other factors influencing SOC stocks, probably soil depth and stone content. AZ1 and AZ2 contain almost no shallow soils whereas these dominate in AZ4. Stone content in AZ4 is roughly 3-4 times higher in AZ4 than in the lower two AZs (calculated from the SSM).

4.2.2 SOC stock changes

Regional-scale changes in SOC stocks in GL soils (1990 – 2018) are shown in Figure 52 and national-level changes in Figure 53. Across this period, annual SOC change rates for the whole country range from -0.22 to +0.20 t C ha^{-1} yr^{-1}, with an average of -0.038 t C ha^{-1} yr^{-1} (range: -0.798 to +0.748 t CO_2 equivalents; mean: -0.140 t CO_2 equivalents). Taking into account the large uncertainty associated with the SOC stock change estimates (section 3.5), annual SOC changes are not statistically significantly positive or negative.

In most years SOC stock changes for lower elevations are slightly negative (Figure 52, lower elevations characteristic of region F2), whereas higher elevation regions generally show positive SOC changes (Figure 52, higher elevations characteristic of regions F4_C and F4_W). Accordingly, positive as well as negative SOC trends were obtained for single strata, though negative trends dominated. Annual changes in SOC stocks ranged from -0.64 to +0.71 t C ha^{-1} (data not shown) and lie within the range calculated for measurement data from the Swiss national soil monitoring: -1.2 to +1.0 t C ha^{-1} (A. Gubler unpublished data; categories: permanent grassland, not including vineyards and parks as in the GH G inventory), see also Figure 54.

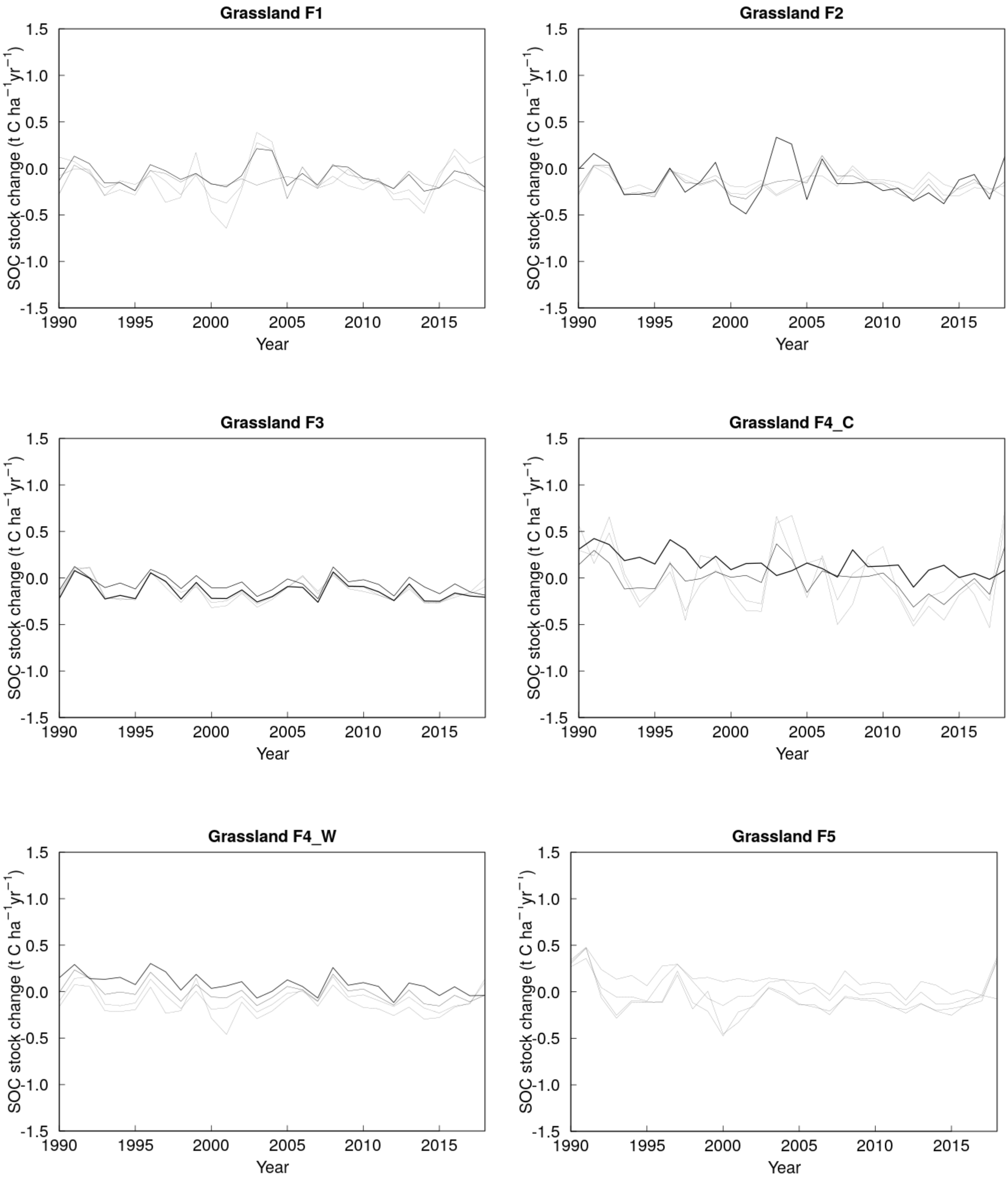


Figure 52: Annual SOC stock changes (0-30 cm) for GL for six productivity regions (section 2.2.1.1); the line thickness is proportional to the relative surface of each stratum.

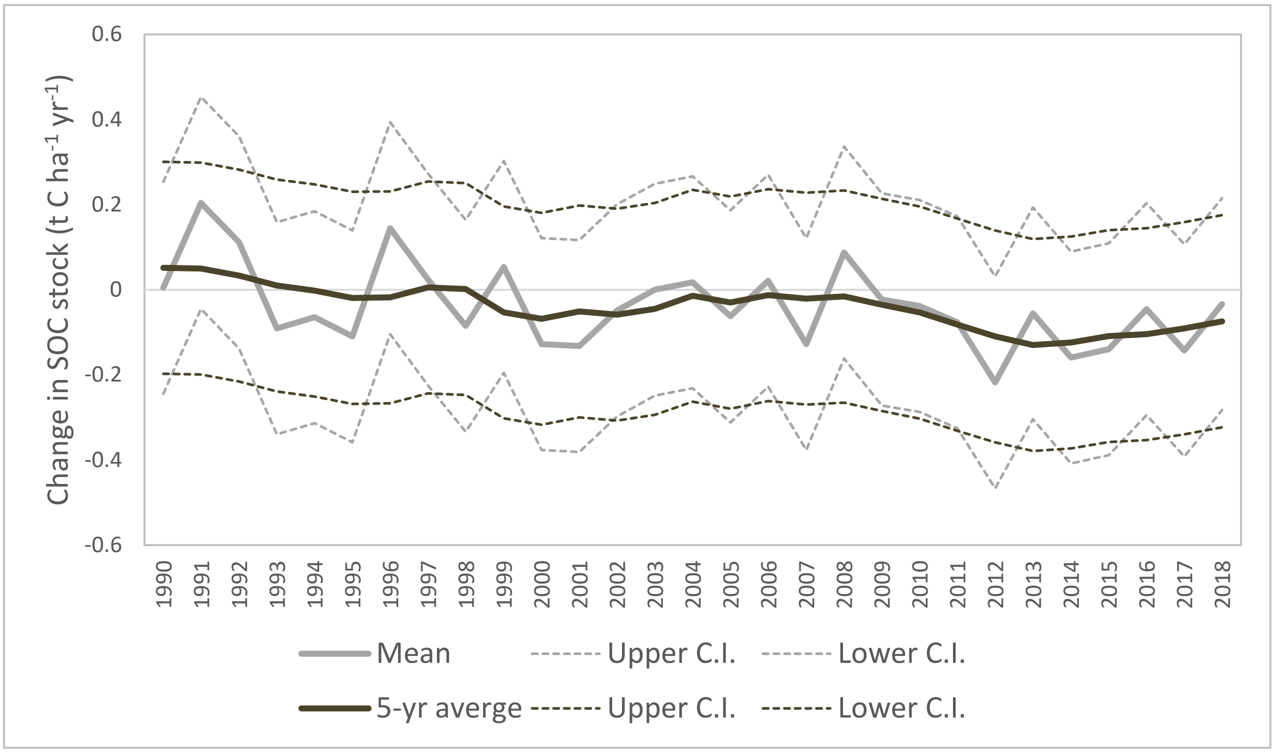


Figure 53: Annual national SOC stock changes for GL soils (0-30 cm) showing annual (grey) and 5-yr average (green) values, calculated using a weighted average across all strata; dashed lines show the upper and lower CIs, using absolute values derived from UA.

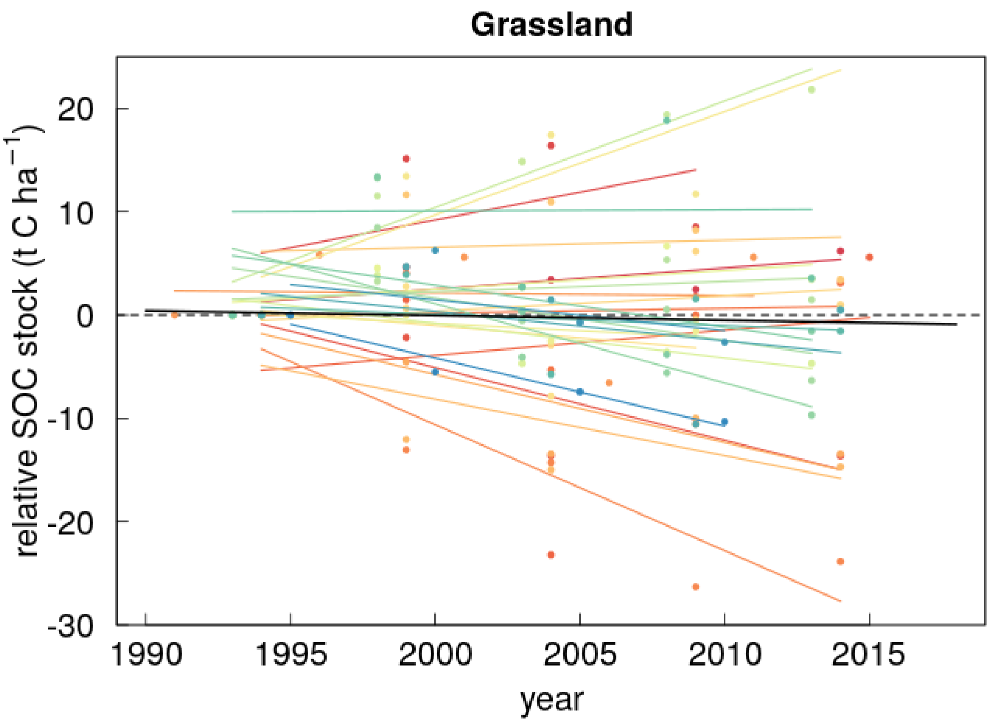


Figure 54: Comparison of simulated and measured SOC stocks for GL using stocks of first measurement of each time series as the baseline (for simulated stocks, the 1990 stocks form the baseline); solid black line shows linear fit of simulated stocks across all strata; dots show measured stocks from 26 NABO soil monitoring sites and coloured lines, the linear fit of each monitoring site; dotted line shows line of zero change.

Using eddy covariance measurements, Ammann et al. (2007) showed SOC losses on extensively used GL (no fertilisation, low cutting frequency, -1.5 to +0.04 t C ha^{-1} yr^{-1}) for the site Oensingen (already used for testing models, section 2.1.3), and SOC increases on intensive field (0.3 to 2.7 t C ha^{-1} yr^{-1} for the whole profile) over five years. Measurements at the same site could confirm this (Leifeld et al. 2011). These findings are reflected in this project, as more intensively-managed grasslands tend to have a more positive C balance than extensively-managed grasslands.

As discussed above for cropland, a direct comparison of long-term experiments and simulations for strata is nonetheless hampered. An example to illustrate this are the changing patterns in the application of OrgAm to GL in the year-round farming regions: We estimate that the amount of OrgAm-C being applied nationally to grassland (and leys) has decreased by ca. 4 % since 1990. This might be important for SOC stock changes across the whole country, but such a gradual decrease in OrgAm application rate is usually not applied in controlled trials where experimental factors are kept constant; the nationally-important pattern is therefore not detected on the local scale.

As stated in section 4.1.2, the only study we know of that reports SOC changes at the national scale for Switzerland is Stumpf et al. (2018). For the three grassland categories, they report small losses in SOC between -1.0 and -1.3 g kg^{-1} (-3.3 and -4.1 %) between 1995-1999 and 2011-2015. If we convert our stock changes to changes in % and report them for the same years (difference between 1995-1999 and 2011-2015) the changes for AZ1, AZ2 and AZ3 are -4.1, -3.8 and -1.9 %. For the lower two AZs, there is congruence between the results. Comparison of results for mountainous regions is not possible as high elevation areas (> 1500 m asl) were not considered in Stumpf et al. (2018).

4.2.3 Current SOC stocks

The total topsoil SOC stock under permanent grassland for the year 2017 amounts to 57.39 million t C (lower and upper 95 % CI based on the UA of SOC stock changes: 42.9 and 62.0 million t C). This was calculated based on simulated SOC stocks, applying area-weighting of crops, clay classes and strata, as described in section 2.2.8.

4.3 Limits of the System

The model-based SOC inventory described in this report has been developed specifically for the reporting of SOC stock changes for Switzerland's annual national GHG reporting under the UNFCCC. Thus it is important that data are 1) collected systematically for the whole country, covering as many farms as possible, 2) collected consistently across the time period, 3) consistent as far as possible with those used in the Agriculture part of GHGI. These specifications place constraints on the system, which can be summarized as the system had to be simple enough that the data were available (Köck et al. 2013). One of the important consequences of this is that a relatively simple model was chosen to simulate SOC, as discussed in section 4. In addition to this, there are a number of specific limitations in the system, explained below.

OrgAm application

The OrgAm model is simplified in several aspects. Firstly, it does not account for imports or exports of OrgAm into or out of the country, though this is known to occur. Because information on manure and slurry imports / exports is held by individual cantons, it is (currently) unknown a) how important this might be for overall SOC stocks and b) how much imports and exports have changed over time.

Secondly, the OrgAm-model treats the OrgAm production as a national 'pool', which is distributed in part according to farmers' preference and in part according to crop requirements. It does not account for the spatial production of OrgAm or its physical movement, although we know that OrgAm is moved between farms. This movement is recorded in the 'HODUFLU' database of the FOAG[17]. Incorporating this information would be an improvement to the OrgAm-model but data are available only since 2014, meaning OrgAm movement for years prior to then would have to be based on extrapolation. This is problematic if there has been a change in the spatial distribution of animal husbandry or OrgAm movement since 1990. The database might alternatively show that although movement between farms (and municipalities) occurs, movement between strata is negligible compared to the overall OrgAm production.

[17] https://www.blw.admin.ch/blw/de/home/politik/datenmanagement/agate/hoduflu.html; in French, German and Italian.

Thirdly, the estimate of OrgAm-C storage losses is quite simplistic, because the estimate of the duration of storage is uncertain and assumed to be constant for a given OrgAm type. In reality however, OrgAm application is seasonally determined by plant needs and by restrictions (e.g. spreading during winter months is restricted in many areas due to frozen soils), meaning storage times vary between farms and seasons. This variation is particularly problematic not only because OrgAm-C storage loss is important for the OrgAm-C application rates in general, but because the rate of OrgAm-C loss as a function of time is not linear. It is however unclear how a more accurate estimate of the timing of OrgAm application could be obtained for the whole time series at the regional level.

Lastly, RothC assumes that different types of OrgAm (e.g. slurry or stacked manure) have the same C pool distribution: 2% is assumed to be humified and 49% contributes to the decomposable plant material (DPM) and resistant plant material (RPM) pools each. Other (also simple) SOC models infer different compositions and properties of OrgAm, for example the CCB model (Franko et al. 2011). There has been a significant change in animal housing since 1990 (Kupper et al. 2018). Because OrgAm type is linked to animal housing it is likely there has been a corresponding systematic change in the quality of OrgAm over this period too, warranting the development of different C pool distributions.

Plant C inputs

Currently plant C inputs to soil from GL and leys are assumed to be constant and independent of management intensity or ploughing (e.g. leys that are ploughed in), based on C inputs used in the CCB model (Franko et al. 2011). This approach has been applied in SOC stock modelling in a previous study (Keel et al. 2017, for leys in cropland). Preliminary investigation showed that allometric equations simulating the ploughing-in of grass (to simulate leys) led to unrealistically high plant C inputs, and in this project, constant plant C inputs resulted in satisfactory model-data agreement, though this was based on few data available from long-term experiments. Nonetheless, how the variation in plant C inputs varies across elevation and management-intensity gradients needs to be assessed. The latter is especially important, as there has been a systematic (though small) shift in management intensity in Swiss grassland since 1990 (Figure 23).

Timing of C inputs

The month(s) in which C inputs from OrgAm and plants are added to soils is crop-specific. Currently, the timing of C inputs is constant through time (and for crops, across the strata). The corollary of this is that C inputs are not adjusted according to environmental conditions, such as a drought or a cool summer. It is possible that this could lead to unrealistic situations (e.g. high C inputs to soil from manure and plants during a drought) which, depending on the sensitivity of the model to the timing of C inputs, might lead to inaccurate model outputs. The role of this in the years for which extreme SOC gains were simulated (including 2003, 2018) needs to be investigated. Generally, this issue is more critical for crops, as C inputs are distributed irregularly, whereas C inputs in GL are distributed evenly throughout the year.

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9 Appendix A

Table A - 1: Description of treatments applied at eight experimental sites on cropland and permanent grassland (marked 'GL') in Switzerland that were used to test model performance. The type of fertilizer and average amounts applied over crop rotations are shown. For cropland experiments, the average fresh matter yield of winter wheat is given. Residues were usually removed from the field, if not, the crop types for which residues were retained are listed. For permanent grassland the yield is given in dry matter. In Switzerland the reference yields for permanent grasslands (depending on altitude and management intensity) are 55 dt ha^{-1} (Bals), 98 dt ha^{-1} (Oens), 64 dt ha^{-1} (Watt). For winter wheat the reference yield is 60 dt ha^{-1} (fresh matter) (Richner and Sinaj 2017).

Site	Treatment abbreviation and number of replicates	Fertilization (kg ha^{-1} yr^{-1}) (N, P, K) [a)]	yield (dt ha^{-1})	Residue retention	Cover crops	cutting frequency (if GL)
Bals (GL)	2NPK (n = 3)	NPK fertilizer (75, 35, 200)	75.3			2 cuts
Bals (GL)	2O (n = 3)	unfertilized	38.3			2 cuts
Bals (GL)	2PK (n = 3)	PK fertilizer (0, 35, 200)	65.6			2 cuts
Bals (GL)	3NPK (n = 3)	NPK fertilizer (75, 35, 200)	70.8			3 cuts
DOK	D1 (Biodynamic farming,) (n=12)	composted FYM and slurry (45, 10, 80)	42.8	Potato and sugarbeet	green manure 3 out of 28 years	
DOK	D2 (Biodynamic farming) (n=4)	composted FYM and slurry (90, 20, 160)	41.6	Potato and sugarbeet	green manure 3 out of 28 years	
DOK	DOK-C (n=4)	Unfertilized	31.3	Potato and sugarbeet	green manure 3 out of 28 years	
DOK	K1 (Conventional farming) (n=12)	stacked FYM and slurry (70, 15, 110)	52.5	Potato and sugarbeet	green manure 3 out of 28 years	
DOK	K2 (Conventional farming) (n=4)	stacked FYM and slurry (140, 35, 220)	51.6	Potato and sugarbeet	green manure 3 out of 28 years	
DOK	M2 (mineral fertilizer)	NPK fertilization (95, 35, 225)	51.0	Potato and sugarbeet	green manure 3 out of 28 years	
DOK	O1 (Organic farming) (n=12)	rotted FYM and aerated slurry (50, 10, 85)	42.6	Potato and sugarbeet	green manure 3 out of 28 years	
DOK	O2 (Organic farming) (n=4)	rotted FYM and aerated slurry (95 ,20, 170)	42.1	Potato and sugarbeet	green manure 3 out of 28 years	
Haus	PN (n=4)	optimal NPK fertilizer (130, 35, 135)	57.3	wheat and rapeseed		
Oens (GL)	EXT (extensive) (n=1)	unfertilized	57.8			3 cuts
Oens (GL)	INT (intensive) (n=1)	N fertilizer + slurry (195, 60, 560)	79.2			4 cuts
p24A	C-0 (n=1)	PK fertilizer (0, 30, 100)	27.0	silage maize and rapeseed		
p24A	C-105 (n=1)	High N fertilization (150 ,30, 100)	60.9	silage maize and rapeseed		
p24A	C-35 (n=1)	Low N fertilization (70, 30, 100)	49.7	silage maize and rapeseed		
p24A	C-70 (n=1)	Optimal N (110, 30, 100)	57.8	silage maize and rapeseed		
p24A	FYM35-0 (n=1)	35 t ha^{-1} FYM + PK fertilizer (190, 80, 325)	30.1	silage maize and rapeseed		

p24A	FYM35-105 (n=1)	35 t ha^{-1} FYM + high N (315, 80, 325)	60.4	silage maize and rapeseed		
p24A	FYM35-35 (n=1)	35 t ha^{-1} FYM + low N fertilization (320, 80, 325)	47.3	silage maize and rapeseed		
p24A	FYM35-70 (n=1)	35 t ha^{-1} FYM, optimal N fertilization (275, 80, 325)	56.8	silage maize and rapeseed		
p24A	FYM70-0 (n=1)	70 t ha^{-1} FYM + PK fertilizer (385, 135, 555)	32.3	silage maize and rapeseed		
p24A	FYM70-105 (n=1)	70 t ha^{-1} FYM + high N fertilization(510, 135, 555)	62.1	silage maize and rapeseed		
p24A	FYM70-35 (n=1)	70 t ha^{-1} FYM + low N fertilization(425, 135, 555)	53.4	silage maize and rapeseed		
p24A	FYM70-70 (n=1)	70 t ha^{-1} FYM + optimal N fertilization (465, 135, 555)	59.7	silage maize and rapeseed		
p24A	Green-0 (n=1)	Green manure every two years + PK fertilizer (0, 30, 100)	30.4	silage maize and rapeseed, green manure every two years		
p24A	Green-105 (n=1)	Green manure every two years + high N fertilization(150, 30, 100)	58.8	silage maize and rapeseed, green manure every two years		
p24A	Green-35 (n=1)	Green manure every two years + low N fertilization (70, 30, 100)	51.8	silage maize and rapeseed, green manure every two years		
p24A	Green-70 (n=1)	Green manure every two years + optimal N fertilization (110, 30, 100)	57.2	silage maize and rapeseed, green manure every two years		
p24A	Slurry-0 (n=1)	Slurry + PK fertilizer (100, 50, 270)	31.9	silage maize and rapeseed		
p24A	Slurry-105 (n=1)	Slurry + high N fertilization (225, 50, 270)	59.8	silage maize and rapeseed		
p24A	Slurry-35 (n=1)	Slurry + low N fertilization (140, 50, 270)	49.2	silage maize and rapeseed		
p24A	Slurry-70 (n=1)	Slurry + optimal N fertilization (185, 50, 270)	57.8	silage maize and rapeseed		
p24A	Straw-0 (n=1)	Cereal straw + PK fertilizer (15, 35,180)	26.2	wheat, barley, oat, silage maize and rapeseed		
p24A	Straw-105 (n=1)	Cereal straw + high N fertilization (165, 35,180)	57.7	wheat, barley, oat, silage maize and rapeseed		
p24A	Straw-35 (n=1)	Cereal straw + low N fertilization (80, 35, 180)	50.1	wheat, barley, oat, silage maize and rapeseed		
p24A	Straw-70 (n=1)	Cereal straw + optimal N fertilization (125, 35, 180)	54.4	wheat, barley, oat, silage maize and rapeseed		
p29C	MP_CA (n=3)	optimal NPK fertilization (135, 30, 125)	52.3	rapeseed and maize	cover crops sown in 2000	

p29C	MP_CL (n=4)	optimal NPK fertilization (135, 30, 125)	47.4	rapeseed and maize	cover crops sown in 2000	
Watt (GL)	Watt-C (n=4)	Unfertilized	44.8			3 cuts
Watt (GL)	Watt-N2P2K2 (n=4)	NPK fertilizer (30, 10, 55)	66.5			3 cuts
Watt (GL)	Watt-N4P4K4 (n=4)	NPK fertilizer (60, 25, 110)	76.9			3 cuts
ZOFE	Compost (n=5)	Compost (120, 45, 85)	26.8	potato		
ZOFE	Compost + PK (n=5)	Compost + PK fertilizer (120, 65, 225)	40.5	potato		
ZOFE	Ctrl (n=5)	Unfertilized	20.4	potato		
ZOFE	FYM (n=5)	FYM (90, 25, 65)	35.2	potato		
ZOFE	FYM+PK (n=5)	FYM + PK fertilizer (90, 60, 300)	38.8	potato		
ZOFE	N0P2K2 (n=5)	PK fertilizer (0, 40, 165)	31.7	potato		
ZOFE	N1P1K1 (n=5)	NPK fertilizer (140, 20, 85)	43.9	potato		
ZOFE	N2P2K2Mg (n=5)	NPKMg fertilizer (140, 40, 165)	45.9	potato		
ZOFE	N2P2K2 (n=5)	NPK fertilizer (140 ,40, 165)	49.0	potato		
ZOFE	Peat + PK (n=5)	Peat + PK fertilizer (25, 60, 295)	32.8	potato		
ZOFE	SS (n=5)	Sewage sludge (134, 110, 10)	33.5	potato		
ZOFE	SS + PK (n=5)	Sewage sludge + PK fertilizer (134, 120, 295)	37.4	potato		

10 Appendix B

Table B - 1: Measured and modelled changes in SOC stocks (t C ha^{-1} yr^{-1}) for experimental sites on cropland and permanent grassland (marked 'GL') in Switzerland that were used to test model performances. Note that for grassland the model stock changes are identical for the two combinations of RothC and allometric equations because C inputs are identical. The simulated stock change(s) that most closely resemble(s) the measured stock change is / are shown in bold. * = Treatments relevant to typical Swiss agricultural practice.

		Annual SOC stock changes (t C ha^{-1} yr^{-1})			
Site	Treatment abbreviation and number of replicates	Measurements	CCC-CCB	RothC-Swiss	RothC-CCB
Bals (GL)	2NPK (n = 3)	-0.53	0.02	**-0.34**	**-0.34**
Bals (GL)	2O (n = 3)	-0.93	0.02	**-0.34**	**-0.34**
Bals (GL)	2PK (n = 3)	-0.78	0.02	**-0.37**	**-0.37**
Bals (GL)	3NPK (n = 3)	-0.44	0.02	**-0.35**	**-0.35**
Oens (GL)	EXT (extensive) (n=1)	-0.24	0.49	**-0.60**	**-0.60**
Oens (GL)	INT (intensive) (n=1)	0.19	0.50	-0.41	-0.41
p24A	C-0 (n=1)	-0.18	-0.12	-0.2	**-0.19**
p24A	C-105 (n=1)*	-0.14	-0.08	**-0.1**	-0.09
p24A	C-35 (n=1)*	-0.17	-0.1	**-0.14**	-0.13
p24A	C-70 (n=1)*	-0.16	-0.09	**-0.11**	**-0.11**
p24A	FYM35-0 (n=1)	-0.09	-0.08	**-0.09**	-0.08
p24A	FYM35-105 (n=1)	-0.06	**-0.05**	-0.01	-0.01
p24A	FYM35-35 (n=1)	-0.09	**-0.05**	-0.03	-0.03
p24A	FYM35-70 (n=1)	-0.07	**-0.05**	-0.01	-0.01
p24A	FYM70-0 (n=1)	-0.01	-0.04	**0.01**	0.02
p24A	FYM70-105 (n=1)	0.12	-0.01	**0.08**	**0.08**
p24A	FYM70-35 (n=1)	0.03	**-0.01**	0.07	0.07
p24A	FYM70-70 (n=1)	0.08	-0.01	**0.08**	**0.08**
p24A	Green-0 (n=1)	-0.11	-0.1	-0.16	**-0.15**
p24A	Green-105 (n=1)*	-0.05	**-0.06**	**-0.06**	**-0.06**
p24A	Green-35 (n=1)*	-0.06	**-0.08**	-0.1	-0.09
p24A	Green-70 (n=1)*	-0.07	**-0.07**	**-0.07**	**-0.07**
p24A	Slurry-0 (n=1)*	-0.1	**-0.11**	-0.15	-0.14
p24A	Slurry-105 (n=1)	-0.06	**-0.07**	**-0.07**	**-0.07**
p24A	Slurry-35 (n=1)	-0.06	**-0.09**	-0.11	-0.1
p24A	Slurry-70 (n=1)	-0.04	**-0.08**	**-0.08**	**-0.08**
p24A	Straw-0 (n=1)*	-0.14	-0.08	-0.19	**-0.18**
p24A	Straw-105 (n=1)*	-0.07	-0.01	-0.11	**-0.1**
p24A	Straw-35 (n=1)*	-0.1	-0.02	-0.14	**-0.13**
p24A	Straw-70 (n=1)*	-0.1	-0.02	**-0.12**	**-0.12**
Watt (GL)	Watt-C (n=4)	0.21	**0.03**	-0.24	-0.24
Watt (GL)	Watt-N2P2K2 (n=4)	0.23	**0.03**	-0.22	-0.22
Watt (GL)	Watt-N4P4K4 (n=4)	0.23	**0.03**	-0.14	-0.14
ZOFE	Compost (n=5)*	-0.22	-0.11	**-0.18**	-0.16
ZOFE	Compost + PK (n=5)*	-0.15	-0.07	**-0.15**	-0.13
ZOFE	Ctrl (n=5)	-0.23	-0.11	-0.3	**-0.28**
ZOFE	FYM (n=5)	-0.21	0.03	-0.2	**-0.18**
ZOFE	FYM+PK (n=5)*	-0.19	-0.05	**-0.16**	-0.14
ZOFE	N0P2K2 (n=5)	-0.26	-0.11	-0.29	**-0.27**
ZOFE	N1P1K1 (n=5)*	-0.2	-0.11	-0.25	**-0.24**
ZOFE	N2P2K2Mg (n=5)*	-0.27	-0.06	**-0.27**	-0.25
ZOFE	N2P2K2 (n=5)*	-0.24	0.01	-0.27	**-0.25**
ZOFE	Peat + PK (n=5)	-0.11	-0.05	-0.18	**-0.16**
ZOFE	SS (n=5)	-0.18	-0.11	**-0.19**	**-0.17**
ZOFE	SS + PK (n=5)	-0.1	**-0.04**	-0.17	**-0.16**