Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER

Agroscope
Agroecology and Environment (AOU)
Climate and Agriculture group

Chloé Wüst-Galley, Sonja G. Keel, Jens Leifeld | December 2019

Internal report

A model-based carbon inventory for national greenhouse gas reporting of mineral agricultural soils

Contact: Chloé Wüst-Galley
Agroscope
Reckenholzstrasse 191, 8046 Zürich / Schweiz
T: +41 58 466 77 74, F: +41 58 468 72 01
chloe.wuest@agroscope.admin.ch

www.agroscope.ch | gutes Essen, gesunde Umwelt

Table of contents

Table of figures

Table of tables

Summary

A model-based soil organic carbon (SOC) inventory for mineral soils under permanent grassland and cropland in Switzerland has been developed, to be used for national greenhouse gas reporting under the UNFCCC. The inventory system is based on the soil carbon (C) model RothC and incorporates the management of the 19 most important crops and 6 grassland categories. An allometric equation is used to derive the amount of plant C inputs to the soil based on annual measured 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 size of the different C pools in RothC is estimated using a pedo-transfer function, which proved to be a good alternative to the estimation with a spin-up (model simulation until a steady-state is reached). For national-scale simulations the country is stratified into 24 regions with similar climatic conditions and agricultural production types (characterized e.g. by the steepness of slopes or accessibility). For each of these 24 strata a simulation is run for 19 different crops and 6 grassland categories, for 10 different soil clay classes. The final SOC time series for each stratum is then calculated as an area-weighted average of each combination of crop/grassland and clay class. This was found to be an acceptable alternative to simulating real crop rotations. The system is dynamic, capturing inter-annual variability in SOC changes due to, for example, meteorological conditions or herd sizes (which influence C inputs to soil through organic amendments). Furthermore, it is flexible allowing for continuous improvements as well as the representation of some future changes in management. Finally, the inventory system can also serve as a tool for sensitivity analysis or to explore specific GHG mitigation options that increase SOC stocks. In the National inventory report, the results are aggregated for three elevation zones and are reported separately for permanent grassland and for cropland. An initial uncertainty analysis based on Monte Carlo simulations considering uncertainty in the input parameters reveals that the average relative uncertainty of year-to-year SOC stock changes is greater than 100 %. This indicates that at the national scale, for the period 1990 to 2017 and across all crop and grassland types, mineral agricultural soils cannot be considered a statistically significant C sink or source.

Zusammenfassung

Wir haben ein modell-gestütztes Bodenkohlenstoff (Boden-C) Inventar für mineralische Böden unter Ackerland und Dauergrünland entwickelt, welches für die Klimaberichterstattung zuhanden des UNFCCC verwendet werden kann. Das Inventarisierungssystem beruht auf dem prozessbasierten Boden-C Modell RothC und benötigt jährliche Ertragsdaten der 19 wichtigsten Ackerkulturen und von 6 Graslandkategorien. Mit Hilfe einer allometrischen Funktion werden die C Einträge in den Boden in Abhängigkeit von gemessenen Erträgen ermittelt. Meteorologische Daten beziehen wir von Meteoschweiz. Der Tongehalt des Bodens wird anhand einer Bodeneignungskarte grob abgeschätzt. Um die initialen Boden-C-Vorräte zu berechnen, benutzen wir einen Ansatz, welcher die Vorräte in Abhängigkeit von Tongehalt, Höhenlage und Landnutzungstyp berechnet. Die Grösse der einzelnen C-Pools im Modell RothC werden mithilfe einer Pedotransferfunktion berechnet. Dieser Ansatz hat sich als gute Alternative zum klassischen spin-up (Simulation bis zum Erreichen eines Gleichgewichtszustandes) bewährt. Für die Simulationen auf der nationalen Skala wird die gesamte Fläche in 24 Regionen eingeteilt (stratifiziert), welche ähnliche klimatische Bedingungen aufweisen und in der gleichen landwirtschaftlichen Zone liegen (z.B. charakterisiert durch ähnliche Zugänglichkeit oder ähnliches Relief). Für jedes dieser 24 Straten wird eine Simulation für alle möglichen Kombinationen von 25 verschiedene Ackerkulturen und Graslandkategorien mit 10 Tonklassen (Bodenkörnung) durchgeführt. Um die Zeitreihe des Boden-C-Vorrats für jedes Stratum zu berechnen, werden flächengewichtete Mittelwerte für jede Kultur/Grasland-Boden Kombination bestimmt. Dieser Ansatz erwies sich als gute Alternative zur Simulation von echten Fruchtfolgen. Generell sind die Berechnungen dynamisch und erfassen die interannuelle Variabilität der Veränderungen des Boden-C Vorrats z.B. als Folge der meteorologischen Verhältnisse, Änderungen der angebauten Kulturen oder des Tierbestandes (welcher den C Eintrag in den Boden durch Hofdünger beeinflusst). Das System ist flexibel gestaltet und kann kontinuierlich verbessert und an (gewisse) zukünftige Bedingungen angepasst werden. Das Inventarisierungssystem kann auch als Werkzeug für Sensitivitätsanalysen oder für die Abschätzung von Treibhausgasminderungsmassnahmen in Zusammenhang mit Boden-C-Senken verwendet werden. Für das Nationale Treibhausgasinventar werden die Resultate für Ackerland und Dauergrünland jeweils in aggregierter Form für 3 Höhenstufen dargestellt. Eine erste Unsicherheitsanalyse basierend auf Monte Carlo Simulationen, welche die Unsicherheit der Parameter der Eingangsdaten berücksichtigt, wurde durchgeführt. Die Analyse zeigt, dass die mittlere relative Unsicherheit der Jahr-zu-Jahr Änderungen der Boden-C-Vorräte grösser ist als 100%. Dies weist darauf hin, dass mineralische Böden unter beiden Landnutzungen über die ganze Landwirtschaftsfläche für den Zeitraum 1990-2017 C-neutral sind, mit Ausnahme von klimatischen Extremjahren.

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 terres cultivées en Suisse. Il sera utilisé au titre de l'UNFCCC dans les rapports nationaux de gaz à effet de serre. Ce système d'inventaire repose sur le modèle de Carbone du sol RothC et dépend des rendements annuels des 19 cultures les plus importantes et des 6 catégories de prairies. Basée sur les récoltes, une équation allométrique est utilisée pour quantifier l'apport du Carbone des plantes dans le sol. 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, par exemple, 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, le pays est divisé en 24 régions homogènes présentant des conditions climatiques similaires et des types de production agricole semblables (caractérisés par exemple par l'inclinaison des pentes ou leur accessibilité). Pour chacune de ces 24 strates, une simulation est réalisée pour 25 types de cultures et prairies différentes, associée avec 10 catégories différentes d'argile du sol. La série temporelle finale du COS pour chacune de ces strates est calculée comme une moyenne pondérée à l'échelle de la région pour chaque combinaison de culture et de type de sol. Cela s'est avéré être une alternative acceptable aux simulations de réelles rotations de cultures. Le système est dynamique et tient compte de la variabilité interannuelle des changements du COS liés, par exemple, aux conditions météorologiques, aux types de plantes cultivées et à la taille des troupeaux. De plus, sa flexibilité permet des améliorations continues, ainsi que la prise en compte de changements futurs dans le mode de gestion. Enfin, ce système d'inventaire peut également être utilisé comme outil pour des analyses de sensibilité ou pour explorer des options spécifiques d'atténuation des émissions de GES qui augmentent les stocks de COS. Dans le rapport d'inventaire national, les résultats sont regroupés en trois zones d'altitude et sont présentés séparément pour les prairies permanentes (GL) et les terres cultivées (CL). Une première analyse d'incertitude basée sur des simulations par Monte Carlo, tenant compte de l'incertitude sur les paramètres d'entrée, révèle cependant que l'incertitude relative moyenne années après années des stocks de COS est supérieure à 100%, ce qui indique que ces deux types d'utilisation des terres 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 LULUCF
ET	evapotranspiration
EZ	elevation zone
FOAG	Federal Office for Agriculture (Bundesamt für Landwirtschaft / office fédéral de l'agri-culture)
FOEN	Federal Office for the Environment (Bundesamt für Umwelt / office fédéral de l'envi-ronnement)
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 LULUCF
LULUCF	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
SOC	soil organic carbon
SOM	soil organic matter
SFU	Swiss Farmers' Union (Schweizer Bauernverband / union suisse des paysans)
SIS	surface incoming shortwave
SSM	soil suitability map
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 (Ciais et al. 2013). Changes in SOC stocks are therefore relevant for greenhouse gas (GHG) budgets. In mineral soils, C losses (throughout this report C refers to SOC) are associated primarily with CO_2 emissions of soils and C 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. Due to the large area covered by soils, even small SOC changes can result in significant changes of CO_2 in the atmosphere.

Inventory / UNFCCC

As an Annex I party, Switzerland submits an annual GHG inventory covering 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 (LULUCF).
Until 2018, a rather 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). In the past, it was recommended that Switzerland develop a tier 3 approach to estimate SOC stock changes in agricultural soils[1]. For this purpose Köck et al. (2013) developed a framework for a tier 3 approach, implementing a modelling-based approach (as opposed to a repeated measurement approach, Köck et al. 2013 page 16). The present report describes the implementation of this tier 3 approach.

Peculiarities of the Swiss farming landscape

Swiss farming 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. It contains flat land in the central plateau and in wide mountain valleys, as well as hilly and mountainous regions; agricultural is practiced throughout this diverse landscape. The topographic gradient of agricultural land is long, for example, grassland occurs between ca. 190 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, the diversity of topographic landscapes affects agricultural management through financial, bio-physical or logistical constraints. Correspondingly, agricultural management is also very diverse across the country. 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 (see 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), as well as grazing- or mowing-intensity are very variable.

1.1 Scope

Within this project we designed a system to model SOC stocks of agricultural mineral soils over permanent grassland and cropland, for the upper 30 cm of soil. Annual SOC stocks are modelled, for the years 1990 to present, and from these stocks, year-to-year stock changes are calculated.
The land use categories recommended by the IPCC for the reporting of LULUCF in the GHG inventory are sub-divided into 18 combination categories (CCs) by Switzerland. Chapter 6.2.1 of FOEN (2018) describes the land use statistics (LUS) and the CC nomenclature system in more detail. This project concerns agricultural mineral soils of two of these CCs, cropland (CL, CC21) and permanent grassland (GL, CC31). CL includes arable and tillage land in agricultural areas, and leys. GL includes grass and herb vegetation in agricultural areas, with the exception of leys. As outlined in Köck et al. (2013), the tier 3 modelling approach for the GHG inventory initially does not model SOC stocks under other grassland types, namely those in vineyards and horticulture, brush meadows, copses, orchards and particularly shrubby or stony mountain (incl. agricultural) grasslands (section 2.2.2.1).

[1] **UNFCCC 2007**: Report of the individual review of the greenhouse gas inventory of Switzerland submitted in 2006 (FCCC/ARR/2006/CHE), § 94 and 97. **UNFCCC 2011**: Report of the individual review of the annual submission of Switzerland submitted in 2010 (FCCC/ARR/2010/CHE), § 94.

SOC stock changes are being estimated for CL remaining CL and GL remaining GL. No land use changes are being modelled (e.g. CL to GL), because data to calibrate or validate such simulations are lacking. Regarding the GHG inventory, this is also consistent with land-use change between other land use categories.
SOC stocks need to be modelled at a local or regional scale, rather than simply at the national scale. This is because SOC stocks and dynamics are site-dependent, influenced by parameters that vary with location, including meteorological conditions and clay content. Additionally, SOC dynamics are management-dependent as they are affected by, for example, fertilisation by organic amendments, residue management and soil cover, themselves related to different crops and grassland categories. Together, these necessitate the modelling of SOC to be crop- / grassland-specific and location-specific.
The model used in this project (RothC, see section 2.1.5) simulates SOC stocks for a location with homogeneous conditions (e.g. an experimental site or a field). In order to carry out SOC stock simulations at the national scale, these so called 'point-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 raster-based modelling 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 for GHG inventories of several other countries (e.g. Denmark, Finland, Japan, Canada).

1.2 Aims

The final goal of this 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 1990 to present and should account for the diversity of Switzerland's physical landscape and of its farming systems. Furthermore, the system should be flexible allowing for improvements and for changes in management to be incorporated. An initial uncertainty analysis (UA) should also be carried out, which should serve as both an initial estimate of uncertainty associated with the system and as the basis for a sensitivity analysis and a more thorough UA in the future.

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 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 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). If plant residues are added to soil, the C is allocated to short and medium turnover pools. If manure is added, some C is directly allocated to a slow turnover C. CCB is the only model that distinguishes between different types of organic fertiliser (different types of manure, slurry, compost, sewage sludge etc.); in the other models only one type of organic fertiliser is considered. All selected 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 for their potential application in the Swiss GHG inventory was evaluated 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 twenty 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). Each compartment decomposes by a first-order process with its own characteristic rate. 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). New C from plant residues is always added as DPM or RPM. For agricultural crops and improved grassland (i.e. grazed or improved by e.g. additions of lime), 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 is dry (topsoil moisture deficit, TSMD), or covered by plants. It is also affected by the soil clay content. The model uses a monthly time step. To calculate initial SOC stocks and pool distributions 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 with 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 (W), ethanol solubles (E), acid hydrolysables (A), and compounds neither soluble nor hydrolysable (N). In addition, there is a humus fraction (H) 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 precipitation (PPN), by first order kinetics. The model uses a yearly 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). The model uses a yearly 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. The model uses a monthly time step.

2.1.2 Estimation of carbon inputs to soil

<u>Carbon inputs from plants</u>
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). 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), 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 classes of crops (e.g. grains) or single species. 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 based on yields 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: 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 case of grass-clover ley and fallow, a constant C input of 2.51 t C ha^{-1} yr^{-1} was assumed; for crop names see Table 8, page 44.

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	See SB
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	Bolinder et al. (2015)
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).

2.1.3 Simulation of long-term trials

To test the models and allometric equations, data from eight Swiss long-term experiments where SOC stocks were measured at least twice (Table 2) were used. Data from sites Watt and p29C were used to verify the chosen model RothC (2.1.5), whereas data from the other six sites were used for testing (2.1.4). From each of these sites, annual yields per plot of several different treatments 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. In addition, measured clay content of the soil and meteorological data were necessary for simulations of SOC. The simulated SOC time series were compared against measured SOC stocks. All possible combinations of models and allometric equations were tested (Figure 1).

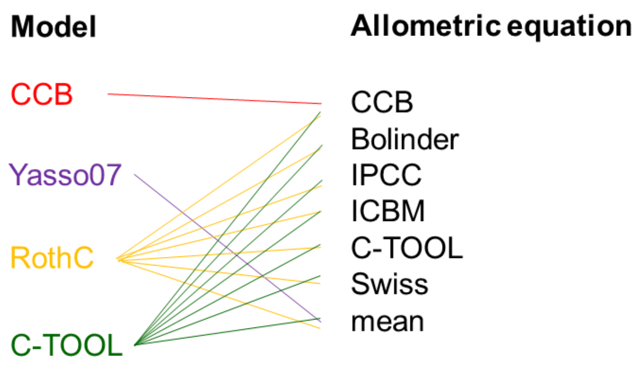


Figure 1 Combinations of models and allometric equations tested.

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 the cited references and a summary of the SOC stock changes is 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 a 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 (that were repeated three times, but started in different years, subplots A, B, C). Here, only data of the intensive treatments of subplots A were used. Experiment p24A in Changins tests a large number of 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 cropland and grassland sites; MAT = mean annual temperature, MAP = mean annual precipitation. The sites Hausweid and p29C are used for model confirmation in section 2.1.5.

Name of experiment	Land use	Elevation (m asl.)	MAT (°C)	MAP (mm)	Clay content (%)	Start or duration 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, ratio of variances) are summarized in a single diagram and different simulations can be easily compared (coloured letters in Figure 2 to Figure 7). In the diagrams, the simulation that resembles the observed data best lies closest to the reference point (black circle on the x-axis). All diagrams show results for simulated SOC stocks.

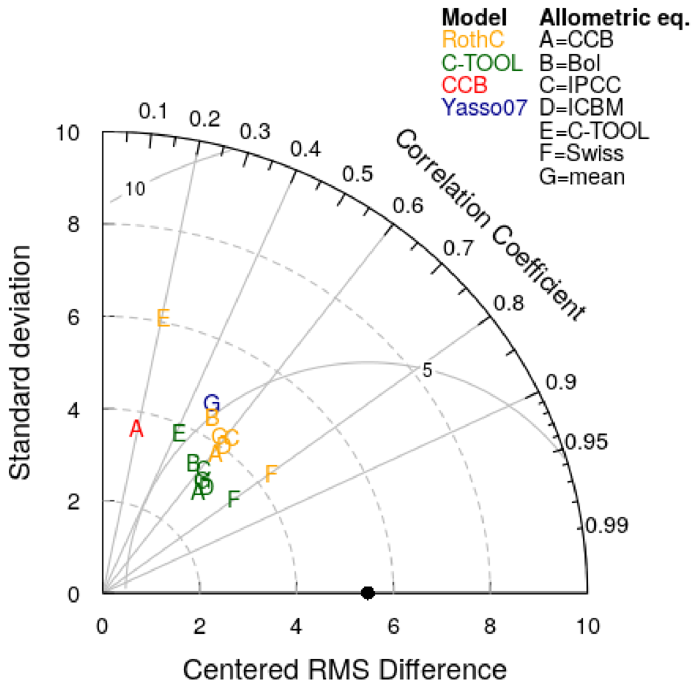


Figure 2 Taylor diagram for the long-term experiment ZOFE; letter colour refers to the model used; the letter indicates which allometric equation was used to estimate plant C inputs to the soil; each single letter refers to the average SOC stocks across all treatments.

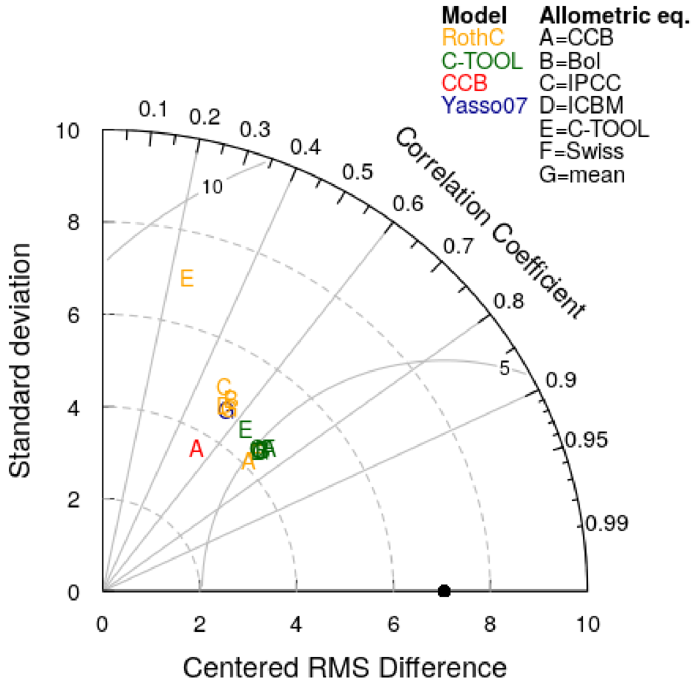


Figure 3 Taylor diagram for the long-term experiment DOK; the meaning of letters and colours is as given above.

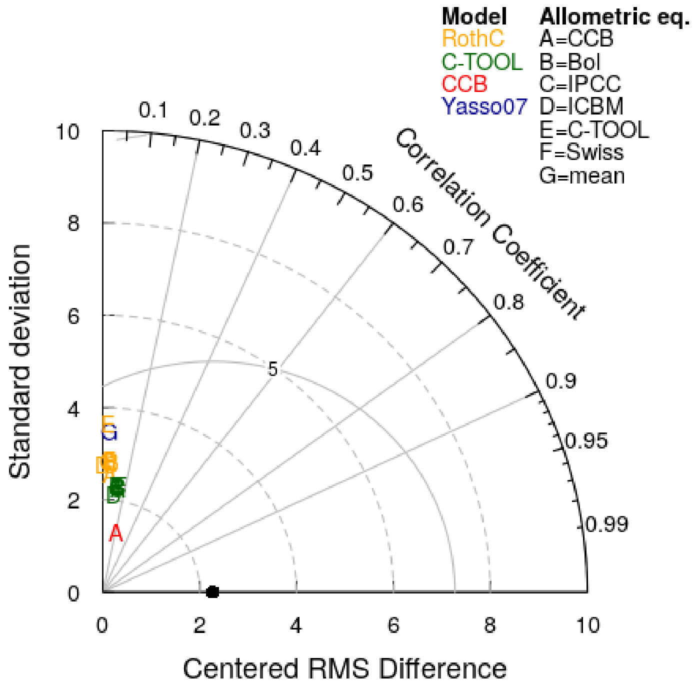


Figure 4 Taylor diagram for the long-term experiment p24A; the meaning of letters and colours is as given above.

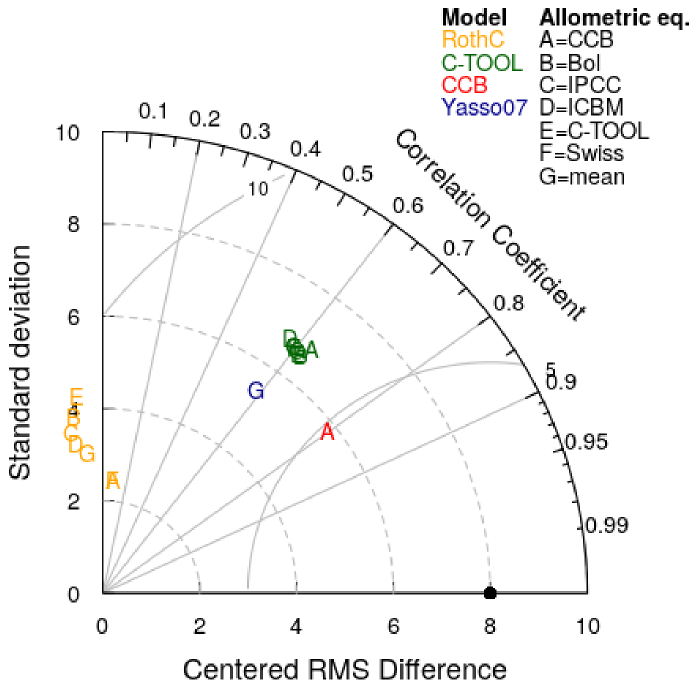


Figure 5 Taylor diagram for the long-term experiment Watt; the meaning of letters and colours is as given above; letters left of the diagram area indicate a negative correlation of simulated and measured stocks.

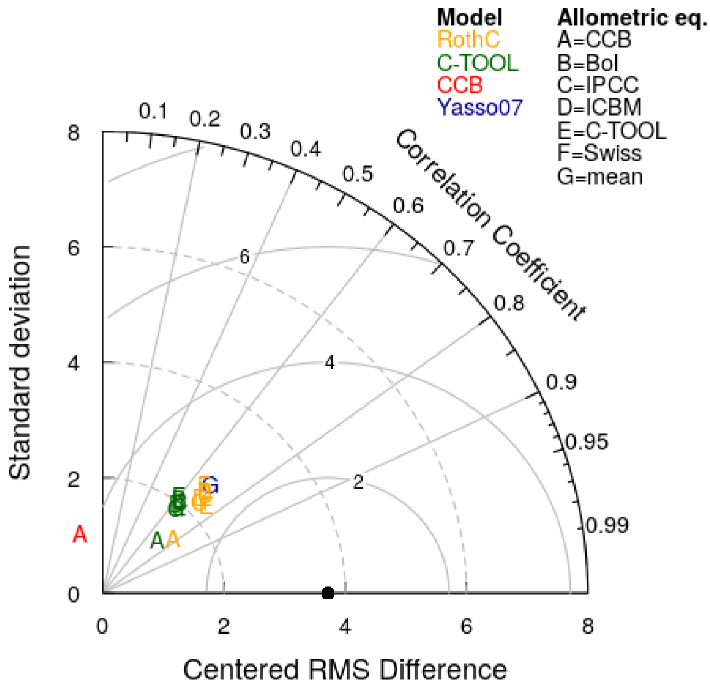


Figure 6 Taylor diagram for the long-term experiment Oensingen; the meaning of letters and colours is as given above.

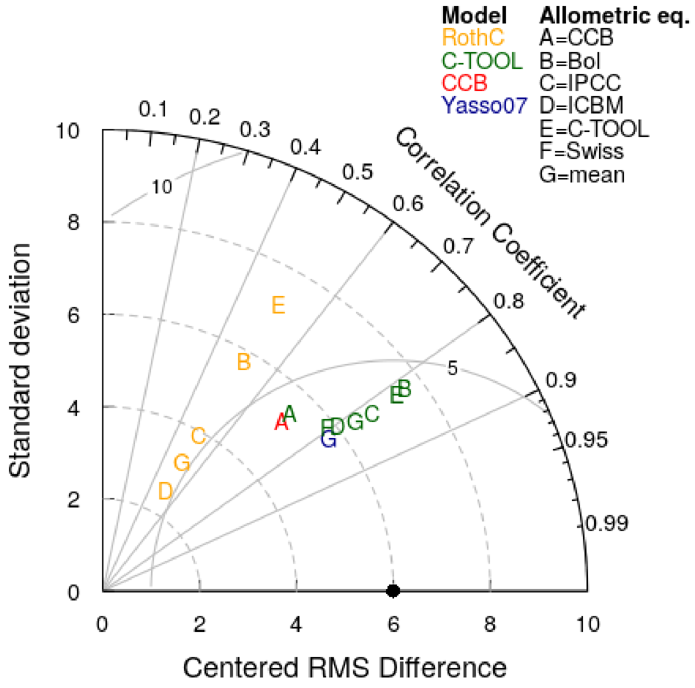


Figure 7 Taylor diagram for the long-term experiment Balsthal; the meaning of letters and colours is as given above.

Based on the results of the Taylor diagrams, the number of models and allometric equations was reduced to two each for further testing: RothC and CCB were the best models and CCB and Swiss the best equations (Figure 2, Figure 4, Figure 5 and Figure 6). 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 remained for the final tests (RothC-Swiss, RothC-CCB, CCB-CCB). Simulations of the most important treatments (i.e. those representing Swiss farming practice most closely) were compared for these three combinations.

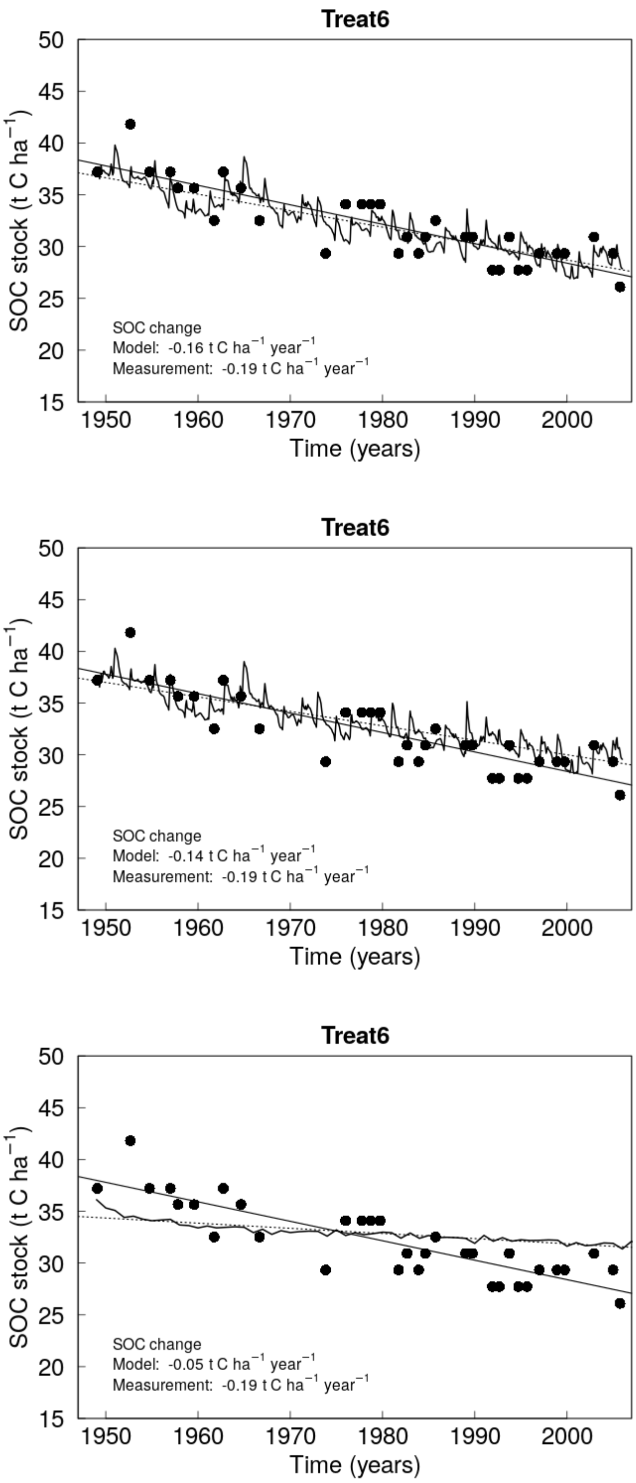


Figure 8 Simulations for the long-term experiment ZOFE (treatment manure + PK fertiliser, 90, 60, 300 kg NPK ha^{-1} yr^{-1} on average); the uppermost panel shows the simulation with RothC-Swiss, the middle panel shows the simulation with RothC-CCB and the lowest panel CCB-CCB; uneven lines = simulation, symbols = measured values, straight line = linear function of simulated values, dotted line = linear function of measured values.

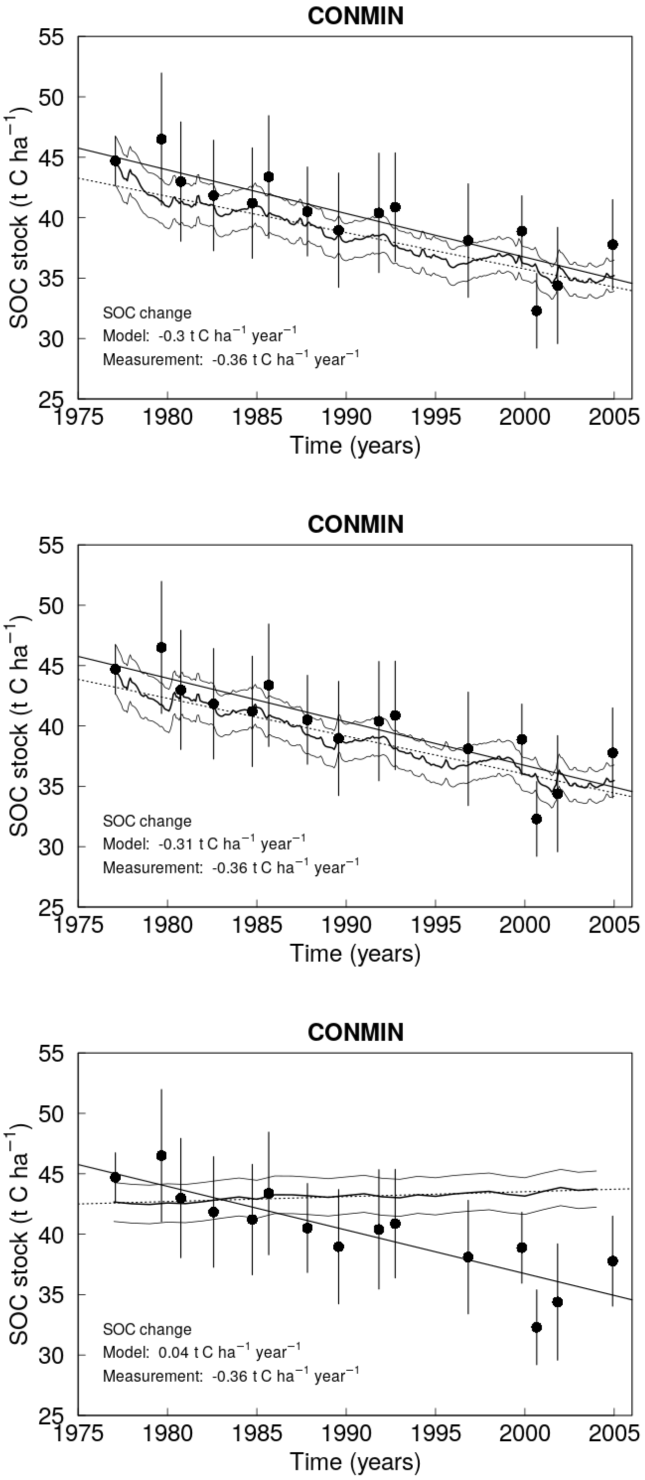


Figure 9 Simulations for the long-term experiment DOK with mineral fertiliser (treatment M2 with mineral fertiliser, 95, 35, 225 kg NPK ha^{-1} yr^{-1} on average); the uppermost panel shows the simulation with RothC-Swiss, the middle panel shows the simulation with RothC-CCB and the lowest panel CCB-CCB; uneven lines = simulation (mean ± standard error), symbols = measured values (error bars = measurement of different plots), straight line = linear function of measured values; dotted line = linear function of simulated values.

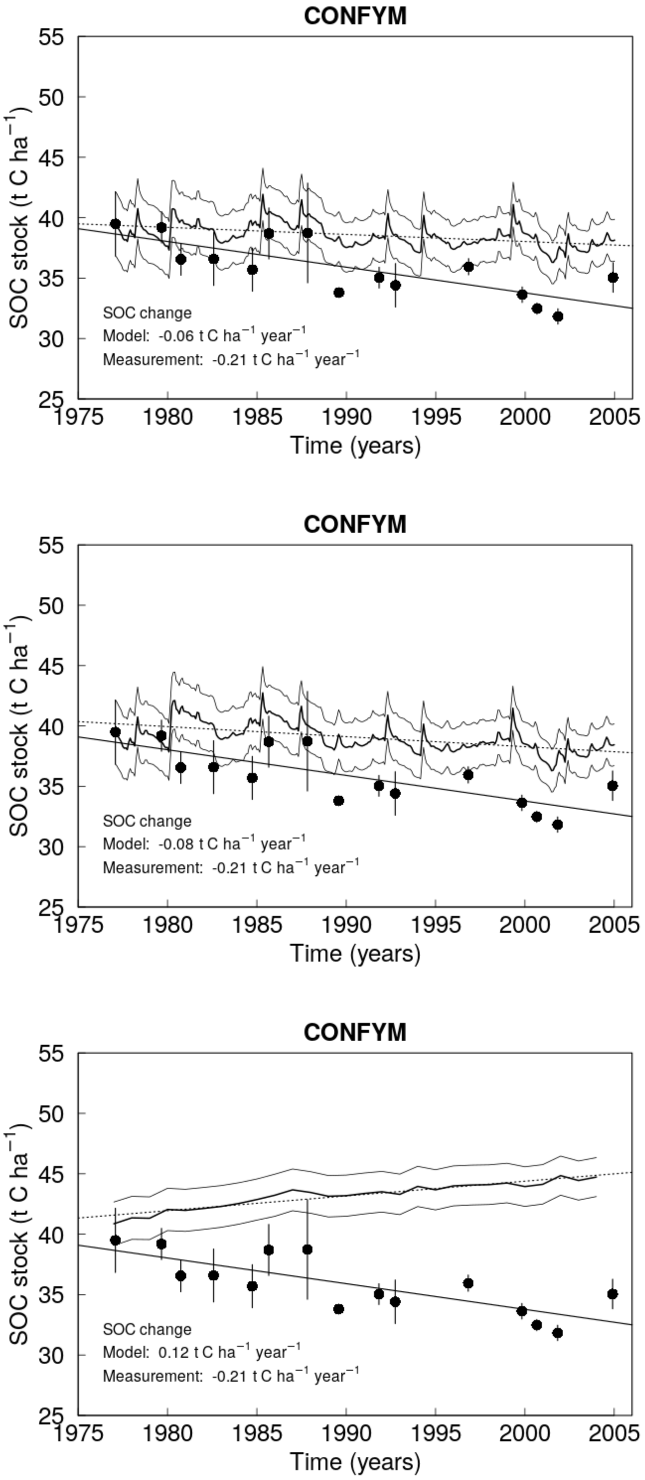


Figure 10 Simulations for the long-term experiment DOK with farmyard manure and slurry (treatment K2 with farmyard manure and slurry, 140, 35, 220 kg NPK ha^{-1} yr^{-1} on average); the uppermost panel shows the simulation with RothC-Swiss, the middle panel shows the simulation with RothC-CCB and the lowest panel CCB-CCB; uneven lines = simulation (mean ± standard error), symbols = measured values (error bars = measurement of different plots), straight line = linear function of measured values, dotted line = linear function of simulated values.

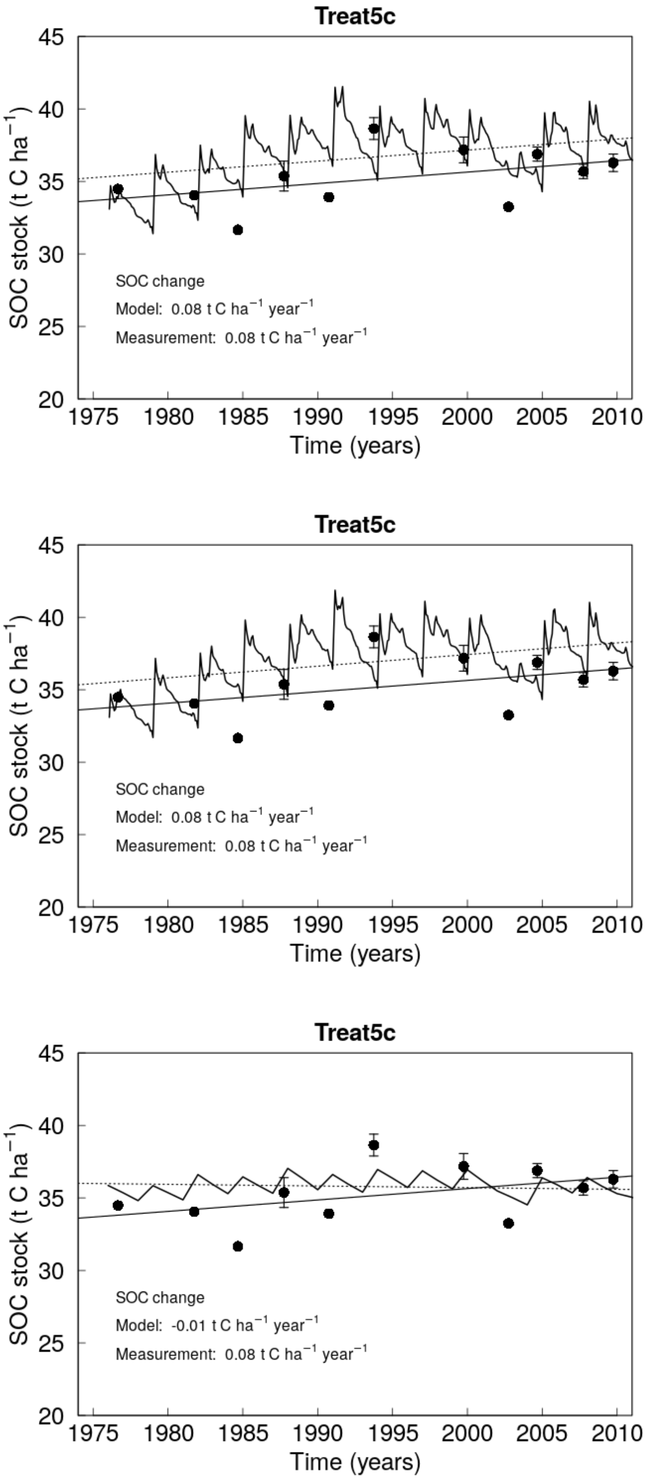
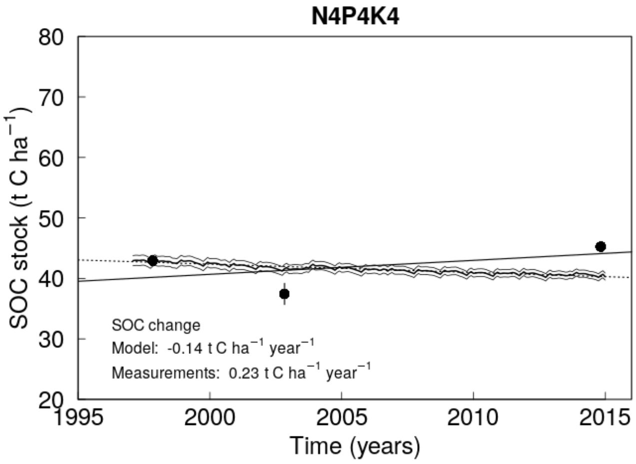


Figure 11 Simulations for the long-term experiment p24A (treatment FYM70-70 with mineral fertiliser and farmyard manure, 465, 135, 555 kg NPK ha^{-1} yr^{-1} on average); the uppermost panel shows the simulation with RothC-Swiss, the middle panel shows the simulation with RothC-CCB and the lowest panel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



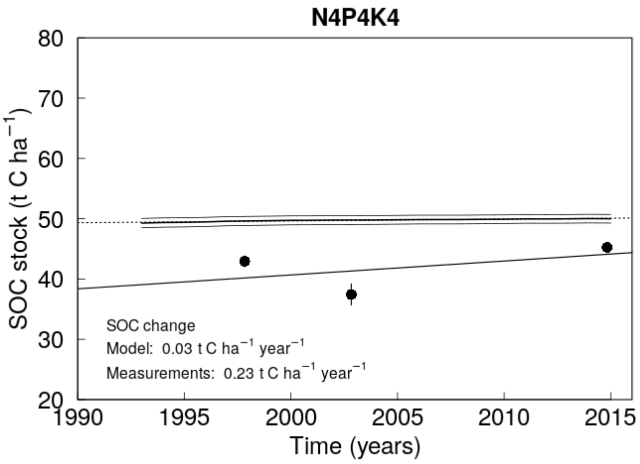


Figure 12 Simulations for the long-term grassland experiment Watt (treatment with mineral fertiliser, 60, 25, 110 kg NPK ha^{-1} yr^{-1} on average and 3 cuts per year); the upper panel shows the simulation with RothC-Swiss (for grasslands RothC-CCB is identical), the lower panel CCB-CCB; uneven lines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

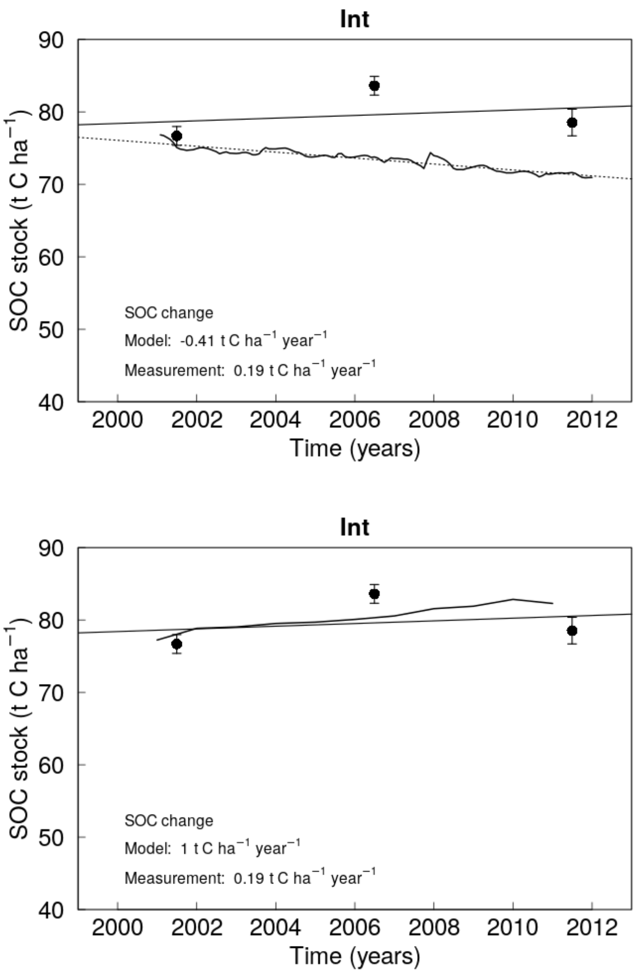


Figure 13 Simulations for the long-term grassland experiment Oensingen (treatment with mineral and organic fertiliser, 195, 60, 560 kg NPK ha^{-1} yr^{-1} on average); the upper panel shows the simulation with RothC-Swiss (for grasslands RothC-CCB is identical), the lower panel CCB-CCB; uneven lines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

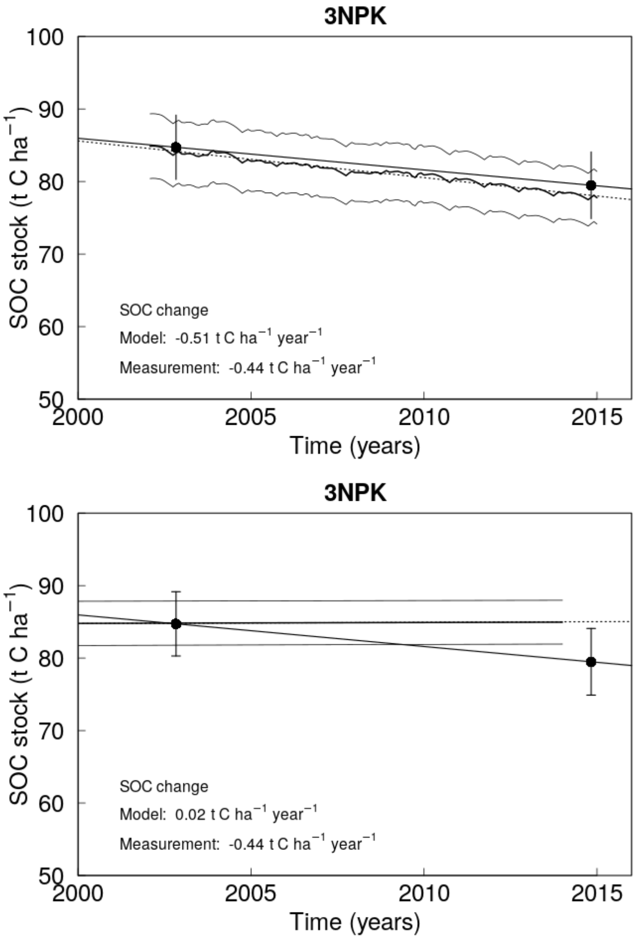


Figure 14 Simulations for the long-term grassland experiment Balsthal (treatment with NPK fertiliser three grass cuts, 75, 35, 200 kg NPK ha^{-1} yr^{-1} on average); the upper panel shows the simulation with RothC-Swiss, and the lower panel CCB-CCB; uneven lines = simulation (mean ± standard error), symbols = measured values (error bars = measurement of different plots), straight line = linear function of measured values, dotted line = linear function 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 size 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 in addition they are of rather short duration. Whether the allometric equation Swiss or CCB was used in combination with RothC made little difference. Equation Swiss, which is 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.

2.1.5 Model verification

As a final step of the model selection process, we simulated, with RothC, the SOC of additional long-term experiments (or single treatments thereof) that had not been used for model evaluation and selection (i.e. independent data). Some sites show unusually high variability in the measured data, which cannot be captured by the model (Figure 15, uppermost panel; Figure 16), but overall, we found a good agreement between modelled and measured SOC trends. **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.**

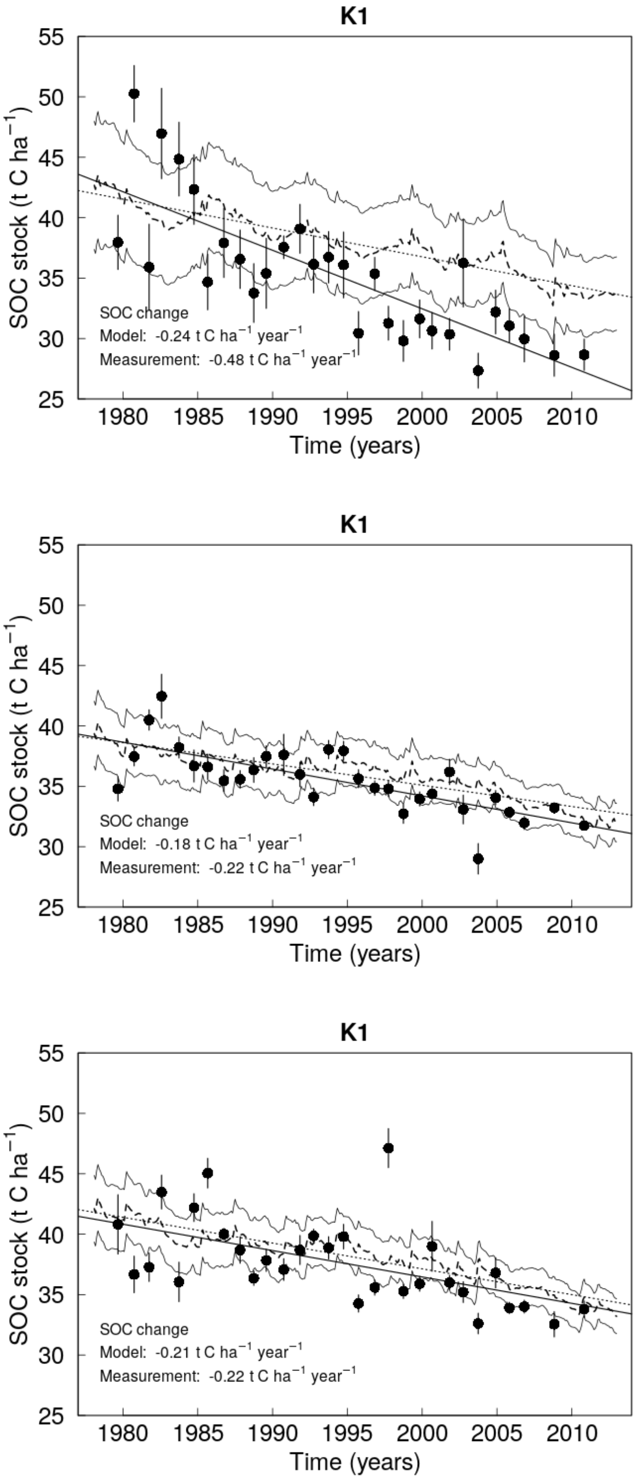


Figure 15 Simulations for conventional low intensity treatments at long-term experiment DOK ; the three panels show the same crop rotations running temporally shifted (subplots A, B, C, top to bottom); uneven lines = simulation (mean ± standard error), symbols = measured values (error bars = measurement of different plots), straight line = linear function of measured values, dotted line = linear function of simulated values.

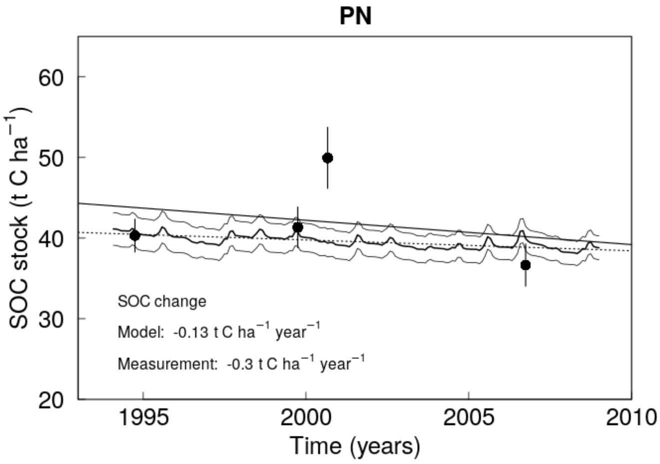


Figure 16 Simulation for conventional tillage treatment at long-term experiment Hausweid (NPK fertiliser, 130, 35, 135 kg ha^{-1} yr^{-1}); uneven lines = simulation (mean ± standard error), symbols = measured values (error bars = measurement of different plots), straight line = linear function of measured values, dotted line = linear function of simulated values.

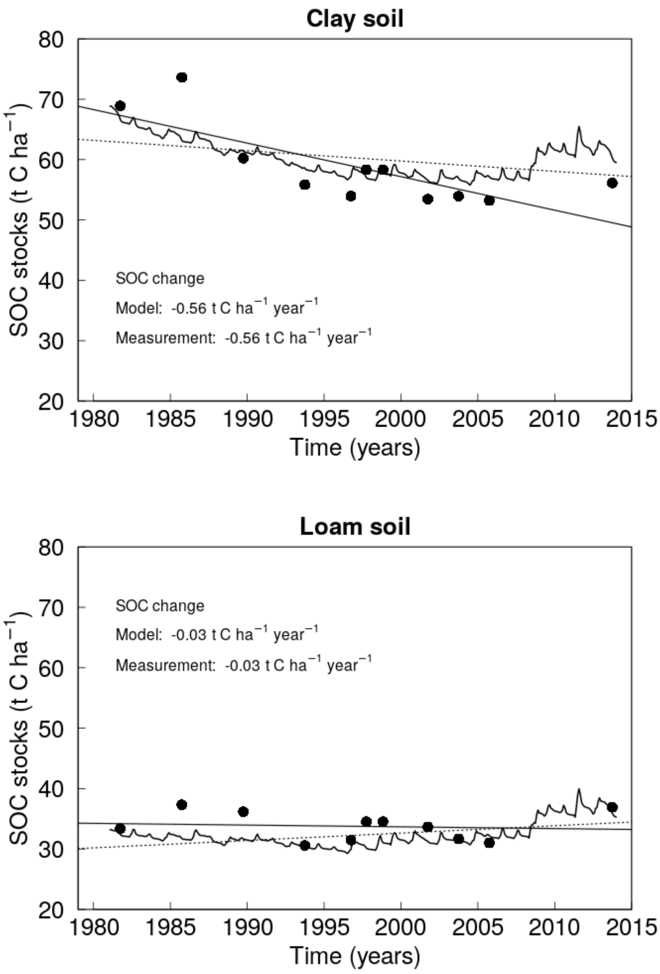


Figure 17 Simulation for conventional tillage treatment at long-term experiment p29C (NPK fertiliser, 135, 30, 125 kg ha^{-1} yr^{-1}) with different soil types; uneven line = simulation, symbols = measured values, straight line = linear function of measured values, dotted line = linear function of simulated values.

2.2 Input data and calculations

2.2.1 Stratification

As described in section 1.1, the upscaling from the point simulation to the national scale was carried out using a system of discrete regions, or 'strata' (singular 'stratum'), which should be – for variables important for SOC change – representative for the surface that they cover. The complexity of the Swiss agricultural landscape (see section 1) however makes such a system for upscaling complicated and the following considerations must be noted: Firstly, in spite of high regional variation in the landscape (e.g. due to elevation), the strata should not be too small because the spatial resolution of some agricultural data is low (e.g. at the national or agricultural zone [AZ] level [see below for explanation]) meaning small strata would incur false precision of results. Secondly, the boundaries of the strata should comprise those spatial boundaries relevant to agricultural practice or to input data. For example, year-round farming occurs only in particular AZs, meaning these zones need to form part of the strata. Likewise, the boundaries of soil texture classes need to be incorporated as information on clay content (derived from soil texture) is used directly by RothC. Thirdly, it must be remembered that regional upscaling using strata can never avoid small-scale variation, e.g. temperature gradients resulting from topographic variation. Thus, assigning (input) data to these strata needs to be done in such a way that biases do not occur. This procedure is described and carried out in the individual relevant sections below.

2.2.1.1 Data sources

Two spatial data sets were used to create the strata.
Firstly, the "agricultural zones" (AZs, "Landwirtschaftliche Zonen" / "zones agricoles") from the Federal Office for Agriculture (FOAG), specifically the summer pastures, mountain area, hill zone and the valley zone (Figure 18 and Table 3)[2]. These AZs were used to create the strata for two reasons. Firstly, they are defined in legislation[3] meaning any future policy changes concerning SOC could be spatially restricted according to where the corresponding farming practices occur. Secondly, we expect variation in management within the AZs to be low (lower than, say, the elevations zones [EZs] used in Switzerland's GHG inventory, see section 2.2.8.2), because they were defined based on variables that influence management practices (e.g. accessibility, prevalence of steep slopes). Additionally, the AZs delimit the region where summer pasturing ("summer pastures") or year-round farming take place.

[2] See also documentation available to download here: https://www.blw.admin.ch/blw/de/home/instrumente/grundlagen-und-querschnittsthemen/landwirtschaftliche-zonen.html; in German, French and Italian.

[3] 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.

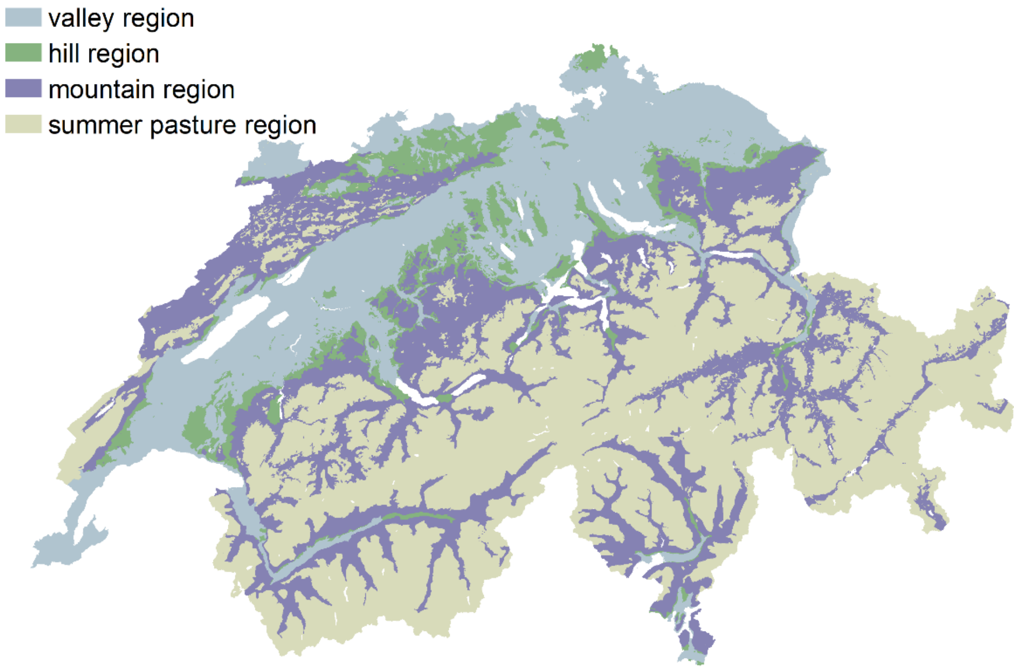


Figure 18 The four AZs used in this project; AZ boundaries © FOAG.

Table 3 The four AZs used to construct the strata.

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

The second data set used to create the strata is the production regions from the national forest inventory (NFI)[4], 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 LULUCF sector, 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 northern and southern Switzerland.
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, according to the climate regions published by MeteoSwiss (Schüepp and Gensler 1980), for this project. 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 4 and Figure 19.

[4] https://www.lfi.ch/index-en.php

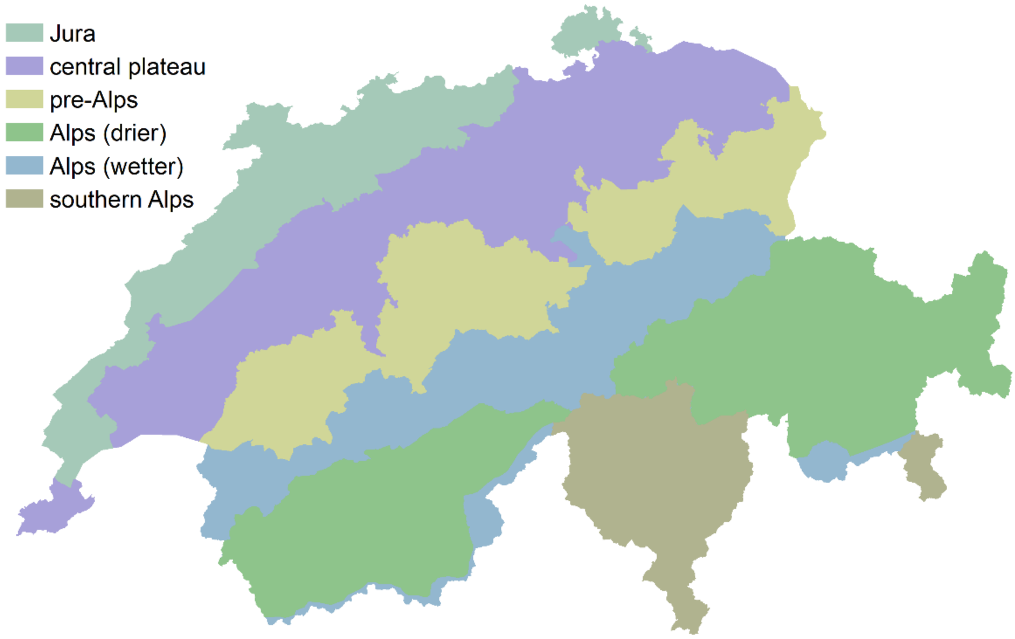


Figure 19 The six NFI production regions used to construct the strata (NFI regions adapted for this project); NFI production regions: Schweizerisches Landesforstinventar © 2012 Eidg. Forschungsanstalt WSL, CH-8903 Birmensdorf; 'drier' and 'wetter' Alps boundaries deduced from the Climate Regions of Switzerland © MeteoSwiss.

Table 4 The six NFI production regions, 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

A further potential data set considered for use in the strata was the 12 climate regions from MeteoSwiss (Schüepp and Gensler 1980), which represent more or less homogeneous regional climates (Müller 1980) and it would be possible to use these 12 regions *instead of* the of the NFI production regions to create the strata. We therefore tested whether a stratum system built with this data set (i.e. 12 climate regions × 4 AZs) would perform better than one built with the NFI data set (i.e. 6 [adapted] NFI regions × 4 AZs, see section 2.2.1.2 for how strata systems were built). These strata systems were compared by inspecting annual temperature and PPN variation within the resulting strata, for all years between 1981 and 2010. Strata built using the climate regions accounted for statistically significantly (results not shown) more variation in annual PPN for a third of the years tested than strata built using the NFI regions. For temperature, both strata schemes performed equally (results not shown). Based on these results, and the fact that strata built using climate regions result in a stratification scheme *incompatible* with that of the LULUCF sector otherwise, **the strata system used in this project is a combination of the six (adapted) NFI regions and the four AZs.**

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 20.

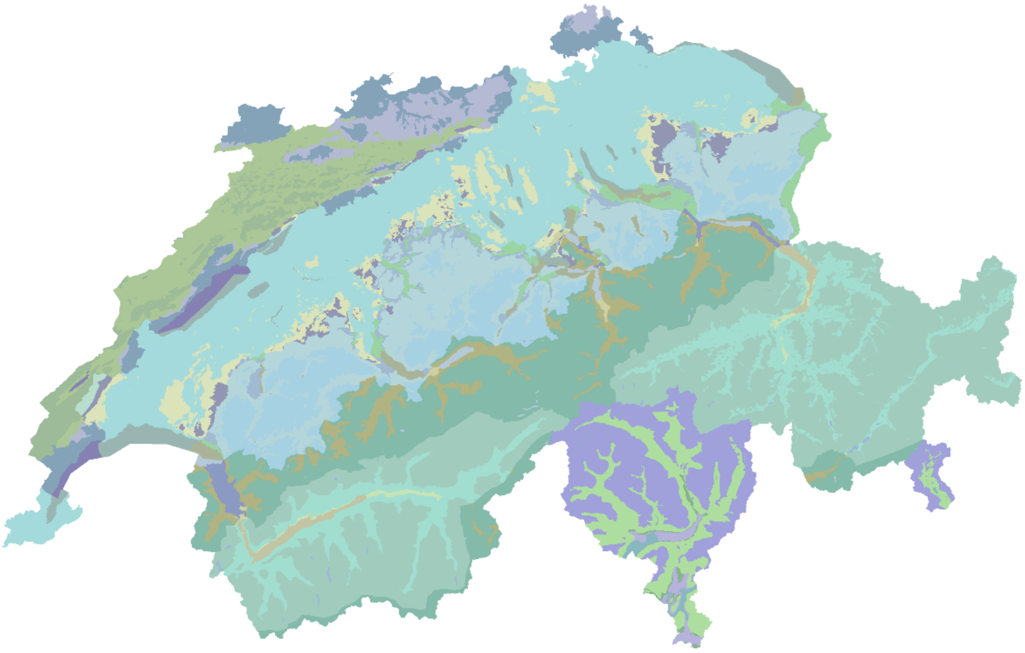


Figure 20 The 24 strata obtained from a union of the AZs and NFI regions.

The 24 strata were coded by concatenating the 'A codes' and 'F codes' of the two input data sets (Table 3 and Table 4). 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 (Arealstatistik)

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, with land use and land cover determined for each point. The main data source is a series of aerial photographs from Swisstopo, interpreted with the aid of additional material such as topographic maps, information on zoning, nature conservation areas, as well as the Federal Register of Buildings and Dwellings and buildings- and business registers[5]. The points on the aerial photographs are classified by the FSO according to both land use (46 categories) and land cover (27 categories) and these two classifications have been combined to generate a nomenclature system (see next section). The combination of two classification systems, land use and land cover, is necessary to differentiate between the properties and management of a given land cover: For example, 'grass and herb vegetation' (= land cover type) that is in a recreational area (= land use types), will be managed quite differently to the same land cover type in an agricultural or forest setting. The LUS are available for 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.

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

2.2.2.1 Nomenclature system: 18 combination categories

The land use and land cover classifications from the LUS are combined into 18 "combination categories" (CCs). This nomenclature system was developed for Switzerland's GHG inventory (tables 6-2 and 6-6 in FOEN 2018) and is used throughout this project. SOC in agricultural soils is being modelled for cropland (CL, CC21) and permanent grassland (GL, CC31). The CL category includes arable land in agricultural areas; leys are included in CL. The category GL includes grass and herb vegetation in agricultural areas, with the exception of leys, and covers ca. 65 % of grassland in agricultural and non-productive areas in Switzerland. 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 other grassland types were excluded 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 page 129). However, the model system has been developed so that such categories can be incorporated in the future.
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 on daily PPN sums and mean daily temperature were obtained from MeteoSwiss[6]. The grids have a spatial resolution of 1.25 minutes (= 0.02083 decimal degrees), 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, representing 10-minute interval measurements. 86 to 91 climate stations deliver data for this data set at any point in time. 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 biased towards 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. The daily temperature values were averaged to obtain monthly values, and daily PPN values were summed to obtain monthly sums. 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

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

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 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 temperature, a PPN and an ET value for each month from 1990 to present. A weighted average mean was used to obtain these values for each stratum (example given in Figure 21), 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 biased distribution would introduce a bias into the calculation of the mean temperature or PPN values, which would be (typically) under- or over- estimated, respectively.

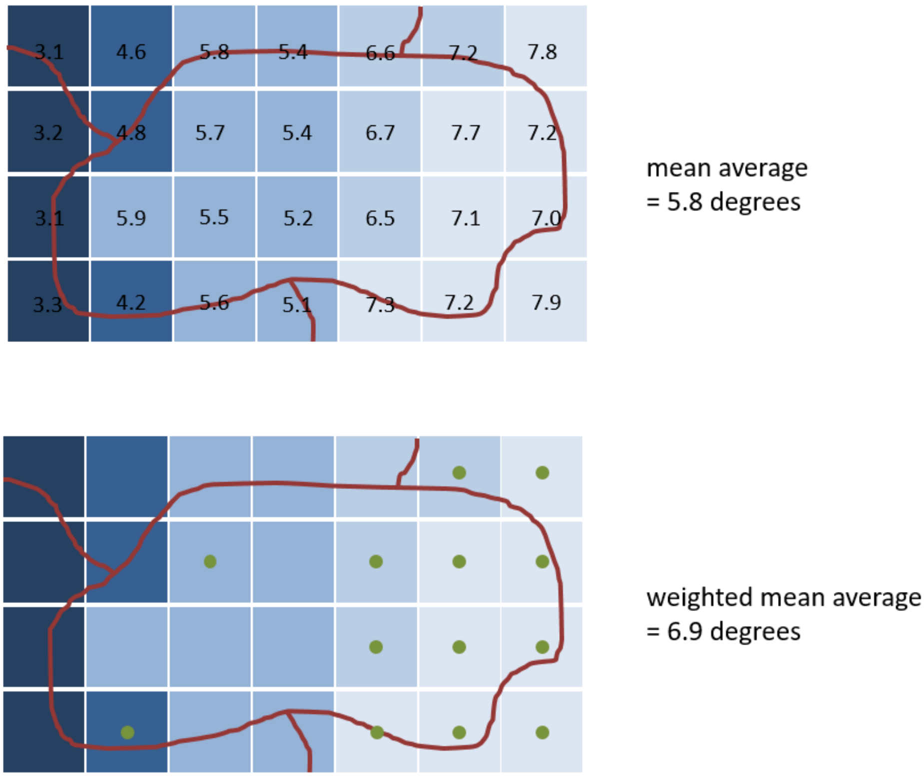


Figure 21 Assigning climate parameter values to a given stratum (example): In the upper panel the mean of the temperature values (numbers given in squares) is calculated for the stratum (red outline); in the lower panel the distribution of the CL points (green dots) is incorporated; in this example these 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.

2.2.4.1 Soil suitability map ("Bodeneignungskarte")

The Swiss soil suitability map (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 is available from the FSO (2000), which was rasterised as part of this project to form a 200 m raster map. The map does not portray clay content. It is however indicated that information on soil porosity (portrayed in the SSM) can be used to derive soil texture. Each mapping unit of the SSM was classified into one of the twelve soil texture classes indicated in Table 5, based on soil porosity. Clay content was assigned to each soil texture classes 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 5 and Figure 22). For upscaling, the clay class containing mires and raised bog peat (0 % clay) was given a weighting of zero (section 2.2.8), as this project considers only mineral soils.

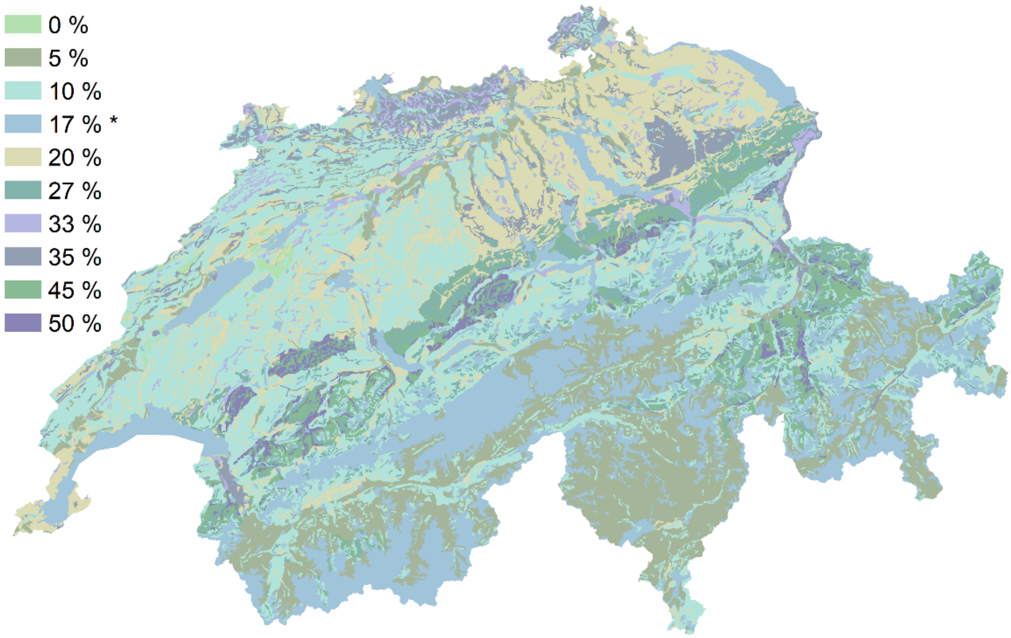


*Figure 22 The ten clay classes as derived for this project from the SSM, according to clay content (%); * = no information on soil porosity given in the SSM therefore a weighted average clay content was assigned (see text for details).*

Table 5 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 6.

Table 6 Summary of agricultural data required for the modelling of SOC stocks in this project (table continued on next page); 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)	the % surface populated by 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 residues					
yield of main crops (2.2.5.2)	the harvest (volume per surface area) for each crop	annual	national (per crop)	CL: yes GL: not used	-
by-products	relationship between main 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	-
When is the soil covered? (Applicable only to crops; grassland assumed to be permanently covered)					
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	sowing date, per crop	annual	national (per crop)	yes	-
harvest date	harvest date, per crop	annual	national (per crop)	yes	-
Organic amendments (OrgAm) (2.2.5.3)					
OrgAm-C application (2.2.5.3)	how much OrgAm-C each crop / grassland category receives	monthly	CL: national; GL: per stratum	no	estimated using an OrgAm-model utilising information from below
OrgAm-C production	amount of OrgAm-C produced	annual	CL: national; GL: per stratum	no	a function of animal population, OrgAm production rate and its C content
OrgAm-C application	amount of OrgAm-C added to each crop or grassland category	annual	CL: national; GL: per stratum	no	a function of how much OrgAm farmers apply to different crops or to grassland, and the nutrient requirements of individual crop / grassland category
C application, month	month in which manure and slurry are 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. CL and GL points cover ca. 1,338,000 ha in Switzerland (section 2.2.2.1). 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)[7], an annual survey forming the basis of subsidies (direct agricultural payments) 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)[8]. The survey covers 98 % of all 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. Cantonal data can be downloaded from the FSO website, through the STAT-TAB data bank[9], but 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 8 and their surface shown in Figure 23. 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 used fresh as winter fodder but in the summer pasture area, SPA) cover a very small surface and were not considered further.

The grassland type 'pastures' was sub-divided for use in 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 applied to the 'total pastures' for the years 1990 to 1998.

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

---

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

[8] An exception to this are the 'meadows in the summer pasture area', defined as meadows that have been mown as part of a long tradition, that are mown annually and that serve as winter fodder (Verordnung über landwirtschaftliche Begriffe und die Anerkennung von Betriebsformen (Landwirtschaftliche Begriffsverordnung, LBV); SR 910.91) for year-round farms. In terms of surface area, these meadows are unimportant (<0.1 % of agricultural grassland surface) and were not considered further.

[9] https://www.pxweb.bfs.admin.ch/pxweb/de/?rxid=8037ac5c-253d-4899-b23f-0a52193500be; in German, French and Italian; in English but with limited data availability: https://www.pxweb.bfs.admin.ch/pxweb/en/

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 24 and a summary of the information used to derive extents is given in Table 7. Linear interpolation, using data from 1990 and 1996, was used to gap-fill for years 1991 to 1995. The relative contributions of grassland and cropland to Swiss agricultural surface is shown in Figure 25. A summary of all crops and grassland categories considered in this project is shown in Table 8.

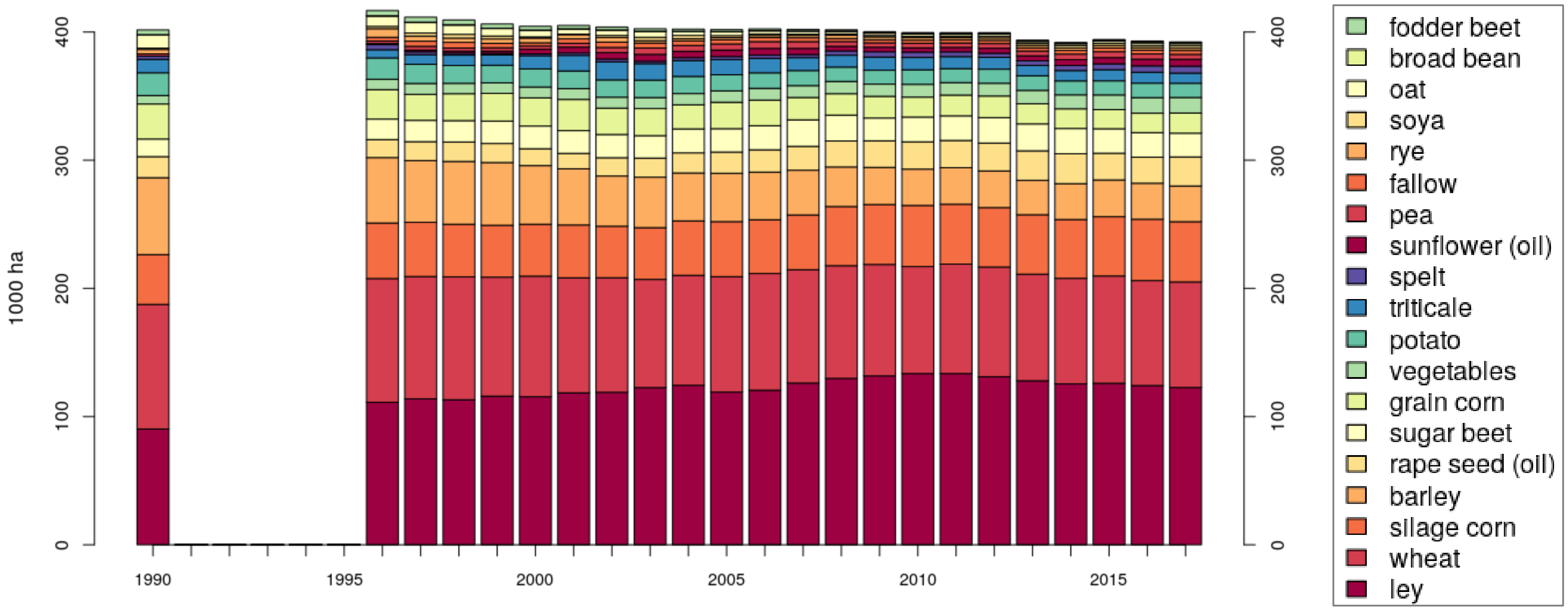


Figure 23 Extent of the most common 19 crops in Switzerland (1990-2017); values for years for which data were unavailable (1991 to 1995) were gap-filled using data from 1990 and 1996 (not shown).

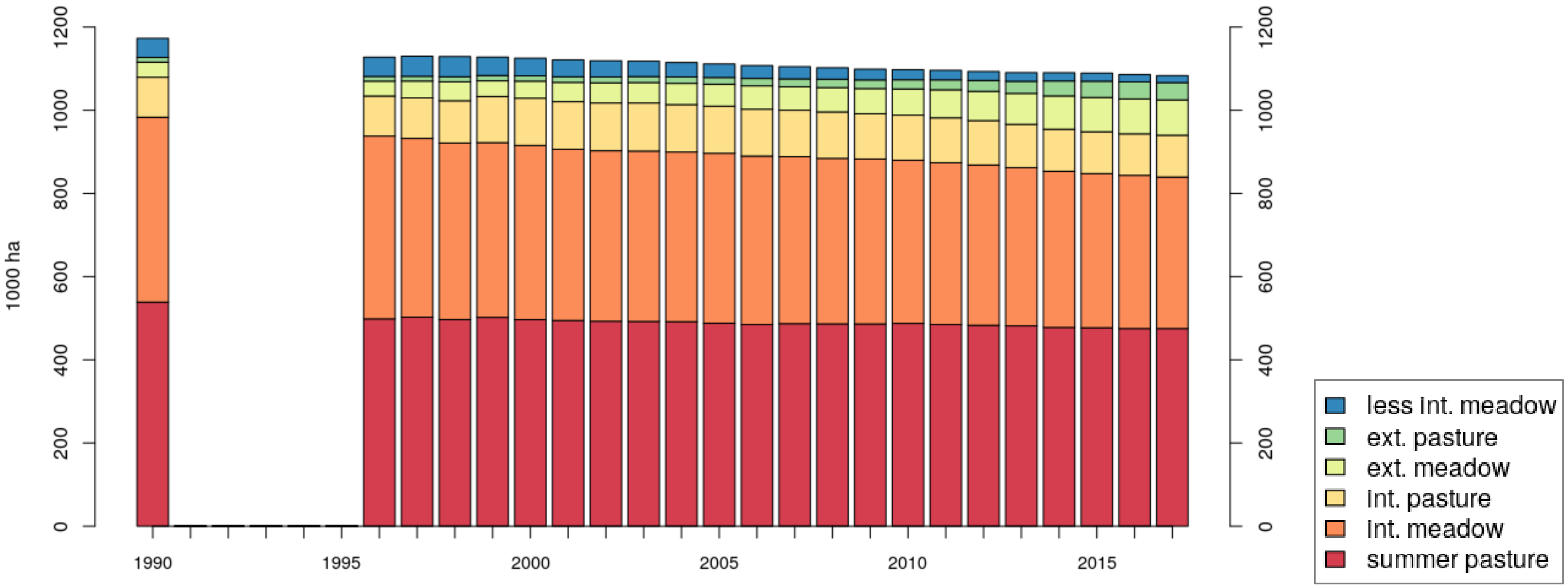


Figure 24 Extent of the six most common grassland categories in Switzerland(1990-2017) used in this project; values for years for which data were unavailable (1991 to 1995) were gap-filled using data from 1990 and 1996 (not shown).

Table 7 Summary of the six grassland categories considered for the SOC modelling.

Grassland type	Area information 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 mana-ged 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 25.

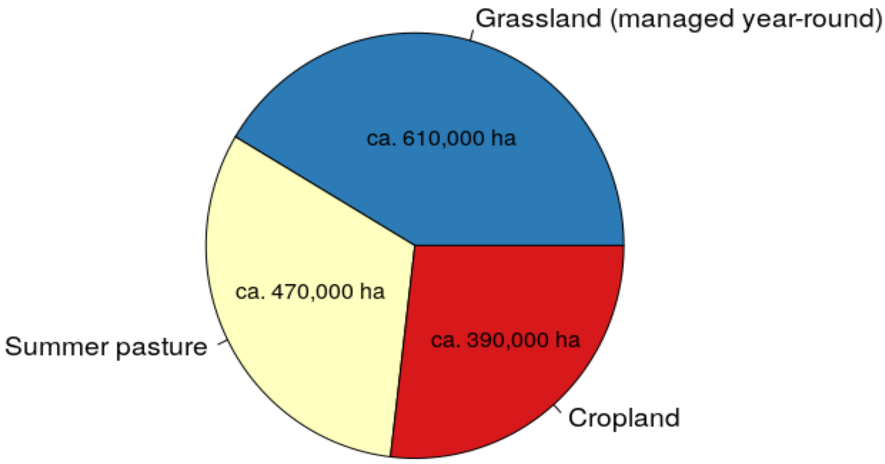


Figure 25 Approximate extent of cropland and grassland in Switzerland (managed year-round and as summer pasture), according to the FSS from the FSO (for cropland and year-round managed grass-land) and unpublished data from the FSO (for summer pasture) as detailed in main text.

Table 8 The 19 crops and six grassland categories considered in the project to simulate stocks under cropland (CL) or grassland (GL).

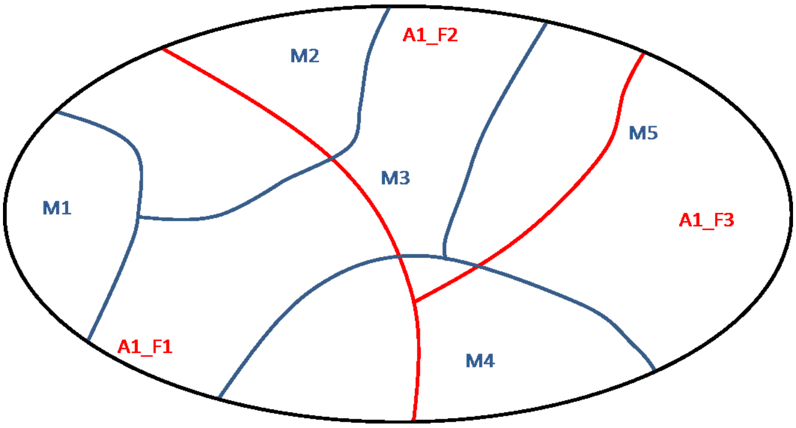
Crop / grassland category	Code	CL / GL
barley (*Hordeum vulgare* L.)	BA	CL
broad bean (*Vicia faba* L.)	BB	CL
extensive meadow	EM	GL
extensive pasture	EP	GL
fallow	FA	CL
fodder beet (*Beta vulgaris* L.)	FB	CL
grain corn (*Zea mays* L.)	GC	CL
grass-clover ley (main species: *Poa pratensis* L., *Lolium 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, and that of the summer pastures is national. Because the spatial resolution of the upscaling in this project is the strata, and 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[10], all crops and grassland from the UAA (i.e. all categories excluding the summer pastures) were assumed to occur in

[10] 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.

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: 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 (Figure 26).
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 further 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 26 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) according to the picture (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 hectares of potatoes (PO) and wheat (WH), as given in middle matrix; matrix multiplication is used to obtain the hectares of PO and WH in each stratum, as given in the right-hand matrix.

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")[11]. 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

[11] https://www.sbv-usp.ch/de/medien/publikationen/statistische-erhebungen-und-schaetzungen-ses/; in German and French.

taken (using as weightings the extent of winter- and summer- wheat and barley, also available in these 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 manures and fresh waste, as well as inputs derived from anaerobic digestion) are a source of C inputs into soils. For this project, information on the amount of OrgAm-C added to each stratum, for each crop and grassland category each month is required. 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 considerations 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, i.e. of the livestock population. Secondly, different types of OrgAm (e.g. liquid slurry, stacked manure) are preferentially used for different crops or grassland categories. Thirdly, especially for grassland, OrgAm requirements vary with elevation, meaning the location of the different grassland types is important. Fourthly, depending on management intensity or nutrient requirements, crops and grassland categories require different amounts of OrgAm. 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 2018), originating from published figures from the FSO, available online[9] and from 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 2018). 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 (2018, 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[12].
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[13], 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 the similar 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 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

[12] 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 / or do not form a trend over time.

[13] https://agrammon.ch

and liquid slurry together, deep litter or poultry waste (for poultry only) could be calculated. The amount of time animals spent at pasture is also given, allowing the amount of 'fresh manure' to be determined.

Information regarding the **spreading of different OrgAm types** onto broad crops groups or grassland was also obtained from the AGROMMON 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), as estimated annually for the Agriculture sector of Switzerland's GHG inventory (FOEN 2018, 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), was 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 (see section 4.3 for comment on this).

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).

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 9).

Table 9 Studies used to estimate OrgAm-C loss during storage as well as the loss of OrgAm-C loss (given as %) 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 for crops, typical yields for meadows, and typical livestock unit capacity for pastures, as proxies. For crops, a set of single nutrient requirements is provided i.e. differences due to elevation are not given. Relative nutrient requirements were thus calculated irrespective of stratum for this project. 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). Summer pastures receive manure only from those animals grazing there meaning calculating relative nutrient requirements is superfluous. 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**[14] were also taken into account, as shown in Table 10.
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 10 Summary of fertiliser regime for the six grassland categories.

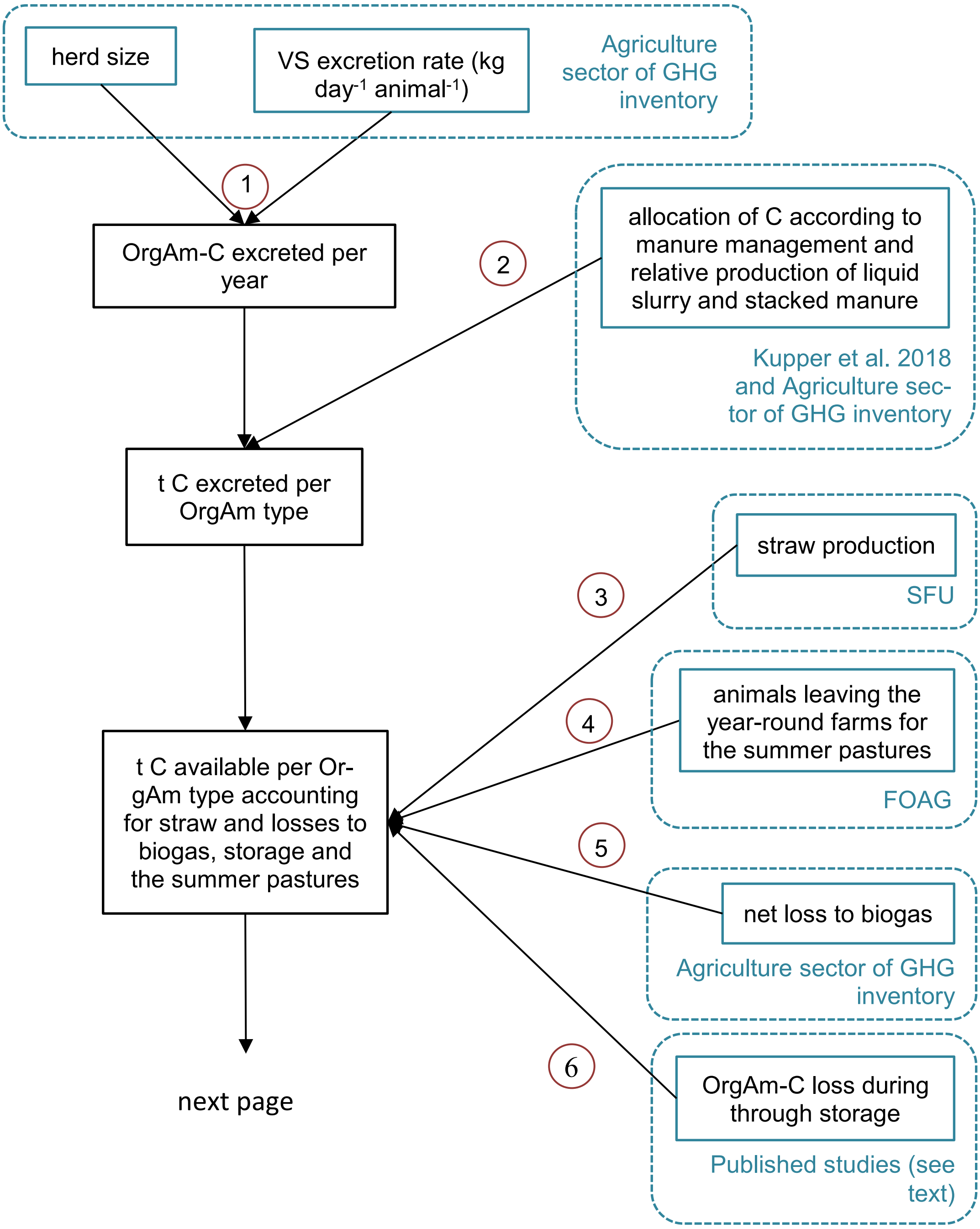
Grassland category	Fertiliser limits
extensively-managed meadow	No fertilisation, in accordance with legislation[14]
extensively-managed pasture	No OrgAm (except that from grazing animals), in accordance with legislation[14]
intensively-managed meadow	Relative nutrient requirements an average of those 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[14]; grazing assumed in Autumn
summer pasture	No OrgAm (except that from grazing animals) assumed, roughly in accordance with legislation[14]

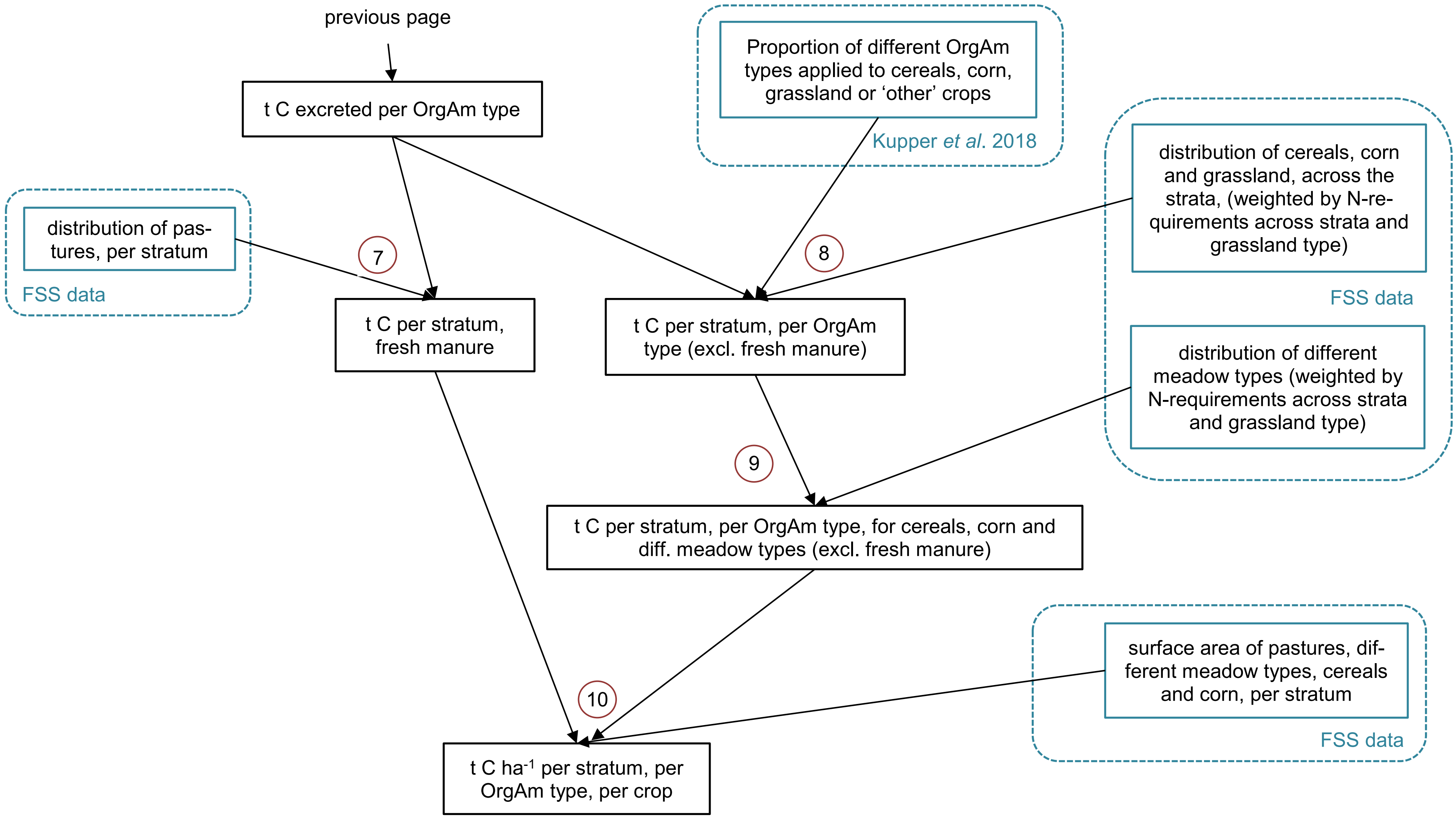
Calculations (the OrgAm-model)
All calculations pertaining to CL and GL, other than the summer pastures, were carried out for strata in valley, hill and mountain zones; calculations pertaining to summer pastures were carried out for strata in the summer pasture zone. The OrgAm-model estimates the annual OrgAm-C application rate

[14] 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.

(t C ha^{-1}) for each crop or grassland category and for each stratum. Figure 27 shows the outline of this model. The 'steps' in the descriptions below refer to steps indicated in that figure.
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 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. Within the year-round agricultural zones, the application of the OrgAm-C is thus assumed to be free of any geographical constraints, i.e. it is 'applied' to crops / grassland categories according to where it is (according to fertilisation guidelines) needed. The consideration of such movement of OrgAm between farms is however a recommendation for future work (section 4.3).

Figure 27 Overview of OrgAm-model to calculate 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 continued on next page.




previous page
t C excreted per OrgAm type
Proportion of different OrgAm types applied to cereals, corn, grassland or 'other' crops
Kupper *et al*. 2018
distribution of pastures, per stratum
FSS data
7
8
distribution of cereals, corn and grassland, across the strata, (weighted by N-requirements across strata and grassland type)
FSS data
t C per stratum, fresh manure
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 diff. meadow types (excl. fresh manure)
surface area of pastures, different meadow types, cereals and corn, per stratum
10
FSS data
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 moving into the SPA 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) – from each model were used to calculate a OrgAm-C loss (%) for each OrgAm type, assuming a OrgAm storage duration of 1.5 months. 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 %.
The duration of OrgAm storage used in this project for slurry, stacked manure and deep litter (1.5 months) corresponds to 4 applications of OrgAm per year, based on guidelines of agricultural practice (see text on 'data sources' in this section). This value is however tentative and in reality also variable; an improved estimate of OrgAm-C lost through storage is therefore recommended (section 4.3).
The total amount of OrgAm-C available for agriculture, including summer pastures, and taking into account loss due to storage and biogas, and inputs through straw, is given in Figure 28.
Steps 7 to 10 concern only the valley, hill and mountain zones; summer pastures are dealt with in step 11.
Step 7: It was assumed that fresh manure falls on pastures. It is however common for farmers to graze animals for a short period on meadows 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, forcing the quotient C-input / C-output of intensive pastures to be ca. 0.28; this value is based on an average of six years of C budget calculations for pastures in Switzerland (Ammann et al. 2007; Ammann et al. 2009).
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 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 27): 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 29 (crops), Figure 30 (grassland in strata in A1 zone) and Figure 31 (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 29 to Figure 31) 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 receive a certain proportion of OrgAm according to the farmer surveys.

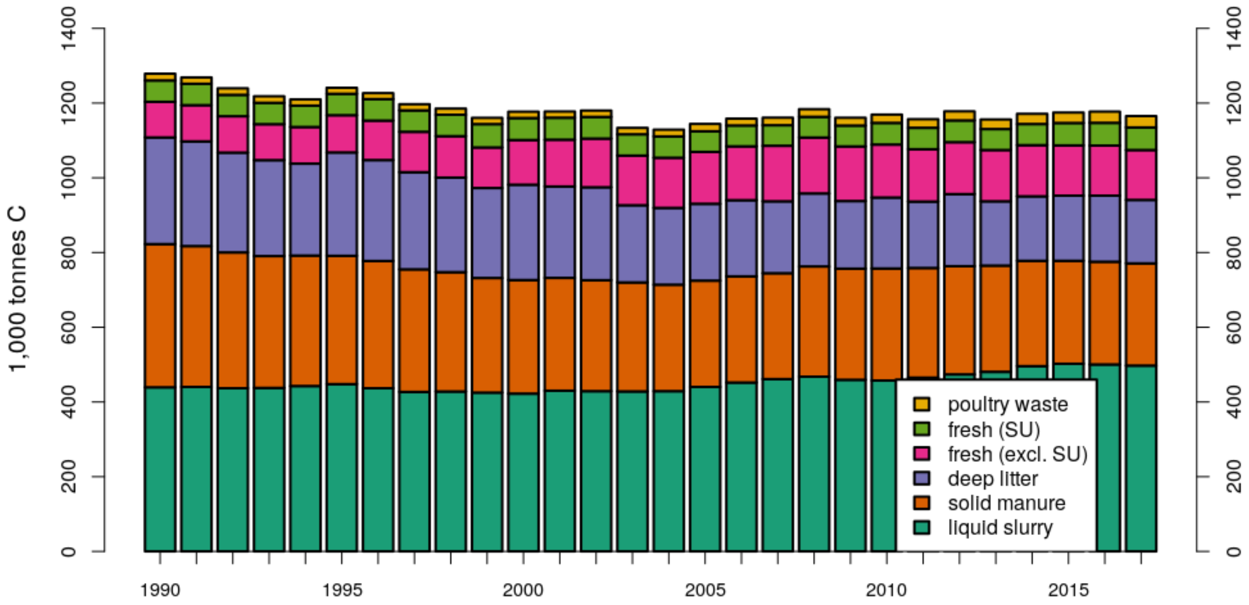


Figure 28 OrgAm-C availability (1990-2017) as calculated by the OrgAm model; calculated as a function of that produced, losses and inputs from anaerobic digestion (both as calculated by the Agriculture sector of Switzerland's GHG inventory), additionally accounting for losses due to storage, and input from straw; SU = summer pastures.

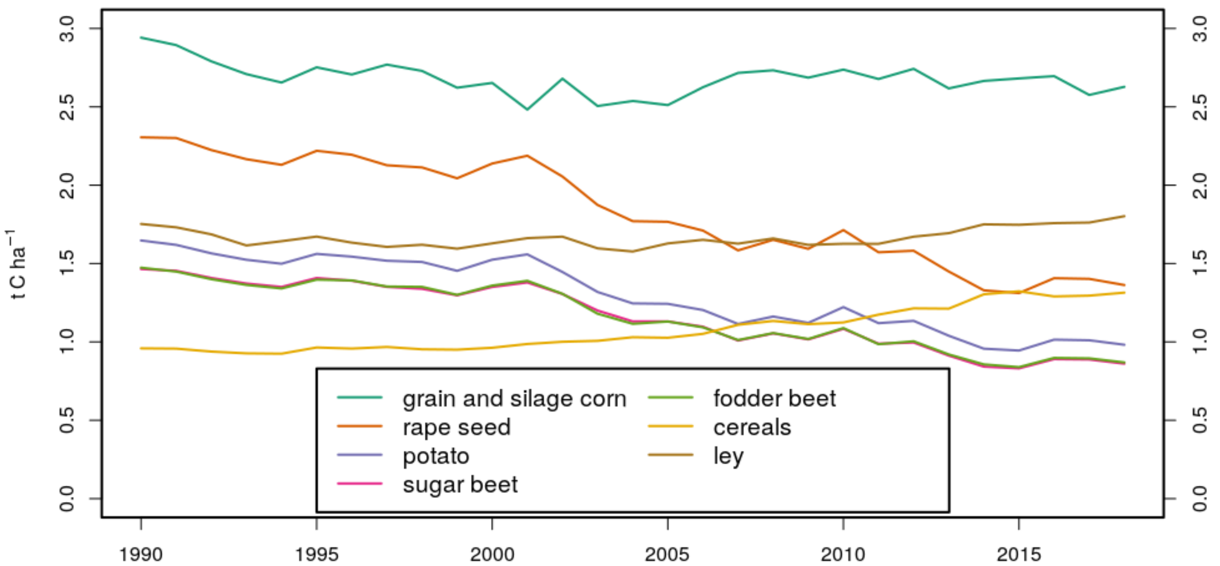


Figure 29 OrgAm-C application to crops (1990 to 2017) as calculated by the OrgAm-model, crops not listed assumed not to receive OrgAm.

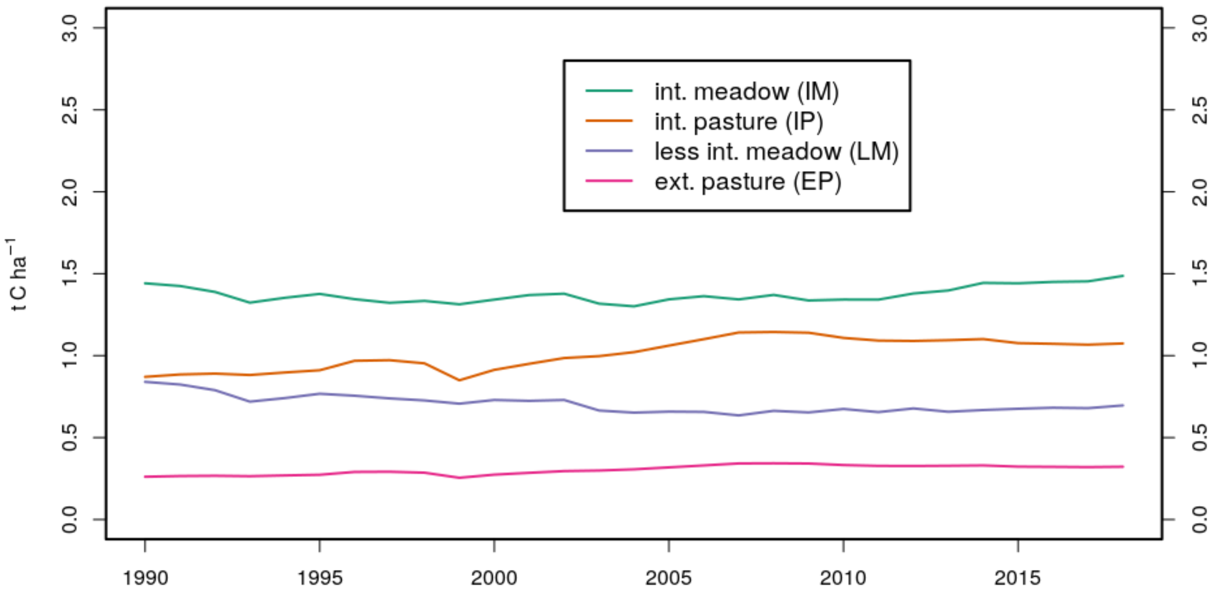


Figure 30 OrgAm-C application to lowland grassland (strata in AZ1, 1990 to 2017) as calculated by the OrgAm-model; extensively-managed meadows are assumed not to receive OrgAm and summer pastures do not occur in the AZ1.

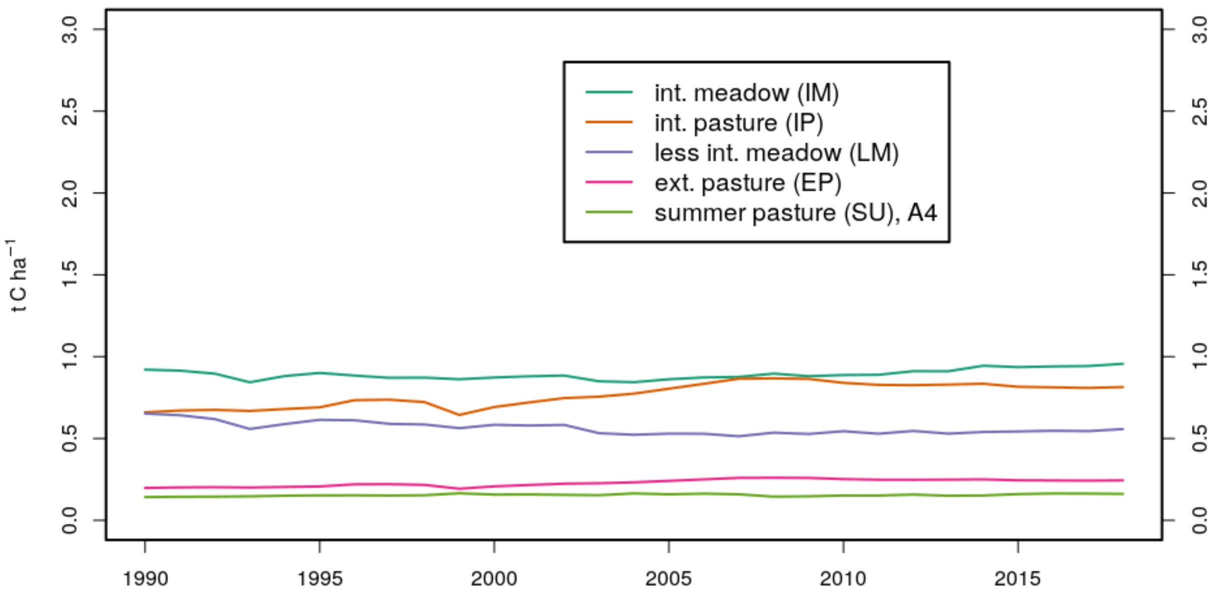


Figure 31 OrgAm-C application to upland grassland (strata in AZ3, except for summer pasture in AZ4, 1990 to 2017) as calculated by the OrgAm-model; extensively-managed meadows are assumed not to receive OrgAm.

Control and verification of OrgAm-model

The OrgAm-model was checked in several ways. Firstly, the amount of OrgAm-C applied to crops and grassland (ha^{-1}) was multiplied by their surface area and compared to the amount of OrgAm-C available for a given year. For 2017, the deviation of these values is < 0.3 %.

Secondly, 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 and 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 27), 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 type to convert OrgAm-C to OrgAm-N, and that it is possible that inaccuracies were introduced in this conversion.

A third 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 to a certain extent, 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 deem this validation valid. 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 as recommended by the fertiliser guidelines – could be compensated with mineral fertiliser, which is not considered in the OrgAm model. A second weakness of this validation is that it again requires the calculation of OrgAm N application which itself might introduce error. 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 %), 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[14] 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 preceding particular 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), where 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 the combination. Using this publication, 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 area (in ha, in 2014, using data from the FSS, section 2.2.5.1) of each preceding crop resulting in a crop combination *requiring a catch crop* was summed. In a second step, for each main crop, the area of each preceding crop 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 with a catch crop. The results are shown in Table 11 and were used for this project. This probability takes into account the recommendation of cover crops for each crop combination, as well as the relative occurrence of each crop combination.
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[15], as mandated by FOAG. The AEI data set contains detailed field-specific information on farming practices from ca. 250 to 300 farms, since 2009 (data used for this project: 2009 to 2015). 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 11). 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

[15] www.agrarmonitoring.ch

crop, the total cover crop plant C input was multiplied by the probability of that main crop being preceded (or, depending on the main crop, succeeding) by a cover crop (Table 11), 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 (or succeeding) 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 8). These parameters were obtained or derived from Appendix 7a in Nemecek et al. (2005), from Richner and Sinaj (2017), online information of SFU[16] and 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.

[16] https://www.landwirtschaft.ch/

Table 11 Parameters for main crops and cover crops used for modelling: Date when crop was sown, harvested, when it first covered the soil, when the first input of carbon occurs, the drymatter fraction, whether a cover crop was assumed, the fraction of cover crops used (see main text for details), the date when cover crops first covered the soil and were 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.

Code	**Cate-gory**	**sowing**	**har-vest**	**First cover**	**First C input**	**Drymatter 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]	---	---

2.2.6 Modelling 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[14, 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 however presents a difficulty 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 much 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.
The annual SOC stocks of the simulations were compared as follows: For the rotations, the mean results from the 30 rotations were used directly. For the second option, the SOC stocks from the leys and the two dummy crops were averaged, weighting the results 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, this weighted-average, 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 value per year.
All options thus had the same C inputs across the 30 years.

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 32), 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 a small over-estimate of average SOC stocks of the 30 rotations after 25 years (since 1985, i.e. excluding the first 4 years where deviation is small due to identical C stocks at the beginning of the simulations), by on average 2.12 % (Figure 33). 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 (Figure 34), of on average 1.01 % (again since 1985).

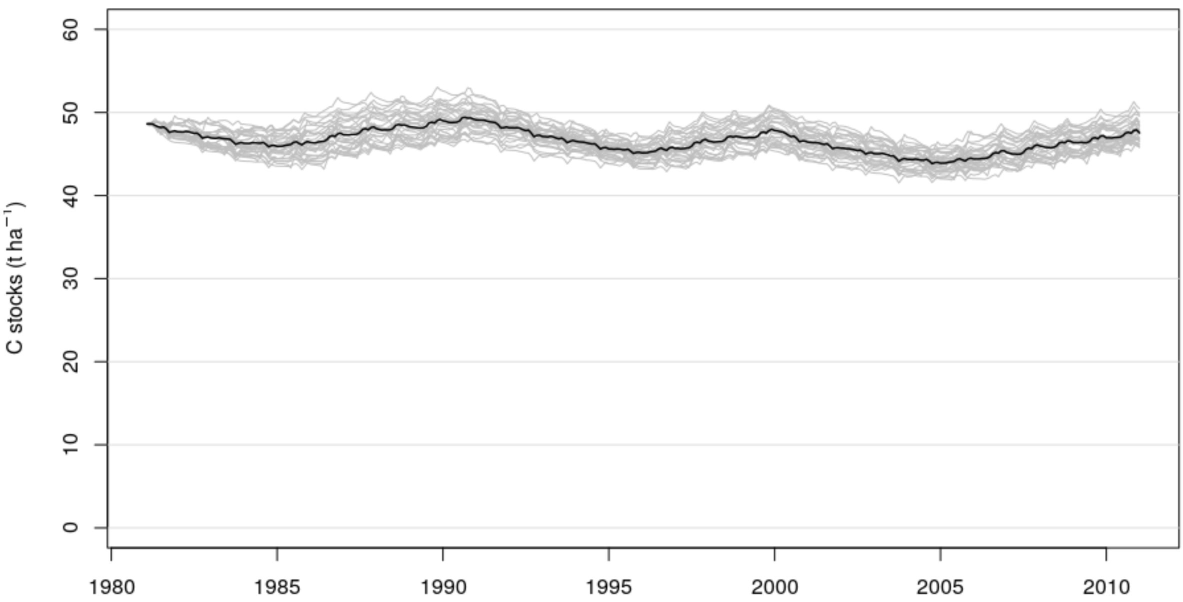


Figure 32 The modelled SOC stocks of 30 rotations, option one (1981 to 2014); grey = the individual crop rotations; black = average across the 30 rotations.

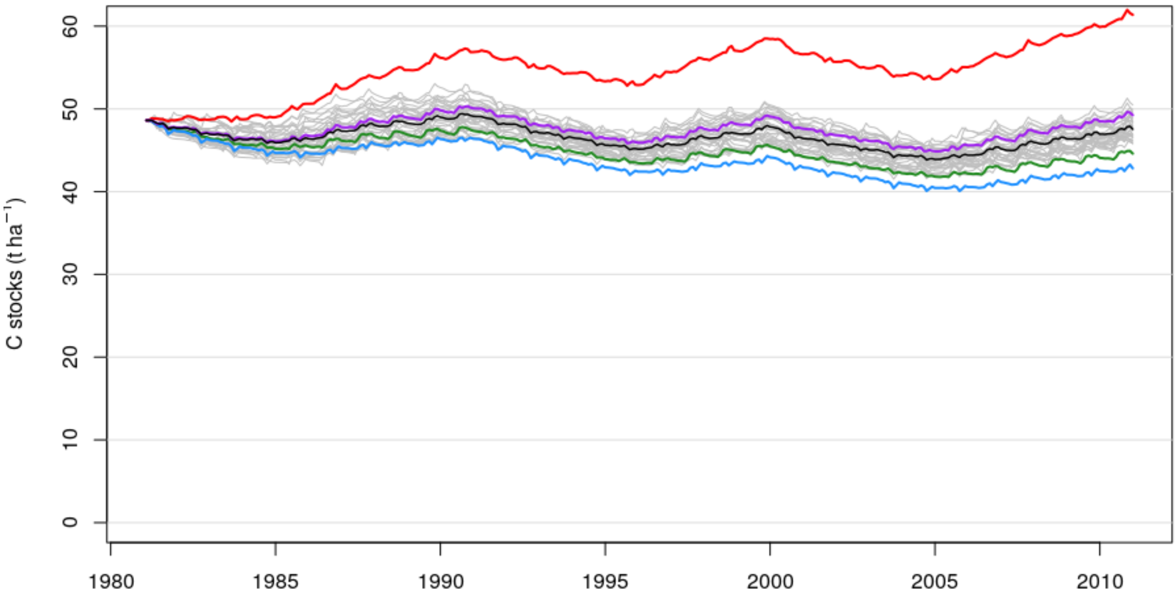


Figure 33 The modelled SOC stocks of dummy crops, option two (1981 to 2014); grey = the individual 30 crop rotations; black = average across the 30 rotations (grey and black as in Figure 32); red = leys; green = dummy summer crop; blue = dummy winter crop; purple = weighted average of dummy crops and leys.

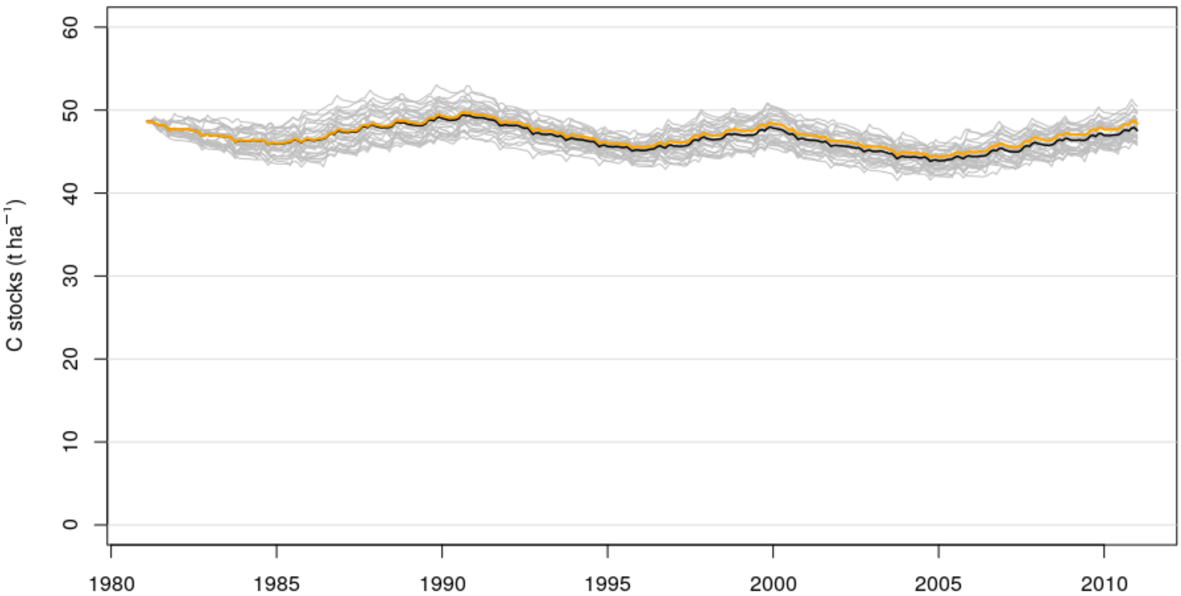


Figure 34 The modelled SOC stocks of continuous crops, option three (1981 to 2014); grey = the individual 30 crop rotations; black = average across the 30 rotations (grey and black as in Figure 32); orange = weighted average of the eleven crops (modelled as continuous crops).

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 for technical reasons much more realistic; ii) the over-estimation of C stocks is very 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 (e.g. Figure 32).

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 (but see section 4.3).

2.2.7 Initial carbon stocks 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 with pre-defined (and usually inter-annually constant) carbon inputs and climate data that is run until SOC stocks reach an equilibrium. For RothC a simulation of 10’000 years is recommended. This approach was used for long-term experiments where we had some information regarding the management prior to the start of the experiment (see section 2.1.3). However, this approach is time consuming and computationally intensive and we lack the necessary information at the national scale (i.e. for each stratum). We therefore tested an alternative approach, where the SOC stock is derived from a function that relates SOC to environmental parameters, and the distribution of SOC pools is determined by a pedo-transfer function. Based on these initial conditions, simulations were run for the years 1975-1990, so called ‘historic simulations’, to account for differences in management 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 greenhouse gas inventories, 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[17].
A mistake in the extraction of soil depth information from the SSM (see below, section “Input data”) led to incorrect calculation of initial SOC stocks for the 2019 GHG inventory submission (FOEN 2019). This has resulted in a deviation between the SOC stocks and the SOC stock changes given in this report and those from that submission. With the exception of the UA (section 3), all calculations given in this report have been carried out using the corrected soil depth information, as will GHG inventories henceforth.

[17] Project: Nationwide digital mapping of C stocks in soils for Switzerland’s greenhouse gas inventory (“Landesweite digitale Kartierung von Kohlenstoffvorräten in Böden für das Treibhausgasinventar Schweiz ”).

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

SOC stocks were calculated as:

$$SOC_{d1-d2}\ (\mathrm{t\ ha^{-1}}) = \%SOC \times (1 - fs) \times d \times \rho d \qquad \text{Eqn. 1 from Leifeld et al. (2005)}$$

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:

$$\rho d\ (\mathrm{t\ m^{-3}}) = 1.49 \times \%SOC^{-0.29} \qquad \text{Eqn. 2 from Leifeld et al. (2005)}$$

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:

$$\%SOC = \text{elevation (m)} \times f1 + \text{clay (\%)} \times f2 + c \qquad \text{Eqn. 3 from Leifeld et al. (2005)}$$

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:

$$\%SOC = \text{clay (\%)} \times f1 + c \qquad \text{Eqn. 4 from Leifeld et al. (2005)}$$

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. For these soils, 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 layer ("subsoil"), calculated as follows: Following Leifeld et al. (2003), 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 carried out 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 carbon (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 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 35) 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.

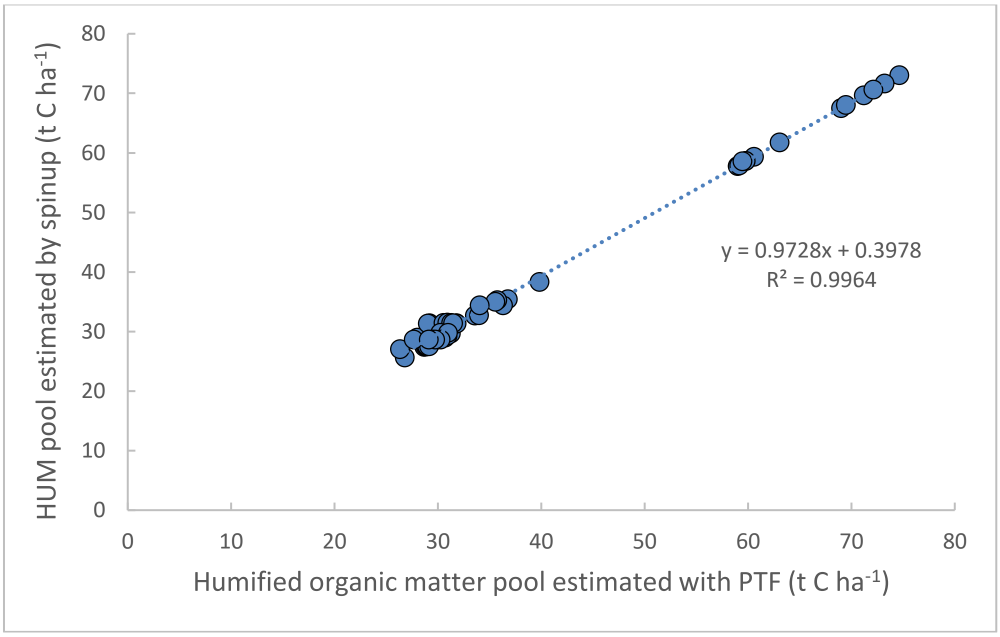
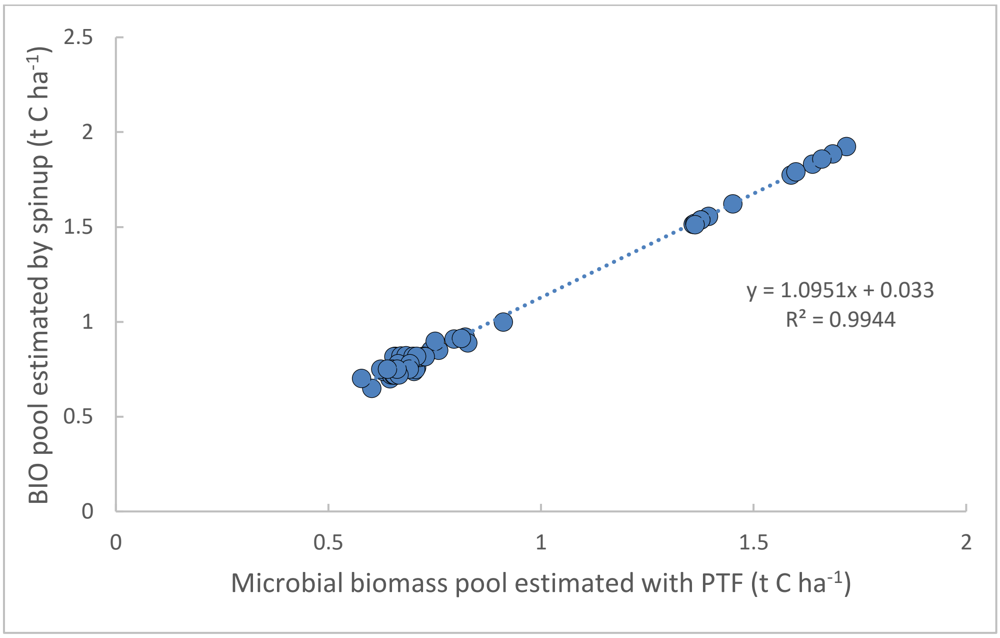
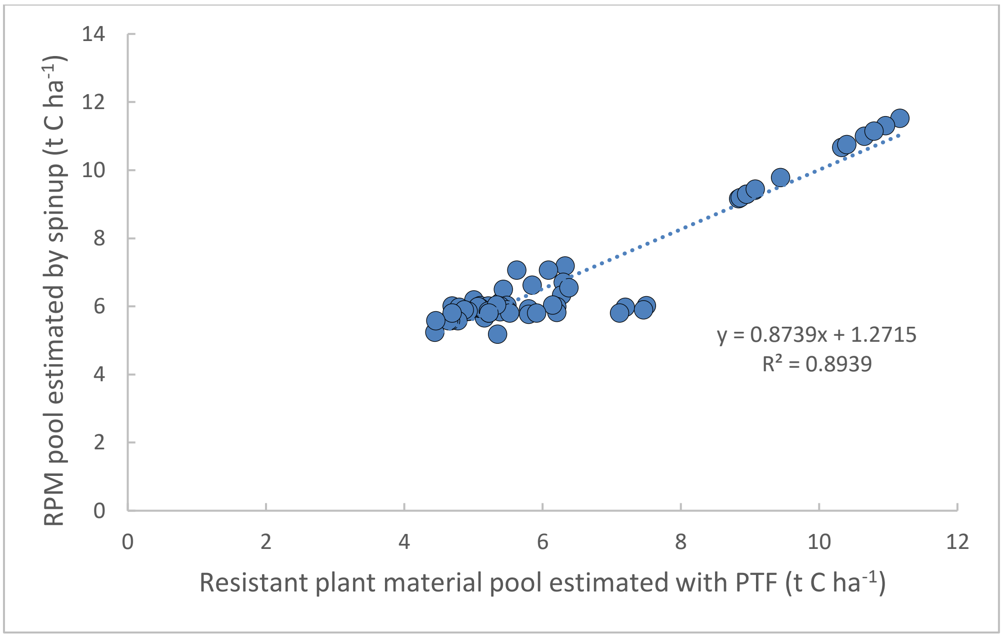


Figure 35 The size of three different conceptual C pools for five experimental sites (Balsthal, DOK, Hausweid, Oensingen, ZOFE) estimated with the PTFs from Weihermüller (see main text) or by spin-up; each symbol represents a plot. Plots continued overleaf.





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, using the initial SOC stocks and the pool distribution calculated for each stratum, as described above, for 1975. For simplicity the data were averaged across all clay classes, giving each class the same weight.

Historical data

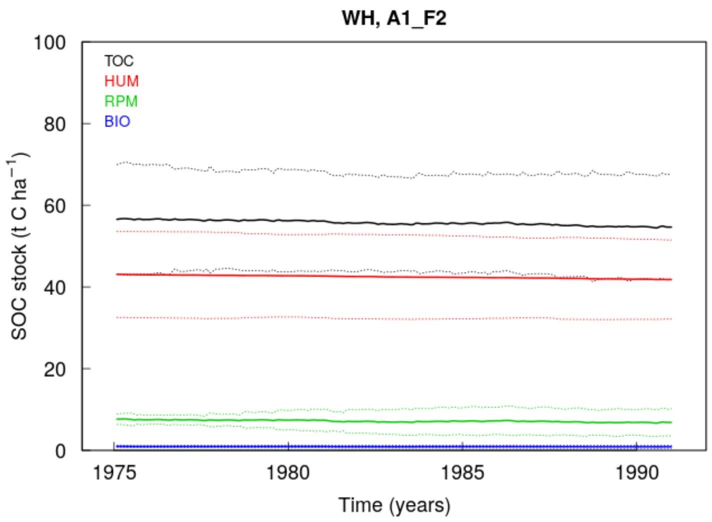
Historical input data for RothC are described in the following sections; for all other input parameters not mentioned here, the 1990 value was applied to the time period 1975-1990.

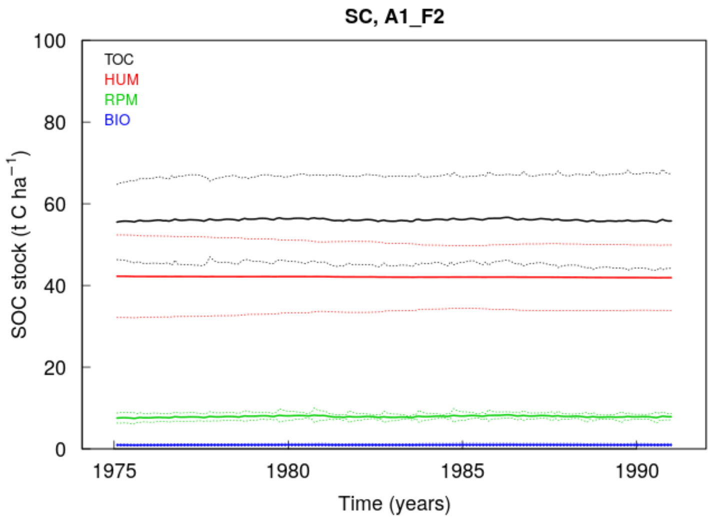
Climate data were available as gridded data (section 2.2.3.1) from MeteoSwiss for temperature and PPN. For the calculation of ET, SIS radiation data were available from 1983 onwards. For the years prior to 1983, monthly values were calculated as the mean value for the corresponding month, for the period 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[18], containing national statistics for years prior to 1990; interpolation was used to estimate yields for the (4-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 1975-1990 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 1975-1990. Information on the distribution of crops / grassland categories 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 36). The results for the most important grassland categories and strata were very similar (Figure 37). 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.

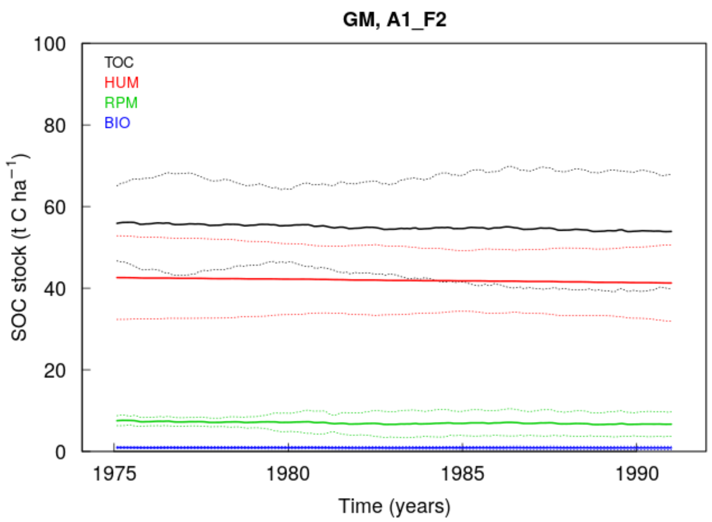
Figure 36 Historic simulations of total organic carbon (TOC) stocks (CL) for stratum A1_F2 (central plateau) (figures on page 69), and the three conceptual C pools HUM, RPM, BIO of RothC for wheat (WH), silage corn (SC) and grass-clover ley (GM) averaged over ten different clay classes (± standard deviation shown as dotted lines).

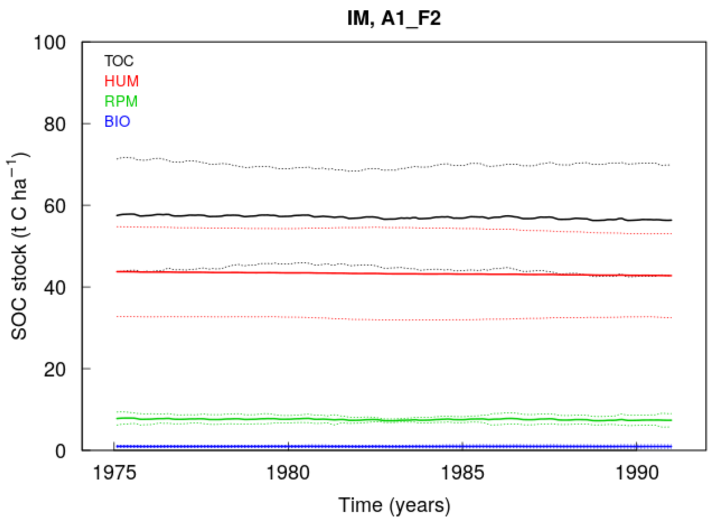
Figure 37 Historic simulations of total organic carbon (TOC) stocks (GL) for the most important grassland strata (figures on page 70) and the three conceptual C pools HUM, RPM, BIO of RothC for intensive meadows (IM) and summer pastures (SU) averaged over ten different clay classes (± standard deviation shown as dotted lines).

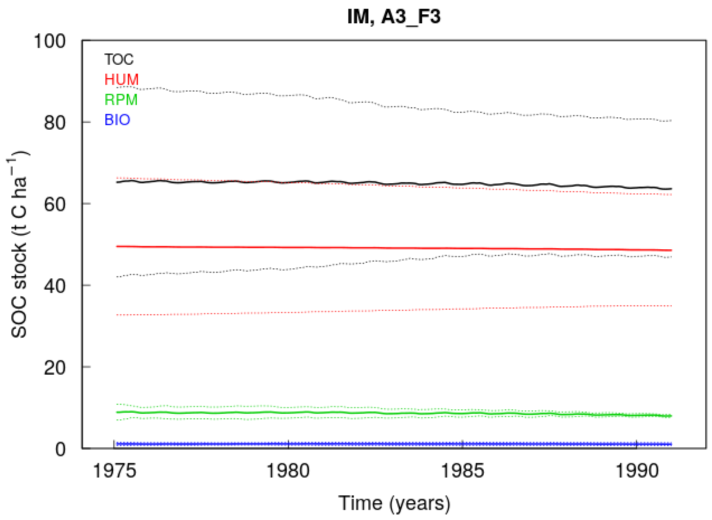
[18] https://www.bfs.admin.ch/bfs/de/home/dienstleistungen/historische-daten.html; in German and French.

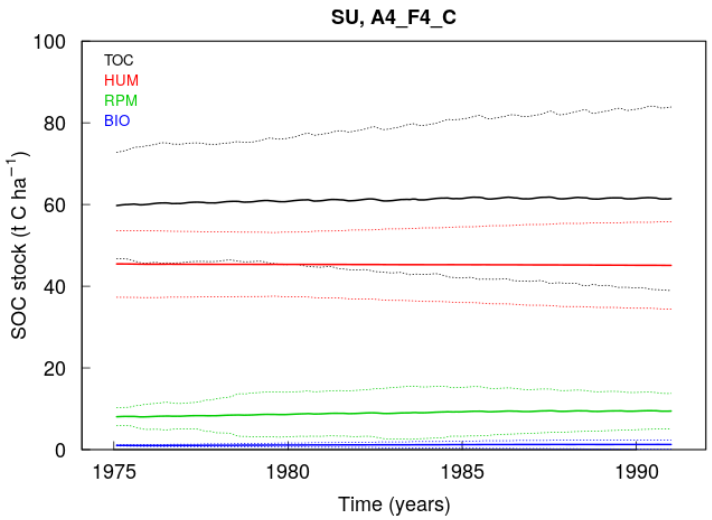

WH, A1_F2
TOC
HUM
RPM
BIO
SOC stock (t C ha−1)
100
80
60
40
20
0
1975
1980
1985
1990
Time (years)


SC, A1_F2
TOC
HUM
RPM
BIO
SOC stock (t C ha−1)
100
80
60
40
20
0
1975
1980
1985
1990
Time (years)


GM, A1_F2
TOC
HUM
RPM
BIO
SOC stock (t C ha−1)
100
80
60
40
20
0
1975
1980
1985
1990
Time (years)


IM, A1_F2
TOC
HUM
RPM
BIO
SOC stock (t C ha^{-1})
Time (years)


IM, A3_F3
TOC
HUM
RPM
BIO
SOC stock (t C ha^{-1})
Time (years)


SU, A4_F4_C
TOC
HUM
RPM
BIO
SOC stock (t C ha^{-1})
Time (years)

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

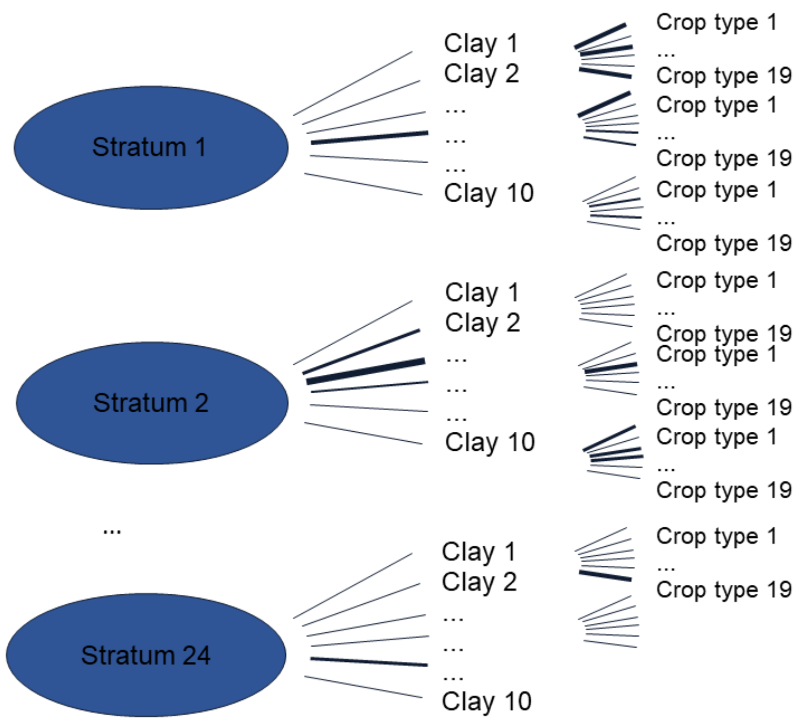
As described in section 2.2.1, a system of strata were used to scale simulations to the national level. As described in section 2.2.6, we account for the fact that crops are grown in rotations by simulating SOC stocks for individual ("continuous") crops and weighting the simulation results of each crop according to the crop frequency in each stratum (per year).
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 x 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' (Figure 38a) and, secondly, their 'soil area fraction' (Figure 38b). 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 change each year, in accordance with changing cultivation surfaces of individual crops (or grassland categories). Table 12 and Table 13 indicate the crop area fractions (status 2017) for CL and GL, respectively. The soil 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 (see section 2.2.4.1) in a GIS. This matrix (Table 14) does not change each year. The clay class corresponding to 0 % clay (section 2.2.4.1) was given a weighting of zero, as this project considers mineral but not organic soils.
In Switzerland, CL is concentrated in the central plateau: the stratum overlapping most closely with this region (A1_F2) contains 63 % of CL (Table 15) and is dominated by wheat, silage corn and grass-clover ley (WH, SC, GM, Table 12). 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 15).

2.2.8.2 From strata to elevation zone

In Switzerland's GHG inventory, SOC stocks and changes are aggregated for three elevation zones (EZs) for CL and GL. EZ1 includes all areas below 601 m asl., which are mainly in the central plateau of Switzerland. EZ2 includes areas between 601 and 1200 m asl., whereas everything above 1200 m asl belongs to EZ3. To calculate the SOC stocks and SOC changes for each EZ, SOC stocks per stratum were weighted by the fraction each stratum contributes to the respective EZ for CL, and for GL (Table 16 and Table 17). CL is predominantly in EZ1 and almost absent from EZ3 (Table 16) whereas GL is more evenly distributed across EZs.

2.2.9 Calculating stock changes

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



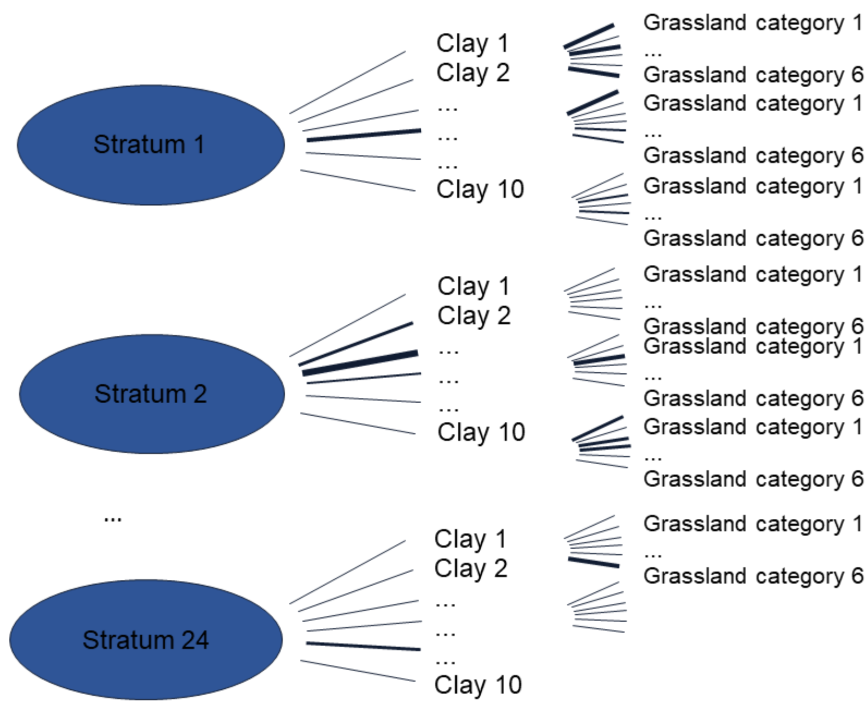


Figure 38 Calculation of annual SOC stocks for individual strata for CL (above) and GL (below); stocks of strata calculated as weighted averages across simulations for all possible clay-crop / -grassland combinations.

Table 12 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.

Stratum	BA	BB	FA	FB	GM	GC	OA	PE	PO	RA	RY	SB	SC	SF	SO	SP	TR	VE	WH
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																			

Table 13 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						

Table 14 Relative frequency of the clay classes in each stratum; more important stratum / clay class combinations are shaded bright red.

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 15 Fraction of CL and of GL in each stratum for 2017; more important stratum / land use combinations are shaded bright red.

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

Table 16 The fraction of CL strata contributing to each EZ with the proportion of CL (in total) in each EZ given in the upper row; more important strata are shaded bright red.

	EZ1	**EZ2**	**EZ3**
Proportion of CL (total)	0.670	0.328	0.002
A1_F1	0.14	0.04	0.00
A1_F2	0.69	0.36	0.00
A1_F3	0.04	0.03	0.00
A1_F4_C	0.02	0.00	0.00
A1_F4_W	0.02	0.00	0.00
A1_F5	0.01	0.00	0.00
A2_F1	0.05	0.03	0.00
A2_F2	0.02	0.21	0.00
A2_F3	0.00	0.06	0.00
A2_F4_C	0.00	0.01	0.00
A2_F4_W	0.00	0.00	0.00
A2_F5	0.00	0.00	0.00
A3_F1	0.01	0.11	0.12
A3_F2	0.00	0.03	0.00
A3_F3	0.00	0.10	0.02
A3_F4_C	0.01	0.02	0.83
A3_F4_W	0.01	0.00	0.01
A3_F5	0.02	0.00	0.01
A4_F1	0.00	0.00	0.01
A4_F2	0.00	0.00	0.00
A4_F3	0.00	0.00	0.00
A4_F4_C	0.00	0.00	0.01
A4_F4_W	0.00	0.00	0.00
A4_F5	0.00	0.00	0.00

Table 17 The fraction of GL strata contributing to each EZ with the proportion of GL (in total) in each EZ given in the upper row; more important strata are shaded bright red.

	EZ1	EZ2	EZ3
Proportion of GL (total)	0.220	0.366	0.414
A1_F1	0.10	0.01	0.00
A1_F2	0.55	0.09	0.00
A1_F3	0.07	0.01	0.00
A1_F4_C	0.01	0.00	0.00
A1_F4_W	0.02	0.00	0.00
A1_F5	0.01	0.00	0.00
A2_F1	0.08	0.01	0.00
A2_F2	0.05	0.09	0.00
A2_F3	0.03	0.04	0.0
A2_F4_C	0.00	0.00	0.00
A2_F4_W	0.01	0.00	0.00
A2_F5	0.01	0.00	0.00
A3_F1	0.02	0.16	0.01
A3_F2	0.00	0.04	0.00
A3_F3	0.02	0.32	0.02
A3_F4_C	0.00	0.06	0.12
A3_F4_W	0.02	0.06	0.03
A3_F5	0.02	0.02	0.01
A4_F1	0.00	0.03	0.03
A4_F2	0.00	0.00	0.00
A4_F3	0.00	0.04	0.15
A4_F4_C	0.00	0.00	0.36
A4_F4_W	0.00	0.01	0.21
A4_F5	0.00	0.00	0.06

3 Uncertainty analysis

An initial UA was carried out to calculate uncertainty in the annual (year to year) SOC change for all years between 1990 and 2017 (i.e. 1990 to 1991, 1991 to 1992….2016 to 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 UA is an *initial* analysis that was carried out with three main aims. The first aim was to estimate the magnitude of error associated with the annual SOC changes reported in Switzerland's GHG inventory. The second aim was to provide a basis for a future sensitivity analysis, with a view to i) deciding where to concentrate efforts to improve the data basis in the future and ii) understanding which changes have led to SOC stock changes over the last three decades. The third aim was to serve as the basis for a future comprehensive UA.
The UA is an initial UA for the following 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; 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, 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 18), covering in total ca. 49 % of crops, 36 % of year-round grassland and 40 % of summer pastures.

Table 18 The crop or grassland / clay / strata combinations considered in the UA.

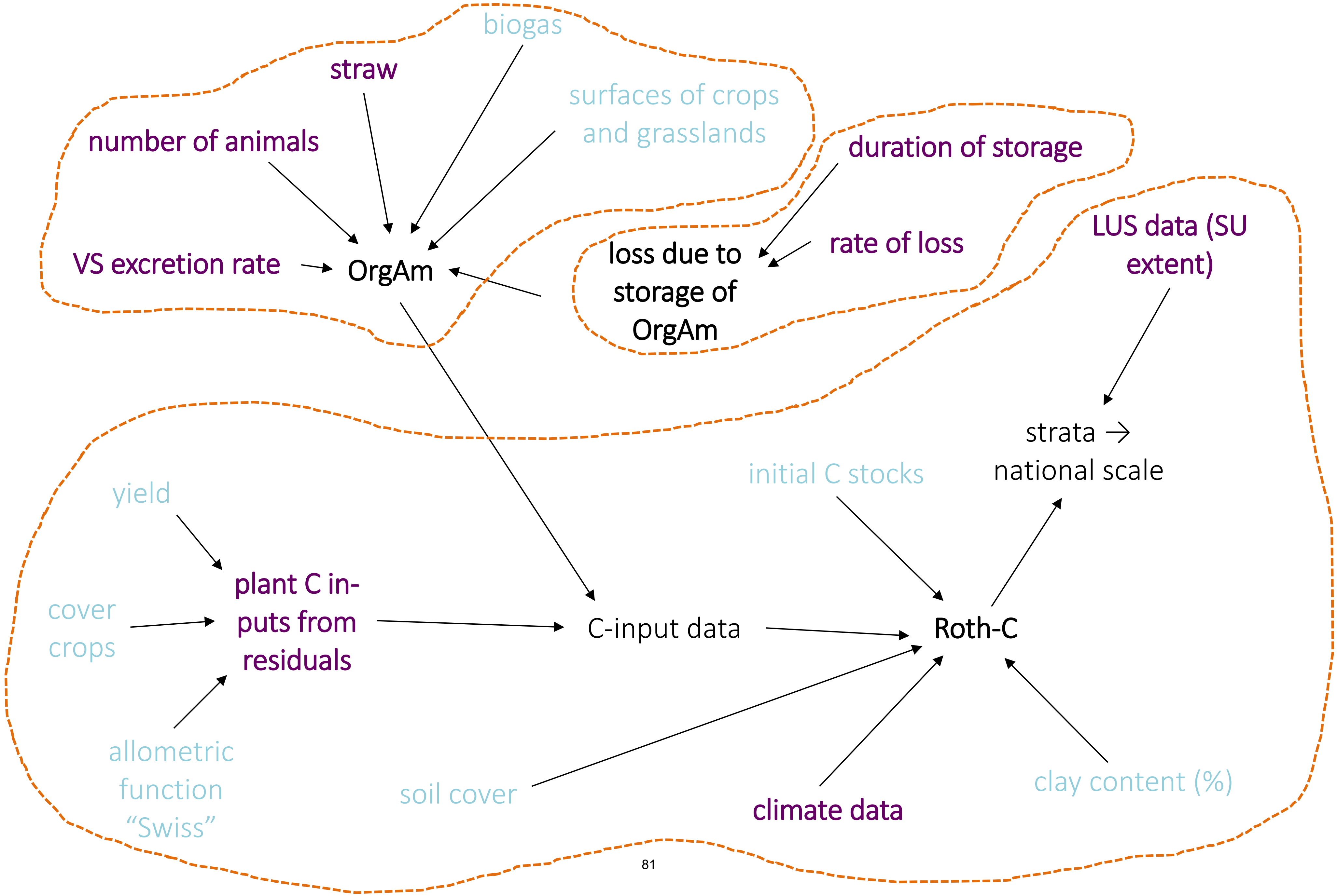
Land use	Strata	Clay class (based on clay content)	No. of crop or grassland types	No. of combinations	% of CL or GL surface represented
Cropland	A1_F2	10 and 20 % clay	10 out of 20 (BA, GC, GM, PO, RA, SB, SC, TR, VE, WH)	20	ca. 49
Grassland (year-round)	A1_F2, A3_F3 and A3_F1	10 and 20 % clay	5 out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

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 39): 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 39 Overview of the UA (overleaf) 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.


biogas
straw
surfaces of crops and grasslands
number of animals
VS excretion rate
OrgAm
duration of storage
loss due to storage of OrgAm
rate of loss
LUS data (SU extent)
strata → national scale
initial C stocks
yield
plant C in-puts from residuals
cover crops
C-input data
Roth-C
allometric function "Swiss"
soil cover
climate data
clay content (%)

3.3 Data sources

Variation in the following input parameters was considered: climate data (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, the largest one was accounted for. Fourthly, whether the variation between variables is correlated with one another or not. These points are discussed further in the context of the individual input parameters in the following sub-sections.

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 topsoil moisture deficit (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 sys-

tematically 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 19). 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 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 19 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 total plant C inputs was incorporated in the MC analysis, with a PDF parameterised using variation in crop yields. Variation in crop yields were used, rather than variation in other parameters of the allometric function, because it is expected that variation in yields across the country is one of the major sources of uncertainty in plant C inputs in general. The reason for this is that the 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 parameterised 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 20. With the exception of summer crops in 2015 – an unusually dry and hot summer – and of silage corn (high variation across the years), 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 allowed us to designate a single error estimate for each crop for the whole period, i.e. to assume the error was 100 % correlated through time. For each crop, this variation in yields (CV [%], Table 20) was then applied to the plant C inputs (in general, not just the plant yields). Variation in plant C inputs of the different crops were not assumed to be correlated to one another.

Table 20 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*

** includes crops not considered in UA and thus not listed in table.*

3.3.3 Organic amendments

Error 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 39).

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 was estimated by considering i) uncertainty in storage duration and ii) the uncertainty of OrgAm-C loss rate of with each OrgAm type.
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 (see section 2.2.5.3). For each OrgAm type except fresh manure, OrgAm-C loss values from 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. These two uncertainty estimates were incorporated in an MC analysis, alongside the uncertainty in duration of OrgAm storage, to estimate the uncertainty of OrgAm-C loss through storage. The

three PDFs (for three OrgAm types) were each parameterised as follows: The two parameter estimates (from the statistical model) describing the relationship between storage time and OrgAm-C loss were assumed to follow a normal distribution and their standard errors were obtained directly from the statistical model. The uncertainty in the duration of OrgAm storage (Table 21) 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 through the year. For each OrgAm type, an MC analysis (5,000 iterations) was used to produce a distribution OrgAm-loss values from which values were then randomly picked during the main OrgAm-C MC analysis (Figure 39 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 21 OrgAm-C storage duration uncertainty as implemented in the UA, as well as 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	none	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 20). 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 22), which was subsequently fed into the main MC analysis of OrgAm-C (Figure 39).

Table 22 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 considerable uncertainty in the surface of summer pastures needs therefore 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[19]) 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 39). Ten thousand iterations were run. Inspection of the 95 % CIs of the MC analyses for two crops and one grassland category suggests that this was sufficient, as – in accordance with the IPCC guidelines (IPCC 2006a) – the CIs 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 46). The 2.5th and 97.5th percentile values of the final MC distributions of 10,000 iterations were used to quantify the uncertainty SOC change (a 95 % CI), as described in McMurray et al. (2017), for CL and for GL.

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

3.5 Monte Carlo analysis results and discussion

SOC changes were calculated as change between the years 1990 to 2017 (Figure 40 to Figure 43) and between adjacent years (Figure 44 and Figure 45, selected years shown). Both types of stock change values were calculated as the difference between mean SOC stocks of any two given years. Figure 40 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 generally 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 (resulting 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 median of the 2.5th percentiles of annual SOC stock changes (1995 to 2017) were -0.179 and the median of the 97.5th percentiles were 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, error 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[17]; 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 46). 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 46: If we assume the error is (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 we assume the error is not correlated, 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 that error is uncorrelated leads to estimates of uncertainty that are more than an order of magnitude greater (Figure 46).
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: Across the range of 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.

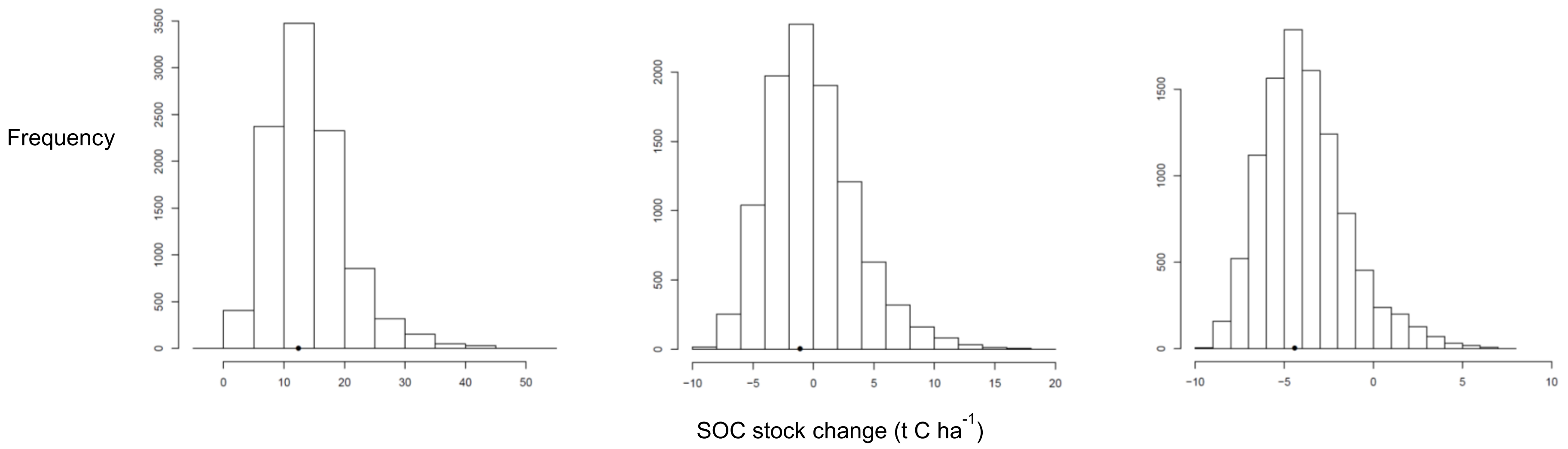


Figure 40 Uncertainty in SOC stock changes (1990 to 2017) of three CL soils as calculated by UA (histogram of results from 10,000 iterations) and the main analysis for the main crop stratum A1_F2, assuming a clay soil content of 10 % (black dot at base of graph); left-hand graph = rape seed, middle graph = silage corn; right-hand graph = wheat.

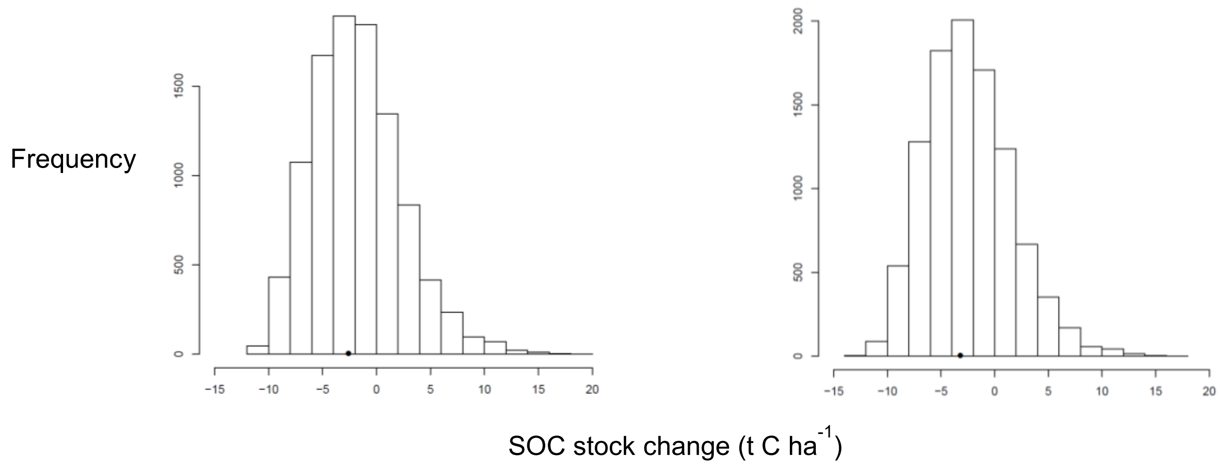


Figure 41 Uncertainty in SOC stock changes (1990 to 2017) of two lowland GL soils as calculated by UA (histogram of results from 10,000 iterations) and the main analysis (black dot at base of graph) for the stratum A1_F2, assuming a clay soil content of 10 %; left-hand graph = intensive meadows, right-hand graph = intensive pastures.

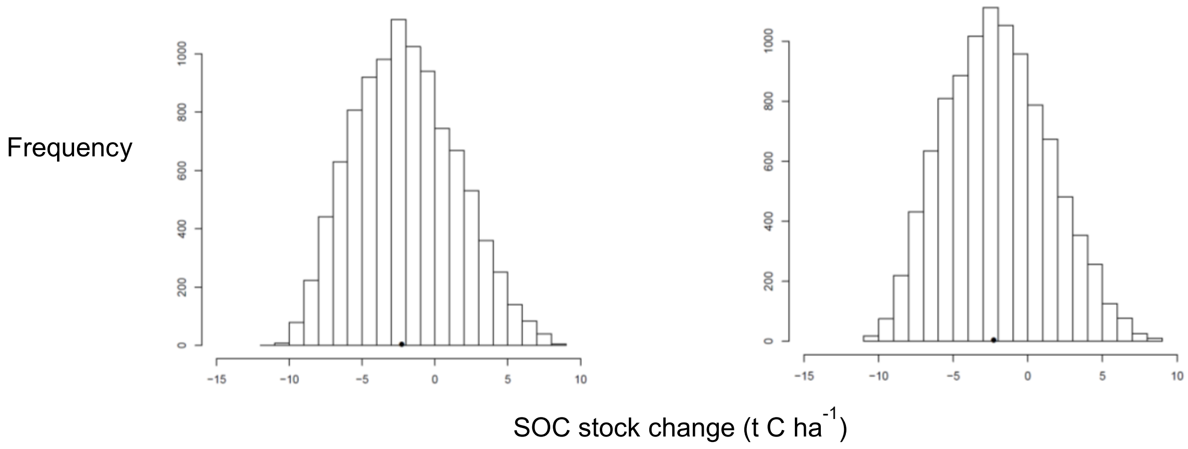


Figure 42 Uncertainty in SOC stock changes (1990 to 2017) of two mountain zone GL soils as calculated by UA (histogram of results from 10,000 iterations) and the main analysis (black dot at base of graph) for the stratum A3_F3, assuming a clay soil content of 10 %; left-hand graph = intensive meadows, right-hand graph = intensive pastures.

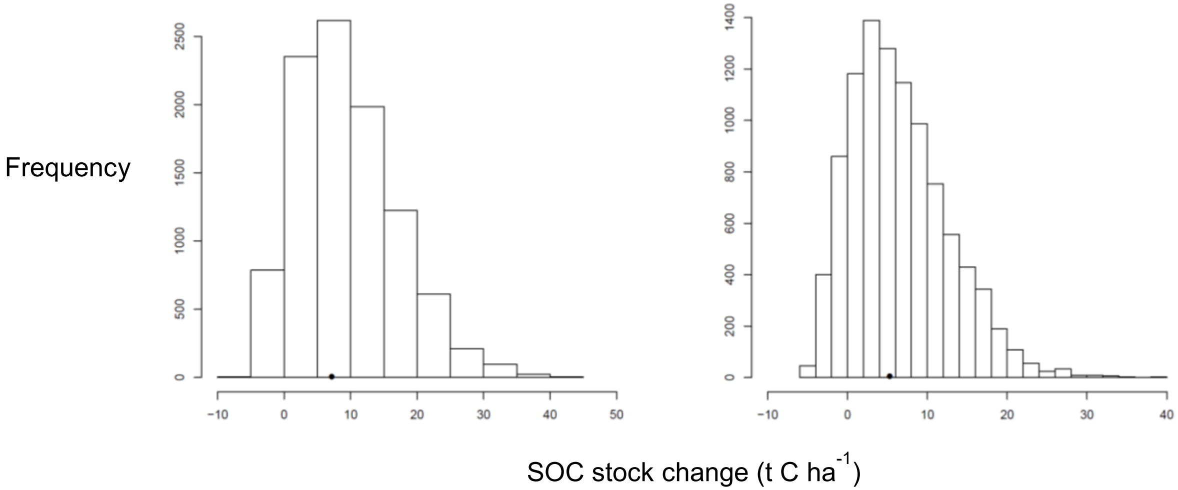


Figure 43 Uncertainty in SOC stock changes (1990 to 2017) of two summer pasture soils as calculated by UA (histogram of results from 10,000 iterations) and the main analysis (black dot at base of graph), for the strata A4_F4_C (left-hand graph) and A4_F4_W (right-hand graph), assuming a clay soil content of 5 %.

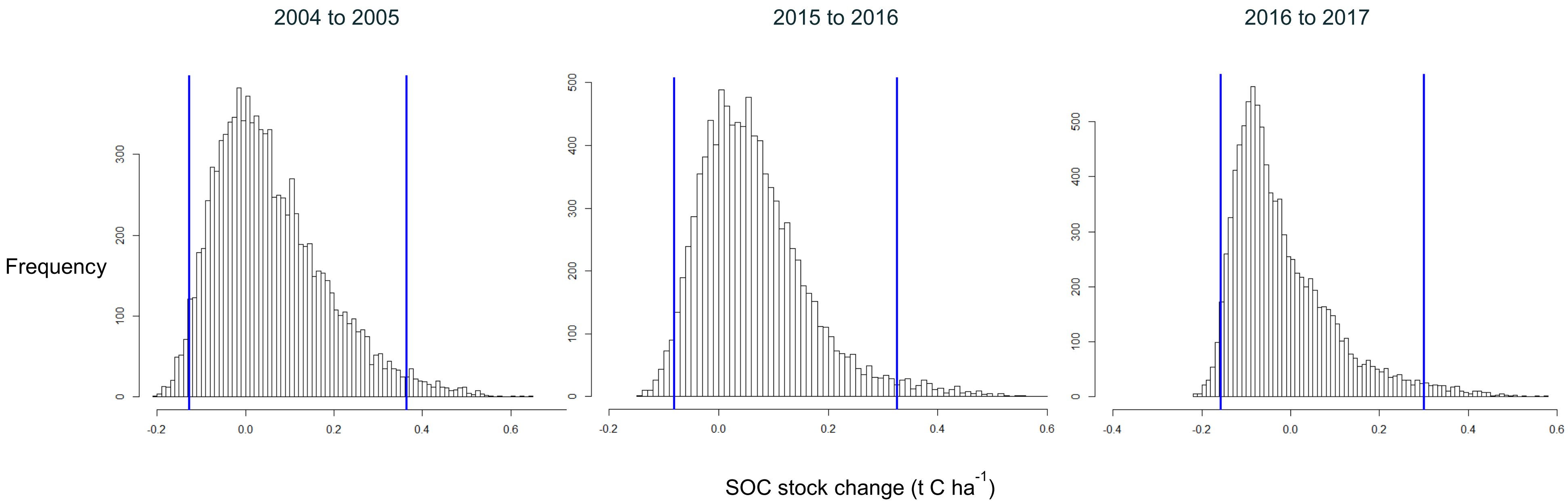


Figure 44 Uncertainty in annual SOC changes for GL, as calculated by UA (histogram of results from 10,000 iterations) for selected years; estimates a weighted-average of results from individual grassland categories, selected strata and clay content types, as described in main text; blue lines (2.5th and 97.5th percentiles) represent the 95 % CI boundaries.

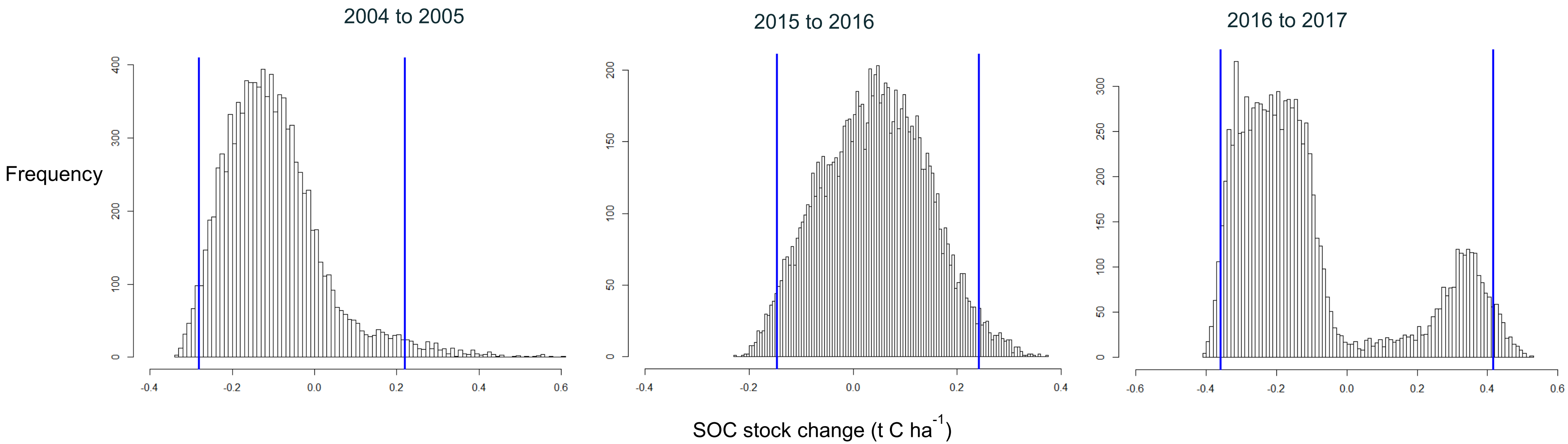
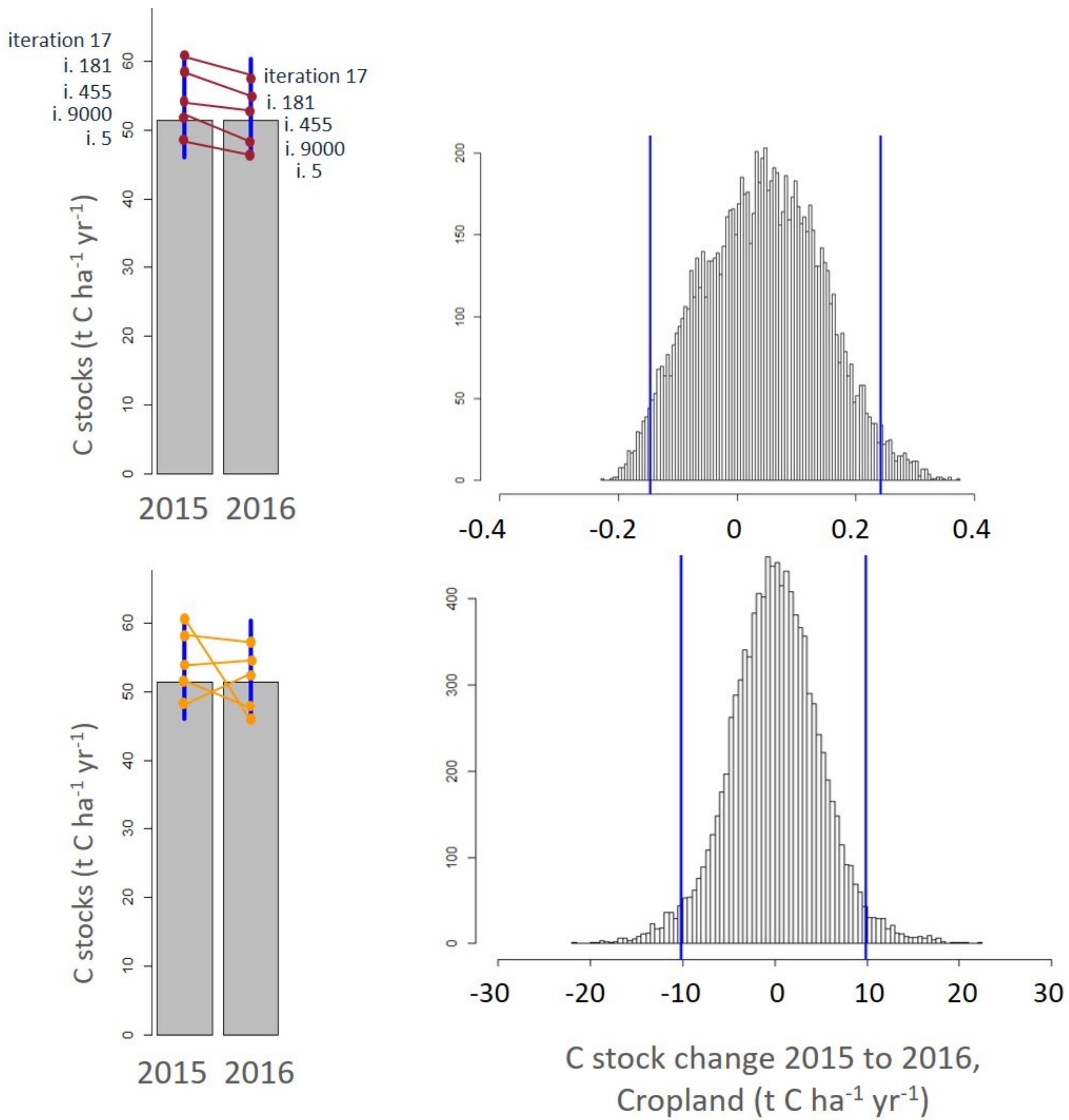


Figure 45 Uncertainty in annual SOC changes for CL, as calculated by UA (histogram of results from 10,000 iterations) for selected years; estimates a weighted-average of results from individual crops, selected strata and clay content types, as described in main text; blue lines (2.5th and 97.5th percentiles)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

Figure 46 Uncertainty in annual SOC changes 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, upper 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 stock change (yellow lines, right bar-chart), with histogram showing the corresponding distribution of SOC stock change uncertainty.


iteration 17
i. 181
i. 455
i. 9000
i. 5
C stocks (t C ha-1 yr-1)
2015 2016
-0.4 -0.2 0 0.2 0.4
-30 -20 -10 0 10 20 30
C stock change 2015 to 2016,
Cropland (t C ha-1 yr-1)

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 (18 for cropland) with similar agricultural management and climatic conditions. Within these strata, ten different clay classes and 25 crop and 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. These can either be implemented rapidly, where processes are already defined in RothC, or with re-programming, where a new process needs to be defined in RothC. Additionally, because input parameters can be easily varied, the inventory system can also serve as a tool to test the effect of altering particular parameters. This allows investigation in two avenues. Firstly, it allows, by means of a sensitivity analysis, 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). Secondly, it allows the testing of specific GHG mitigation options to increase SOC stocks.
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, there is no representation of irrigation, no-till or pH dependency of decomposition rates, and many other influencing factors are not considered. 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, and for a system within which management and 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 carbon 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 (for CL) elevation. Although it would be feasible to implement such dynamic parameters, we lack the required information at the national scale.
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 will discuss those results of this project most relevant for reporting in the national GHG inventory: simulated SOC stocks and changes. We will also compare the results with other studies from Switzerland and other countries, in so far as this is possible.
It must be noted that because of continual improvements in the inventory system, recalculations (for the whole period 1990 to present) are frequently carried out. The corollary of this is that results appearing in this report will differ slightly from those appearing in a GHG inventory of a given year. One recalculation, described in section 2.2.7.1, corrected a mistake in the calculation of initial SOC stocks. The correction has been implemented in this report, resulting in an incongruence between the results shown here and in the 2019 GHG inventory submission.
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 soils in Switzerland are generally not a statistically significant C sink or source**.

4.1 Cropland

4.1.1 Initial SOC stocks

Under cropland, SOC stocks (year 1990) for the 18 single strata range between 36.1 t C ha^{-1} and 60.0 t C ha^{-1} (data not shown). This range includes the constant SOC stock presented for the entire Swiss cropland in previous GHG inventory submissions (Table 23) and 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). Furthermore, the Swiss range includes the mean stock of cropland soils for Germany (Jacobs et al. 2018, 61 t ha^{-1} for 0-30 cm depth), though the Swiss SOC stocks are generally lower than those of these two studies. Table 23 shows the SOC stocks aggregated for the three EZs. It is important to note that EZ3 is almost irrelevant for CL, containing only ca. 0.2 % of CL (Table 16).

Table 23 SOC stocks for CL soils in 1990 (0-30 cm depth), as estimated in this project.

	EZ1	EZ2	EZ3
Previous estimate for CL (in GHG inventories)	53.4	53.4	53.4
New estimate	50.2	50.1	42.3

The lower SOC stocks in the highest EZ can be explained by the fact that shallow (CL) soils occur with a relatively high frequency in EZ3, compared to in the lower EZs (Figure 47), which are overwhelmingly dominated by deep soils: The ratio of CL occurring in deep:shallow soils in EZ1 = 373:1, in EZ2 = 404:1, in EZ3 = 12:1.

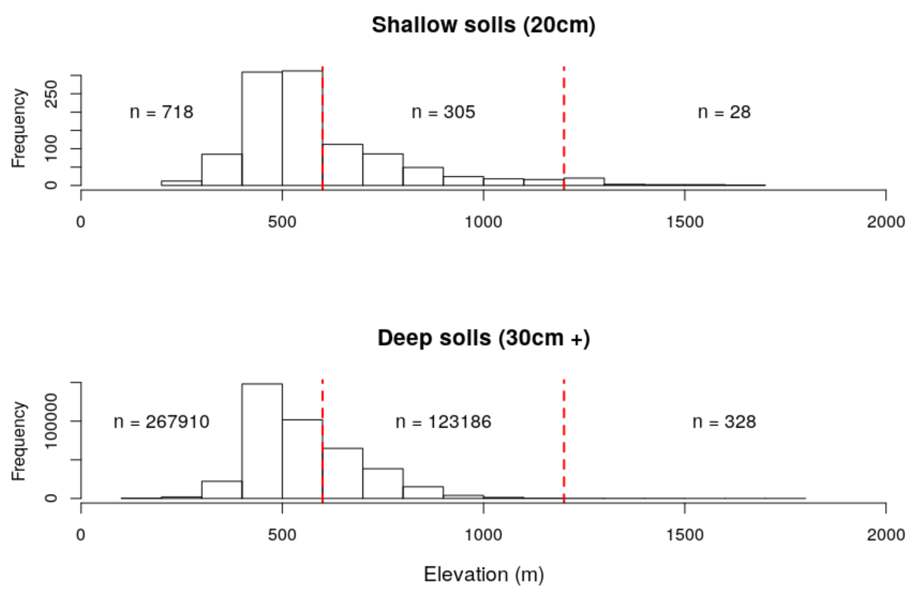


Figure 47 Distribution of CL points over shallow or deep soils in the three EZs (as calculated for this project) demonstrating that the relative frequency of shallow soils is higher in the highest EZ than in the lower EZs; red dotted lines = boundaries of the three EZs (see section 2.2.8.2). Note different scales on y-axes.

4.1.2 SOC stock changes

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 48). Within the most important stratum A1_F2, annual SOC changes vary between -0.50 and +0.63 t C ha^{-1}, 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%).

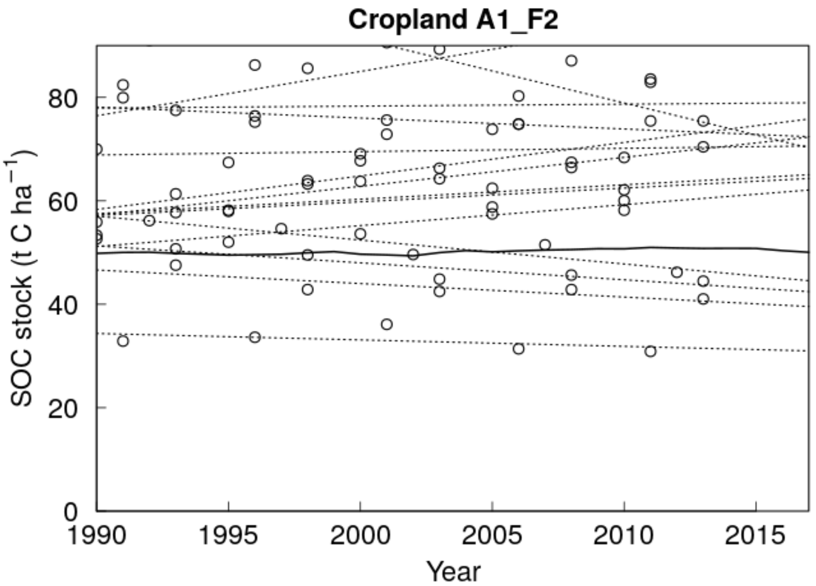


Figure 48 Comparison of simulated and measured SOC stocks for CL; simulated stocks from the dominant CL stratum in EZ1 (A1_F2, solid line); measured stocks from 16 soil monitoring sites within this stratum (open symbols), dotted lines show linear fit of each monitoring site.

For one very small stratum (A2_F5) some annual SOC changes seem unrealistically high (-3.07 to +2.18 t C ha^{-1} yr^{-1}). 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.

For reporting in the GHG inventory, the results are aggregated into three EZs as described in section 2.2.8.2. There is almost no CL above 1200 m above sea level (asl) (EZ3), and we therefore only discuss the results for EZ1 (<601 m asl) and EZ2 (601-1200 m asl). 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, with the exception of the statistically significant sink in 2003, and vary around zero (Figure 49 and Figure 50).

The positive peak in 2003 (i.e. soil was a SOC sink, Figure 50 and Figure 49) is probably due to the dry and hot summer of that year, which caused an unusually long period of accumulated TSMD in RothC. In the model TSMD strongly reduces SOC decomposition rates leading to an accumulation of SOC. It is difficult to validate the response of the model under these extreme conditions, as SOC stocks are usually not measured at 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 (Figure 51), measured SOC stocks also show that soils were a sink in the year 2003, but not exceptionally so. However, 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 that summer could be found. What is well known though, is that soil respiration rates 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 our results 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 tend to 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 was successfully simulated by RothC (section 2.1.3). Because we cannot account for land use change at a regional scale, this additionally makes a comparison between our simulations and the results of specific sites difficult.
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 losses in SOC of -0.23 and -0.35 g kg^{-1} (-0.93 and -1.52%) between the two periods 1995-1999 and 2011-2015. If we convert our stock changes for EZ1 and EZ2 to changes in % for the same years (difference between 1995-1999 and 2011-2015) we get small increases of 1.9% and 2.3% respectively. Overall, our results agree with those of Stumpf et al. (2018) in that changes in SOC in this project were also not statistically significant. A direct comparison is difficult, because the authors report C content (%) whereas this project calculates C stocks (and thus accounts for changes in bulk density). Furthermore, CL categories used in Stumpf et al. (2018) are not directly comparable to the categories used here.

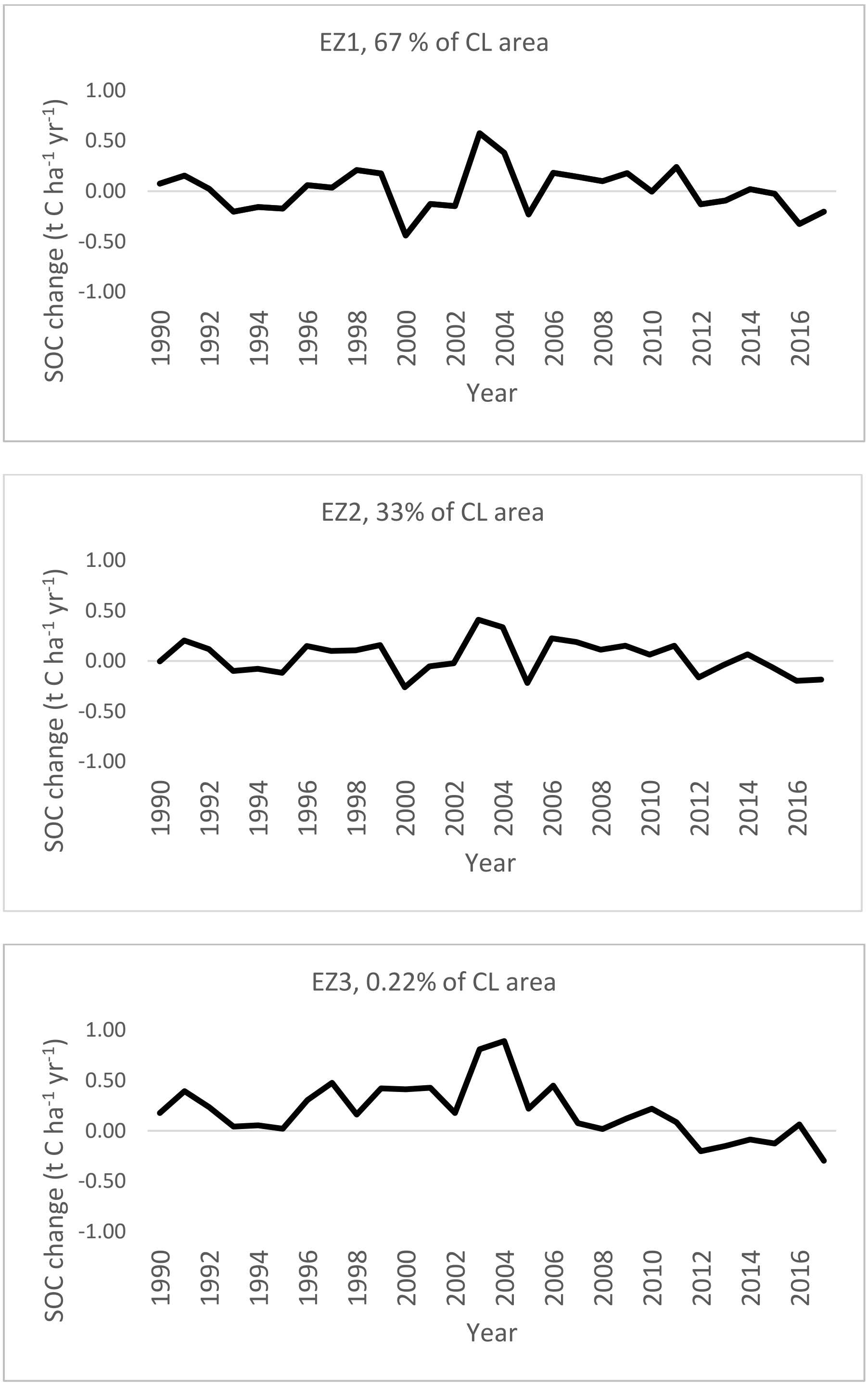


Figure 49 Annual SOC stock changes (0-30 cm) for CL for three EZs; note that EZ1 dominates the total CL area, while EZ3 is irrelevant (Table 16).

Figure 50 Annual SOC stock changes (0-30 cm) for CL soils calculated using weighted average results from three EZs (black line); grey lines show the upper and lower CIs, absolute values derived from UA.

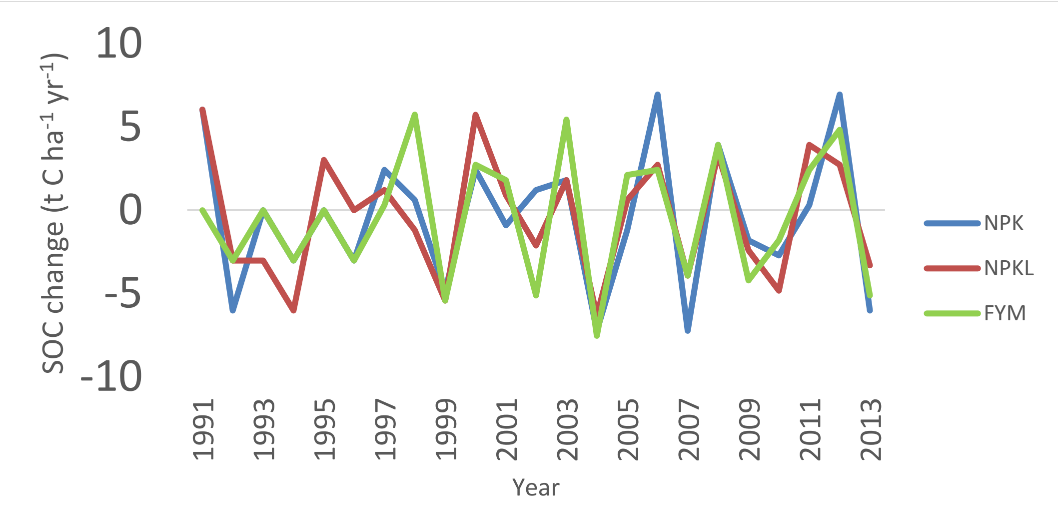


Figure 51 Annual SOC stocks changes at an experimental site in Zurich; derived from annual measurements of SOC contents (usually performed in November or December) and a single measurement of bulk density in the upper 0-20 cm of the soil profile. The experiment, "Demo87", tests the effect of different fertilisation treatments NPK fertiliser (120,35,220 kg N,P,K ha^{-1} yr^{-1} on average), NPK plus liming, 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.

<u>Comparison to other countries</u>
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 standard deviation for Switzerland is reduced to 0.17 t C ha^{-1} if the exceptional year 2003, during which Europe experienced a heat wave, is omitted.

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} (64.0 ± 17.4 t C ha^{-1}; mean ± SD). 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). A potential explanation for this discrepancy is 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. 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 initial SOC stocks aggregated per EZ is within the range of the constant SOC stocks used in previous GHG inventories for the same EZ on permanent grassland (Table 24).

Table 24 SOC stocks for GL soils in 1990 (0-30 cm depth), as estimated in this project.

	EZ1	EZ2	EZ3
Previous estimate for GL (in GHG inventories)	62.02	67.50	75.18
New estimate	60.44	65.26	62.60

In contrast to previous GHG inventory submissions, the SOC stocks do not consistently increase with elevation; the SOC stocks of EZ3 are lower than those of EZ2. Investigation of the distribution of GL points showed that, as expected, SOC concentration increases with increasing elevation (Figure 52), implying the decreasing SOC stocks are related to other factors, probably including soil depth and stone content. The ratio of GL occurring in deep:shallow soils is EZ1 = 37:1, in EZ2 = 12:1, in EZ3 = 1:1, i.e., compared to in lower EZs, GL soils in the higher EZs are more likely to occur over shallow than over deep soils (Figure 53). Additionally, stone content is much higher in the highest EZ (mean stone content in EZ 1 = 14 %, in EZ2 = 20 %, in EZ 3 = 41 %). Both shallower and stony soils decrease SOC stocks for a given SOC content (%) and might therefore explain the lower stocks in upland soils.
Germany's first agricultural soil inventory shows that topsoils (0-30 cm) under grassland store on average 88 t C ha^{-1} (Jacobs et al. 2018). Again, a possible explanation for the lower SOC stocks compared to Germany might be the high abundance of shallow soils in Switzerland (Figure 53), typically related to its mountainous topography. Additionally, the high abundance (48%) of soils with >30 % stones (diameter >2 mm) in Switzerland compared to only 20% of the sampling sites with >10 % stones in Germany, is also a likely explanation for the difference.

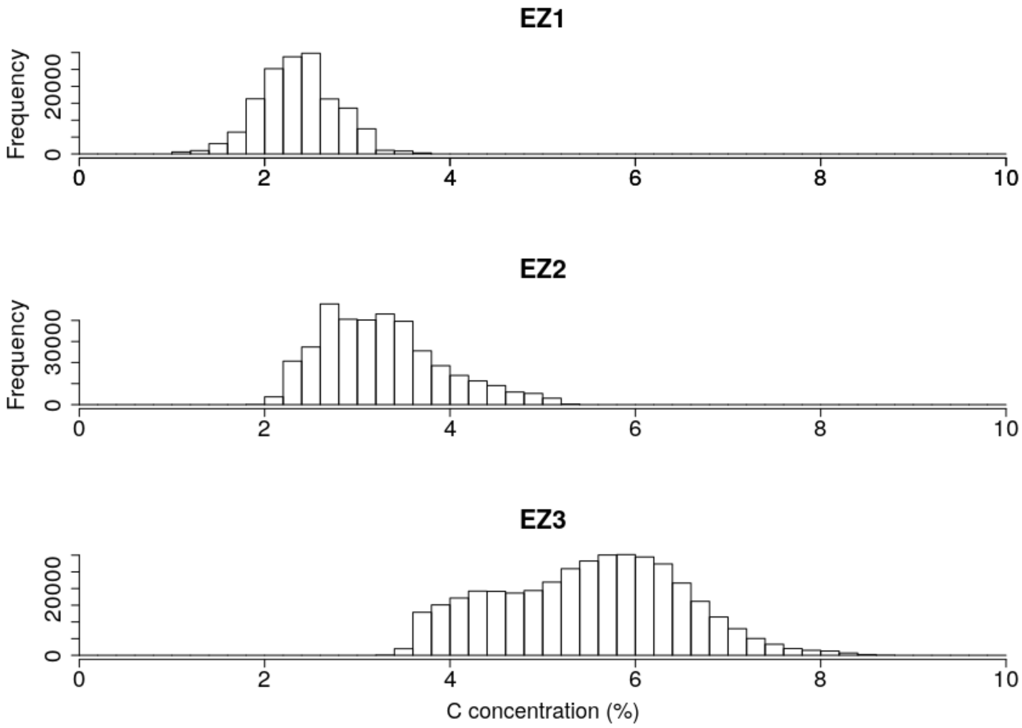


Figure 52 Initial SOC concentration (%) in the three different EZs, for GL (as calculated for this project).

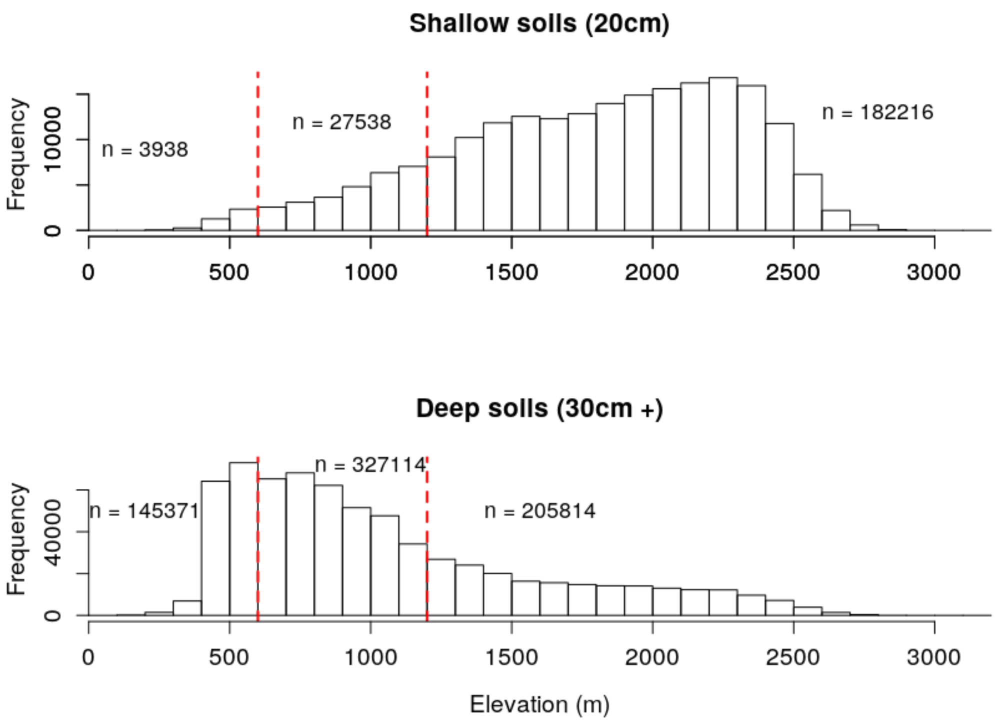


Figure 53 Distribution of GL points over shallow or deep soils in the three EZs (as calculated for this project) demonstrating that the relative frequency of shallow soils is higher in the highest EZ than in the lower EZs; red dotted lines = boundaries of the three EZs (see section 2.2.8.2).

4.2.2 SOC stock changes

For single GL strata positive as well as negative SOC trends were obtained, but negative trends clearly dominated. Annual changes in SOC stocks ranged from -0.64 to +0.67 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; linear fits per sites, data from 1991-2015, N = 26 sites, categories: permanent grassland, not including vineyards and parks as in the GHG inventory).

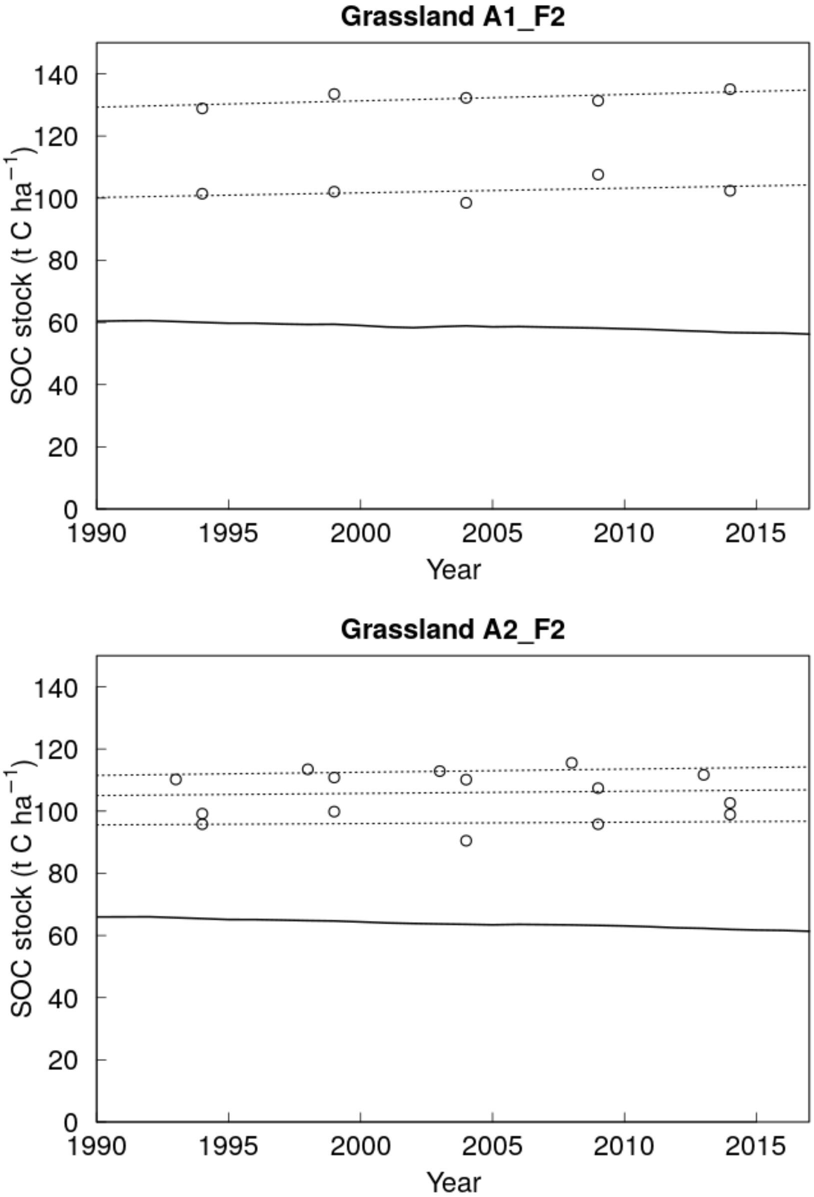


Figure 54 Comparison of simulated and measured SOC stocks for GL; simulated stocks for a specific stratum (solid line) and measured values for all sites of the Swiss national soil monitoring that lie within the stratum (A. Gubler unpublished data, open symbols), dotted lines show linear fit of each monitoring site.

In most years SOC stock changes for EZ1 and EZ2 are slightly negative, whereas EZ3 shows positive SOC changes (Figure 55). However, averaging across the different EZs and 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, and vary around zero (Figure 56).
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 (0.3-2.7 t C ha^{-1}

yr^{-1} for the whole profile). 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 already discussed above, 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 unlikely to occur in a short-term field experiment; the nationally-important pattern is therefore not detected on the local scale.
As mentioned already 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 EZ1, EZ2 and EZ3 are -3.9, -2.8 and 1.1%. For the two lower EZs, there is congruence between the results. Comparison of results for EZ3 is hampered by the exclusion of high elevation areas (everything above 1500 m asl) in Stumpf et al. (2018). These are mostly summer pasture areas that represent 9% percent of the total agricultural area and are thus an important part of EZ3 in our study.

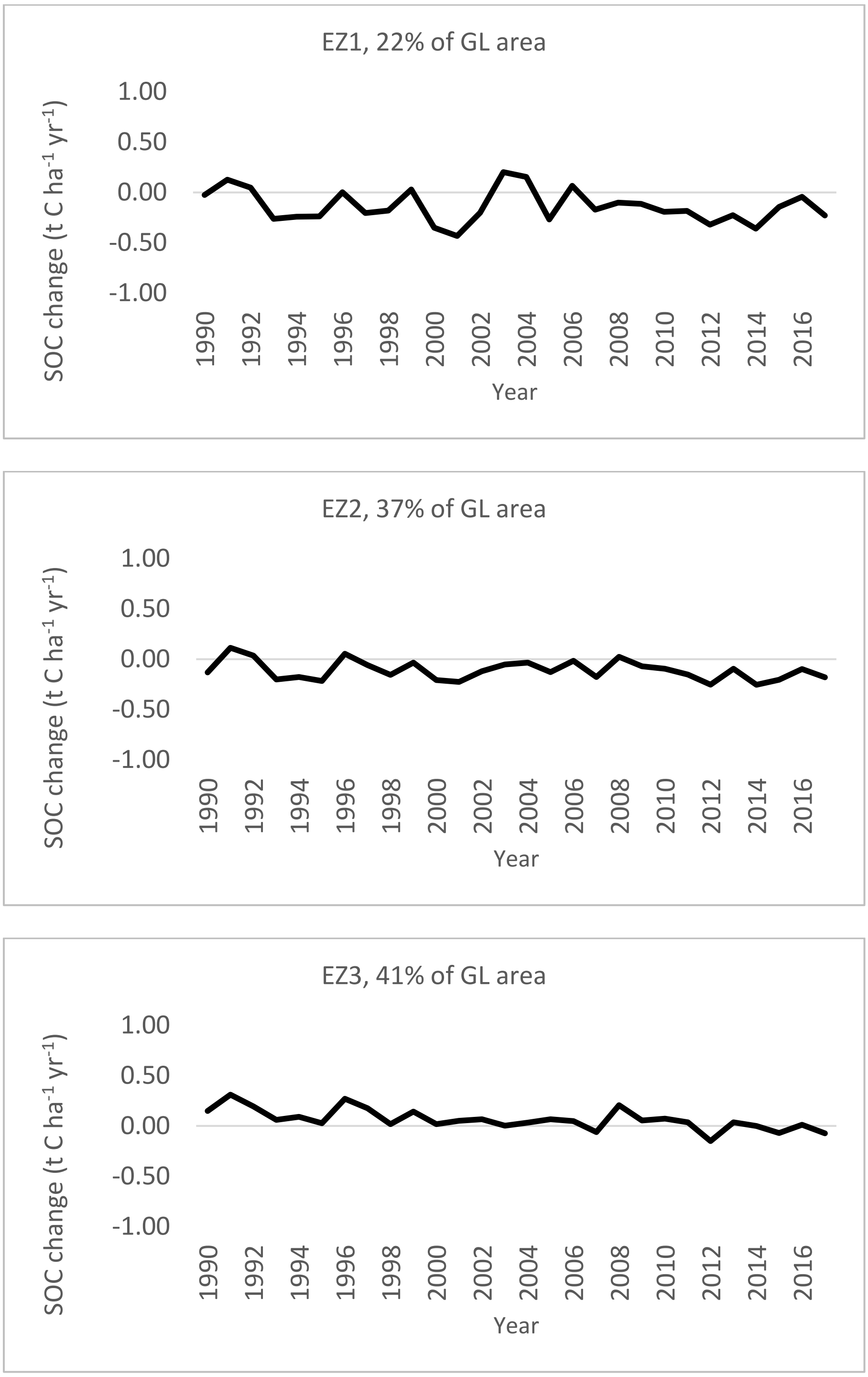


Figure 55 Annual SOC stock changes (0-30 cm) for GL for three EZs.

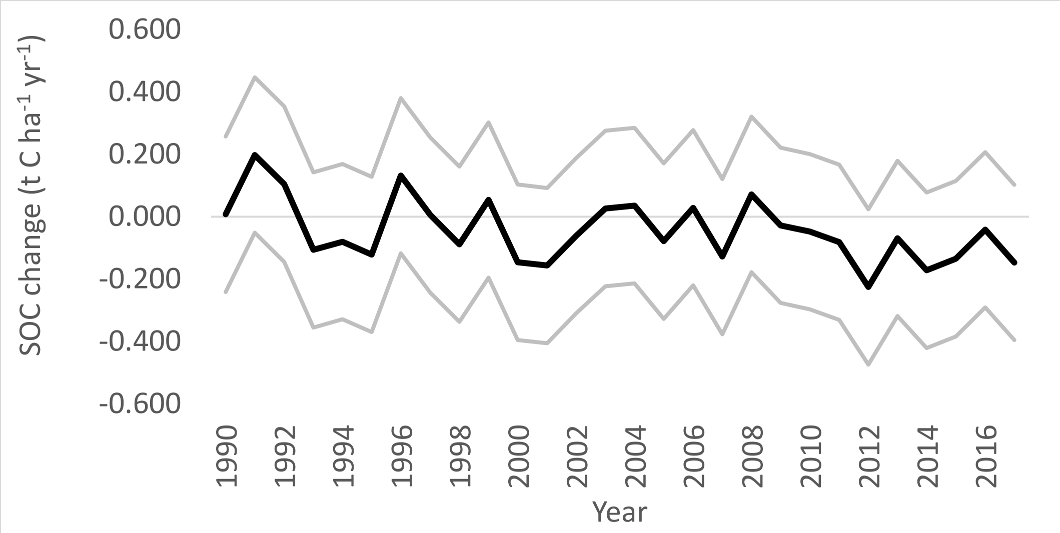


Figure 56 Annual SOC stock changes (0-30 cm) for GL soils calculated using weighted average results from three EZs.

4.3 Ideas for improvement

The model-based SOC carbon inventory described in this report has been developed as a flexible system, allowing the incorporation of improvements in the future, suggestions of which are listed in this section. It should be emphasised that this collation of ideas is not a list of planned improvements for the near future.

<u>OrgAm application</u>
There are several components of the OrgAm model that could be improved. Firstly, the OrgAm-model currently does not account for imports or exports of OrgAm into or out of the country; incorporating these would improve the accuracy of the OrgAm-model. The importance of this improvement is however unknown, because information on manure and slurry imports and exports are not held centrally, but rather with the individual cantons, which would need to be contacted individually.
Secondly, the OrgAm-model currently treats the OrgAm production as a national 'pool', which is distributed according to farmers' behaviour and according to crop requirements. It does not account for the spatial production of OrgAm and its physical movement, although we know that some regions of the country are particularly important for animal husbandry and others less so, meaning it is likely that OrgAm is transferred between farms. The movement of OrgAm between farms is recorded in the 'HODUFLU' database of the FOAG[20] meaning that information on the OrgAm movement between is available. 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 and OrgAm trading 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.
Thirdly, the OrgAm-model assumes that a) all straw produced in Switzerland is used for animal bedding and that b) animal bedding (in farms) comes solely from straw. Both these assumptions need to be investigated. There exist companies in Switzerland selling bedding material composed of other materials (most frequently wood but also linen, cannabis and paper), indicating the latter assumption is possibly not upheld. However, it is unclear how much of these bedding materials are sold to farmers. If the amounts were high, accounting for additional bedding material would be a worthwhile improvement to the OrgAm-model.
Fourthly, the estimate of OrgAm-C storage losses is quite simplistic, especially because information on the duration of storage is uncertain and assumed to be constant for a given OrgAm type. In reality

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

however, application of OrgAm 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 will vary between farms and seasons. This variation is particularly problematic because i) the rate of OrgAm-C loss as a function of time is not linear and ii) OrgAm-C storage loss is important for the OrgAm-C application rates in general. An improvement to the OrgAm-model would therefore be to create a more complex model of OrgAm-C loss, accounting for irregular duration of OrgAm storage throughout the year.
Fifthly, the grazing duration on summer pastures is assumed to have been constant since 1990. This should be checked and if a systematic pattern is found, corrected accordingly. This would represent an improvement to the OrgAm model because a shift in the amount of OrgAm-C moving to the mountains would change how much OrgAm-C is exposed to different meteorological conditions, altering decomposition rates of SOC and C inputs.
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. A sensitivity analysis could be performed with varying C pool distributions to test how different compositions affect SOC trends and if deemed necessary, an improvement to the project would be to incorporate any differences in pool distributions into the model.

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, it resulted in satisfactory model-data agreement, though this was based on few data available from long-term experiments. Nonetheless, it needs to be assessed how the variation in plant biomass input varies across elevation or management-intensity gradients, with and without ploughing (if at all). Data gaps need to be identified and field experiments carried out to fill them.

Strata
Currently, the strata system is a combination of (four) AZs and (six) adapted NFI regions. An alternative strata system (twelve climate regions x four AZs) was tested but not used (see end of section 2.2.1.1). The comparison of both strata systems identified that the strata system including the climate regions was better able to explain the variation in PPN. The importance of PPN in the simulation of SOC was at the time unknown. The UA however demonstrated that PPN is very important for SOC stock changes in strata prone to summer drought, most importantly those in the valley zone. This indicates that it might be prudent to incorporate the climate regions into the strata system, either by replacing the current strata system with one combining the (four) AZs and the (twelve) climate regions, or, by incorporating the climate regions in strata where PPN gradients are large. Indeed, the valley zone contains one very large stratum, the central plateau, where CL is concentrated, across which there are large PPN gradients especially during the summertime (during which there are also droughts), when PPN levels most strongly affect SOC stock change. It should be investigated to what extent the climate regions are able to account for the variation in PPN in this stratum and if necessary, sub-divide the central plateau stratum accordingly.

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. 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) needs to be investigated. Generally, this issue is more critical for crops, as C inputs are distributed irregularly, whereas in the case of GL, C inputs are distributed evenly throughout the year. We plan to analyse the sensitivity of our system to these assumptions in more detail.

5 Quality control

5.1 Transparency

The aim of this report, available from the Federal Office for the Environment[21] or Agroscope[22] websites, is to document the steps taken for the modelling of SOC stocks and stock changes in Swiss agricultural, mineral soils for the GHGI. It thus contains information necessary for the evaluation of the model-based inventory under the UNFCCC. As an unpublished internal report, it can be updated as appropriate. It describes the data sets, the derivation of input data, the initialisation and running of RothC as applied to this project, and the up-scaling of the outputs to the national scale. The data sets or information sources used are listed in section 2.1, with reference to where they were obtained from. In most cases, these data sets remain property of individual organisations (e.g. cantons, research organisations) and / or must be obtained from these organisations. The methodology described in section 2.2.6 describes the initialisation and running of RothC as applied to this project. Section 2.2.8 describes how the results were up-scaled to the national scale. The assumptions used throughout, especially in the derivation of input data and in the up-scaling to the national scale are described in the appropriate sections.

5.2 Consistency

Almost all input data or information sources are consistent through time, meaning that the same data source was used in 1990 as for the most recent year. Exceptions to this are: the estimate of proportion of OrgAm spread on crops or grassland, which was estimated by experts for the years 1990 and 1995, and obtained by a postal survey for the years 2000, 2005, 2010, 2015 (section 2.2.5.3); the estimate of animals (and thus OrgAm) moving to the summer pastures, where survey data was used post-1999 and an average of later years (1999-2016) was used for earlier years (section 2.2.5.3); and information regarding the usage of cover crops, which was consistent though time but whose applicability for earlier years is uncertain section 2.2.5.4).
As far as possible, the input data are consistent with the Agriculture Sector and the Biomass part of LULUCF of the Swiss GHGI. More specifically, these include: Herd sizes, rate of OrgAm-C production by animals, the (net) loss of OrgAm-C to biogas plants, the surface of summer pastures as used for the calculation of OrgAm-C application, crop yields and crop surfaces.

5.3 Comparability

The few other countries that employ a model-based (tier 3) approach use models of similar complexity as RothC (e.g. Sweden, Canada, Denmark). Regarding the use of discrete regions for up-scaling, our approach is also similar to the approach used in other countries (e.g. Canada, Japan).

5.4 Completeness

CL and GL from the whole country is included for the whole period (1990 to present).

5.5 Accuracy

The majority of data sets used in this project are published or are available publically as 'finished' products, implying that they are of sufficient quality for use as input data for the GHG inventory. Data

[21] https://www.bafu.admin.ch/bafu/en/home/topics/climate/state/data/climate-reporting/references.html
[22] https://www.agroscope.admin.ch/agroscope/de/home/themen/umwelt-ressourcen/klima-lufthygiene/co2-und-treibhausgase-in-landwirtschaftlichen-Boeden/inventar-bodenkohlenstoff.html

were obtained from different types of sources: i) census information, deemed to be complete (or 99 % so); ii) established monitoring networks; iii) surveys, e.g. Agrammon postal survey, where it was attempted to obtain a non-biased representation of farming; or iv) published data. An exception to this are the soil parameters required for modelling (SOC content, clay content), for which there are no appropriate data. Two current projects[17 and 23] however aim to remedy this using a digital soil modelling approach.
Comparison with data from the Swiss monitoring network shows that the model does not consistently over- or underestimate SOC on cropland (Figure 49).

[23] Project: Technical and methodological basis for the digital mapping of soil properties ("Technische und methodische Grundlagen für die digitale Kartierung von Bodeneigenschaften").

6 Acknowledgements

We would like to acknowledge the following people or organisations for providing us with data or helping with data processing: Daniel Bretscher for providing data used in the Agriculture sector of the GHG inventory, Annelie Holzkämper for processing of meteorological data, Pierluigi Calanca for derivation of ET estimates, Thomas Kupper and the Agrammon project for data regarding manure management and manure application, Andreas Gubler for providing soil data from NABO sites, the NABODAT team for providing soil data from several cantons and the AEI team for providing data and discussion. We would additionally like to thank Daniel Bretscher, Pierluigi Calanca and Christoph Ammann for numerous discussions relating to this project, as well as Andreas Schellenberger for continual support. Lastly, we would like to thank Thibault Moulin for help with the translation of the summary into French.

7 References

Aeby, P, A Burri, M Clerc, et al. (1995) Ackerbau. Zollikofen, Switzerland: Landwirtschaftliche Lehrmittelzentrale.

Ammann, C, CR Flechard, J Leifeld, A Neftel and J Fuhrer (2007) The carbon budget of newly established temperate grassland depends on management intensity. Agriculture, Ecosystems and Environment **121**: 5-20.

Ammann, C, C Spirig, J Leifeld and A Neftel (2009) Assessment of the nitrogen and carbon budget of two managed temperate grassland fields. Agriculture, Ecosystems and Environment **133**: 150-162.

Andrén, O, T Kätterer and T Karlsson (2004) ICBM regional model for estimations of dynamics of agricultural soil carbon pools. Nutrient Cycling in Agroecosystems **70**(2): 231-239.

Bolinder, MA, O Andrén, T Kätterer, et al. (2007) Soil carbon dynamics in Canadian Agricultural Ecoregions: Quantifying climatic influence on soil biological activity. Agriculture, Ecosystems and Environment **122**(4): 461-470.

Bolinder, MA, T Kätterer, C Poeplau, G Börjesson and LE Parent (2015) Net primary productivity and below-ground crop residue inputs for root crops: Potato (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* L.). Canadian Journal of Soil Science **95**(2): 87-93.

Bretscher, D and T Kupper (2012) Categorization of livestock animals in Switzerland. Zurich, Switzerland, internal report: Agroscope Reckenholz-Tänikon Research Station ART, pp 20.

Bretscher, D and J Leifeld (2008) Uncertainty of agricultural CH_4 and N_2O emissions in Switzerland. Zurich, Switzerland, internal report: Agroscope Reckenholz-Tänikon Research Station ART, pp 22.

Calanca, P, P Smith, A Holzkämper and C Ammann (2011) Die Referenzverdunstung und ihre Anwendung in der Agrarmeteorologie. Agrarforschung Schweiz **2**(4): 176–183.

Canarini, A, LP Kiær and FA Dijkstra (2017) Soil carbon loss regulated by drought intensity and available substrate: A meta-analysis. Soil Biology and Biochemistry **112**: 90-99.

Carsel, RF and RS Parrish (1988) Developing joint probabilities of soil water retention characteristics. Water Resources Research **24**(5): 755-769.

Chadwick, DR (2005) Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. Atmospheric Environment **39**(4): 787-799.

Ciais, P, C Sabine, G Bala, et al. (2013) Carbon and other biogeochemical cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. TF Stocker, D Qin, G-K Plattner et al. (Eds.) Cambridge, UK and New York, USA: Cambridge University Press.

Coleman, K and DS Jenkinson (2008) A model for the turnover of carbon in soil. Model description and windows users guide. Harpenden, UK: Rothamsted Research, pp 44.

Coleman, K, DS Jenkinson, GJ Crocker, et al. (1997) Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. Geoderma **81**(1-2): 29-44.

Emmel, C, A Winkler, L Hörtnagl, et al. (2018) Integrated management of a Swiss cropland is not sufficient to preserve its soil carbon pool in the long term. Biogeosciences **15**(17): 5377-5393.

Falloon, P, P Smith, K Coleman and S Marshall (1998) Estimating the size of the inert organic matter pool from total soil organic carbon content for use in the Rothamsted carbon model. Soil Biology and Biochemistry **30**(8–9): 1207-1211.

Fließbach, A, H-R Oberholzer, L Gunst and P Mäder (2007) Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agriculture, Ecosystems and Environment **118**(1-4): 273-284.

Flisch, R, S Sinaj, R Charles and W Richner (2009) Grundlagen für die Düngung im Acker- und Futterbau. Agrarforschung Schweiz **16**(2): 1-97.

Flückiger, E, S Dubach, R Elmer, et al. (2008) Futterbau und Futterkonservierung. Zollikofen, Switzerland: Landwirtschaftliche Lehrmittelzentrale.

FOEN (2018) Switzerland’s greenhouse gas inventory 1990–2016: National inventory report 2018. Bern, Switzerland: Federal Office for the Environment, pp 643.

--- (2019) Switzerland's greenhouse gas inventory 1990–2017: National inventory report 2019. Bern, Switzerland: Federal Office for the Environment, pp 632.

Franko, U, H Kolbe, E Thiel and E Ließ (2011) Multi-site validation of a soil organic matter model for arable fields based on generally available input data. Geoderma **166**(1): 119-134.

FSO (2000) Digitale Bodeneignungskarte der Schweiz; 1:200,000. Neuchâtel, Switzerland: Federal Statistical Office.

Gan, YT, CA Campbell, HH Janzen, RL Lemke, P Basnyat and CL McDonald (2009) Carbon input to soil from oilseed and pulse crops on the Canadian prairies. Agriculture, Ecosystems & Environment **132**(3-4): 290-297.

Gottschalk, P, JU Smith, M Wattenbach, et al. (2012) How will organic carbon stocks in mineral soils evolve under future climate? Global projections using RothC for a range of climate change scenarios. Biogeosciences **9**(8): 3151-3171.

Gubler, A, D Wächter, P Schwab, M Müller and A Keller (2019) Twenty-five years of observations of soil organic carbon in Swiss croplands showing stability overall but with some divergent trends. Environmental Monitoring and Assessment **191**(5): 277.

Häberli, R (1980) Bodeneignungskarte der Schweiz. Bern, Switzerland: Swiss Office for Spatial Development / Federal Office for Agriculture / Federal Office for Forestry.

Hao, X, C Chang and FJ Larney (2004) Carbon, nitrogen balances and gas emission during cattle feedlot manure composting. Journal of Environmental Quality **33**(1): 37-44.

Hermle, S, T Anken, J Leifeld and P Weisskopf (2008) The effect of the tillage system on soil organic carbon content under moist, cold-temperate conditions. Soil & Tillage Research **98**(1): 94-105.

Herzog, F, B Oehen, M Raaflaub and E Szerencsits (2003) Warum es die Alpwirtschaft nicht gibt: Versuch einer Beschreibung. In: Zukunft der Schweizer Alpwirtschaft. S Lauber, F Herzog, I Seidl et al. (Eds.) Zurich, Switzerland: Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf / Forschungsanstalt Agroscope Rechenholz-Tänikon: 19-35.

Hirte, J, J Leifeld, S Abiven, H-R Oberholzer and J Mayer (2018) Below ground carbon inputs to soil via root biomass and rhizodeposition of field-grown maize and wheat at harvest are independent of net primary productivity. Agriculture Ecosystems and Environment **265**: 556-566.

Holzkämper, A, D Fossati, J Hiltbrunner and J Fuhrer (2015) Spatial and temporal trends in agroclimatic limitations to production potentials for grain maize and winter wheat in Switzerland. Regional Environmental Change **15**(1): 109-122.

IPCC (2006a) 2006 IPCC guidelines for national greenhouse gas inventories. Volume 1, chapter 3. Uncertainties. HS Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (Eds.) Japan: Institude for Global Environmental Strategies IGES.

--- (2006b) 2006 IPCC guidelines for national greenhouse gas inventories. Volume 4, chapter 10. Emissions from livestock and manure management. HS Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (Eds.) Japan: Institute for Global Environmental Strategies IGES.

--- (2006c) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4, chapter 11. N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. HS Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (Eds.) Japan: Institute for Global Environmental Strategies IGES.

Jackson, RB, J Canadell, JR Ehleringer, HA Mooney, OE Sala and ED Schulze (1996) A global analysis of root distributions for terrestrial biomes. Oecologia **108**(3): 389-411.

Jacobs, A, H Flessa, A Don, et al. (2018) Landwirtschaftlich genutzte Böden in Deutschland – Ergebnisse der Bodenzustandserhebung. Braunschweig, Germany: Johann Heinrich von Thünen-Institut, pp 316.

Jenkinson, DS, SPS Andrew, JM Lynch, et al. (1990) The turnover of organic carbon and nitrogen in soil. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences **329**(1255): 361-368.

Keel, SG, T Anken, L Büchi, et al. (2019) Loss of soil organic carbon in Swiss long-term agricultural experiments over a wide range of management practices. Agriculture, Ecosystems and Environment **286**: 106654.

Keel, SG, J Leifeld, J Mayer, A Taghizadeh-Toosi and JE Olesen (2017) Large uncertainty in soil carbon modelling related to method of calculation of plant carbon input in agricultural systems. European Journal of Soil Science **68**(6): 953-963.

Keller, A, J Franzen, P Knüsel, A Papritz and M Zürrer (2018) Bodeninformations-Plattform Schweiz (BIP-CH). Thematische Synthese TS4 des Nationalen Forschungsprogramms «Nachhaltige Nutzung der Ressource Boden» (nfp 68). Bern, Switzerland: Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung, pp 124.

Klossner, M, T Kupper and H Menzi (2014) Historische Entwicklung der Ammoniakemissionen aus der Schweizer Landwirtschaft von 1866 bis 2010. Zollikofen, Switzerland: Hochschule für Agrar-, Forst- und Lebensmittelwissenschaften HAFL, pp 85.

Köck, K, J Leifeld and J Fuhrer (2013) A model-based inventory of sinks and sources of CO_2 in agricultural soils in Switzerland: Development of a concept. Zurich, Switzerland: Forschungsanstalt Agroscope, pp 189.

Kupper, T, C Bonjour, B Achermann, B Rihm, F Zaucker and H Menzi (2013) Ammoniakemissionen in der Schweiz 1990-2010 und Prognose bis 2020. Zollikofen, Switzerland: Hochschule für Agrar-, Forst- und Lebensmittelwissenschaften.

Kupper, T, C Bonjour, H Menzi, D Bretscher and F Zaucker (2018) Ammoniakemissionen der schweizerischen Landwirtschaft 1990-2015. Zollikofen, Switzerland: Hochschule für Agrar-, Forst- und Lebensmittelwissenschaften.

Larney, FJ, AF Olson, PR DeMaere, BP Handerek and BC Tovell (2008) Nutrient and trace element changes during manure composting at four southern Alberta feedlots. Canadian Journal of Soil Science **88**(1): 45-59.

Leifeld, J, C Ammann, A Neftel and J Fuhrer (2011) A comparison of repeated soil inventory and carbon flux budget to detect soil carbon stock changes after conversion from cropland to grasslands. Global Change Biology **17**(11): 3366-3375.

Leifeld, J, S Bassin and J Fuhrer (2003) Carbon stocks and carbon sequestration potentials in agricultural soils in Switzerland. Schriftenreihe der FAL **44**: 1-109.

--- (2005) Carbon stocks in Swiss agricultural soils predicted by land-use, soil characteristics, and altitude. Agriculture, Ecosystems and Environment **105**: 255-266.

Leinweber, P, H-R Schulten and M Körschens (1994) Seasonal variations of soil organic matter in a long-term agricultural experiment. Plant and Soil **160**(2): 225-235.

Liebisch, F, EK Buenemann, O Huguenin-Elie, B Jeangros, E Frossard and A Oberson (2013) Plant phosphorus nutrition indicators evaluated in agricultural grasslands managed at different intensities. European Journal of Agronomy **44**: 67-77.

Liski, J, T Palosuo, M Peltoniemi and R Sievänen (2005) Carbon and decomposition model Yasso for forest soils. Ecological Modelling **189**(1-2): 168-182.

Mäder, P, A Fließbach, D Dubois, L Gunst, P Fried and U Niggli (2002) Soil fertility and biodiversity in organic farming. Science **296**(5573): 1694-1697.

Maltas, A, H Kebli, HR Oberholzer, P Weisskopf and S Sinaj (2018) The effects of organic and mineral fertilizers on carbon sequestration, soil properties, and crop yields from a long-term field experiment under a Swiss conventional farming system. Land Degradation & Development **29**(4): 926-938.

Mayer, J, F Buegger, ES Jensen, M Schloter and J Heß (2003) Estimating N rhizodeposition of grain legumes using a ^{15}N in situ stem labelling method. Soil Biology and Biochemistry **35**(1): 21-28.

McMurray, A, T Pearson and F Casarim (2017) Guidance on applying the Monte Carlo approach to uncertainty analyses in forestry and greenhouse gas accounting. Arkansas / Virginia, USA: Winrock International, pp 26.

MeteoSwiss (2011) MeteoSwiss grid-data products: Documentation for users. Zurich, Switzerland: Federal Office of Meteorology and Climatology: unpublished, pp 4.

--- (2013) Daily precipitation (final analysis): RhiresD. Zurich, Switzerland: Federal Office of Meteorology and Climatology: unpublished, pp 4.

--- (2017) Daily mean,minimum and maximum temperature: TabsD, TminD, TmaxD. Zurich, Switzerland: Federal Office of Meteorology and Climatology: unpublished, pp 4.

--- (2018) Daily, monthly and yearly satellite-based global radiation. Zurich, Switzerland: Federal Office of Meteorology and Climatology: unpublished, pp 3.

Møller, HB, SG Sommer and BK Ahring (2004) Biological degradation and greenhouse gas emissions during pre-storage of liquid animal manure. Journal of Environmental Quality **33**(1): 27-36.

Müller, G (1980) Die Beobachtungsnetze der Schweizerischen Meterologischen Anstalt Konzept 1980. Zurich, Switzerland: Swiss Meteorological Institute, pp 66.

Nemecek, T, O Huguenin-Elie, D Dubois and G Gaillard (2005) Ökobilanzierung von Anbausystemen im schweizerischen Acker- und Futterbau. Zurich, Switzerland: Agroscope FAL Reckenholz, pp 245.

Oberholzer, HR, J Leifeld and J Mayer (2014) Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science **177**(5): 696-704.

Patni, NK and PY Jui (1987) Changes in solids and carbon content of dairy-cattle slurry in farm tanks. Biological Wastes **20**(1): 11-34.

Penn, C, J Vitale, S Fine, et al. (2011) Alternative poultry litter storage for improved transportation and use as a soil amendment. Journal of Environmental Quality **40**: 233-241.

Penttilä, A, EM Slade, A Simojoki, T Riutta, K Minkkinen and T Roslin (2013) Quantifying beetle-mediated effects on gas fluxes from dung pats. PLOS ONE **8**(8): e71454.

Petersen, BM, JE Olesen and T Heidmann (2002) A flexible tool for simulation of soil carbon turnover. Ecological Modelling **151**(1): 1-14.

Posselt, R, RW Mueller, R Stöckli and J Trentmann (2012) Remote sensing of solar surface radiation for climate monitoring — the CM-SAF retrieval in international comparison. Remote Sensing of Environment **118**: 186-198.

Priestley, CHB and RJ Taylor (1972) On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review **100**: 81-82.

Rehbein, K, U Grob, L Klauser, J Franzen and A Keller (2017) Bodendatensatz Schweiz – Dokumentation Version 2 (Mai 2017). Zurich, Switzerland: Agroscope, Servicestelle NABODAT.

Richner, W and S Sinaj (2017) Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD). Agrarforschung Schweiz **8**(6): Special publication. 276 pp.

Riley, WJ, F Maggi, M Kleber, et al. (2014) Long residence times of rapidly decomposable soil organic matter: application of a multi-phase, multi-component, and vertically resolved model (BAMS1) to soil carbon dynamics. Geoscientific Model Development **7**(4): 1335-1355.

Sägesser, H and P Weber (1992) Allgemeiner Pflanzenbau. Zollikofen, Switzerland: Landwirtschaftliche Lehrmittelzentrale.

Schüepp, M and G Gensler (1980) Klimaregionen der Schweiz. In: Die Beobachtungsnetze der Schweizerischen Meteorologischen Anstalt. Konzept 1980. Arbeitsberichte der Schweizerischen Meteorologischen Anstalt, Nr. 93, Anhang Ib. G Müller (Eds.) Zürich, Switzerland: Swiss Meteorological Institute.

Sierra, CA, M Mueller and SE Trumbore (2012) Models of soil organic matter decomposition: the SoilR package, version 1.0. Geoscientific Model Development **5**(4): 1045-1060.

Sommer, SG (2001) Effect of composting on nutrient loss and nitrogen availability of cattle deep litter. European Journal of Agronomy **14**(2): 123-133.

Sommer, SG and P Dahl (1999) Nutrient and carbon balance during the composting of deep litter. Journal of Agricultural Engineering Research **74**(2): 145-153.

Stumpf, F, A Keller, K Schmidt, A Mayr, A Gubler and M Schaepman (2018) Spatio-temporal land use dynamics and soil organic carbon in Swiss agroecosystems. Agriculture, Ecosystems and Environment **258**: 129-142.

Sulman, BN, JAM Moore, R Abramoff, et al. (2018) Multiple models and experiments underscore large uncertainty in soil carbon dynamics. Biogeochemistry **141**(2): 109-123.

Taghizadeh-Toosi, A, BT Christensen, NJ Hutchings, et al. (2014) C-TOOL: A simple model for simulating whole-profile carbon storage in temperate agricultural soils. Ecological Modelling **292**: 11-25.

Taylor, KE (2001) Summarizing multiple aspects of model performance in a single diagram. Journal of Geophysical Research Atmospheres **106**(D7): 7183-7192.

Thomet, P and B Koch (1993) Längerfristige Auswirkungen von Düngung und Schnittregime auf eine Heumatte. Landwirtschaft Schweiz **6**(2): 107-114.

Tiquia, SM, TL Richard and MS Honeyman (2002) Carbon, nutrient, and mass loss during composting. Nutrient Cycling in Agroecosystems **62**(1): 15-24.

Tuomi, M, R Laiho, A Repo and J Liski (2011a) Wood decomposition model for boreal forests. Ecological Modelling **222**(3): 709-718.

Tuomi, M, J Rasinmäki, A Repo, P Vanhala and J Liski (2011b) Soil carbon model Yasso07 graphical user interface. Environmental Modelling & Software **26**(11): 1358-1362.

Tuomi, M, T Thum, H Järvinen, et al. (2009) Leaf litter decomposition-estimates of global variability based on Yasso07 model. Ecological Modelling **220**(23): 3362-3371.

USDA (2008) Agricultural Waste Management Field Handbook. Chapter 4: Agricultural Waste Characteristics. Washington D.C, USA: U.S. Department of Agriculture, pp 32.

Vullioud, P (2005) Optimale Fruchtfolgen im Feldbau (3. Auflage). Agrarforschung **12**(7): pp 3.

Walther, U, P Weisskopf, H-R Oberholzer and K Knecht (2001) 50 Jahre organische und mineralische Düngung: Humusgehalte, N-Ausnutzung und N-Bilanzen. Archiv für Acker- und Pflanzenbau und Bodenkunde **46**: 265-280.

Warren, J, C Penn, J McGrath and K Sistani (2008) The impact of alum addition on organic P transformations in poultry litter and litter-amended soil. Journal of Environmental Quality **37**: 469-476.

Weihermüller, L, A Graf, M Herbst and H Vereecken (2013) Simple pedotransfer functions to initialize reactive carbon pools of the RothC model. European Journal of Soil Science **64**(5): 567-575.

Wichern, F, J Mayer, RG Joergensen and T Müller (2007) Rhizodeposition of C and N in peas and oats after ^{13}C-^{15}N double labelling under field conditions. Soil Biology and Biochemistry **39**(10): 2527-2537.

Wieder, WR, AS Grandy, CM Kallenbach and GB Bonan (2014) Integrating microbial physiology and physio-chemical principles in soils with the MIcrobial-MIneral Carbon Stabilization (MIMICS) model. Biogeosciences **11**(14): 3899-3917.

Wiesmeier, M, R Hübner, R Dechow, et al. (2014) Estimation of past and recent carbon input by crops into agricultural soils of southeast Germany. European Journal of Agronomy **61**: 10-23.

Wood, JD, G R.J., C Wagner-Riddle, KE Dunfield and M A. (2012) Relationships between dairy slurry total solids, gas emissions, and surface crusts. Journal of Environmental Quality **41**(3): 694-704.