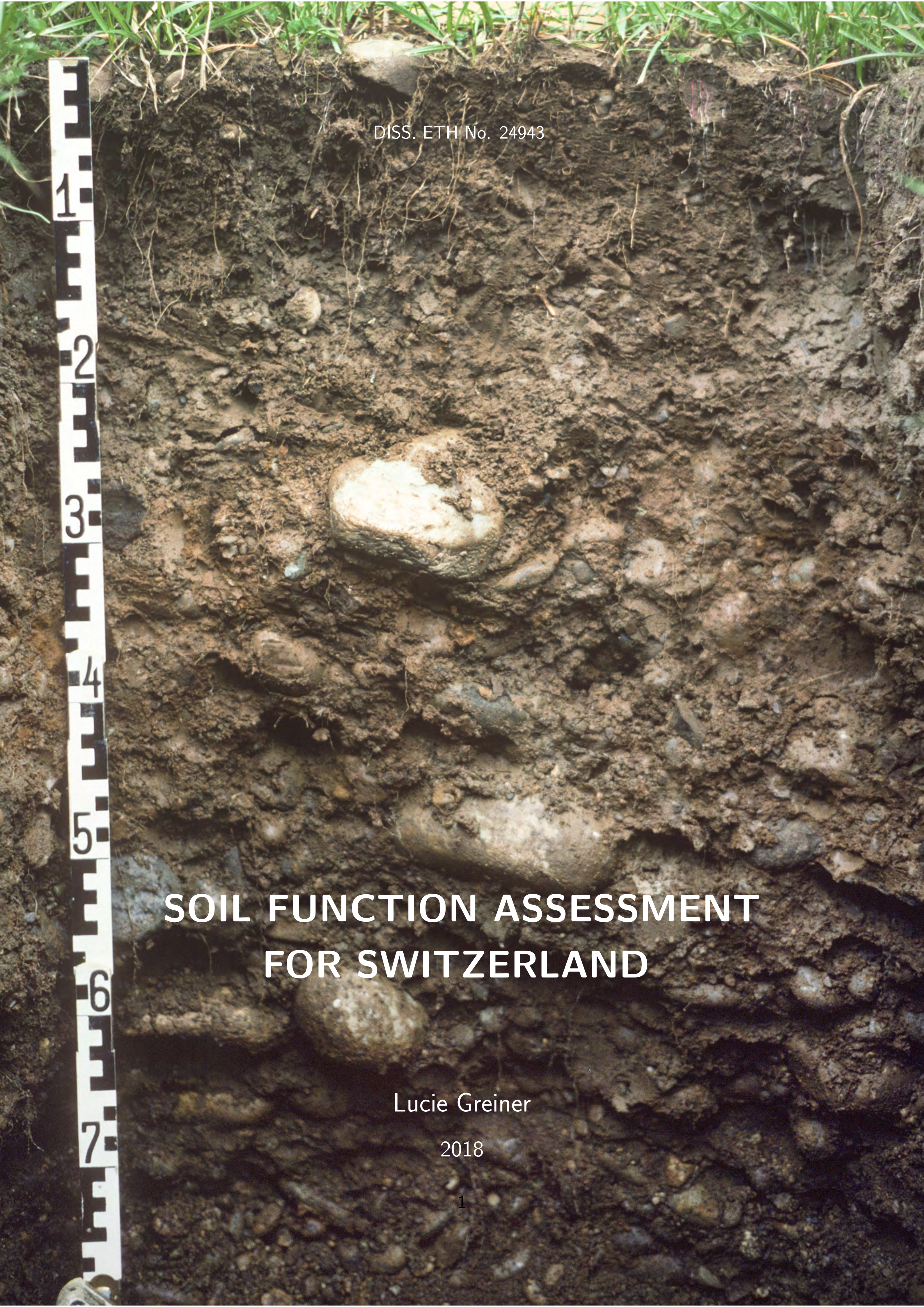

DISS. ETH No. 24943

SOIL FUNCTION ASSESSMENT FOR SWITZERLAND

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2018

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A thesis submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZURICH

(Dr. sc. ETH Zurich)

presented by

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2018

Cover: Peter Schwab (soil profile and photography). Parabraunerde. 08.02.1989

Contents

Abstract

Soil provides functions that support life and are essential to human society and the environment. For instance, soil regulates water and nutrient cycles, sequesters carbon, prevents contaminants leaching into groundwater, buffers acidic inputs, contributes to biodiversity by providing a habitat for organisms, and supports biomass production. The ecosystem service (ES) concept is widely used to evaluate the values of natural resources and allows them to be included in decision-making processes. Up to now, however, little account has been taken of soil in any ES assessments. ES mapping studies that included soil in their foci were reviewed in this thesis. About 60% of these studies used at least one soil property as an indicator of soil-related ESs and more than two soil functions were considered in a minority of studies. Better integration of soil into ESs requires tools that are effective and readily applicable.

In this thesis, a set of operational soil function assessment (SFA) methods is proposed. This set of SFA methods is intended to act as a starting point to allow the ways soil systems underpin a wide range of ESs to be quantified. The work described in this thesis was part of two projects in Swiss National Research Programme (NRP) 68 "Sustainable use of soil as a resource", namely PMSoil and OPSOL. The PMSoil project was focused on digital soil mapping (DSM) approaches and provided spatial information on soil properties, and the aim of the OPSOL project was to develop a land-use decision model for use in spatial planning processes.

10 SFA methods were selected from various national and international methods. The methods were adapted and used in a study of an agricultural area on the Swiss Plateau. Soil property maps for four soil depths were available for the study area. These were produced using digital soil mapping techniques and each had a raster resolution of 20 m. Pedotransfer functions were used to derive secondary soil properties from the results of previous studies performed by this and other research groups. The resulting maps for the 10 soil functions revealed distinctive spatial patterns for most of the regulation, habitat, and production functions, clearly indicating the multiple roles in which soils support ESs. These soil functions are linked to the inherent properties of the soils, the terrain, and climate conditions. Assessment of how reasonable the soil function maps were was undertaken by comparing soil function fulfilment with the soil type, land use, and hydromorphic features of the soil for more than 7000 soil profiles.

It was concluded that a quite comprehensive set of soil functions that can be used to assess the multi-functionality of soils can be determined using a relatively small number of basic properties of soil to at least 1 m deep. The soil function maps indicated spatial variability in soil function fulfilment and were easy for stakeholders to understand because they were presented using a simple ordinal assessment scale. These maps could improve awareness of the multi-functionality of soil and allow visualization

of the ways soil systems underpin the supply of ESs. SFA methods for production function are already well established, but methods for assessing habitat and regulation functions need to be developed further. Four different approaches to aggregating soil functions to give a total assessment value (a soil index) were tested. The soil index maps had quite different spatial patterns, indicating that merging soil functions can average out spatial variations in certain functions. It was concluded that soil function maps could be aggregated to provide single soil index maps. Stakeholders, though, should take into consideration the importance of each soil function.

Uncertainties in soil function maps are required to allow informed and transparent decisions to be made about the sustainable use of soil resources. In general, uncertainties in soil properties propagated using the SFA methods led to substantial uncertainties in the mapped soil functions. Two types of uncertainty map were proposed, each of which is easy for stakeholders to understand. The cumulative distribution functions for the soil function fulfilment scores indicated that the SFA methods responded differently to the propagated soil property uncertainties. Different methods may not be comparable in terms of uncertainty propagation even if the methods are comparable in terms of complexity and assessment scale.

This thesis contains an operational framework for assessing soil functions to facilitate the incorporation of SFA into decision-making, thereby highlighting the multiple functions of soils, which will enable the sustainable use of soil resources to be promoted during spatial planning.

Zusammenfassung

Der Boden erfüllt wichtige Funktionen für Mensch und Umwelt: unter anderem reguliert er Wasser- und Nährstoffkreislauf, sequestriert Kohlenstoff, verhindert die Versickerung von Schadstoffen ins Grundwasser, puffert saure Einträge, beherbergt eine enorme Vielfalt an Bodenorganismen und ist eine wichtige Grundlage für die Biomasseproduktion. Mit Hilfe des Ökosystemdienstleistungskonzepts (ÖSD-Konzept), welches breit angewandt wird, können natürlichen Resourcen Werte zugeschrieben und diese Werte effektiv in Entscheidungsprozesse eingebracht werden. Boden als natürliche Ressource wurde aber bis anhin bei der Anwendung des ÖSD-Konzept wenig miteinbezogen. Wir haben in bestehenden ÖSD-Studien mit Bodenfokus recherchiert: 60% der Studien benutzten bloss eine Bodeneigenschaft als Indikator für den Beitrag des Bodens zu ÖSD und nur eine Minderheit der Studien bewertet zwei oder mehrere Bodenfunktionen, welche zu ÖSD beitragen. Um Boden vermehrt in das ÖSD-Konzept integrieren zu können, braucht es einfach anwendbare Methoden zur Bewertung von Bodenfunktionen.

Im Rahmen dieser Arbeit schlagen wird eine Zusammenstellung von Methoden zur Bodenfunktionsbewertung (BFB) vorgeschlagen, welche es erlauben, den multifunktionalen Beitrag des Bodens zu ÖSD in vereinfachter Weise zu quantifizieren. Die in dieser Arbeit präsentierten Resultate wurden als Teil von zwei Projekten des Nationalen Forschungsprogramms (NFP) 68 "Nachhaltige Nutzung der Resource Boden" erarbeitet. Das Projekt PMSoil erstellte mittels digitaler Bodenkartierung Bodeneigenschaftskarten und das Projekt OPSOL erarbeitete ein Landnutzungsentscheidmodell für Raumplanungsfragen.

10 BFB-Methoden wurden aus verschiedenen nationalen und internationalen Quellen ausgewählt, adaptiert und auf ein landwirtschaftliches Studiengebiet im Schweizer Mittelland angewendet. Für die Anwendung der BFB-Methoden vewendeten wir von PMSoil für das Studiengebiet erstellte Bodeneigenschaftskarten für vier Tiefen und in einem Raster von 20 m und Pedotransferfunktionen aus der Literatur oder eigenen Studien. Die Erfüllung von Bodenfunktionen ist abhängig von räumlich heterogenen Bodeneigenschaften, Terrain- und Klimabedingungen, welche je Bodenfunktion unterschiedlich wichtig sind. Entsprechend zeigten die aus den BFB resultierenden Karten verschiedene räumliche Muster.

Die Plausibilität der Karten evaluierten wir anhand von Daten zu Bodentyp, Landnutzung und Wasserhaushaltseigenschaften von über 7000 Bodenprofilen. Mit einer relativ kleinen Anzahl an Bodeneigenschaften (mindestens bis zu 1 m Tiefe) kann bereits ein relativ grosser Umfang an Bodenfunktionen bewertet werden. Die entstandenen Bodenfunktionskarten zeigen die räumlich unterschiedlichen Kapazitäten des Bodens, verschiedene Bodenfunktionen zu erfüllen, in einer ordinalen Skala an. Solche Karten eignen sich zur Verwendung in Raumplanungsprozessen. Sie zeigen die vielfältigen Werte und Beiträge des Bodens zu ÖSD über die Darstellung seiner Multifunktionalität. Während BFB-Methoden zur Bewertung der Biomasseproduktion weitgehend etabliert

sind, zeigte sich, dass Methoden zur Regulierungs- und Habitatfunktion des Bodens weiterentwickelt werden müssen. Es wurden ausserdem vier Ansätze zur Erstellung einer Bodenindexkarte aus den Bodenfunktionskarten evaluiert. Die Bodenindexkarten zeigten für dasselbe Studiengebiet unterschiedliche oder sehr unterschiedlich prononcierte räumliche Muster. Wir schliessen daraus, dass das Aggregieren von Bodenfunktionskarten zu einer Bodenindexkarte mittels standortbezogener Gewichtung durch die relevanten Akteure erfolgen sollte.

Um Entscheidungsfindungen zur Bodennutzung in der Raumplanungen zu unterstützen, liegen idealerweise Unsicherheitsangaben zu den Bodenfunktionskarten vor. Das Integrieren der Unsicherheiten der Bodeneigenschaften durch in BFB zeigte, dass Bodenfunktionskarten trotz ordinaler Skalierung noch beträchtliche Unsicherheiten enthalten. Zur einfachen Kommunikation dieser Unsicherheiten schlagen wird zwei Arten von Karten vor. Zur Beschreibung der BFB-Methoden im Hinblick auf Unsicherheiten in den Eingangsdaten verwendeten wir kumulative Häufigkeitsverteilungen für unser Studiengebiet. Deren Vergleich zeigte, dass BFB-Methoden Unsicherheiten in unterschiedlichem Mass transportieren, auch wenn sie vergleichbar sind im Hinblick auf ihren Vereinfachungsgrad und die verwendete Bewertungsskala.

Diese Arbeit stellt einen operativen Rahmen zur BFB vor, welcher den Miteinbezug von Boden und Bodenfunktionen in ÖSD erleichtert, die vielfältigen Funktionen des Bodens betont und veranschaulicht und einen Beitrag leistet zur nachhaltigen Nutzung der Ressource Boden in Raumplanungsprozessen.

Acknowledgements

First of all, I would like to thank Armin Keller for his support and insights.

Many thanks to Adrienne Grêt-Regamey for hosting this thesis at her institute.

Many thanks to all (former) NABO-members for their support, advice, information, discussions, fun coffee breaks, lunch hours and ping pong: Michael Müller, Julia Franzen, Peter Schwab, Andreas Gubler, Dani Wächter, Anna Hug, Reto Meuli, Leta Klauser, Urs Grob, Kirsten Rehbein, Raniero Della Peruta, Felix Stumpf.

Also many thanks to all PMSoil and OPSOL project members, in particular to Madlene Nussbaum for support in many technical questions, Andreas Papritz for letting us work in a well-structured project, Stephan Zimmermann for conceptual and forest soil support, Thomas Drobnik for discussions on the interface between environmental resources and spatial planning.

Last but not least, I would like to thank family and friends for their support and incredible sense of humor.

List of Abbreviations

AAC	Available air capacity
AWC	Available water capacity
BS	Base saturation
cdf	Cumulative distribution function
CEC	Cation exchange capacity
DSM	Digital soil mapping
ES	Ecosystem service
PTF	Pedotransfer function
SFA	Soil function assessment
SFF	Soil function fulfillment
SHC	Saturated hydraulic conductivity
SOM	Soil organic matter
WSC	Water storage capacity

Chapter 1

Introduction

1.1 Background

Soil is a valuable resource that performs essential functions for humans and the environment and supports the provision of various ecosystem services (ESs). Land take is one of the most severe threats to soil, because sealed soil almost completely loses its ability to fulfil essential functions and support ESs (Breure et al., 2012). The urban area on the Swiss Plateau has increased by 25% since 1985, mostly at the expense of the most valuable agricultural soils (Altwegg 2015). Such development is a common problem in about 75% of European countries (EEA, 2017).

Bouma et al. (2012) presumed two main reasons for the unsustainable use of soil resources, 1) that we are barely aware of our dependence on soil functions and 2) that relevant actors do not generally have spatial information on soil states and the capacities of soils to fulfil various functions. The capacity of soil to fulfil various functions depends on the properties of the soil (Calzolari et al., 2016). Soil properties can vary spatially a great deal (FAO 2017). Soil function maps showing the capacities of soils to fulfil functions can address both reasons mentioned above for the unsustainable use of soil resources. Soil function maps improve our awareness of the capacities of soils and the spatial variability of these capacities (Bouma et al., 2012). Soil function maps are also easily understandable communication means that allow soil resources to be managed through spatial planning (Schulte et al., 2014), where many different interests have to be taken into account (Valujeva et al., 2016).

The soil function concept has been on the political agenda since soil functions were described in the European Commission soil protection strategy (EU, 2006). Lists of soil functions have been drawn up, and soil functions have been integrated into theoretical frameworks such as the ES concept (Bouma, 2010; Dominati et al., 2014; Haygarth and Ritz, 2009; Hewitt et al., 2015; Robinson et al., 2013). The ES concept assigns social and economic values to natural resources. Soil functions have also been integrated into the soil security concept proposed by Koch et al. (2013) and McBratney et al. (2014), in which soil is placed in the societal context in terms of food security, water security, climate stability, biodiversity, and other aspects of sustainability.

Soil function assessment (SFA) is the first stage of a comprehensive ES mapping exercise (Calzolari et al., 2016), and efforts have been made in several studies to move from theoretical frameworks to more operational approaches by statically assessing soil functions or developing soil function proxies (Dominati et al., 2014; Haslmayr et al., 2016; Makó et al., 2017; Schulte et al., 2014; Tóth et al., 2013). However, multiple soil functions have been assessed jointly at spatial scales relevant to spatial planning in only very few studies (Calzolari et al., 2016), and no overview of SFA methods suitable for communicating the values and functions of soils to non-soil scientists using soil function maps has been published. An assessment of soil functions needs to be accompanied by an assessment of the uncertainties involved (Vrebos et al., 2017). To the best knowledge of the author, uncertainties are indicated as standard when digital soil mapping (DSM) is performed (e.g., FAO, 2017a) but they have not yet been assessed where SFAs have been performed.

A SFA requires spatially explicit soil information, which can be provided by conventional soil mapping surveys or through DSM approaches (Haslmayr et al., 2016). Little such information is available for soils in Switzerland, and soil maps at scales relevant to spatial planning (1:5000) are available for less than one third of the agricultural area of Switzerland (about 1×10^6 ha) and for only small areas of forest (Grob et al., 2015). There is some momentum for mapping soil properties and functions in Switzerland because a soil protection strategy is currently being developed by the federal agencies responsible for spatial development, agriculture, and the environment. This strategy is focused on the interplay between soil properties, functions, and use (FOEN, 2017).

The quality of a soil function map depends on a well-established SFA process being used, and four interacting components: 1) reliable soil data; 2) pedotransfer functions (PTFs) to derive soil parameters that are difficult or expensive to measure; 3) a catalogue of SFA methods; and 4) other environmental data needed for the SFA. Such an SFA process has not yet been established in Switzerland.

The overall aim of this work is to connect the four components and propose a framework for the provision of soil function maps to establish linkages between stakeholders in the soil science, soil mapping, and spatial planning fields and other potential end users of soil function maps.

A schematic overview of the SFA process is shown in Figure 1.1. First, the set of soil functions and sub-functions has to be defined (A in Figure 1.1), then the methods, inputs, and outputs need to be matched (B in Figure 1.11), and then the degree to which the SFA results should be aggregated needs to be assessed (C in Figure 1.11).

This thesis covers the scientific and technical tasks involved in the process of producing soil function maps and contributes to reaching a common understanding of soil functions. Connecting soil functions with ESs and the needs of stakeholders is an ongoing co-learning process for the stakeholders (Bouma, 2014). The cascade model of Haines-Young and Potschin (2013) was adapted and used to define the links between

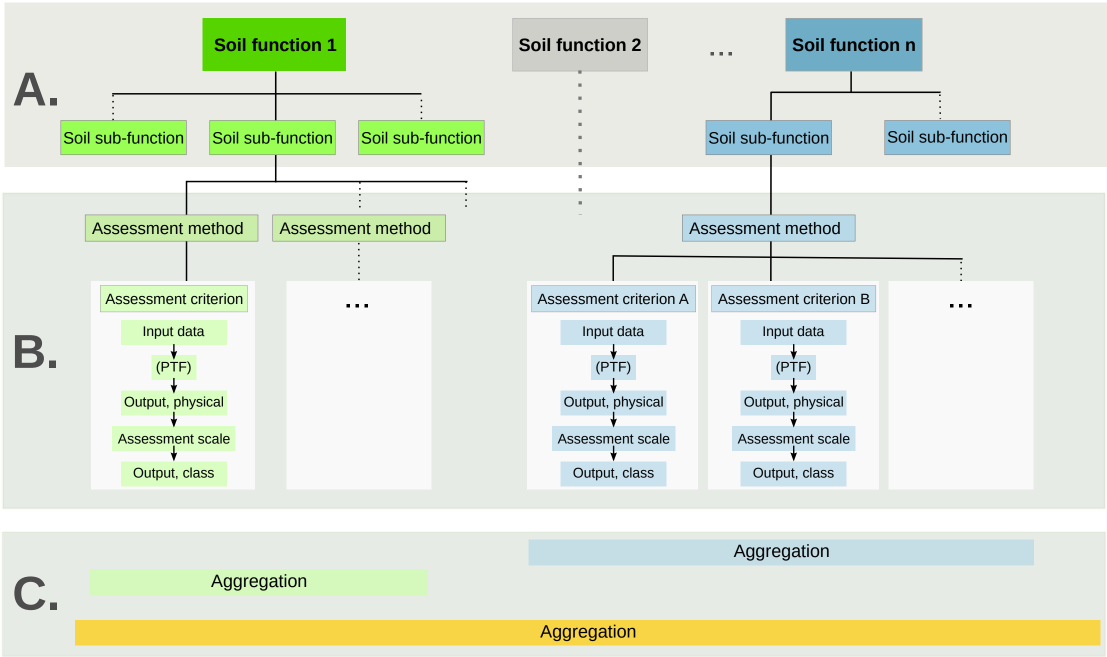

Figure 1.1: Schematic of the soil function assessment process

soil properties, soil functions, and ESs (Grêt-Regamey et al., 2017b). The soil function maps produced are used to determine the supplies of soil-based ESs, and the supplies are matched to the demands for the ESs to establish the local or regional values of the ESs, as described by Drobnik et al. (2018). The cascade model developed was used as the cornerstone of various projects that form part of the Swiss National Research Programme (NRP) 68 "Sustainable use of soil as a resource". NRP 68 is focused on linking soil properties and processes to soil functions and then to ES assessments.

1.2 About this thesis

1.2.1 Research projects

The results presented in this thesis were obtained from parts of two connected projects in the Swiss NRP 68 "Sustainable use of soil as a resource". In the NRP 68 project PMSoil, soil legacy data were harmonised and soil property maps were produced using DSM approaches to map soil functions. The soil function maps thus produced, were used in the NRP 68 OPSOL project and included in a land use decision model. In the OPSOL project, the consequences of soil functions being taken into account in land-use decisions were evaluated.

The "Predictive mapping of soil properties for the evaluation of soil functions at regional scale" (PMsoil) was a joint project performed by ETH Zürich, the Swiss Federal Institute for Forest, Snow, and Landscape Research, the Swiss Soil Monitoring Network, and the University of Zürich. The project covered part of the process involved in obtaining spatial soil property information to allow SFAs to be performed. The information was obtained through soil mapping surveys, geographical information system models, remote sensing, and advanced geostatistical models. The project had four work packages, namely:

A. harmonisation of legacy soil data from different sources and collected over long periods;

B. multi-scale terrain modelling using different approaches and an evaluation of hyperspectral remote sensing data for DSM;

C. evaluation of statistical modelling approaches to DSM, especially geoadditive models; and

D. evaluation of pedotransfer functions and soil function assessments.

The wide range of soil science disciplines involved in completing the tasks involved in these work packages meant that more than 20 scientists were involved in the PMsoil project, and numerous workshops and meetings were needed to coordinate the PMsoil project workflow.

The project "Matching soil functions and soil uses in space and time for sustainable development and land management - operationalising cross-scale interactions in a virtual collaborative decision support system" (OPSOL) was a joint project performed by ETH Zürich, the Swiss Soil Monitoring Network, the Swiss Federal Institute for Forest, Snow, and Landscape Research, Flury and Guiliani GmbH, and the University of Zürich. The OPSOL project was focused on spatial planning; legal, economic, and political factors affecting land-use decisions; spatial development and land management decisions; and the decision-making process itself. The OPSOL project had four work packages, which were:

A. developing a 3D virtual decision-support system;

B. generating a land-use decision model to account for soil functions while being responsive to new policies, and mapping land-use patterns for different policies and socio-economic boundary conditions;

C. developing a catalogue of SFA methods and mapping selected soil functions for case study areas; and

D. defining the current mechanisms governing soil uses and suggesting a mechanism for steering spatial planning taking soil resources into consideration.

Study areas each of several hundred square kilometres in the cantons of Zürich and Berne were used in the PMSoil and OPSOL projects. The study areas are shown in Figure 1.2. This thesis presents results for the two agricultural case study areas. The

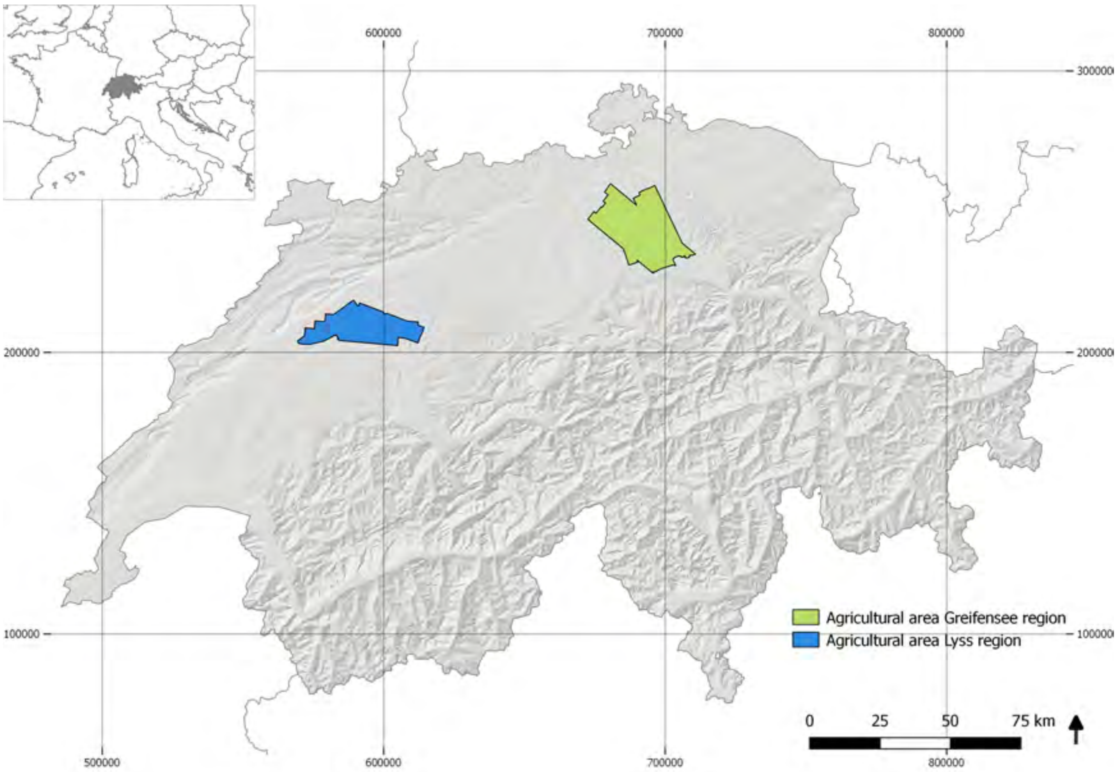

Figure 1.2: Locations of the study areas of PMSoil and OPSOL.(Coordinate Reference System: CHLV1903. Digital elevation model 25 m ©SWISSTOPO. EU administrative boundaries: NUTS 2013, ©EuroGeographics).

study areas were selected because of the availability of legacy soil data, the availability of remote sensing data, and the needs of the stakeholders in the soil protection agencies of the cantons. Contrasting agricultural land management practices were also taken into consideration to allow a regional soil monitoring tool to be developed as part of the NRP 68 project "Modelling agricultural management and soil functions" (iMSoil). The work presented in this thesis was part of work package D in the PMSoil project and of work package C in the OPSOL project.

1.2.2 Main aims and research questions

The main aims of the work presented in this thesis were:

1. to develop a conceptual framework for SFA methods and to set up guidelines for soil protection and planning agencies including a catalogue of SFA methods adapted to soil information available for Switzerland;

2. to evaluate and adapt selected national and international SFA methods for two case study areas in Switzerland;

3. to process soil information available for the two case study areas and create maps for selected soil functions, including uncertainties, thereby providing a scientific

basis for the stakeholders to take informed land-use decisions; and

4. to link the SFA framework and the results with the decision-support system for land use, spatial development, and land management developed in the OPSOL project.

The first three aims are addressed in the three publications presented in Chapters 2- 5. The SFA framework and results are linked with the decision-support system developed in the OPSOL project in all three publications because the concepts, application, and results of SFA are assessed from the perspective of the different project partners and adjusted to the needs and boundary conditions in each publication. Requirements for soil function maps outside the system developed in the OPSOL project are addressed in Chapter 4.

The main research questions are shown below.

1. How is soil represented in the ES community and what are the main gaps in terms of the abilities of the assessment methods to determine the contributions of soils to ESs? Which soil data are required by the assessment methods and what data sources (from the global scale to the local scale) can be used?

2. How can we transfer existing SFA methods to Swiss soils? Can existing SFA methods be adopted or must new SFA methods be developed using Swiss soil data classifications? What soil functions should be assessed to capture soil multifunctionality? How can the reasonableness of a soil function map be evaluated? What are the benefits and pitfalls of combining soil function maps to give an overall soil indicator?

3. How can we quantify and visualise the accuracy of a soil function map?

1.2.3 Procedures and methods

The research questions outlined above are addressed here by presenting a conceptual approach to assessing soil functions, providing a list of 10 adapted SFA methods, and demonstrating the application of these methods in our study area. The possibility of merging separate soil function maps into one "indicator" map (i.e., an overall assessment value for soil functions expressed as a soil index) is also explored. Ways of visualising the uncertainties associated with soil function maps were developed.

As described in Chapter 2, the conceptual approach was explored and a list of SFA methods drawn up by screening a vast number of publications by the soil mapping and applied soil science community and by the ES community. The conceptual possibilities were discussed with partners in the PMSoil and OPSOL projects.

The current focus was on reviewing the ES literature on the representation of soil and quantification of the supply of soil-based ESs. The applied soil science literature for

SFA methods and the data requirements of these methods were screened. The SFA methods were ranked using eligibility criteria allowing a set of methods to be proposed for estimating the contributions of soil to the supply of soil-based ESs. The minimum soil dataset required to assess the selected soil functions was defined. Partners in the PMSoil and OPSOL projects produced a factsheet on integrating soil functions and ESs (Grêt-Regamey et al., 2017b).

10 SFA methods were applied using soil property maps generated using digital soil mapping approaches in another PMSoil project work package and the reasonableness of the SFA results was considered for more than 7000 soil profiles with regard to the soil type, land use, drainage class, and soil quality rating (Mueller et al., 2007). Soil profile data were processed and interfaces established to input soil data into MATLAB scripts to adapt the SFA methods and apply them to the study areas to assess how reasonable the results were. We used SFA methods from different sources, thus were the methods unified and adapted mainly in relation to waterlogging, soil depth, and bulk density, and the SFA scales were then calibrated. The SFA methods for profiles and raster data were programmed, soil function maps produced and the SFA results were then statistically analysed. Each static SFA method was aimed at simplifying and assessing a soil function that is studied and described in a separate research field. It is therefore not a trivial matter to apply a static simplifying SFA method while attempting to retain the essence of the soil function. Members of the Swiss Soil Monitoring Network provided expertise on the different soil functions. The aggregation of soil function maps into an overall indicator map was considered by comparing four aggregation options and outcomes.

The uncertainties involved in soil property predictions were propagated through SFA methods using a high-capacity computing device. Methods for visualising easy-to-understand maps were used to indicate the uncertainty in the SFA results, and the influences of uncertainty in the soil properties (caused by uncertainty in the input data) on the SFA results and the behaviours of the SFA methods were graphically and statistically analysed.

1.2.4 Structure of the thesis

The thesis is structured to reflect the process of generating soil function maps. Chapters 2, 3, and 5 are articles that have been peer-reviewed or are in revision. Chapter 4 has not been submitted for peer-review but describes key parts of the process nevertheless.

In Chapter 2, ES assessment studies are reviewed in terms of methodological approaches for incorporating the capacities of soils to contribute to ESs. The results are linked to operational tools developed by the applied soil science community. The soil function concept is presented and coupled to the ES concept in this chapter.

Chapter 3 contains 10 selected static SFA methods for approximating the multi-functionalities of soils and the potential contributions of soils to ESs in a spatially explicit manner. These SFA methods are applied to the agricultural study area in the Greifensee region of the Canton of Zürich.

Chapter 4 contains SFA results for the study area in the Lyss region of the Canton of Berne for three soil functions in more detail, taking the demand for soil information and soil function maps by policymakers and policy implementers into consideration.

The SFA for the Greifensee study area is described in more detail and insights are drawn in Chapter 5. Predictive soil property distributions from a digital soil mapping source are used, and the distributions are propagated using the 10 SFA methods for the same study area. The ranges of the results and variability in the results are assessed, as are the sensitivities of the SFA methods to uncertain input data.

The conclusions and the outlook are given in Chapter 6, and the Appendix contains supplementary material for Chapters 2 - 5.

Chapter 2

Review of methods for quantifying the contributions of soils to ecosystem services

Chapter 2 was published as Greiner, L., Keller, A. Grêt-Regamey, A. & Papritz, A. Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services. Land Use Policy, 2017, 69, 224-237. DOI: 10.1016/jlandusepol.2017.06.025

Abstract

Soils and their functions are critical to ensure the provision of various ecosystem services (ES). Many authors nevertheless argue that there are a lack of satisfactory operational methods for quantifying the contributions of soils to the supply of ES. In this study, we review ES mapping studies that have taken the roles of soils in ES supply into account, and propose soil function assessment (SFA) methods approved by German Federal States in spatial planning procedures to use in assessments of ES supply.

We found 181 ES mapping studies in which the roles of soils in ES supply were considered. At least one soil property was used as an indicator of soil-related ES in 60% of the publications, and 13% of the publications were mainly focused on the roles of soils in supplying ES. More than two soil functions were considered in a minority of cases, indicating that the multi-functionality of soils has barely been taken into account in previous ES studies. Several decades ago, the soil science community has adopted the concept of soil functions to bring different aspects of soil to the fore and to emphasize the multifunctionalities of soils and their vastly different chemical, physical, and biological properties. We provide a set of approved SFA methods that cover the multi-functionalities of soils and are applicable to ES supply assessments.

We propose that this set of operational SFA methods is a starting point for quantifying

how soil systems underpin the supply of a wide range of ES. The minimal soil dataset required for these SFA methods is relatively small, and much progress has been made nationally and globally over the last decade in improving soil data infrastructure and online access for end users. These improvements will facilitate the incorporation of SFA into ES studies and thereby improve information for land use decisions. We recommend that ES assessments include the essential and multifunctional roles of soils to promote sustainable land use.

2.1 Introduction

The ecosystem Service (ES) approach is increasingly used to incorporate ecological sustainability into political decision-making (Grêt-Regamey et al., 2015). In particular, land use policies should foster spatial planning procedures that drive not only new urban areas and transport infrastructure but also take into account ecological aspects such as the provision of essential ES. In this context, quantifications and maps of ES must be transparent and accurate if they are to be accepted and applied with confidence by policy makers. The body of literature dealing with and illustrating the importance of the ES concept is growing, but relatively few data-driven ES studies and ES assessments using appropriate quantification methods have been published (Baveye, 2017; Liekens et al., 2013; Seppelt et al., 2011). Several publications proposed that more effort should be made to develop accurate and practical methods for quantifying ES (Boyanova et al., 2014; Crossman et al., 2013; Daily et al., 2009). There are two noteworthy models including multiple ES - also soil-based ES - that are increasingly used in ES assessment studies: The Integrated Valuation of Ecosystem Services and Tradeoffs model (InVEST) (Sharp et al., 2014) and the Artificial Intelligence for Ecosystem Services model (ARIES) (Villa et al., 2014). ES are increasingly incorporated into political instruments (Bouwma et al., 2017) and there is a particular need for spatially explicit ES quantifications for use in land-use planning to support the sustainable use of also soil resources (Van der Biest et al., 2013; van Wijnen et al., 2012).

2.1.1 Soil is important for ES supply

Soils are critical to various ecosystem goods and services and underpin the delivery of a wide range of ES, including food production, water and climate regulation, energy provision and biodiversity (Haygarth and Ritz, 2009; Grêt-Regamey et al., 2017c; McBratney et al., 2014; Volchko et al., 2013). Soil is the skin of the earth and the central interface between atmosphere, hydrosphere, lithosphere and biosphere. Therefore, soil contributes to many ES (Bouma, 2010; Dominati et al., 2014), and several publications stress that human wellbeing relies greatly on soil resources (Amundson et al., 2015; Banwart, 2011). Huber and Kurzweil (2012) and Dominati et al. (2010) suggested that soil needs to be integral to ES assessments, and soils importance in this regard has been highlighted in several studies (Adhikari and Hartemink, 2016; Bouma, 2014; Bouma et al., 2012; Haygarth and Ritz, 2009; Hewitt et al., 2015; Robinson et al., 2013). Bouma et al. (2015) demonstrated the importance of soil and the use of soil information for six case studies clearly showing the necessity to include soil in ES assessments.

2.1.2 Integration of soil in assessments of ES supply

Soil has hardly been considered or has not been well represented in previous ES studies (Breure et al., 2012; Dominati et al., 2010). Although 'soil formation' or 'soil fertility' were explicitly mentioned as services in publications by MEA (2005); CICES (2013); Crossman et al. (2013); de Groot (2011); Haines-Young and Potschin (2008), operational tools for quantifying soil-related ES were not provided in these studies. A number of recently published literature reviews have focused on evaluating ES mapping tools (Bagstad et al., 2013; Crossman et al., 2013; Grêt-Regamey et al., 2017c; Nelson and Daily, 2010; Vigerstol and Aukema, 2011; Waage et al., 2011) or on providing overviews of ES mapping case studies (Egoh et al., 2012; Layke et al., 2012; Martínez-Harms and Balvanera, 2012; Pagella and Sinclair, 2014; Schägner et al., 2013; van den Belt and Blake, 2014). The question of whether and how soil is incorporated into ES studies was not addressed in these reviews. Adhikari and Hartemink (2016) recently reviewed the literature on the relationships between soils and ES and compiled the key soil properties related to individual ES. However, these authors did neither provide operational methods for quantifying the contributions of soils to ES and linking soil properties to ES.

2.1.3 Soil functions

In the ES community, soils are often called *natural capital stocks* to value and quantify their contributions to ES e.g.,Hewitt et al. (2015); Robinson et al. (2009, 2013). In the last two decades the soil science community has adopted the concept of soil functions to place value on the roles soils play in sustaining the wellbeing of humans and of society in general Bouma (2014); FAO and ITPS (2015); Haygarth and Ritz (2009). Soil functions are closely related to soil quality, which was defined by an American Soil Science Society working group in 1995 as *the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries* (Karlen et al., 1997), emphasising the multi-functionality of soils and their chemical, physical and biological properties. The capacity of soils to deliver ES is largely determined by its functions, and each individual soil function can be seen as providing a soil-related contribution to ES Bouma (2014). The soil science community has been developing an understanding of soil systems for more than 100 years (Hartemink, 2015), and closely related concepts, such as soil quality indicators, soil health and soil protection,were developed some decades ago (Doran, 2002; Karlen et al., 2003; Wienhold et al., 2004). The European Commission's soil protection strategy (EU, 2006) was an important initiative that brought the concept of soil functions to the attention of the wider public and placed the concept on the political agenda, even though the strategy was not later adopted. Seven soil functions were defined in the strategy (EU, 2006): (i) production of food and biomass, (ii) storage, filtering and transformation of compounds, (iii) habitats for living creatures and gene pools, (iv) the physical and cultural environment, (v) source of raw materials, (vi) carbon pool, and (vii) archive of geological and archaeological heritage. Koch et al. (2013) and McBratney et al. (2014) recently proposed an integrative framework termed *soil security*, aimed at maintaining and optimising soil functionality to value the contributions of soils to environmental and social benefits. The authors defined soil security as *[...]the maintenance and improvement of the global soil resource to produce food, fibre and freshwater, contribute to energy and climate sustainability, and to maintain the biodiversity and the overall protection of the ecosystem*. The soil security framework can therefore be seen as one soil-related component in the overall ES approach defined by MEA (2005). The roles of soils in ES were highlighted in the United Nations sustainable development goals for 2015 to 2030 in goal 15, *...to protect, restore and promote sustainable use of terrestrial ecosystems...* (United Nations, 2016). Nevertheless, it is still challenging to move from these general, theoretical frameworks to specific operational approaches that can be applied in practice.

2.1.4 Outline and objectives

In the following, we review ES mapping studies that take into account the roles of soils in delivering ES, compile how soil functions were linked to ES in the studies, and identify the main gaps concerning the assessment methods. The aim of this review is to support the quantification and mapping of soil-related ES. To address the main gaps in the assessment methods, we gathered soil function assessment (SFA) methods from the applied soil science community in selected European countries, and provide a selection of assessment methods that are applicable to ES assessment studies. Finally, we discuss what soil data is required by the assessment methods and the sources of available data from global to local scale.

2.2 Definitions and methods

2.2.1 Search of the literature published by the ecosystem service community

We combined several information sources for our search of ES studies that consider soil-related issues. We first screened literature reviews of ES mapping and quantification provided by the Ecosystem Service Partnership Thematic Working Group for Ecosystem Service Mapping platform (ESP, 2015). We found a total of 15 reviews focusing on the assessment, quantification and/or mapping of ES (Table 2.1). Three reviews focusing

Table 2.1: Reviews of ecosystem services (ES) assessment and mapping (n=15)

Review type	*Authors*
ES mapping studies	Crossman et al. (2013); Egoh et al. (2012); Martínez-Harms and Balvanera (2012); Pagella and Sinclair (2014); Schägner et al. (2013); van den Belt and Blake (2014)
ES assessment tools	Bagstad et al. (2013); Nelson and Daily (2010); Vigerstol and Aukema (2011); Waage et al. (2011)
ES indicators	Layke et al. (2012)
Framework for mapping and assessing ES (not focused on soil)	Maes et al. (2012)
Framework for mapping and assessing ES (focused on soil)	Adhikari and Hartemink (2016); Jónsson and Davíasdóttir (2016); Schwilch et al. (2016)

directly on soil-related issues were published recently (Adhikari and Hartemink, 2016; Jónsson and Davíasdóttir, 2016; Schwilch et al., 2016) but do not provide operational tools how to take into account the role of soils in ES mapping studies. In this review we go one step further and focus on SFA methods that can link soil functions to ES.

All the studies potentially quantifying the supply of soil-based ES found (264) and tools mentioned (4) in the 15 reviews were included in our literature review. We also compiled publications and tools available through the IPBES Catalogue of Assessments on Biodiversity and Ecosystem Services platform IPBES (2015) and used ScienceDirect® to search for the terms *ecosystem service* and *mapping* and *soil* in titles or abstracts of publications. The studies described in the publications were extensively screened. Then, we updated the reference list at the end of 2016, searching ScienceDirect® again using the same key terms. Given the large number of hits, we limited the search to publications in which at least one of the top ten most cited soil-related ES studies found in the first step of our review were cited. This yielded more than 400 publications in which the roles of soils in ES were at least mentioned. We screened these publications and selected those mentioning at least one soil-related ecosystem service. We narrowed the search by excluding publications potentially using dynamic modelling or focusing on specific soils, such as flooded soils in wetlands and on the coast, or forest soils. It became clear that issues related to soil biodiversity and ES (a relatively new discipline in soil science) have been investigated in numerous studies. Most of these studies involved basic research on soil biota, but the development of meaningful and widely applicable soil biological indicators is still ongoing Lavorel et al. (2017); Pulleman et al. (2012); Rutgers et al. (2012); Thomsen et al. (2012). We therefore decided to exclude these studies. More information on soil biodiversity and its role in ES for different soils, climate types and land uses are available through the European Union Ecological Function and Biodiversity Indicators in European Soils project EcoFinders (2017). A list of soil biological indicators for soil biodiversity and ES was recently suggested and evaluated as part of the EcoFinders project Griffiths et al. (2016). We classified the ES studies using the domains (1) mapping, (2) conceptual, (3) reviews and (4) combinations of the first three categories. We also classified them based on the level of detail with which soil was considered. In level 1, soil was the main focus of the study and soil-related ES were provided. In level 2, soil was not the focus of the study, but soil was at least considered with one indicator or method when ES were assessed or mapped. In level 3, soil was mentioned but not taken into account when ES were assessed or mapped.

2.2.2 Search of the literature published by the applied soil science community

We used the cascade model developed by Haines-Young and Potschin (2008) to develop an understanding of how soil functions can contribute to ES. This model is often used as a general framework in ES studies (e.g., Schwilch et al., 2016). The steps required to link key soil properties and soil processes to soil functions and to link soil functions to ES and related benefits and values are shown in (Figure 2.1).

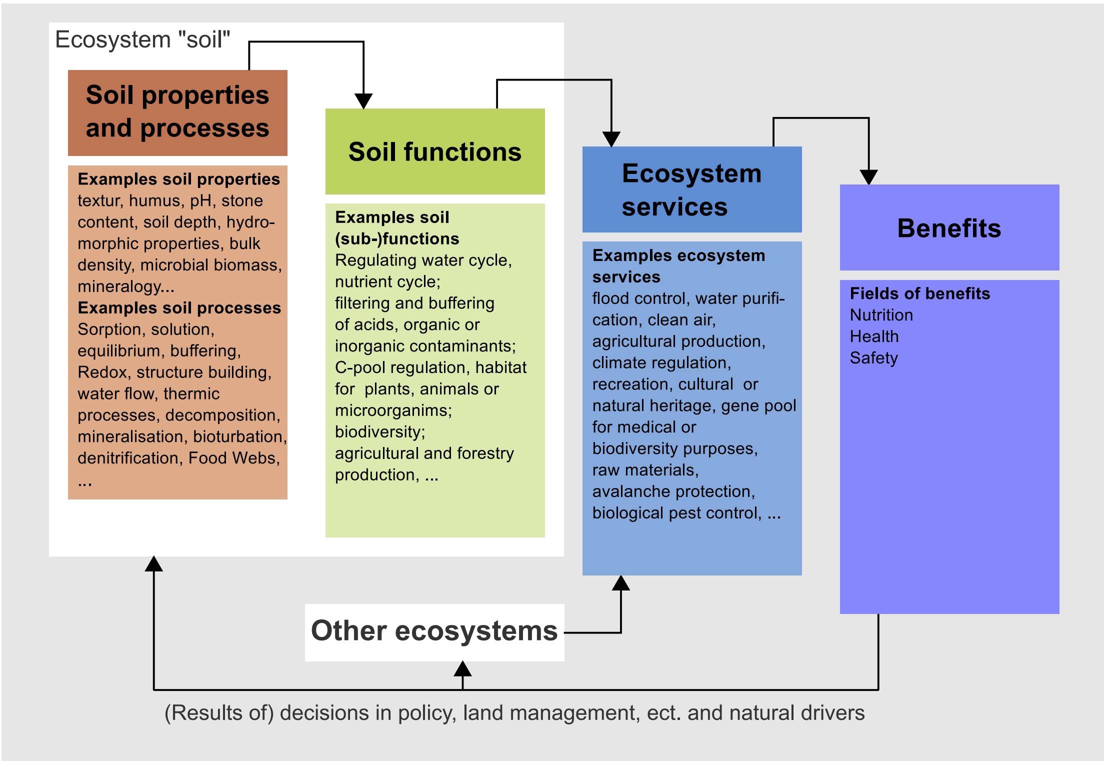

Figure 2.1: Assessment of the contributions of soil functions to ecosystem services using the cascading framework developed by Haines-Young and Potschin (2008)

The baseline of the data processing chain is usually given by soil mapping surveys in which the spatial distributions of soils are investigated, involving, amongst other things, field observations (soil profile descriptions), chemical analyses of soil properties and the generation of soil maps. Soil properties can be quite static (e.g., texture, stone content and soil depth) or dynamic (e.g., soil pH, organic matter content, water content and nutrient content). Temporal changes in the dynamic soil properties in agricultural soils

Table 2.2: Selected soil functionsand sub-functions used to characterise the multi-functionality of soils. [in brackets:terminology according to EU (2006)]

Soil function Soil sub-function	**Examples of assessment criteria**
Regulation function [storage, filtering, transformation of compounds; C-pool]	
Water cycling	*Water purification, plant available water, water infiltration,*
Nutrient cycling	*Nutrient storage capacity, prevention of nitrate leaching or gas exchange, nutrients in soil available to plants*
Filtering and buffering of organic compounds	*Filtering of, for example, persistent organic pollutants, antibiotics or pesticides, degradation of soil pollutants*
Filtering and buffering of inorganic compounds	*Filtering of trace elements*
Acidity buffering	*Buffering of nitrogen oxides*
Soil carbon storage	*Soil carbon pool*
Habitat function [habitats for living creatures and gene pools]	
For natural plant populations	*Support for vegetation, soil types providing niches for plant species*
Production function [production of food and biomass]	
Agricultural production	*Crop yield, forage, bioenergy*

partly depend on land management practices. Numerous studies have been conducted in which the multivariate and complex relationships between land management practices and changes in soil properties have been investigated with the aim of allowing the soil functions of arable soils to be maintained or improved (e.g., Schulte et al., 2014, 2015; Valujeva et al., 2016). Soil processes such as sorption, degradation, heat and gas exchange, nutrient leaching and water flow have been determined in conjunction with changes in the soil properties and the capacity of the soil to fulfil its functions. As suggested by Bouma (2014), we avoid using the term *soil services* because it suggests that soils can act independently. Using food production (one of the most frequently considered services) as an example: the yield depends strongly on the soil conditions, but other factors such as the climate, crop and pest management, fertilisation, machinery infrastructure, and the socio-economic boundary conditions of the agricultural land, also affect the yield. In line with the soil function classification described by EU (2006) and further studies in which soil functions were taken into account (Calzolari et al., 2016; Dominati et al., 2014; Haygarth and Ritz, 2009), we used the main soil functions and sub-functions shown in Table 2.2 to cover the multi-functionality of soils.

In addition to these soil functions, soils can also represent cultural archives of geological and archaeological heritage, supporting cultural services which have quite a potential *to motivate and sustain public support for ecosystem protection* (Daniel et al., 2012) The archive function is not considered here because it can be mostly assessed independently of the soil itself. The same is true for soil functions, such as the extraction of raw materials and the role of soil in the human physical and cultural environment. These soil functions are not considered here as well. We classified each soil assessment method into one of three approaches.

Indicator approaches This class of approaches defined soil indicators derived from key chemical, physical and biological soil properties serving as simplified and one-dimensional proxies for soil functions or soil quality (e.g., Karlen et al., 2003; de Paul Obade and Lal, 2016; Wienhold et al., 2004).

Static approaches The second class of approaches were static approaches using simplified empirical rules to quantify soil functions (e.g., Lehmann et al., 2013; Calzolari et al., 2016). Static approaches assess the general capacity of a soil to fulfil a specific function, but the impacts of land use and land management practices are not taken into account. Static approaches are particularly suitable in land-use planning to support the sustainable use of soil resources (Lehmann and Stahr, 2010; Mueller et al., 2007).

Dynamic approaches The third class of approaches comprised semi-dynamic or dynamic approaches including soil processes, climate and other site-specific environmental factors as well as temporal and spatial variations in land use and land management practices. This class includes soil and environmental modelling studies, as well as biophysical models developed in different sub-disciplines (e.g., nutrient cycling, water cycling, and soil degradation), taking into account physical, chemical and biological soil processes. Vereecken et al. (2016) recently highlighted the role of soil process modelling in relation to ES and proposed that an international soil modelling consortium should be established to foster communication between workers in different disciplines. A collection of soil biophysical models can be found through a web-based soil modelling platform (ISMC, 2017). Using biophysical soil models is by far the most data-demanding and time-consuming approach, because gathering and processing data, calibrating model parameters, mapping, and validation all require great effort for each case study. However, once a model is appropriately calibrated for a region of interest, this is the most powerful approach for modelling the impacts of past and future land use and land management practices on soil functions.

Overall, soil indicators and the static approach focus on the status of soils, and the dynamic approach is suitable for assessing trends. Policy-making related to ES requires both soil status and any trends to be assessed in spatially explicit ways (Maes et al., 2012). Both status and trend approaches can be used if sufficient data are available for a study region, but only the indicator and the static approach are applicable if data are limited. Such a tiered procedure was also recommended by Tallis and Polasky (2011) and Nelson et al. (2011) and shown on an example for ES by Grêt-Regamey et al. (2015). Simple, static and low-data models provide results that are easier to communicate and are better suited to planning and scoping activities than those provided by dynamic models. A static assessment of soil functions is more meaningful - from a soil science point of view - and more helpful for further ES assessment than the even more simplifying indicator approach. Further, it is more easily performed than a dynamic assessment and we think, it should be carried out first before a dynamic soil model is used. We therefore focused our review of the literature published by the soil science community on static approaches. In European countries, static methods for assessing soil functions have commonly been developed by geological or soil survey institutions that are responsible for soil mapping surveys in the countries in which they are based. These institutions are mostly affiliated to government organisations rather than universities, so the documents containing the methods developed to assess soil functions are sometimes written in languages other than English and hardly any documents about methods for assessing soil functions have been published in international scientific journals. We concentrated our search on soil mapping and geological institutions at the national and federal level in selected European countries, including Austria, France, Germany, the Netherlands, Switzerland, and the UK, and we contacted the responsible people or working groups if published documents were not comprehensive. Similar to the review of the literature published by the ES community, we excluded soil functions and sub-functions related to soil biodiversity, forest soils and wetlands.

2.3 Soil functions and ecosystem services

2.3.1 Overview of literature published by the ES community

Reviews

In most of the 15 reviews (see Table 2.1), emphasis was placed on mapping and assessing ES, partly including soil-related provisioning, regulation and supporting services (Crossman et al., 2013; Egoh et al., 2012; Layke et al., 2012). In some of the reviews, the recent literature was summarised with the aim of outlining general concepts for assessing and mapping ES (e.g., Maes et al., 2012; Pagella and Sinclair, 2014). Other reviews focused on economic methods of valuing ES (Jónsson and Davíasdóttir, 2016; Schägner et al., 2013). The main characteristics of the 15 reviews are listed in Appendix A.1, Table A.3. Schwilch et al. (2016) recently proposed a soil-focused ES framework taking threats to soil as the starting point. The aim was to promote sustainable soil management and to develop operational tools to mitigate threats to soil and negative impacts on soil-related ES. The framework was developed as part of the European Union FP7 project RECARE. Implementing this framework at various sites across Europe could provide operational tools for quantifying the roles of soils in ES provision in the near future. Jónsson and Davíasdóttir (2016) screened the literature to identify the many contributions soils make to ES and to illustrate the importance of soil-related ES by demonstrating that economic approaches can be used for that purpose. In contrast, Adhikari and Hartemink (2016) focused on studies that relate soil properties to ES and summarised the inter-relations between soil properties and ES. Soil properties were considered by all three reviews mentioned, and the relevance to provisioning, regulation and supporting services was indicated. However, operational tools for quantifying the contributions of soils to ES were hardly provided in the reviews mentioned above. Only Adhikari and Hartemink (2016) and Egoh et al. (2012) cited some references to case studies in which soil properties were linked quantitatively to ES.

ES literature

In our literature search we found a total of 181 publications in which the roles of soils in ES supply were considered. About half of these publications were about ES mapping, 22% mainly addressed conceptual issues and 10% considered both topics (Figure 2.2). In 60% of the publications at least one soil property was used as an indicator of soil-related ES or at least one method was used to quantify the contributions of soils to ES. In about 27% of the ES mapping studies soil was mentioned in the approach but was not then included in the ES assessment. Notably, 13% of the publications were mainly focused on the roles of soils in ES provision. In some of these studies, the emphasis was on single soil functions, such as nutrient filtering and storage (e.g., Hewitt et al. 2015; Van Wijnen et al. 2012; Wang et al. 2015). Attempts were made in only a few studies to characterize the multi-functionality of soils outlined in Table 2 (e.g., Calzolari et al. 2016; Dominati et al. 2013, 2014; Robinson et al. 2013; Rutgers et al. 2012; Schulte et al. 2014). The full list of the publications found is

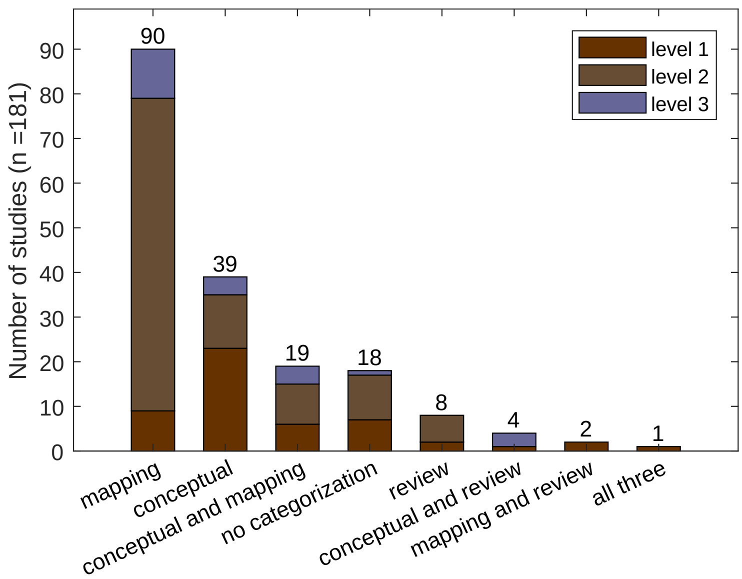

Figure 2.2: Frequency of ES studies in the categories *mapping*, *conceptual*, *review* and combinations of the three first categories including level of soil focus (level 1: soil was the main focus of the study; level 2: soil was at least considered using one indicator or method; level 3: soil was only mentioned.) The studies not categorised were mainly focused on the demand for ecosystem services.

provided in the supplemental information (Appendix A.1, Table A.1), and more information on the key foci of the studies and the soil properties and soil-related ES considered is provided in the supplemental information as well (Appendix A.1, Table A.1).

At least one method of quantifying soil-related ES or a proxy indicator derived from soil properties was documented in 83 of the 181 publications. A soil-related ecosystem service was quantified 220 times in total in these 83 studies (Figure 2.3).

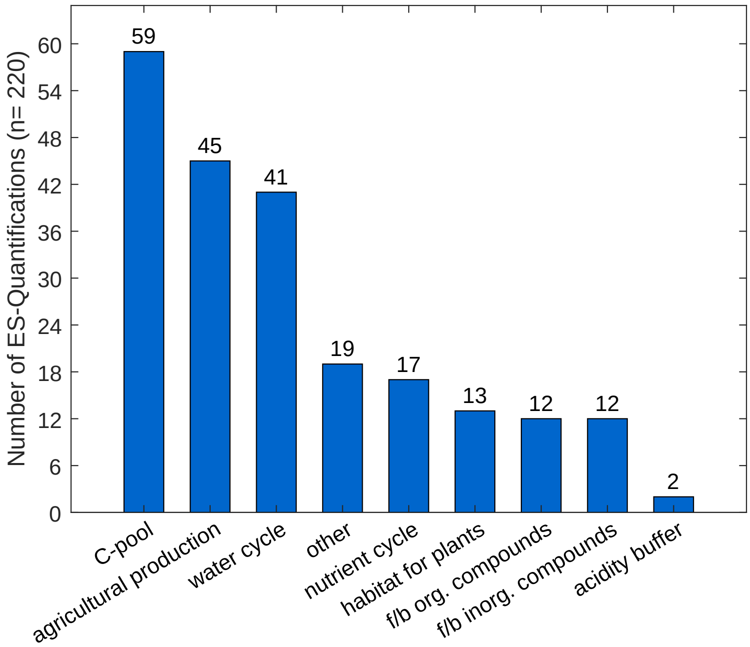

Figure 2.3: Frequency of soil-related ecosystem services (ES) considered in ES mapping studies (the figure is based on 83 ES studies) (f/b = filtering and buffering)

The most prominent soil functions assessed in the studies were contributing ones to regulation services, such as the soil organic carbon pool (C-pool) and the water storage capacity. The soil C-pool is probably the most often used soil-related indicator because organic carbon in soil is one of the key basic soil properties, is easy to understand, and calculating the soil C-pool is simple and requires only a few soil properties. The plant-available water capacity has been used as a proxy to characterise the soil-water cycle in many studies. Such information is often provided in national soil databases and is often derived from pedotransfer functions (see below). Agricultural production, the key provisioning service related to soils, has also been considered in many ES studies. While crop yields, forage production or biomass production have been used as proxies in many studies, the suitability of soils have been assessed and classified based on soil type information, soil properties or soil taxonomic units (e.g., Mueller et al., 2007; Tóth et al., 2013). Other essential soil functions, such as nutrient cycling and the filtering and buffering of chemical compounds, have been incorporated in only a few ES studies (e.g., Calzolari et al., 2016; Dominati et al., 2014; Rutgers et al., 2012). A full list of the soil properties used and the soil-related ES quantified in each of the 83 ES studies is given in Appendix A.1,Table A.1. The frequency with which soil-related ES were considered in the ES mapping studies compared well with frequencies reported by Adhikari and

Hartemink (2016), who found that 41% of the ES studies between 1974 and 2014 (n = 935) were related to regulation services (mainly climate regulating factors such as the C-pool, water regulation and purification), while 34% were related to provisioning services such as food production. Crossman et al. (2013) published a review of ES mapping and modelling in which they found that the most commonly mapped ES associated with soil were soil carbon storage as a proxy for climate regulation, food provision, water supply and the regulation of water flows.

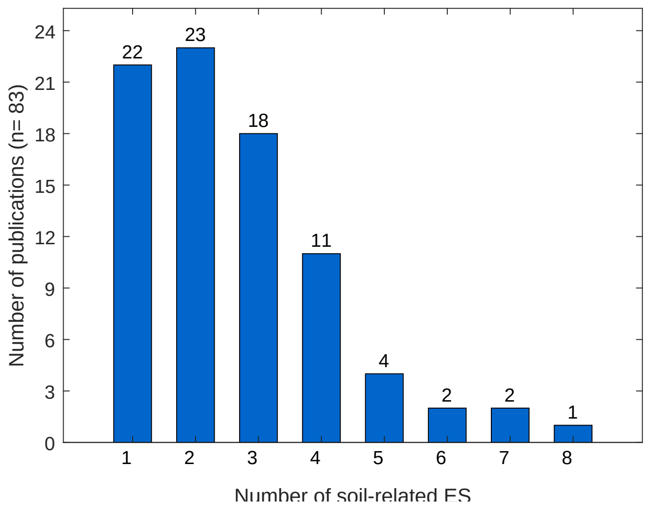

Figure 2.4: Number of soil-related ecosystem services (ES) considered per ES mapping study

The multi-functionality of soils has hardly been taken into account in ES mapping studies (Figure 2.4). A complete list of the soil properties used and the soil-related ES assessed in the 83 ES mapping studies found is given in Appendix A.1,Table A.1. About half of the publications described studies in which only one or two soil functions were included, 22% were studies in which three soil functions were considered, and 24% studies used four or more soil functions. We found that most ES mapping studies took into account one of the three most commonly considered soil functions (soil carbon pool, agricultural production and water cycle), but often ignored the remaining capacities of soil to deliver ES as outlined in Table 1. Notable exceptions to this are the studies by Dominati and Mackay (2013); Dominati et al. (2014); Rutgers et al. (2012) and Schulte et al. (2014) and in particular by Calzolari et al. (2016) who comprehensively assessed soil-related ES for a catchment in northern Italy. The authors used available regional soil profile data and soil maps and other environmental GIS maps to quantify and map the spatial variability of eight soil functions as indicators of soil-related ES. Bouma (2014) and Haygarth and Ritz (2009) also found that the multi-functional role of soils in ES is generally not well assessed. They proposed that a unified ES framework for soil systems should be developed.

ES mapping studies

Soil properties used for mapping In conjunction with the top three soil-related ES mentioned above (Figure 2.3), the most frequent soil properties used in ES mapping studies are the soil organic carbon content, the available water capacity, the clay and silt contents (texture), the soil type, the soil depth and the bulk density (Figure 2.5). The category *other soil data* in Figure 5 includes various soil parameters, such as the C:N ratio, the P and N contents, and physical soil properties such as macro-aggregates. Hydromorphic features of soils, such as waterlogging, the grey colours of bleached soil horizons and water conductivity, have also been used to describe water cycle in soil (e.g., Hewitt et al., 2015; Landuyt et al., 2015). Haygarth and Ritz (2009), Adhikari and Hartemink (2016); Robinson et al. (2013); Dominati et al. (2014) described similar typical soil properties relevant for ES assessment.

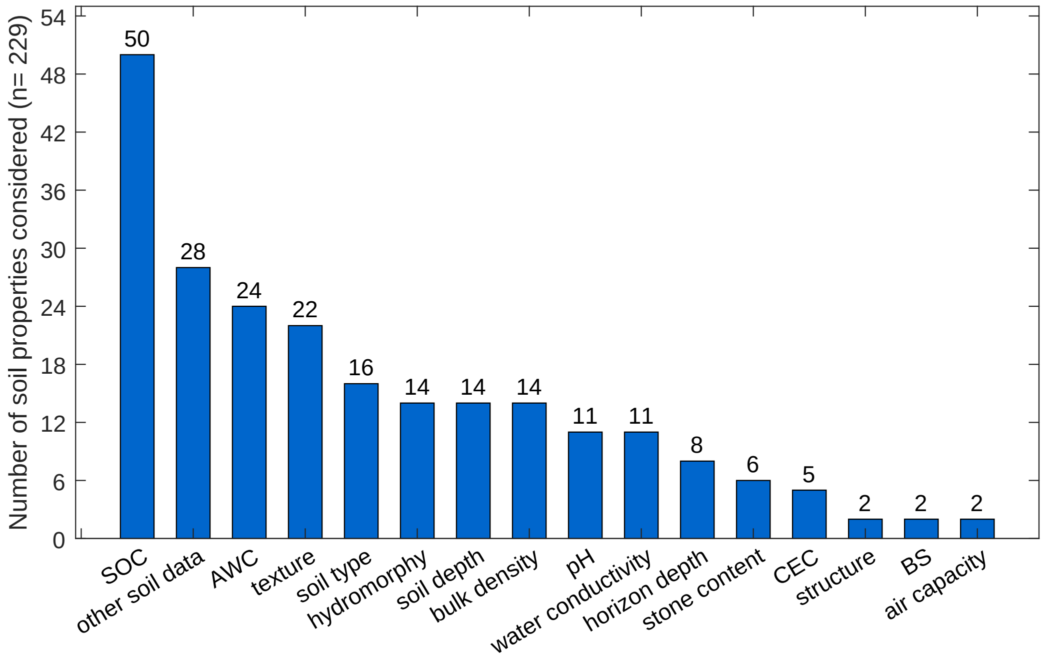

Figure 2.5: Frequencies with which soil properties have been considered in ecosystem service mapping studies (n = 83 studies). (SOC = soil organic carbon, AWC = available water capacity)

Scale In most (60%) of the 83 studies, ES were quantified on a local or regional scale, i.e., from several fields or a small catchment to a larger region of several hundred square kilometres. In a few ES studies (15%), soil-related ES were also quantified at a national level (e.g., Anderson et al., 2009; Bateman et al., 2013; Egoh et al., 2008; Turner et al., 2014), and in some studies, ES were even quantified at a continental scale (Tóth et al., 2013). Where soil property data were applied, they were usually gathered from available soil databases. At a local or regional scale, these were often soil maps (1:5'000 to 1:50'000) and soil profile datasets. In particular, local and regional scales are the scales, where land use policies are defined and implemented.

Soil data sources In some countries government institutions provide national scale soil databases and soil maps with medium resolutions (1:50'000 or lower). However, many authors emphasise the lack of soil data required to assess soil-related ES (e.g., Adhikari and Hartemink, 2016; Liekens et al., 2013; Maes et al., 2012) and other available environmental information such as land use or land cover maps are used as substitutes for missing soil data. This may lead many authors to criticize the ES approach, when applied to soils. (Baveye, 2017) Clearly, the availability of soil databases is key to allowing soil functions to be assessed. In a few cases, the authors performed their own soil surveys (Lavelle et al., 2014; Le Clec'h et al., 2016; Yao et al., 2016) or used soil data from the European Soil Data Centre (Panagos et al., 2012; Schröter et al., 2005) or the Harmonized World Soil Database (FAO, 2012; Maes et al., 2011), see Figure 2.6 The soil data sources used in the ES studies we identified are listed in Appendix A.1,Table A.5.

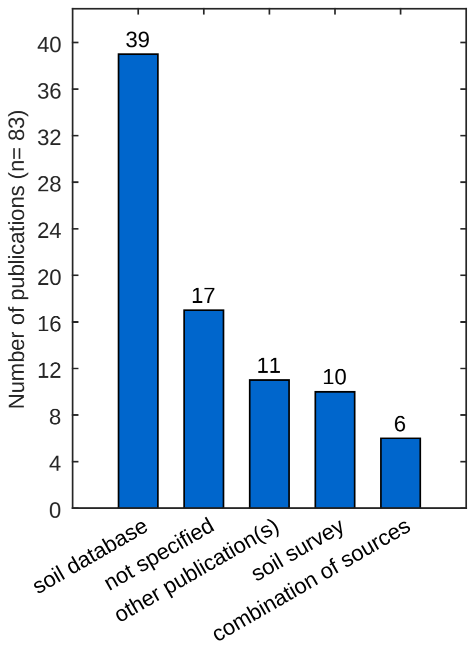

Figure 2.6: Types of soil data sources used in studies quantifying soil-based ecosystem services

Documentation It is essential for transparency and reproducibility that the methods used to assess soil-related ES are documented properly. A good example of method documentation is the ecosystem service assessment tool InVEST (Sharp et al., 2014), which is relatively widely used (e.g., Fu et al., 2014; Harmáčková and Vačkář, 2015; Nelson et al., 2009; Terrado et al., 2014). However, we found that most ES mapping studies applied methods that were incompletely documented. Only about a quarter of the studies provided fully documented methods, another quarter referred to methods used in other studies, and 43% of studies provided only partial information on the quantitative methods used or pointed only partially to other sources.

2.4 Soil functions in the applied soil science community

2.4.1 Overview of soil functions (literature) in considered countries

In our SFA method review, we searched for static SFA methods in Austrian, Dutch, French, German, Swiss, and UK guidelines. We found applicable SFA methods mostly in **German** guidelines. German federal states have had up to 20 years experience in SFA because the Federal Soil Protection Act, which was adopted in 1998, provides a legal basis for protecting soil functions. The main soil functions are explicitly defined in the act. Different federal states provide SFA guidelines (e.g., Lehle et al., 1995; Gröngröft et al., 2001; Hochfeld et al., 2003; Müller and Waldeck, 2011), and a national consortium (Ad-hoc-AG Boden, 2007) even evaluated the available methods and offered meta-information and recommendations for users of SFA methods. On an international level, the TUSEC project - inspired by German SFAs - proposed interesting and well documented SFA methods (Lehmann et al., 2013). In various case studies it has been demonstrated that SFA methods and the related soil function maps were successful in spatial planning procedures to foster the discussion about tradeoffs between the provision of ES and the development of new urban areas, for instance in the German federal state of North Rhine-Westphalia (Feldwisch et al., 2011), Bavaria (Danner et al., 2003) or Hamburg (Hochfeld et al., 2003). **Austria** has had nationwide SFA guidelines since 2013 (ÖNORM, 2013), and these were mostly based on German methods. Several regional studies were recently conducted (Geitner et al., 2005; Knoll et al., 2010). Haslmayr and Gerzabek (2010) performed a case study in which they determined whether German SFA methods could be adopted in Austria. They concluded that this is possible in principle but requires German soil taxonomy to be translated into Austrian soil taxonomy. Legislation in **France** does not yet cover soil functions, but there have been attempts to include and protect soil functions in the *Code de l'Environnement* (Lambert and Schellenberger, 2013). The French Environment and Energy Management Agency (Agence de l'Environnement et de la Maîtrise de l'Energie) has been running a project entitled *Fonctions environnementales et gestion du patrimoine sol*(GESSOL 2011) since 1998. Natural soil functions have been investigated in this project, but no static SFA methods have yet been published. Soil policy in the **Netherlands** has been developing for more than 30 years Netherlands (2010), but the central concept is *soil quality* rather than soil functions, so no SFA methods have been developed. A soil strategy based on soil functions is currently being developed in **Switzerland** and a National Research Programme on *Sustainable*

Use of Soil as a Resource (www.nrp68.ch) runs between 2013-2017. For example, assessment methods are available in Switzerland for determining the suitabilities of different soils for agricultural use (FAL, 1997; Jäggli et al., 1998), for assessing acidity buffering (Blaser et al., 2008; Zimmermann, 2011) and filtering and buffering of heavy metals (Keller and Desaules, 2001). The **UK** has had a soil strategy based on soil functions since 2009 (UK, 2009) and is working on implementing this strategy (Mayr et al., 2006). One SFA mentioned in Wadsworth and Hall (2005), provides an SFA for nutrient cycling.

We are aware that other methods suitable to assess soil functions not labelled as SFA, are available in Switzerland, and that this is probably also the case in the other countries.

2.4.2 Approaches to SFA methods and soil data for use in SFA methods

Suggested SFA methods

In this section, we present a catalogue of SFA methods that can be used in ES assessments to create maps of the soil-based supply of ecosystem services. We provide a list of SFA methods to assess regulation, habitat, and production functions via the eight soil sub-functions in Table 2.3. We selected SFA methods using criteria originally presented by Ad-hoc-AG Boden (2007) and Hochfeld (2004) with slight adaptations.

We determined that the methods should be 1) transferable to other regions, 2) well documented and therefore reproducible and transparent, 3) successfully applied and tested, and 4) simple and therefore easy to interpret. Most of the SFA methods listed in Table were developed in the frame of the german Federal Soil Protection Act mentioned above, and rely on soil data collected with standard soil mapping surveys.

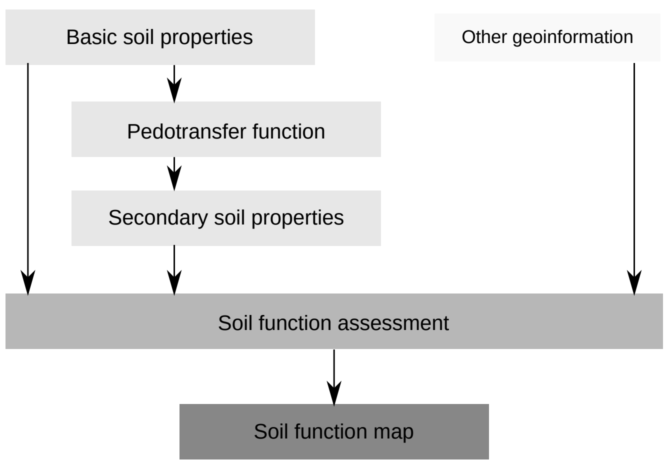

Figure 2.7: Soil function assessment workflow

Table 2.3: Static methods for assessing soil functions used by the applied soil science communities in some European countries, the methods assessment criterion and its soil property data and pedotransfer function requirements.

Soil (sub-)function assessment criteria	Texture	SOM[1]	pH	Bulk density	HP[2]	Stone content	Soil depth	Horizon depth	Other soil properties	**PTF[3]**	**Sources**
Regulation function											
Water cycling											
Soil capacity for water infiltration and storage, to control flooding	x	x		x	x	x	x	x		AWC, AC, Wcond	Danner et al. 2003, Bechler and Thot 2010, Lehmann et al. 2012, Calzolari et al. 2016
Water storage in topsoil available for plants	x	x		x		x	x	x	For peat soils: decomposition of organic material	Wcond	Gröngröft et al. 2001
Groundwater recharge	x	x		x		x	x	x	For peat soils: decomposition of organic material	AWC, RD, Wcond	Müller and Waldeck 2011
Nutrient cycling											
Nutrient availability to plants	x	x	x	x		x	x	x	Clay type	CEC	FAL 1997, Jäggli et al. 1998, Lehmann et al. 2012
Soil capacity for retaining soluble substances (e.g., nitrate)	x	x	x	x	x	x	x	x	Horizon designation, carbonate content	AWC, PR, AC, RD, S-value, BS, ANS, SSAmin, SSAhum	Danner et al. 2003, Müller and Waldeck 2011, Makó et al. 2017
Soil capacity for delivering nutrients to vegetation	x	x		x						Wcond, RD	Gröngröft et al. 2001
Filter and buffer for organic pollutants											
Soil capacity for sorbing and degrading organic pollutants	x	x	x	x	x	x	x	x	For peat soils: decomposition of organic material, horizon designation, soil type, soil structure	CEC, AWC, S-value, AC	Litz 1998, Müller and Waldeck 2011
Soil capacity for retaining organic pollutants	x	x	x	x	x	x	x	x	For peat soils: decomposition of organic material, horizon designation	Wcond, BS, ANS, SSAmin, SSAhum	Hochfeld et al. 2003, Makó et al. 2017
Potential for microbiological decomposition of organic pollutants		x	x						Soil structure	-	Lehmann et al. 2013
Filter and buffer for inorganic pollutants											
Sorption capacity for inorganic pollutants	x	x	x	x	x	x	x	x	For peat soils: decomposition of organic material, soil type	CEC, BS	DVWK 1988, Danner et al. 2003, Lehmann et al. 2013, Makó et al. 2017
Buffer for acids											

Table 2.3: Static methods for assessing soil functions used by the applied soil science communities in some European countries, the methods assessment criterion and its soil property data and pedotransfer function requirements.

Soil (sub-)function assessment criteria	Texture	SOM[1]	pH	Bulk density	HP[2]	Stone content	Soil depth	Horizon depth	Other soil properties	**PTF[3]**	**Sources**
Stocks of exchangeable bases and carbonates	x		x	x		x	x	x	Clay type, carbonate content	CEC, BS	Danner et al. 2003
Resilience against acidification (forest soils)	x	x	x	x		x	x	x		CEC, BS	Müller and Waldeck 2011
Buffering capacity	x				x				Soil type	Soil sulphate absorption capacity	Wadsworth and Hall 2005
State and resilience of soil acidification, risk of aluminium toxicity in soil	x	x	x	x	x	x	x	x		CEC, BS, ratio BC: aluminium cations	Blaser et al. 2008, Zimmermann 2011
Carbon pool											
Stock of soil organic carbon	x	x		x		x	x	x		-	Calzolari et al. 2016
Habitat function (hosting biodiversity)											
Habitat for plants											
Range of soil properties that provide specific conditions for diverse plant species	x	x		x	x	x	x	x	Carbonate content, soil type	AWC, CEC	Danner et al. 2003, Siemer et al. 2014
Natural soil fertility					x					AWC	Bechler and Thot 2010
Soils providing niches for plant species	x	x		x		x	x	x		AWC	Lehmann et al. 2013
Production function											
Agricultural production											
Long-term soil quality and crop yield potential (Münchenberg soil quality rating)	x	x		x	x	x	x	x	Soil structure	AWC, RD, PD, BA	Mueller et al. 2007
Natural soil fertility	x	x		x		x	x	x	Decomposition of organic material	AWC, AC, RD, CEC	Lehmann et al. 2013
Potential utilization and productivity capacity (adapted Storie Index)	x	x	x	x	x	x	x	x		AWC, SAR, EC	O'Geen 2008

[1] SOM = Soil organic matter

[2] HP = Hydromorphic property

[3] PTF = Pedotransfer function. AWC = available water capacity, AC = air capacity, ANS = anion sorption factor, BA= biological activity, BC = sum of base cations, BS = base saturation, CEC = cation exchange capacity (potential or effective), EC = soil electrical conductivity, PD = packing density, PR = percolation rate, PTF = Pedotransfer function, RD = rooting depth, SAR = sodium adsorption rate, SSAmin = specific surface area of mineral soil, SSAhum = specific surface area of humus, S-value = sum of exchangeable base cations, Wcond = saturated hydraulic conductivity

To assess soil functions, soil data, pedotranfer functions (PTFs) and sometimes other geoinformation is required, as shown in Figure 2.7. The assessment itself involves deducing further data (e.g, saturated hydraulic conductivity for a certain depth) and then translating different data to an ordinal scale (e.g., a combination of high saturated hydraulic conductivity and high water storage capacity leads to high capacity in regulating the water cycle). The scale is defined by soil scientists and will probably be specific to the soils of a given region and specific to legislative goals. The scale can be adjusted if necessary. An overview of the available methods and the required soil data and PTFs are presented in Table 2.3, and further information on soil data and PTFs is presented in section 2.4.3.

2.4.3 Availability of soil data and PTFs

The applicability and reliability of an SFA method largely depends on the availability of soil data. Soil data are key to quantifying the contributions of soils to ecosystem services (Dominati et al., 2014; Robinson et al., 2009). As outlined above, the majority of studies that consider at least one soil related ES acquired the necessary soil data from publicly available soil databases. At regional and national level soil data are available in many countries (see below). The majority of soil data origin from soil mapping surveys performed by national institutions. The main aim of a soil mapping survey is to capture the spatial distributions of soils and their properties. The mapping procedure involves, among other things, recording soil profile descriptions, analysing soil properties in the laboratory, describing landscape characteristics, and spatially delineating soil units. The main products of soil mapping surveys are soil maps and soil databases containing the information described above and the results of laboratory analyses ('soil information'). An advantage of performing a static SFA, as presented here, is that almost all the methods shown in Table 2.3 were developed in the context of soil mapping surveys and so rely only on soil data originating from soil mapping campaigns. The minimal basic soil dataset required to meet the data demands of a static SFA method is relatively small. The basic soil properties required for soil horizons up to a depth of at least 1 m (or - if the soil is more shallow than 1 m - up to soil depth) are the soil organic carbon content, texture (clay and silt contents), pH, stone content, bulk density (or pore volume), and soil hydromorphic properties (e.g., indications on stagnant soil horizons, drainage and water logging data). These soil properties can be regarded as the minimum dataset required to allow at least some basic regulation, habitat, and production sub-functions to be assessed (see Table 2.3). Assessing other soil sub-functions requires data for other soil properties, e.g., the carbonate content, soil aggregate classes (to allow the soil structure to be described), nutrient status, cation exchange capacity, and base saturation.

Most SFA methods also require PTFs. PTFs are indispensable for deriving soil properties ('secondary soil properties ') that are difficult to measure or costly to determine from basic soil properties Bouma (1989). PTFs are mostly used when estimating soil hydrological characteristics, such as the saturated hydraulic conductivity or the plant-available water capacity (Wösten et al., 2001; Vereecken et al., 2016). Tools have been developed to improve the applicability of PTFs for soil hydrological properties. Widely used tools include ROSETTA (Schaap et al., 2001), HYPRES (Wösten et al., 2001), and SOILPAR (Acutis and Donatelli, 2003). Each of these PTFs is only applicable to a specific geographical area and only for the ranges of soil property values with which the PTFs were developed but efforts have recently been made to develop common PTFs for soil hydrological properties that are valid at the European scale (Tóth et al., 2015). In general, the PTF concept can be applied to any soil attribute, and numerous PTFs have been developed based on the national soil datasets of many countries for bulk density, cation exchange capacity and base saturation. Overviews of PTFs have been presented by McBratney et al. (2002) and Vereecken et al. (2016). McBratney et al. (2011) noted the importance of checking the validity of a PTF for the particular study region of interest and identified selection criteria.

We anticipate that improved soil data availability will make incorporating soil functions in ES studies substantially easier in future. There is a trend at the international level towards harmonizing and coupling national soil datasets. In the past, many regional and national soil information sources were scattered, and the availability of soil data was often limited, but much progress has been made in the last decade in improving soil data infrastructure and online access for end users. Data infrastructure improvements, soil harmonization programmes, and online interface technologies for the end users of soil data will over the next few years dramatically improve the availability of soil datasets (Rossiter, 2016). The compilation of soil information sources maintained by Rossiter (2016) and a review published by Omuto et al. (2013) provide valuable overviews of soil information sources available worldwide. In many countries, soil data required for local ES assessment studies can be acquired from national soil databases that have fine spatial resolutions. For instance, as well as the overview provided by Rossiter (2016), the European Soil Data Centre (http://esdac.jrc.ec.europa.eu) maintains web directories of sources of regional and national soil information. Several international programmes (e.g., activities initiated by the Global Soil Partnership, the Harmonized World Soil Database, ISRIC World Soil Information, and the GlobalSoilMap consortium) aimed at increasing the availability of harmonized soil datasets at the continental and global level are currently underway. The Global Soil Partnership is a consortium coordinated by the Food and Agriculture Organization that was established in 2012 to improve "*governance of the limited soil resources of the planet...* ". The Global Soil Partnership addresses *five pillars of action*, Pillar 4 being to improve the quantity and quality of soil data. A review of the status of global soil information (Omuto et al., 2013) led to the development of a plan to implement a global soil information system. The backbone of Pillar 4 is a network of international soil information institutions. The most widely used soil dataset at the global scale is the Harmonized World Soil Database (FAO, 2012), which contains soil property data and soil units for fixed soil depths in a raster format (at a spatial resolution of approximately 1 km x 1 km). The International Soil Reference and Information Center (www.isric.org) has made further contributions to addressing increasing demand for soil information. The center has developed spatial data infrastructure and harmonized soil property data further than previously achieved, and has established a World Soil Information Service (Ribeiro et al., 2015). The SoilGrids platform hosted by the center (http://soilgrids.org) is an important tool that provides basic soil property and soil unit data for fixed soil depths at a resolution of 1 km x 1 km using digital soil mapping methodologies (Hengl et al., 2014). An end user can easily access soil data from the SoilGrids platform using a web interface, tablet, or smartphone (using the *Soil-Info* application). The automatic mapping procedure recently added to the SoilGrids platform has been successfully used to map the soil properties of African soils at a spatial resolution of 250 m x 250 m (Hengl et al., 2015). Another initiative is the GlobalSoilMap project, the aim of which is to build a free downloadable database of key soil properties at multiple depths (Sanchez et al., 2009). Global mapping specifications for this project have been defined, and the ambitious goal is to produce maps of basic soil properties using digital soil mapping techniques at a spatial resolution of 100 m x 100 m (Arrouays et al., 2014). At the continental level, the European Soil Data Centre has produced a web-based soil portal that provides access to the European Soil Database and related products at http://eusoils.jrc.ec.europa.eu (Panagos et al., 2012). This soil portal is the focal point for soil data and information in the European Union. The European Soil Database contains four well documented databases of soil geographical units, PTFs, soil profile analysis results, and soil hydraulic properties. Notably, the European Soil Database also contains measurements of the basic soil properties of topsoil at approximately 22000 sites across Europe from the Land Use/Land Cover Area Frame Survey (Tóth et al., 2013). The Land Use/Land Cover Area Frame Survey topsoil database can easily be used to assess soil functions of topsoils or to map soil properties over the whole geographical extent of Europe (Ballabio et al., 2016). The efforts described above to improve the distribution of soil information between disciplines therefore make the information available for use in interdisciplinary ES mapping studies. It should be noted, that in such interdisciplinary studies, soil scientist may offer valuable expertise and knowledge about the soil system and soil processes, interpretation of soil data sets and practice in soil management. Such soil expertise goes far beyond the application of simplified SFA methods and advances the discussions with stakeholders (Bouma et al., 2012).

2.5 Conclusions

Human well-being relies strongly on soil resources, so soil should be better integrated into ES assessments. ES studies should address, in addition to other environmental issues, the crucial roles soils make in supplying ES and allow decisions to be made to support the sustainable use of soils. However, soil has multiple functions and has many functions and sub-functions in terms of regulation, habitat, and production, so multiple soil functions (rather than one general soil function) must be taken into account. Our literature review clearly indicates that the multi-functionalities of soils have barely been taken into account in ES assessment studies to date. The aim of this study was to help people involved in quantifying and mapping ES to better account for the important roles of soils. We linked the ES concept with approved assessment methods developed in recent decades by the applied soil science community. If an ES study is intended to include the multi-functionality of soil, the list of simplified SFA methods presented here could be a useful starting point. The simple static assessment methods described here can easily be applied using available soil databases and are particularly suitable for ES studies in the context of land-use planning. There are approved SFA methods for characterizing various regulation and production functions of soils, but further efforts to establish applicable methods that link soil biology and soil biodiversity to ES are required.

Acknowledgements This study was part of the *Predictive mapping of soil properties for the evaluation of soil functions at regional scale* project (PMSoil; project number 406840-143096) and the *Matching soil functions and soil uses in space and time for sustainable spatial development and land management*project (OPSOL; project number 408640-143092), funded by the Swiss National Science Foundation within the framework of the National Research Programme *Sustainable Use of Soil as a Resource* (NRP 68), www.nrp68.ch.

Chapter 3

Assessment of soil multi-functionality

Chapter 3 is submitted to Geoderma Regional and in revision as Greiner, L., Nussbaum, M., Papritz, A., Zimmermann, S., Fraefel, M., Schwab, P., Grêt-Regamey, A. & Keller, A.. Assessment of soil multi-functionality to support the sustainable use of soil resources on the Swiss Plateau.

Abstract

Spatial information on soils and their abilities to fulfil their functions is key to sustainable soil resource use. Maps indicating how soils fulfil their static functions, e.g., regulating nutrient and water flows, providing appropriate habitats, and supporting biomass production, have allowed soil information to be embedded in spatial planning programmes. We adapted 10 static soil function assessment (SFA) methods and applied them to agricultural soils in a study area on the Swiss Plateau. Soil function maps were created by applying the SFA methods to maps of eight basic soil properties generated previously using digital soil mapping techniques. The soil function maps were compared with results obtained by applying the SFA methods to data for more than 7000 soil profiles to determine how reasonable the maps were. Soil in the study area had distinctive spatial patterns for most of the regulation, habitat, and production functions, clearly indicating the multiple roles played by soil in supporting ecosystem services. The fulfilment of individual soil functions is linked to the inherent soil properties, the terrain, and climatic conditions. The soil function maps agreed well with the SFA results for the profiles in terms of land use, soil type, and drainage class. Four aggregation rulees were tested to give total assessment values (soil indices). Aggregating the 10 soil functions into an overall soil functionality value gave quite diverse spatial patterns, indicating that merging might average out the spatial characteristics

of certain soil functions. We conclude that a quite comprehensive set of soil functions can be assessed using spatial information for eight basic soil properties to a soil depth of at least 1 m and approved pedotransfer functions for secondary soil properties. SFA methods for the production function are well established, but methods for assessing habitat and regulation functions need to be developed further. This is also true for forest soils, for which SFA methods are yet to be established.

3.1 Introduction

Soil is a valuable resource, and land take is one of the most severe soil threats because sealing the soil causes the complete loss of most soil functions. Approximately 107 000 ha were lost each year between 2006 and 2012 through construction activity in Europe (EEA, 2017). In most countries, most land take occurs at the expense of agricultural soils. Diverging land and soil policies aimed at meeting both agronomic and environmental targets and opposing interests have to be balanced in the decision-making process in many countries (Valujeva et al., 2016). Switzerland is a good example of a European country in terms of the very limited soil resources available and the many demands for land. About $1{\times}10^6$ ha of agricultural land (grassland and arable land) are located at the Swiss Plateau, i.e. 0.14 ha of agricultural area per capita. Urban areas increased by nearly 25% (584 km^2) between 1985 and 2009, and roughly 90% of urban areas were developed at the expense of agricultural soil (Altwegg, 2015). Urban development has occurred in many small towns and cities, so soil loss has occurred at urban peripheries across the whole of Switzerland. New regulations were recently introduced to limit urban sprawl, and tools have been developed to support the spatial planning decision-making process (Densham, 1991; Grêt-Regamey et al., 2017a; Matthews et al., 1999). Few tools are available for use in spatial planning procedures to support the sustainable use of soil resources, and those that are available have yet to be used (Tóth, 2012).

The capacity of soils to fulfil essential functions for society and the environment should be considered in the spatial planning decision-making process (Bouma, 2010; Greiner et al., 2017; Haygarth and Ritz, 2009). Easy-to-use and simplified methods for assessing soil functions are required to determine the multi-functionalities of soils and present the results to stakeholders involved in spatial planning.

A number of different concepts have been investigated to help communicate the contributions of soils and soil functions to ecosystem goods and services to humans and society. Among them is the ecosystem services (ESs) concept. Various authors have argued that soils need to be considered in ES studies (Dominati et al., 2010; Robinson et al., 2012; Schwilch et al., 2016), but soils have hardly been considered in previous

ES mapping studies (Greiner et al., 2017). The concepts of soil health (Doran, 2002), soil quality (Karlen et al., 2003), soil security (Koch et al., 2013; McBratney et al., 2014), and soil stocks (Hewitt et al., 2015) also help communicate the importance of soils to workers in various disciplines, stakeholders, and policymakers. A possible approach, which is increasingly being performed in some European countries, is that of quantifying the various individual functions of soils (Feldwisch et al., 2006; Miller, 2012; Lehmann et al., 2013; Tóth et al., 2013; Calzolari et al., 2016; Haslmayr et al., 2016; Valujeva et al., 2016). The concept of Soil Function Assessment (SFA) involves that soils can be rated according to their capacity to fulfill a given function (soil function fulfilment , SFF) (Greiner et al., 2017). The assessment of soil functions can be used to integrate soil into concepts supporting decision making and is focused on the multi-functionality of soils and on quantifying the various individual functions of soils (Dominati et al., 2010; EU, 2006; Haygarth and Ritz, 2009; Schwilch et al., 2016; Tóth et al., 2013). The SFA concept allows soil and its functions to be incorporated into spatial planning procedures in simple terms. Maps showing SFFs for a broad range of soil functions help to communicate soil spatial variability and multi-functionality to spatial planners and workers in other disciplines, who are not familiar with soil taxonomy and soil science (Bouma, 2014; Haslmayr et al., 2016).

Up to now, most relevant publications have focused on mapping aspects of individual soil functions (Makó et al., 2017), on developing soil function proxies (Schulte et al., 2014; Tóth et al., 2013), on specific soil types and land uses (Dominati et al., 2014), or on adapting existing SFA methods to available soil data (Haslmayr et al., 2016). Multiple soil functions have been assessed using a static assessment approach, i.e. considering mainly soil properties that do not change or change very slowly. In contrast to dynamic approaches, the impacts of land use and land management practices are not taken into account opposed to (semi-)dynamic SFA taking into account these factors and more dynamic soil properties as well (Greiner et al., 2017). Multiple soil functions have been assessed - and jointly at spatial scales relevant to spatial planners in very few studies (Calzolari et al., 2016).

The objective of this study was to select a set of simplified SFA methods capturing soil multi-functionality and contributions to ecosystem services (therefore useful for spatial planning) and to apply these methods in a case study. The 10 SFA methods selected covered the production, regulation, and habitat functions of agricultural soils. The methods were applied to a study area on the Swiss Plateau for which maps of basic soil properties have been generated using digital soil mapping procedures (Nussbaum et al., 2017). The benefits and pitfalls of combining individual soil function maps to provide an overall indicator of soil functionality to address the particular needs of spatial planners are discussed.

3.2 Materials and Methods

3.2.1 General approach

We previously reviewed a number of assessment methods developed and approved by the applied soil science community in recent decades to approximate soil multi-functionality using static assessment methods (Greiner et al., 2017). Here, we quantified the general capacity of a soil to fulfil a specific function independent of the land use and of land management practices considering static or slowly changing soil properties for the assessment, defined as 'static SFA'. Such static SFA approaches are well suited to supporting the sustainable use of soil resources in the land-use planning process (Lehmann and Stahr, 2010). We selected 10 methods from this large set of SFA methods (Table 3.1), assessing regulation functions (water, nutrients, heavy metals, organic compounds, acids, carbon), habitat functions (plants, microorganisms) and production function (agriculture).

Our choice of soil functions intends to cover soil multi-functionality in terms of regulation, habitat and production functions and is based on a literature review (Greiner et al., 2017). Our choice corresponds with the one listed in the European soil thematic strategy (EU, 2006) and presented by various other authors (Banwart et al., 2017; Calzolari et al., 2016; Dominati et al., 2014; Haslmayr et al., 2016; Haygarth and Ritz, 2009). We chose the SFA methods according to the criteria of Ad-hoc-AG Boden (2007) and took into account the quality of the documentation available, the transparency and interpretability of the methods, and the frequency with which the methods have been applied to case studies.

We preferred SFA methods relying on measurements of physical, chemical, and biological soil properties. We made exceptions for soil taxonomic information on water regimes and associated hydromorphic features such as waterlogging and stagnant horizons. This was because these are particularly relevant to SFAs because no single physical property is available to describe them, and they are used to assess almost all regulation, habitat, and production functions. We now provide a brief description of the 10 SFA methods used; further information on these is given in Appendix A.2.

Table 3.1: Overview of the selected soil function assessment methods used in this study, together with the soil functions and sub-functions and soil data used.

Soil (sub-)function **Assessment criterion**	**Reference**	Clay	Silt	SOM[1]	Stone content	pH	Depth	Hydromoprhy	Drainage class	**PTF**[2]	**Other data**[3]	**Abbreviation**
Regulation function												
Water cycle												

Table 3.1: Overview of the selected soil function assessment methods used in this study, together with the soil functions and sub-functions and soil data used.

Soil (sub-)function **Assessment criterion**	**Reference**	Clay	Silt	SOM[1]	Stone content	pH	Depth	Hydromorphy	Drainage class	**PTF**[2]	**Other data**[3]	**Abbreviation**
Water infiltration (cm/d) and storage capacity (mm/m^2) combined in a semi-quantitative lookup table	Danner et al. (2003)	x	x	x	x		x	x		BD, SHC, AWC, AAC	Slope, geology, climate	R-water
Nutrient cycle												
Nutrient storage capacity of fine earth to a soil depth of 1 m (mol$_c$/m^2)	Lehmann et al. (2013)	x	x	x	x	x	x	x		BD, CECeff		R-nutric
Nutrient losses												
Retention capacity against nutrient loss, e.g., nitrate (semi-quantitative lookup tables)	Jäggli et al. (1998)	x	x	x	x		x	x	x	BD	Slope, geology, climate	R-nutril
Heavy metals												
Sorption capacity for inorganic pollutants (semi-quantitative lookup tables)	DVWK (1988)_	x		x	x	x	x			BD, AWC, CEC-pot, S-value		R-icont
Organic compounds												
Organic contaminant retention capacities against percolation into groundwater (semi-quantitative lookup tables)	Litz (1998)	x	x	x	x	x	x	x	x	BD	Properties organic compounds, MAT, MAET, climate	R-ocont
Acids and contaminats												
Buffering and binding capacity for acids and contaminants assessed using the soil organic matter content (in kg/m^2), clay content (in kg/m^2), and maximum pH to the assessment depth combined in a semi-quantitative lookup table	Bechler and Toth (2010)	x		x	x	x	x	x		BD		R-acid
Carbon cycle												
Amount of organic matter in soil (C-storage) (kg C/m^2)	-			x	x		x			BD		R-carbon
Habitat function												
Plants												
Soils providing niches for plant species. Very dry, wet, or low nutrient properties (assessed using the available water capacity in mm, the presence of hydromorphic horizon, and the effective cation exchange capacity in cmol$_c$/kg)	Siemer et al. (2014)	x	x	x		x	x	x		BD, AWC		H-plant
Microorganisms												
Amount of microbial biomass (mg/kg dried soil)	-	x	x	x		x	x			MB	Land use	H-microorg

Table 3.1: Overview of the selected soil function assessment methods used in this study, together with the soil functions and sub-functions and soil data used.

Soil (sub-)function **Assessment criterion**	**Reference**	Clay	Silt	SOM[1]	Stone content	pH	Depth	Hydromoprhy	Drainage class	**PTF**[2]	**Other data**[3]	**Abbreviation**
Production function												
Agricultural production												
Capability for agricultural production (semi-quantitative lookup tables)	Jäggli et al. (1998)	x	x	x	x	x	x	x	x	BD	Relief, slope, climate	P-agri

[1]SOM: soil organic matter

[2]AAC: available air capacity in mm, AWC: available water capacity, BD: bulk density, CECpot and CECeff: potential and effective cation exchange capacity, MB: microbial biomass, SHC: saturated hydraulic conductivity, S-value: amount of exchangeably bound basic cations

[3] MAT: mean annual temperature, MAET: mean annual evapotranspiration

3.2.2 Soil function assessment methods

Regulation of the water cycle: water infiltration and storage capacity (R-water)

Soil plays an important role in the water cycle. The presence of soil with a high capacity to retain plant-available water and a large water infiltration capacity decreases the risk of floods (FAO, 2017a; Haines-Young and Potschin, 2013). We assessed the water cycle regulation capacity of soil using an SFA method proposed by Danner et al. (2003) that is comparable to other methods (Bechler and Toth, 2010; Calzolari et al., 2016; Lehmann et al., 2013) and combines assessments of the water storage capacity (WSC, in mm) and saturated hydraulic conductivity (SHC, in cm/day) of a soil to a reference depth of 1 m. If there are soil horizons with stagnic, gleyic or anoxic conditions less than 1 m deep, only the layer above these horizons is taken into account. WSC and SHC were identified using pedotransfer functions (PTF) published in German soil mapping guidelines (Goossens et al., 2005). The WSC is based on the available water capacity and available air capacity, both estimated using PTFs based on the soil texture, bulk density, organic matter content, and stone content of each soil horizon and summed to the reference depth of 1 m. The PTF used to estimate the SHC requires the same input data, and the estimated SHCs for the different soil horizons are weighted according to the depth of the soil horizons to an average SHC along the 1 m soil profile. The final assessment score is based on a lookup table combining the SHCs and WSCs into a simple ordinal assessment scale with five levels (from 1, very low to 5, very high). Higher WSCs and SHCs are given high fulfilment values for this sub-function. It should be noted that this SFA method is only valid for soils with low stone contents typical of agricultural soils.

Regulation of the nutrient cycle: the nutrient storage capacity (R-nutric)

The weathering of parent materials and the decomposition of organic materials are important to the nutrient cycle. Biogeochemical cycles in soil transform, transport, and renew mineral nutrients essential to terrestrial plant growth (Brady and Weil, 2010). The nutrient storage capacity (in mol_c/m^2) of a soil is one of the most important parameters controlling the nutrient cycle. We calculated the nutrient storage capacity using a previously published method (Lehmann et al., 2013), multiplying the fine earth fraction (masses of clay and silt and of organic matter) for each soil horizon by the effective cation exchange capacity (CEC_{eff}) and summing the results to the reference depth of 1 m. CEC measurements were not available for all the soils in our study area (Walthert et al., 2016), so we predicted the CECs using a previously published PTF (Goossens et al., 2005) for mineral soils, which requires data on the texture, stone content, organic matter content, bulk density, and pH of the soil.

Regulation of nutrient losses: retention capacity versus nutrient losses (R-nutril)

The method proposed by Jäggli et al. (1998) was used to evaluate the ability of a soil to prevent soil nutrient loss through runoff and percolation to the groundwater and surface water.. The SFA method takes into account the basic soil properties and the hydromorphic properties of the soil (water logging). Environmental site conditions such as the geology (Swisstopo, 2008), drainage system, slope, altitude, and climate (FOAG, 2012) are also taken into consideration. The method uses combined lookup tables for assessing the capacities of soils to prevent nutrient losses. High retention scores are given for non-compacted soil (topsoil bulk density <1.4 g/cm^3) and deep soil (depth >50 cm) without stagnic or gleyic soil layers on flat sites with slopes $<15\%$, organic matter contents $<30\%$, and clay contents $>10\%$.

Regulation of heavy metals: sorption capacity for inorganic pollutants (R-icont)

Several types of amendments, such as commercial fertilizers, animal manure, compost, waste-derived fertilizers, and pesticides, are applied to agricultural soils. These materials contain macronutrients and trace metals such as cadmium, copper, uranium, and zinc (Bigalke et al., 2017; Keller and Schulin, 2003; Nziguheba and Smolders, 2008). Soil can adsorb and bind such trace elements, making them less available to plants and soil organisms and preventing their transport to deeper soil layers or the groundwater. The fates and behaviours of trace metals in soil have been investigated in many studies, and sorption isotherms describing metal partitioning between the solid phase and soil solution have been developed (e.g., Horn et al., 2004). A simplified approach based on such studies was developed in the 1980s by the German Association of Water, Wastewater, and Waste (DVWK, 1988), with the aim of preventing trace element pollution of groundwater. The SFA method evaluates the capacity of the topsoil (0–30 cm deep) to retain trace metal cations based on the sorption sites on organic matter, clay minerals, and sesquioxides, taking into account the soil pH and redox potential (DVWK, 1988). We assessed the capacities of soils to retain cadmium, copper, and zinc.

Regulation of organic compounds: capacity to prevent organic contaminants from percolating into the groundwater (R-ocont)

Many organic compounds have been synthesized for industrial, agricultural, and other uses (Valentín et al., 2013). In particular, potentially persistent organic contaminants often end up in the soil in agricultural systems (Valentín et al., 2013). For instance, current European agricultural pest management practices have led to pesticide residues in soils (Chiaia-Hernandez et al., 2017), or pharmaceutical antibiotics enter soil through the application of animal manure (Thiele-Bruhn, 2003). The current political debates about the environmental risks posed by pesticide application in Switzerland (FOAG, 2016) and the frequent exceedance of pesticide thresholds for groundwater and surface water (Moschet et al., 2014) led us to apply the SFA method proposed by Litz (1998) to four herbicides frequently used in Switzerland, namely glyphosate, pendimethalin, metamitron, and isoproturon (Franzen et al., 2017). The method agrees with that published in the Food and Agriculture Organization of the United Nations manual on the assessment of soil contamination (FAO, 2000). The chemical properties of the pesticides and parameters describing the behaviours of the pesticides in soil were taken from the Pesticide Property Database (PPDB, 2017). The first step of the SFA method is to assess the potential sorption and fixation of an organic compound to clay and organic material (binding) and the potential ability of a soil to decompose the organic compound through biological activity (decomposition). The second step is to combine these assessment criteria to evaluate the potential for the soil to retain the compound (retention).

The binding of a chemical compound is estimated using lookup tables for the sorption of organic compounds to soil organic matter and clay minerals for topsoil (0–30 cm deep). Sorption constants for relevant compounds and the relationships between the sorption constants and soil pH are also considered. Biological activity (used to evaluate the decomposition of compounds in soil) is related to the annual mean temperature (average 7.2 °C for Switzerland between 1981 and 2010) (Meteoschweiz, 2014) and the degradation time for organic compounds in 90 days in aerobic soil (DT90 aerobic, field). The soil moisture content in spring is derived from the available water capacity and the climatic suitability class of the soil (FOAG, 2012). Other environmental factors considered in the SFA method are the annual climatic water balance (HADES, 2017), the CEC of the soil, the presence of a waterlogged soil horizon in the topsoil, and the volatility of the organic compound of interest (as the Henry constant) (Litz, 1998). The retention of a specific compound in the soil is determined using lookup tables and the potential water connectivity at a given location (Alder et al., 2013). The final results of this SFA method are the mean retention values for the four herbicides mentioned above.

Regulation of acids: buffering of acids in the soil (R-acid)

Nitrogen oxides emitted by traffic and industrial plants and ammonia released by animal manure can be deposited to soil. This is called atmospheric nitrogen deposition, which has increased substantially in recent decades. Nitrogen deposition exceeds the critical load for more than 90% (by area) of the forests and 30% (by area) of the species-rich grassland areas in Switzerland (Bühlmann et al., 2015). Nitrogen deposition unintentionally fertilizes the soil and may slowly acidify the soil, depending on the acid-buffering capacity of the soil. The ability of a soil to buffer acids was accounted for using the SFA method proposed by Bechler and Toth (2010). This SFA method also considers pollutant binding by soil, but we focused mainly on the regulation of acids. The method takes into account soil pH and the amounts of clay and organic matter present to a depth of 1 m. The buffering capacity increases as the amounts of clay and organic matter increase, and the buffering capacities are higher for neutral pH soils than for other soils.

Regulation of the carbon cycle: the amount of carbon stored (R-carbon)

The role of soil in the carbon cycle in the climate change context is often considered in ES assessment studies (Greiner et al., 2017). Carbon storage in soil is often taken into account in national greenhouse gas inventories (NIR, 2017). It has been assumed in recent decades that Swiss forest soils are carbon sinks (NIR, 2017). In the same way as in other studies (e.g., Calzolari et al., 2016; Le Clec'h et al., 2016; Tsonkova et al., 2014), we calculated the carbon stock in soil to a reference depth of 1 m using the organic matter content, bulk density, and stone content of each soil horizon, for the assessment table and an overview see Appendix A.2.

Habitats for plants: soil providing niches for plant species (H-plant)

Soil is an important habitat for many species of microorganisms, flora, and fauna (FAO and ITPS, 2015). The aim of protecting soil habitat functions is to preserve soil biodiversity and related ecosystem services to humans. Indicators for monitoring soil biodiversity are being developed, and many indicators have been suggested (Griffiths et al., 2016). Some indicators involve species richness or the relative abundances of certain (key) species (Wagg et al., 2014), while others use the physical and chemical properties of soil to predict the biodiversity potential of the soil habitat (Aksoy et al., 2017). Many factors determine soil biodiversity patterns, but the relative contributions of the different factors are still largely unknown (Keesstra et al., 2016). We used the method proposed by Siemer et al. (2014) to assess the capacities of soils to provide niches for rare plant species. The method rates sites with extreme soil properties that lead to relatively dry or wet soil conditions. Such extreme soil conditions, in terms of the nutrient and water cycle, provide niches for rare plant populations. This SFA method gives a high score for soil with a low available water capacity ($<$70 mm in total to 1 m deep) and a low CEC ($<$10 cmol$_c$/kg averaged to 1 m deep). Such properties indicate rather dry conditions and low nutrient availability and soil with stagnic, gleyic, or anoxic soil horizons in the topsoil (0–20 cm in wet soil conditions). The method indicates whether such extreme conditions are present and whether the soil can provide a niche for rare plant species.

Habitats for microorganisms: the amount of microbial biomass present (H-microorg)

Microorganisms are important to many processes, such as organic matter decomposition, nutrient cycling, soil structure formation, and pest regulation (Pulleman et al., 2012). We derived the microbial biomass from basic soil properties to indicate soil biological activity. This PTF was derived using data for several hundred grassland sites (using data for soil 0–20 cm deep) and arable sites (using data for soil 0–10 cm deep) across Switzerland. Microbial biomass was measured at these sites in spring before the first fertilizer application of the year (Oberholzer and Scheid, 2007). The equations used by (Oberholzer and Scheid, 2007) were

$\ln(BM) = 3.58 + 0.82 \times * \ln(OM) + 0.15 \times * pH + 0.31 \times * \ln(clay) + 0.005 \times * sand$ (arable land)

and

$\ln(BM) = 3.61 + 0.92 \times * \ln(OM) + 0.28 \times * pH + 0.17 \times * \ln(clay)$ (grassland),

where BM is the microbial biomass in soil (in mg/kg dry soil), OM is the soil organic matter (in %), pH is the soil pH determined in a $CaCl_2$ solution, clay is the clay content of the soil (in %), and sand is the sand content of the soil (in %). A high microbial biomass indicates high potential in terms of the amount of biota present, biological activity, and metabolizable nutrients (which also support a large amount of biota and give rise to high biological activity) (Oberholzer and Scheid, 2007). A similar approach was taken by Beylich et al. (2005), who used the amount of microbial biomass to determine the SFF for soil as a microorganism habitat. The assessment table and a method overview is given in Appendix A.2.

Agricultural production: capability for agricultural production (P-agri)

Soil is one of the most important factors affecting sustainable agricultural production, and soil quality is often assessed in terms of the capacity of the soil to provide food, fibre, and biomass (Adhikari and Hartemink, 2016). Various methods have been developed to assess the suitability of soil for agricultural production (e.g., Kirchmann and Andersson, 2001; Klingebiel and Montgomery, 1961; Mueller et al., 2007; Storie, 1978; Sun et al., 2012). Many of these methods have been adapted to national environmental conditions and agricultural practices. The Swiss method for assessing the suitability of soil for agricultural crops was developed in the context of soil mapping guidelines (FAL, 1997) and was refined by Jäggli et al. (1998). This SFA method combines basic soil properties, climate data (climate suitability classes dependent on the temperature, precipitation, and the length of the growing period (FOAG, 2012)), and the site conditions (slope and topography) and classifies the suitability of a soil for growing crops into 10 classes. The assessment uses a series of generic rules for the rooting depth, drainage class, soil pH, bulk density, stone content, clay content, silt content, and organic matter content, which could restrict crop growth. In the SFA method, the optimal suitability of soil for crop production is defined as a rooting depth $>$50 cm, a stone content $<$10%, a clay content of 10%–30%, a silt content $<$50%, a humus content $<$10%, and a pH $>$5.1, and climate and geomorphology are assumed not to restrict agriculture.

3.2.3 Calibration of the ordinal assessment scales

Non-scientists often find SFF scores on an ordinal scale from low/poor to high/rich are much more comprehensible than physical units (Bouma, 2014). The assessment scale, which transforms physical units to ordinal scores, allows SFF to be evaluated according to the selected criteria, calibrated to a given region or country. This makes sense because soil resources should be managed within the framework of a given region or country, so the soil types found in the region of interest are relevant to the assessment scale. The variations indicate the soil management options. An assessment scale specific to Switzerland was established using the 10 SFA methods on data for about 100 Swiss Soil Monitoring Network (NABO) soil monitoring sites across Switzerland. Comprehensive soil profile data were available for these sites (Gubler et al., 2015). The monitoring sites represented very diverse lithologies, soil types, land uses, altitudes, and climate conditions across the country. The assessment scales for the 10 SFA methods were calibrated according to the frequencies of the physical SFA results for these monitoring sites. For instance, the assessment scale for the nutrient storage capacity is based on one soil property and was defined as 1 (very low), CEC_{eff} = 0–25 mol/m^2 (meaning 20% of the soil monitoring sites had CEC_{eff}s of 0–25mol/m^2); 2 (low), 25–50 mol/m^2; 3 (medium), 50–100 mol/m^2; 4 (high), 100–200 mol/m^2; and 5 (very high), $>$200 mol/m^2 (meaning only 20% of the monitoring sites had CEC_{eff}s $>$200 mol/m^2).

3.2.4 Aggregation of individual soil functions

It has been proposed by a number of researchers that individual soil function maps should be combined to give a single indicator, and rules to achieve this have been published (Feldwisch et al., 2006; Haslmayr et al., 2016; Miller, 2012). Combining individual soil function maps has the clear advantage to be easily communicated to stakeholders and implemented than multiple indicators. We later use the term soil index (SI) for such an aggregated total soil function assessment value. We assessed four approaches to merging the results of the 10 SFA methods into one SI:

Rule A. Experts from the Swiss canton soil agencies assigned weights to individual soil functions. They considered R-water and P-agri to be the most important soil functions, and the other eight soil functions were considered to be less important (but all eight were equally important). We therefore assigned the weights w = 0.25 to R-water and P-agri and w = 0.0625 to the other soil functions.

Rule B. As for rule A, but determined through discussions with experts, who considered water retention and agricultural production most important. We assigned weights of w = 0.375 to R-water and P-agri and w=0.03125 to the other eight soil functions.

Rule C. The method proposed for use in Austria by Haslmayr et al. (2016) is an if-else flowchart. R-water, P-agri, H-plants, and R-acid were considered to be the most important soil functions. Soils in nature reserves were assigned the highest scores.

Rule D. A method proposed by Miller (2012), in which R-water, P-agri, H-plants, and the mean R-nutric, R-nutril, R-icont, R-ocont, and R-acid scores are used to indicate the average filtering and buffering function capacities. This method is also presented as an if-else flowchart.

3.2.5 Study area

We assessed the soil functions of an agricultural area of about 170 km^2 in the area around the Greifensee in the Canton of Zurich, Switzerland (Figure 3.1), its extent was defined by cantonal boundaries and coverage of APEX Swiss earth Observatory flight campaigns (www.seon.uzh.ch). The study involved several work packages. One covered the processes from point-data-harmonization of legacy soil data onwards (Walthert et al., 2016), and predicted soil properties required to perform SFA, using remote sensing (Diek et al., 2016) and refining of terrain modelling (Fraefel et al., 2014) to perform appropriate geostatistics (Nussbaum et al., 2017, 2018). Further details were given by Nussbaum et al. (2017).

There are various landscapes in the Greifensee region, including an aggradation area around the Greifensee, a plain between Volketswil and Uster, and a hillside (Jäggli et al., 1998). The different landscapes evolved on the heterogeneous lithology (Jäggli et al., 1998) of the Quaternary Molasse Basin (SKS, 2017). This resulted in very different soils in different areas, such as Fluvisols around the Greifensee, Luvisols with intermediate-to-deep soil on gravel sediment, Cambisols on moraines, Regosols on gravel-rich drumlins, and Gleysols and Histosols on compacted ground moraines. The region is at 390–840 m a.s.l., and the growing season is approximately 190 d/y. Most slopes are of 10%–15%, but slopes next to moraines are >35% (Jäggli et al., 1998). Agriculture is the predominant land use in the study area, and arable crops dominate in the northern part and grassland systems (dairy and mixed farming) dominate in the southern part.

3.2.6 Data

The data requirements of the 10 SFA methods are shown in Table 3.1. We assessed soil functions for predicted soil properties (20 m grid, Nussbaum et al. (2017)), see Table 3.1, and harmonized legacy soil profiles (n = 7578, Walthert et al. (2016)). The legacy soil data were obtained from a 1:5000 soil mapping survey conducted between 1988 and 1997 (Jäggli et al., 1998). In that survey, about 4000 soil profiles from across the Canton of Zurich were accessed, and 1003 of these were in our study area. In addition to these data for the Canton of Zurich, we used soil profile datasets from the Canton of Berne (n = 2409) and a dataset for Swiss forest soils (n = 1046) (Walthert et al., 2016). In total, 7578 sets of soil profile data were used to assess the reasonableness of the 10 SFA methods. Moreover, NABO network soil profile data for about 100 monitoring sites across Switzerland (Gubler et al., 2015) were used to cover the great range of properties of Swiss soils when deriving the ordinal assessment scales of soil functions (see Section 3.2.3).

The hydromorphic features of the soils played important roles in most of the SFA methods because soil functions can be restricted if the soil water cycle is disturbed by the presence of stagnic, gleyig, or anoxic soil horizons. Information on hydromorphic features was obtained from the results of soil mapping surveys in which taxonomic data were provided that needed to be transformed into classes suitable for SFA (Appendix A.2).

The bulk density was predicted using a PTF calibrated using data for Swiss soils (Nussbaum and Papritz, 2015). Other PTFs were used according to the SFA methods.

Several SFA methods (R-water, R-nutril, R-ocont, H-microorg, and P-agri) required, in addition to soil data, information on the terrain (see Appendix A.2), climate, geological and geomorphological situation, organic compound properties, and land use for each site. The required data and the data sources used are described earlier in the materials and methods section.

3.2.7 Evaluation of the reasonableness

SFA results cannot be validated (Calzolari et al., 2016) but we can find indications how reasonable our SFA results are. We concentrated this evaluation on the harmonized soil legacy data to avoid questions of validity of predicted soil properties translating through SFA. We compared the SFA results for the three main soil types of the study region (Walthert et al., 2016), as well as for land use and drainage class (n = 4117-7578 soil profiles, depending on soil function, Walthert et al. (2016)). The validation and evaluation of the input raster soil properties were described in previous publications

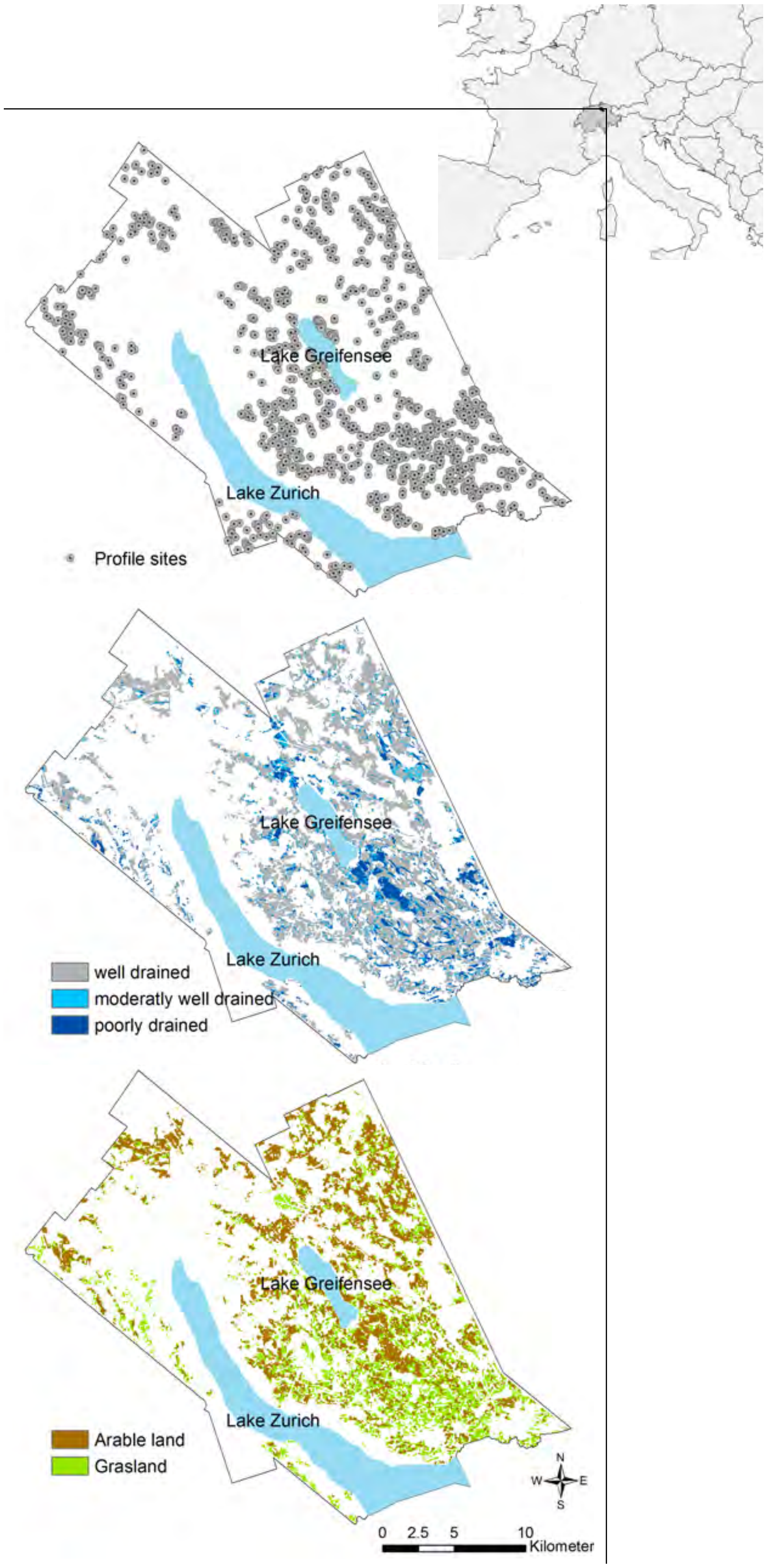

Figure 3.1: Maps of the study area, showing sites with profiles (n = 1003) that have been assessed (Walthert et al., 2016), drainage classes (Nussbaum, Walthert, et al., 2017), and land uses ("Arealstatisik" 2009, 72 classes, © BFS 2010, GEOSTAT. The administrative boundaries were provided by NUTS, 2010 (© EuroGeographics). The white areas indicate non-agricultural land.

Table 3.2: Soil property grid data and soil property summary statistics Greifensee region (Nussbaum, 2017)(N = number of samples used to calibrate the model, Min = minimum, Max = maximum, Std = standard deviation, see the study area for the profile locations, definition of Rooting depth and Drainage classes in Appendix A.2)

	Unit	Depth (cm)	N	Min	Max	Mean	Median	Std
Soil properties on a standard depth basis								
Clay	% mineral fine earth	0-10	913	8	60	26	25	7.4
		10-30	913	8	59	26	25	7.4
		30-50	864	6	64	27	26	8.1
		50-100	852	2	60	26	26	9
Silt	% mineral fine earth	0-10	913	12	60	32	32	6.2
		10-30	913	17	60	33	32	6.3
		30-50	866	15	66	33	32	7.4
		50-100	852	5	71	34	33	9
Soil organic matter	% total fine earth	0-10	1255	1	32	5	4	3.2
		10-30	1165	1	49	5	4	3.6
		30-50	723	0	65	2	1	4.9
		50-100	443	0	68	2	1	5.9
pH	-	0-10	1220	3.3	8.1	6.5	6.7	0.6
		10-30	1121	3.3	7.8	6.5	6.7	0.6
		30-50	412	4.4	8.1	6.7	6.8	0.7
		50-100	371	4.2	8.4	6.7	6.8	0.7
Stone content	cm^3 stone content per cm^3 of total soil, in %	0-10	743	0	35	8	7	6.3
		10-30	744	0	35	10	8	6.7
		30-50	739	0	56	13	8	8.7
		50-100	719	0	65	13	11	10.8
Soil properties on a grid node basis								
Depth of stagnic, gleyic, or anoxic horizon	cm	-	776	0	210	77	80	37.5
Rooting depth	cm	-	745	19	204	67	65	23.6
Drainage class	Well-drained Moderately well-drained Poorly drained	-	1:481 2:97 3:166					

Nussbaum et al. (2017, 2018). The influences of uncertainties in the predicted soil properties on the SFA results require further investigation (Greiner et al., 2018). We used PTFs calibrated using Swiss soil legacy data or based on soil data mostly from southern Germany, which we assume would be similar to and agree well with Swiss soil conditions.

3.3 Results

3.3.1 Mapping soil multi-functionality

The regulation, habitat, and production functions for the soils in the study area had distinctive spatial patterns (Figure 3.2) that indicated in which areas individual soil functions could potentially contribute to ecosystem services. There were clear differences in SFF in different parts of the study area, and these were linked to the inherent soil properties, the terrain, and the climate. The selected SFA methods were therefore able to discriminate between the capacities of different soils in the study area to fulfil multiple functions. The SFF area fractions for each soil function are shown in Table 3.3.

Regulation functions

The water regulation function (R-water) was generally higher for arable soils in the north-eastern part of the study area than elsewhere, where very deep (>1 m deep) Cambisols are found. In contrast, the shallower soils (0.5–0.8 m deep) west of the Greifensee had low or medium R-water SFF values. Overall, about 110 km^2 (64%) of the agricultural area had medium SFF soils. These results were confirmed to be reasonable by applying this SFA method to the soil profile dataset. On average, the SFF scores were significantly higher for the drainage class 1 soil profiles than for the other drainage classes (Table 3.4). Also on average, the SFF scores were significantly higher for arable soils than for grassland soils (Table 3.4) mainly because of differences in soil properties and soil depth. The multi-functionalities of three selected soil profiles representing the main soil types found in the study area are shown in Figure 3.3. Cambisols were found on 63% of the agricultural area, Gleysols on 20%, and Luvisols on 11%, and together these soil types accounted for more than 90% of the total agricultural area. Cambisols and Luvisols generally had higher R-water SFF values than Gleysols because the Gleysol R-water is usually restricted by the presence of stagnic and gleyic soil horizons. Sometimes, dependent on the Cambisol, Gleysol, and Luvisol soil properties, the WSC and SHC rooting depth and hydromorphic characteristics had rather similar R-water SFF scores (Figure 3.3), indicating that soils with stone contents >10% were not taken into account by this SFA method, leading to overestimates of R-water SFF. The SFA method therefore needs to be modified to allow it to be applied to soils with higher stone contents.

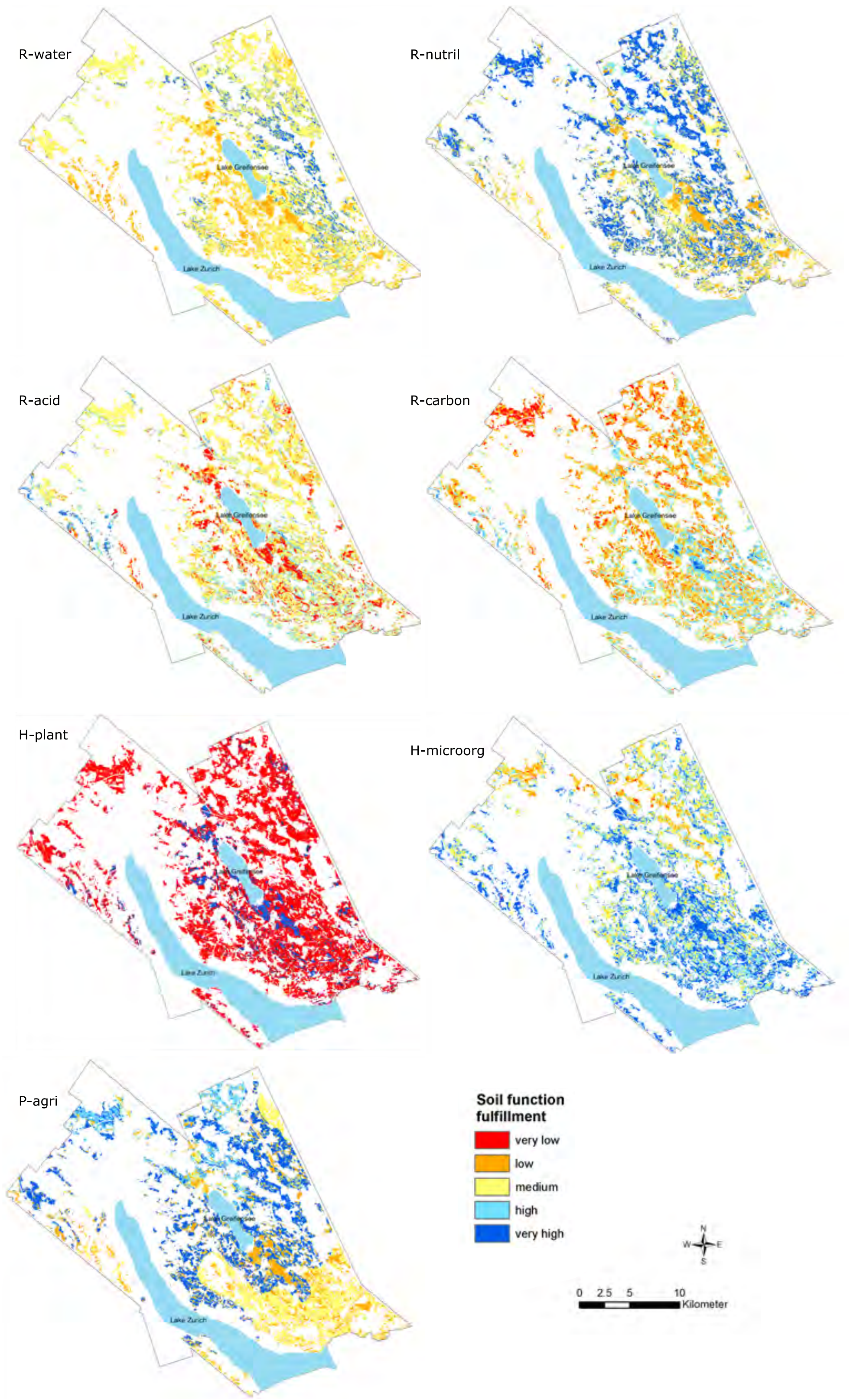

Figure 3.2: Selected soil function maps for the agricultural land in the Greifensee study area (total agricultural area 170 km^2, 20 m $\times$ 20 m raster data, white areas are urban, forest, and other land-use types)

Table 3.3: Multi-functionalities of soils in the case study area: soil function fulfilment of the 10 soil function assessment methods used (% of the total area (170 km^2))

Method	**Very low (%)**	**Low (%)**	**Medium (%)**	**High (%)**	**Very high (%)**
R-water	0	23	64	2	11
R-nutric	0	0	0	1	99
R-nutril	0	15	35	2	48
R-icont	0	0	0	4	96
R-ocont	99	1	0	0	0
R-acid	14	11	56	17	2
R-carbon	10	37	26	25	2
H-plant	86	0	0	0	14
H-microorg	0	7	31	26	36
P-agri	0	23	30	9	38

The soils in the study area are well suited to the prevention of soil nutrient losses (R-nutril), almost half of the study area having very high SFF scores and low scores only being found for soils in some small areas close to the Greifensee (Figure 3.2). Poorly drained soils, shallow soils, or organic soils are present in these areas, and agricultural land management fertilization plans need to be developed taking into account the risks of nutrient losses to surface and groundwater in these areas. Cambisols generally had very high soil nutrient retention capacities, dependent on the climatic conditions, and the hydromorphic properties, texture, organic content, bulk density, soil depth, and geology restricted these retention capacities only a little (Figure 3.3). In contrast, most Gleysols had low SFF values for soil nutrient retention because they are frequently waterlogged, and the Luvisols had medium R-nutril SFF scores .

The acid-buffering capacity (R-acid) SFF scores were high to the west of the Greifensee and medium and low in the north-eastern part of the study area. The soil parameters that controlled this SFA method were the amount of organic matter present (10%–90% quantiles 8–16 kg/m^2), clay content (31–253 kg/m^2), and maximum pH within the soil profile (pH 6.4–7.1). This SFA method hardly discriminated between the main soil types, and some soils in all the main soil types had high SFF scores (Figure 3.2).

The carbon pools (R-carbon) in agricultural soils varied widely across the study area, with low SFF scores (carbon pools <10 kg/m^2) mainly in the northern part and medium SFF scores (carbon pools 13–15 kg/m^2) and high SFF scores (carbon pools 15–21 kg/m^2) in the southern part. The carbon pools for the selected soil profiles were relatively low (Figure 3.2). The Cambisol and Luvisol carbon pools were 11.8 and 12.2 kg/m^2, respectively, but Gleysols under wet conditions could preserve organic matter (carbon pool 22.3 kg/m^2). The three remaining regulation functions R-nutric, R-icont, and R-ocont insufficiently discriminated between soils in the study area. The underlying assessment rules for the nutrient storage capacity (R-nutric) and the trace metal retention capacity (R-icont) led to almost all the soils having high SFF scores. An important reason for this was that the basic soil properties of the grassland and arable soils were in ranges indicating that the soils would effectively store nutrients and trace metals. For instance, the soils were generally neutral or only slightly acidic because of the addition of fertilizers and lime to agricultural soils. Only at $<$pH 5.5, usually found for forest soils, did the R-icont SFA method assign low SFF scores for trace metal retention. The assessment of the retention capacities of the soils for the four selected herbicides (R-ocont) gave very low SFF scores throughout the study area. A closer analysis of the SFA method indicated that the climate conditions (water balance and mean annual temperature) and associated assessment rules rather than the soil properties determined R-ocont for the study area. The method proposed by Litz (1998) therefore needs to be refined to allow the behaviours of organic compounds in regions with relatively low annual temperatures ($<10\ ^\circ C$) and relatively high precipitation rates (<1000 mm/y) to be assessed.

Applying the assessed regulation functions to the comprehensive soil profile dataset containing more than 7000 soil profiles indicated that the results were reasonable in terms of the drainage classes and land-use types (Table 3.4). The R-water, R-nutril, and R-acid SFF scores were, on average, highest for well-drained soils (drainage class 1), lower for intermediate soils (drainage class 2), and lowest for poorly drained soils (drainage class 3). The opposite was found for R-carbon, indicating that the carbon pools were higher for frequently waterlogged soils than for other soils. The regulation functions R-nutric, R-icont, and R-ocont were less able than the other functions to discriminate between drainage classes, as was also the case for the raster data for the study area. The R-water and R-nutril SFF scores were, on average, significantly higher for arable soils than for grassland soils. The differences between the other regulation functions for arable and grassland soils were less pronounced.

Habitat functions

The simple H-plant SFA method indicated that 14% of the soils in the study area are suitable for providing niches for rare plants (Figure 3.2) because they have the wet or dry conditions required by certain plants, have low nutrient availabilities, and are shallow. Most of the areas with soil suitable for rare plants are in former peatland areas in the southern part of the Greifensee area. Dry and shallow soils with great plant diversity are found in the north-western part. The areas with high H-plant scores generally contrasted with the areas with high P-agri, R-water, R-acid, and R-nutril scores but matched areas with high H-microorg scores. The estimated microbial biomasses (H-microorg) in the study area were 645–1536 mg/kg (the 10%–90% percentiles). About a third of the study area had low SFF scores, a third had medium SFF scores, and a third had high SFF scores, and the SFF scores were generally lower in the north-eastern part of the area, where the soil organic matter contents tend to be lower, than elsewhere (Figure 3.2). Both habitat soil functions for the soil profile dataset gave very reasonable results. The SFF scores for both functions clearly increased as the drainage

Table 3.4: Areas in the study area for each drainage class and land use. The mean soil function fulfilment values determined using the soil function assessment methods with regard to the drainage class based on the soil profile dataset and land use at the profile sites are shown (n=7578 soil profiles).

	Proportion of the study area	R-water	R-nutric	R-nutril	R-icont	R-ocont	R-acid	R-carbon	H-plant	H-microorg	P-agri
Drainage class											
Well drained	74%	3.46	4.88	4.29	4.54	1.07	3.93	2.17	1.05	2.35	3.10
Moderately well drained	11%	2.84	4.97	2.82	4.71	1.09	3.14	3.11	1.78	3.14	2.35
Poorly drained	15%	2.61	4.93	2.00	4.85	1.16	2.61	3.96	2.90	3.94	2.06
Land use											
Arable land	59%	3.62	4.82	3.80	4.51	1.12	3.54	2.72	1.46	2.52	2.98
Grassland	41%	3.15	4.79	3.30	4.54	1.06	3.54	2.75	1.53	3.52	2.49

class number increased (Table 3.4). The biological activity (H-microorg) scores were often higher for Gleysols than for well-drained soils such as Cambisols (Figure 3.3), and were higher for grassland soils (average 1209 mg/kg) than arable soils (845 mg/kg) (Table 3.4).

Production function

Soils in the northern part of the study area are the most productive in terms of crop production. About 38% of the soils had very high P-agri SFF scores. This SFA method indicated that soils in the southern part of the area were of medium suitability for crop production, and there was a pronounced spatial delineation between medium and very high SFF scores (Figure 3.2). This sharp boundary was mainly caused by the spatial resolution of the climate suitability classes accounting for the annual average temperature, precipitation, and altitude. The soil properties and features most important to the P-agri SFA method (e.g., rooting depth, drainage class, stone content, clay content, and humus content) did not explain this sharp boundary. Improving the spatial resolution of the climate suitability classes therefore yields a smoother spatial pattern in the P-agri function. However, applying the SFA method to the soil profile datasets indicates that the method was very reasonable and consistently differentiated between different soil types (Figure 3.3), drainage classes and land-use types (Table 3.4).

3.3.2 Aggregation of soil functions

The different aggregation rules gave quite different results, i.e., the spatial patterns in the SIs determined using the different aggregation rules were quite heterogeneous (Figure 3.4). The stakeholder-driven rules A and B gave similar results, but rule B (in which more weight was given to P-agri and R-water than to the other eight soil

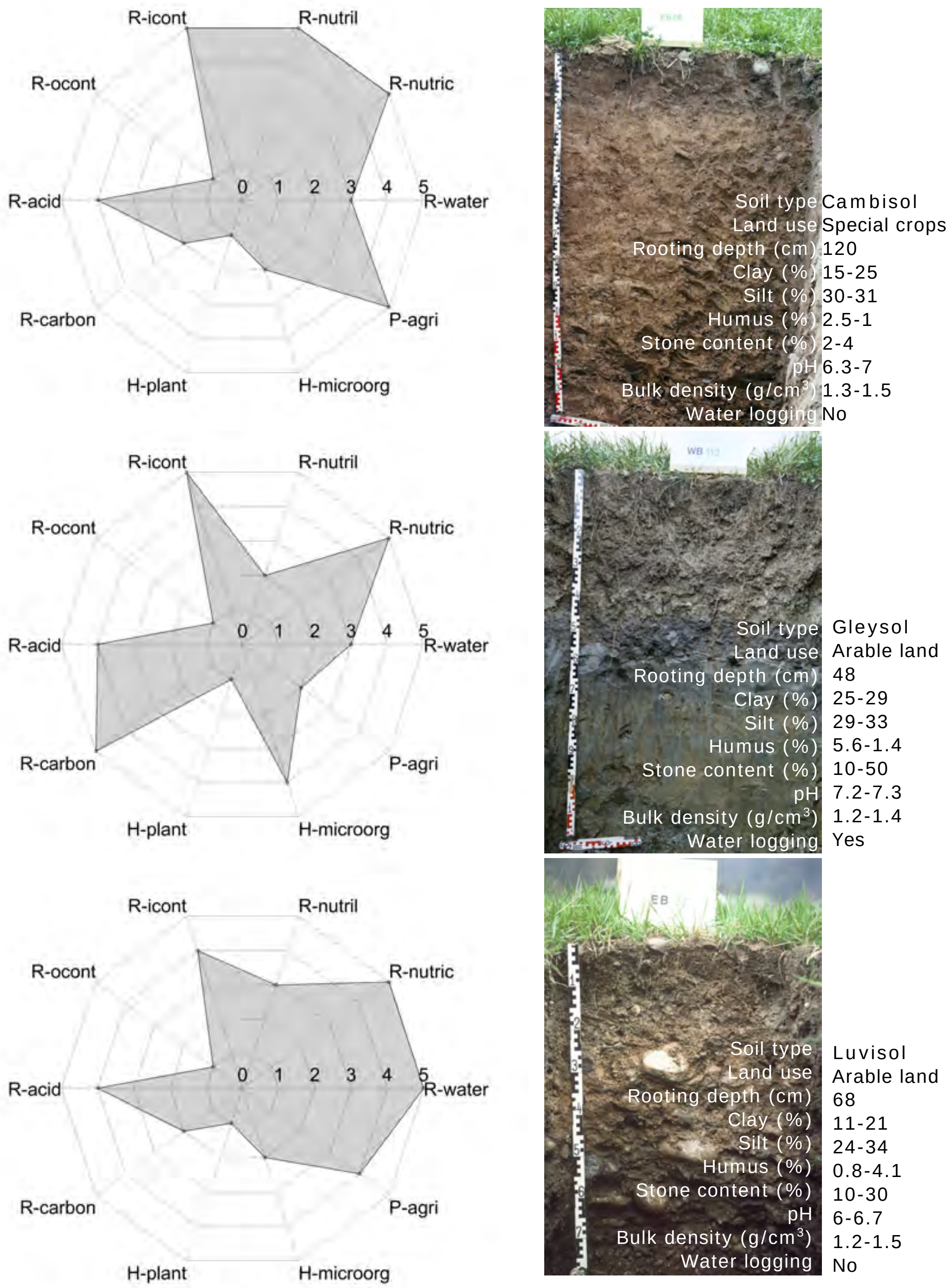

Figure 3.3: Soil function assessment results (1 = very low soil function fulfilment, 5 = very high soil function fulfilment), photographs of soil profiles, and soil properties for the profiles in the study area. The profile photographs (© Peter Schwab, Swiss Soil Monitoring Network) are symbolic, they are within in a 20-25 km range of the study area.

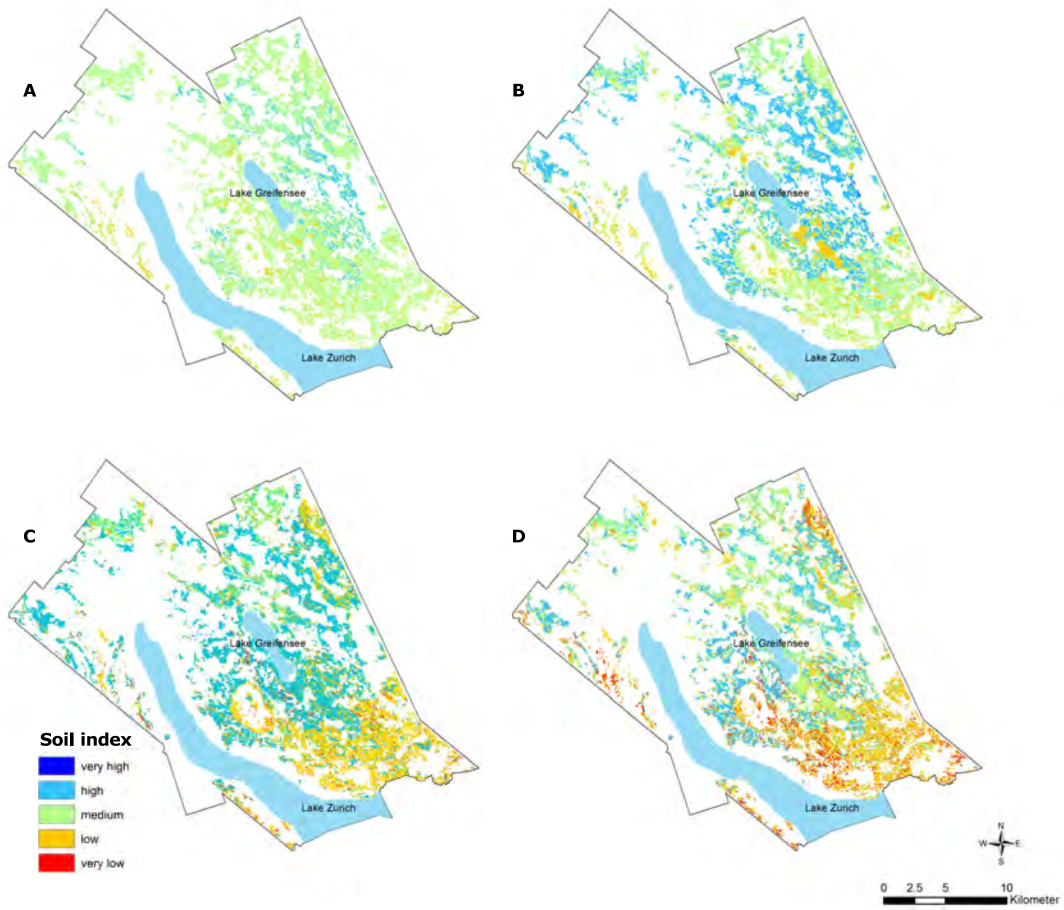

Figure 3.4: Aggregation of the soil function maps into a soil index (SI) using four different aggregation rules

functions) gave more variable results than rule A. The spatial patterns in P-agri and R-water clearly affected the spatial pattern in the rule B, and the spatial pattern was more distinct for rule B than for rule A. Rule B gave low SIs for 14% of the study area, medium SIs for 48% of the area, and high SIs for 37% of the area. In contrast, the Austrian aggregation rules (rule C) gave a somewhat different spatial pattern in the SI, low SIs for 35% of the study area, mainly in the southern grassland areas, medium SIs for only 8% of the area, and high SIs for 52% of the area. Rules B and C gave contrasting low, medium, and high SI scores. In particular, rule C gave high SI scores to conservation areas rich in plant diversity (H-plant). The area fraction for high SI scores was higher when rule C was used than when the other aggregation rules were used. The aggregation rules developed by Miller (2012) (rule D) gave more homogeneous distributions of low SI scores (30% of the study area), medium SI scores (36% of the study area), and high SI scores (26% of the study area) than rule C, but the spatial patterns of the SI scores determined using rules C and D were similar. All the aggregation scenarios produced hardly any very low or very high scores, indicating that extreme SFFs for individual soil functions were usually averaged out.

3.4 Discussion

3.4.1 SFA approach

We assessed a set of static soil functions using simplified empirical rules to quantify soil functions to assess the general capacity of a soil to fulfil a specific function independent of land use and land-management practices. The static approach has the advantage that the SFA results are easy to understand and so can easily be communicated during spatial planning procedures (Lehmann and Stahr, 2010) and allow the gaps between scientists, soil policy professionals, and stakeholders outside the soil science community to be bridged (Bouma et al., 2012). A limitation of the assessment method is that the scores produced cannot be validated, but the reasonableness of the results can be evaluated in terms of land use, soil type, and drainage class for a comprehensive soil profile dataset containing >7500 soil profiles. In general, soil functions can be validated by supplementing the static approach with a dynamic approach using biophysical environmental models that take into account soil processes, climate, land use, land management practices, and other environmental factors (Veereecken et al., 2016). Many biophysical models (addressing, for instance, the water, nutrient, and carbon cycles in soil or crop growth) have been developed (ISMC, 2017), but it is demanding and time consuming to process the data and calibrate the model for each case study. We still, however, advocate using dynamic approaches and modelling the effects of land use and land management practices to validate static soil functions.

The proposed set of static SFA methods needs to be developed further from the soil science perspective as well as from the spatial planning perspective. From the soil science perspective, SFA methods for capturing soil multi-functionality need to be established and refined, and soil process models are needed to underpin or further develop the simplified views used in static SFA methods. From the spatial planning perspective, the demands and level of details the soil function maps have to be provided for their needs. Here, we presented SFAs for agricultural soils mainly based on methods developed for agricultural soils. Proper inclusion of forest soils probably requires methods to be adapted and the strongly varying acidity buffering capacities of forest soils to be included (Blaser et al., 2008), implying that complementary methods will be required.

3.4.2 SFA results

Regulation functions

R-water and its results are easy to understand. The method directly assesses the soil properties and gave spatially variable results for our study area. The results, except for stone-rich Luvisols, were reasonable . We therefore consider R-water to be a suitable method for bringing soil regulation functions in the water cycle into spatial planning procedures. However, the method requires adapting for soils with high stone contents.

Furthermore, R-water relies on four PTFs, and the suitabilities of these PTFs and effects of the PTF accuracies should be investigated.

Nearly all the R-nutric results for the agricultural study area had very high scores because we adjusted our assessment scale to variability in Swiss soil profiles, which include forest soils with quite low CECeff values that are not found for agricultural soils. The method used here was an indicator approach because it directly links CECeff to SFF, and it needs to be developed further.

The R-nutril results for the study area were variable and reasonable. However, the R-nutril method has two disadvantages. 1) The method uses, in addition to soil properties, geological, climatic, and slope data as input data. This could be criticized because non-soil data are already very influential in the spatial planning process and soil data should be given more weight. 2) The method can also be criticized because the lookup tables, including for several soil properties used in this method, mean that interpreting the results is not straightforward, which could impede the use of R-nutril maps in spatial planning procedures.

The same was true for R-icont as for R-nutric. The assessment classes covered Swiss soil variations but did not allow for variation within the study area. The scale needs to be adapted, but the method is straightforward and quite easily accessible.

Nearly all the raster cells and profiles in the study area and for the profile data had very low R-ocont SFF scores. Therefore, the evaluation was not meaningful. There were four main reasons the SFA results were uniform. 1) No K_{clay} (the concentration of a substance bound to clay minerals divided by the concentration of the substance dissolved in the soil water) values were available for the compounds we considered, so we had to make assumptions to estimate the values. These estimated values (115 for glyphosate and 100 for the other compounds) gave medium maximum scores when assessing the binding capacities of the soils. 2) The annual mean temperature, an important input factor when assessing decomposition, was quite low, preventing high SFF from being achieved from the start. 3) We looked at herbicides, which are not volatile. 4) Averaging the binding and decomposition results and then adding the climate and water connectivity factors led to mostly very low SFF scores, and the maximum SFF scores were low (class 2).

The R-ocont method classified soil properties nearly 10 times through the assessment, and the values were averaged and rounded in intermediate steps. Much information was lost in each classification step. This would have made interpreting the results and evaluating the reasonableness of the method difficult. This method might work better if it were perfectly fitted to local conditions. Providing only five classes is an asset of the SFA because it allows the soil function map produced to be interpreted quite easily. In this method, too many classification steps caused a great loss of information and makes interpretation difficult. As a general rule, SFA methods should access soil properties directly.

We used this very generalizing method on the regulation of potential contaminants and acidity buffering to see how the results compared with the results of the more specific R-icont and R-ocont methods. R-icont and R-ocont did not give variable results for our study area, so this evaluation could not be performed. R-acid gave variable results for our study area, and although applying the method to the example soil types gave similar results and yielded no land use differentiation factor, differences in the SFA results for the different drainage classes contributed to the reasonableness of the results. This method is straightforward, and the results can be directly and meaningfully interpreted.

The method used to assess the capacities of soils to regulate the carbon cycle is easy to understand, and the results were reasonable and showed informative variations for our study area. However, it is a simple proxy indicator and needs to be investigated further. The humus content (rather than C_{org}) is often measured, and this humus content has to be deduced using a conversion factor (FAL, 1997; Jäggli et al., 1998). The accuracy of this transfer function needs to be investigated further.

Habitat functions

The H-plant method was a special case, only distinguishing between sites with extreme soil conditions and other sites. It is doubtful whether a dual criterion is sensible or helpful in spatial planning processes and allows for the necessary considerations to be made.

The H-microorg method gave variable and reasonable results for our study area. Assessing soil biology and biodiversity would of course require a more elaborate approach than the mere placeholder we used. We used this method to indicate that this aspect is very important and should be included when aspiring to illustrate soil multi-functionality. SFA methods for this aspect are currently being developed (Aksoy et al., 2017; Griffiths et al., 2016).

Production function

The P-agri method gave variable results for our study area, but a strong artefact was included through using the rather coarse climatic suitability map (scale 1:200 000) with a lower resolution than the soil data (20 m pixel width). The results seemed reasonable according to our evaluations. Like for R-nutril, P-agri did not only take the soil properties into consideration but also used geomorphology and climate data in various lookup tables, so the same criticisms as were made of R-nutril could be made of P-agri, i.e., non-soil properties are weighted strongly in spatial planning procedures, and interpreting the results is not easy, impeding application of the results. These criticisms may not be as important as for R-nutril because many people will know that sustainable agricultural production relies on soil properties, and difficulty interpreting results will be less of a disadvantage to P-agri than for less well understood soil functions such as R-nutril.

3.4.3 Aggregation

A soil index (SI) map looks quite different if a different aggregation method is used (Figure 3.4). We do not think it is possible to present a non-political soil quality indicator, and policymakers should explicitly decide on their priorities. Soil protection will benefit if the calculation of an indicator leads to more awareness of soil in the spatial planning community. However, spatial patterns of individual soil functions are likely to be averaged out in a SI, so other researchers, particularly Ad-hoc-AG Boden (2007), have advocated the use of individual soil function maps. Recently, Bünemann et al. (2018) reviewed soil quality concepts and indicators and found that explicit evaluation of soil quality with respect to soil functions and ecosystem services has rarely been implemented. They evaluated also rules to aggregating different soil quality indicators into one soil quality index and stated that soil functions may have very different importance ranks at different sites, and therefore some kind of weighting is required. Political evaluation of the weights of different soil functions ensures stakeholders are aware of soil multi-functionality. Using different indicators for different purposes or regions can result from an open and, if the soil function maps are good, informed decision-making process based on the stated priorities. In the best case, the indicator constructed should show spatial variations, conserving the main spatial variations from the SFA, and take all soil functions into consideration to some extent, with weightings in the aggregated values determined by political means. In other words, the best aggregation rule will best match these best-case options.

In contrast, the aggregation schemes developed by Miller (2012) for German federal states and by Haslmayr et al. (2016) for Austria (rule C and D in this study) are mandatory and do not allow to account for regional differences in the importance of individual soil functions. Soil function maps provide highly simplified and static information, so aggregations of these maps are predominantly suited to decisions about land take. Improvements in SFAs and stakeholder experience using soil function maps, whether aggregated or not, will help to consolidate the role of soil protection in the spatial planning process.

3.5 Conclusions

We have presented a set of 10 static SFA methods for approximating and identifying soil multi-functionality and the potential contributions of soils to ecosystem services in a spatially explicit manner. Individual soil functions were linked to the inherent soil properties and soil function maps were reasonable in terms of land use, soil type and drainage class. SFA methods for assessing the suitability of a soil for agricultural production have been developed, adapted, and refined for decades, but SFA methods for regulation and habitat functions have been developed only recently, or are being developed. In particular, SFA methods need to be developed for the roles of soils in providing habitats for fauna and flora, including plant and soil biodiversity. It is crucial that soil policymakers and communities understand that soil is not only a factor in agricultural production but also regulates many natural processes and provides essential habitat functions. Maps for a broad range of soil functions are useful for communicating spatial variability and soil multi-functionality to spatial planners, and such maps underpin the role of soils in providing ecosystem services. We advocate that a basic set of SFA methods, as outlined in this study, is used as a first step in incorporating soil functions into spatial planning programmes. Aggregating soil function maps to give a single indicator map requires the importance of each function to be assessed. We found no evidence, from the soil protection perspective, favouring specific ways of combining soil function maps.

Acknowledgements This study was part of the "Predictive mapping of soil properties for the evaluation of soil functions at regional scale" project (PMSoil; project number 406840-143096) and the "Matching soil functions and soil uses in space and time for sustainable spatial development and land management" project (OPSOL; project number 408640-143092), funded by the Swiss National Science Foundation within the framework of the National Research Programme "Sustainable use of soil as a resource" (NRP 68), www.nrp68.ch. The Swiss Federal Office of the Environment (FOEN) also provided funding. The soil protection agencies of the Cantons Zürich and Berne provided soil legacy data.

Chapter 4

Assessment of selected soil functions for the case study area Lyss

Chapter 4 was written by Lucie Greiner and Armin Keller

4.1 Introduction

Local soil conditions drive the supply of soil functions. The fulfilment of individual soil functions is linked to the inherent soil properties, the terrain, and climatic conditions. Thus, how soils fulfil their functions often vary largely within and between regions. In the previous Chapter we demonstrated the application of ten SFA-methods for the Greifensee region. For another case study area in the Lyss region, the same workflow that was described in the previous chapter was performed, i.e. harmonization of legacy soil data, prediction of soil properties using remote sensing and terrain modelling to perform appropriate digital soil mapping approaches (Nussbaum et al., 2018). The Greifensee region was chosen because of its diverse land use characteristics (grassland dairy farming and arable farming) and diverse soil types. The soils of the Lyss region located in the middle of the Swiss Plateau are predominantly used for arable farming. The arable soils in the Lyss region belong to the most productive ones in Switzerland in terms of corn and grain yields. In this intermediate Chapter we discuss the demand and document the results of three primary soil functions assessments (SFAs) for the Lyss region: water regulation, habitat for microorganism and agricultural production. We evaluate the results and discuss the aspects of calibration and interpretability of SFA results.

4.2 Materials and Methods

4.2.1 Selection of soil functions according to demand of soil information

In light of the policy and stakeholder demand we selected three soil functions from the regulation, habitat and production functions that were identified in a literature review (Greiner et al., 2017). The choice in the previous chapter corresponds to the list of soil functions in the European soil thematic strategy (EU, 2006) and to the choices presented by various other authors (Banwart et al., 2017; Calzolari et al., 2016; Haygarth and Ritz, 2009). Soil performs many regulation, habitat, and production functions, and the soil function set chosen should capture as far as possible the whole spectrum of soil multi-functionality. From a stakeholder point of view, the SFA methods chosen should be assessed in the context of the particular region of interest, and might, for example, be focused on land-use demands. For instance, Calzolari et al. (2016) assessed eight soil functions for a study area in northern Italy. Five of these were regulation functions, one was a habitat function, one was a production function, and one (supporting human activities and infrastructure) was not related to soil protection. Haslmayr et al. (2016) assessed six soil functions with a slightly different focus (two habitat functions, two regulation functions, one production function, and one archive function). Schulte et al. (2014) developed a conceptual framework to provide soil functions to meet the demand made by soil policies. This functional land management concept was aimed at optimizing the agronomic and environmental return from land based on soil multi-functionality (O'Sullivan et al., 2015). Five key soil functions were selected for use in the framework, three of them regulation functions (water purification, soil carbon storage, and nutrient cycling), one the habitat for biodiversity function, and the other the food production function. These soil multi-functionality domains could be improved by taking into account more soil functions, particularly with respect to regulation and habitat functions (Haygarth and Ritz, 2009; Bouma et al., 2012). Makó et al. (2017) provided a broad set of methods for assessing the filtering and storage aspects of regulation functions. Still, a reduced set of considered soil functions may already support and in some cases cover direct demand for soil information by society, agriculture, spatial planning, soil protection agencies, nature and biodiversity protection agents in general, engineering and monitoring agents and many more (Keller et al., 2018).

For the agricultural area in the Lyss study area, we selected in agreement with the perspective of stakeholders and the policy framework outlined above at least one regulation function, i.e. water infiltration and storage capacity (R-water), one habitat function, i.e. microbial biomass (H-microorg) and one production function, i.e. capability for agricultural production (P-agri). From a methodological point of view the three SFA methods differ in their approach: R-water combines two physical properties in a look-up table using pedotransfer functions (PTF), H-microorg directly estimates a continuous soil property by means of an empirical regression function and P-agri is a combined method including soil properties, several look-up tables as well as climate and terrain information.

4.2.2 Workflow

In general, the assessment of all SFA-methods follow a similar workflow coupling soil and environmental data with assessment criteria to match the needs for soil policies (Figure 4.1). In this context, the different modules have to integrate developments in sampling, modelling, understanding of soil functioning, decision-support and end-user requirements. While the data processing in the data module follows principal knowledge and rules provided in soil science and guidelines, there are no common standards for the interpretation of soil function fulfilment and the definition of the assessment scale to transform for instance physical units into an ordinal scale.

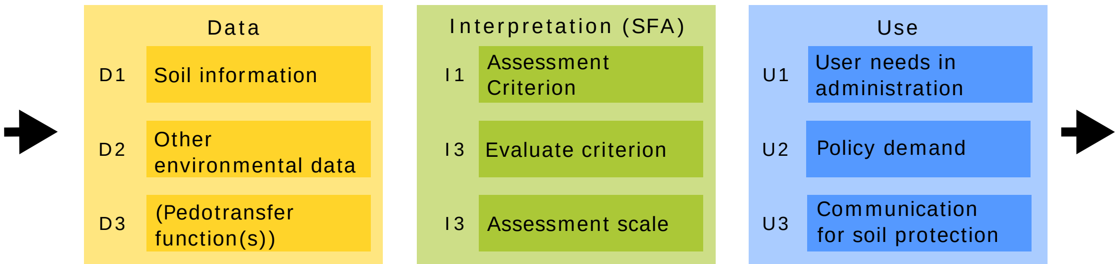

Figure 4.1: General workflow in the assessment of soil functions: bridging the gap between basic soil data and the demand of soil information for sustainable soil policies

4.2.3 Details on soil function assessment methods

Regulation function: water infiltration and storage capacity (R-water) The capacity of soils to store plant available water or the capacity to infiltrate water during heavy rainfall events mitigating flooding are crucial soil functions supporting agricultural production and minimising risks of natural hazards. We assessed the water cycle regulation capacity of soil using an SFA method proposed by Danner et al. (2003) that couples water storage capacity (WSC, in mm/m2) and saturated hydraulic conductivity (SHC, in cm/day) of a soil to a reference depth of 1 m. In this way, the SFA-method accounts for water infiltration as well as for water storage capacity for plants. The detailed description of R-water can be found in Chapter 3.

Habitat function: microbial biomass (H-microorg) Most of the soil functions depend on the local diversity and below-ground abundance of soil organisms and policy relevant, cost-effective soil biological indicators for biodiversity and soil functions are required (Griffiths et al., 2016). Several studies have compared a large range of biological indicators to assist policy-makers (Ritz et al., 2009; van der Putten et al., 2010; Aalders et al., 2009). However, a recent analysis of European soil monitoring networks showed that biological properties are not as often measured in the networks activities as chemical soil properties, also soil physical properties are not as well represented as chemical properties (van Leeuwen et al., 2017). Griffiths et al. (2016) stated that complementary biological indicators are needed to link soil biodiversity to soil functioning, i.e. biological indicators for soil functions related to the services of water regulation, carbon sequestration and nutrient cycle. Microorganisms are important to many processes, such as organic matter decomposition, nutrient cycling, soil structure formation, and pest regulation (Pulleman et al., 2012). In conventional soil mapping studies physical and chemical soil properties are usually measured but hardly any biological soil properties as these are not included in the national soil mapping guidelines (FAL, 1997). For instance, the soil mapping institutions in Germany as well as in Austria do not assess soil as a habitat for microbiology but soil as a habitat for niche plant species using physical soil properties. While mentioning assessment criteria such as biodiversity, natural attenuation capacity, natural soil fertility, or genetic reservoir, soils as a habitat for microorganisms are not assessed (Ad-hoc-AG Boden, 2007; ÖNORM, 2013). In Switzerland, in the last decades, several hundred grassland and arable fields were investigated by Oberholzer and Scheid (2007) to establish baseline values for some soil biological properties for Swiss agro-ecosystems. Among others microbial biomass was measured at these sites in spring before the first fertilizer application of the year, and they developed a regression function for microbial biomass dependent on soil organic matter content, soil pH and clay content separately for grassland and arable land (Oberholzer and Scheid, 2007). This PTF was derived using data for several hundred grassland sites (using data for soil 0 – 20 cm deep) and arable sites (using data for soil 0 – 10 cm deep) across Switzerland. A high microbial biomass indicates high potential in terms of the amount of biota present, biological activity, and metabolizable nutrients (which also support a large amount of biota and give rise to high biological activity) (Oberholzer and Scheid, 2007). A similar approach was taken by Beylich et al. (2005) for German agricultural soils, who used the amount of microbial biomass to determine the SFF for soil as a microorganism habitat.

Production function: capability for agricultural production (P-agri) The Swiss method for assessing the suitability of soil for agricultural crops was developed in the context of soil mapping guidelines FAL (1997) and was refined by Jäggli et al. (1998). This latter SFA method combines basic soil properties, climate data (climate suitability classes dependent on the temperature, precipitation, and the length of the growing period (FOAG, 2012)), and the site conditions (slope and topography) and classifies the suitability of a soil for growing crops into 10 classes. While the best classes (1-4) indicate soils that are capable to support production of tuber crops (e.g. sugar beet, potatos) and grain (e.g. winter wheat, barley), the intermediate classes (5-7) indicate soils suitable for grassland systems, while the classes 8-10 indicate peat soils and wet soils suitable for nature reserves. The assessment uses a series of generic rules - possible restrictions for crop growth in focus - to combine the rooting depth, drainage class, soil pH, bulk density, stone content, clay content, silt content, and organic matter content. Thus, the SFA-method applies a series of clustered if-then statements accounting for possible crop growth limitations (Jäggli et al., 1998).

In our case study area, the climatic suitability for agricultural production is assessed for every raster cell by mean annual temperature, precipitation and length of growing season distinguishing four classes of suitability ordered from very suitable to less suitable climate for agricultural production. This information was obtained from the Federal Office of Agriculture (FOAG, 2012) and clustered to 21 classes. Finally, the SFA-methods P-agri aggregates those 21 classes to four classes. The (available) rooting depth is one of the primary soil variable that determines the capability of a soil to support food production. The Swiss soil classification (FAL, 1997) distinguishes 7 rooting depth classes from extremely deep ($\geq 150cm$) to very shallow ($\leq 10cm$) soils. P-agri defines within this range six rooting depth classes. The hydromorphic features of the soils play an important role for the agricultural production, because it is restricted if the soil water cycle is disturbed by the presence of stagnic, gleyig, or anoxic soil horizons. Information on hydromorphic features was obtained from the results of soil mapping surveys, in which taxonomic data were provided that needed to be transformed into classes suitable for P-agri. The taxonomic data were transformed into drainage classes, that distinguish between well-drained, moderately well-drained and poorly drained soils. Drainage classes are provided by Nussbaum (2017) for every raster cell. Furthermore, terrain attributes such as slope and curvature were classified into 29 combinations for every raster cell. Finally, basic soil properties, i.e. stone, clay and soil organic carbon content, as well as soil pH, were classified according to the assessment tables of P-agri.

4.2.4 Study area

The study area is located in the Swiss Plateau in the Lyss region, Canton Bern, at 430-910 metres above sea level and covers an area of 235 km^2 (Figure 4.2). Together with the Greifensee region presented in the previous chapter, both regions were common study regions for several projects within the National Research Programme 'Soil as a resource' (NRP 68; www.nrp68.ch). Therefore, for the choice of the study region several criteria had to be met. These were (i) soil information had to be available, (ii) grassland and arable soils typical of Swiss agro-ecosystems (iii) the area needed to be under urban development and soil sealing pressure, and (iv) the area needed to be covered by remote sensing activities by APEX Swiss Earth Observatory Network (www.seon.uzh.ch) flight campaigns, which gather spectroscopic data. Further details were given by Nussbaum et al. (2017).

The extent of the Lyss area is defined by cantonal boundaries in the south east and otherwise the availability of spectroscopy data from APEX Swiss Earth Observatory Network (www.seon.uzh.ch) flight campaigns. Four our study, we focused on soils un-

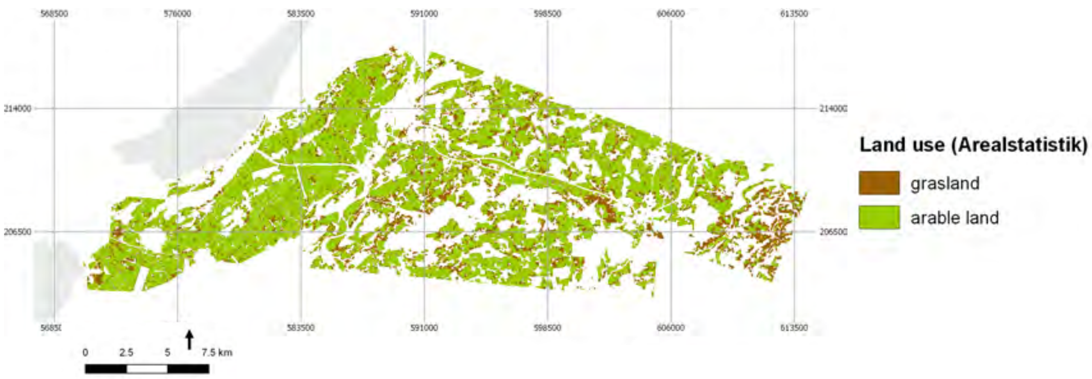

Figure 4.3: Spatial distribution of arable and grassland in the study area Berne-Lyss. ('Arealstatisik' 2009, ©BFS 2010). The white areas indicate non-agricultural land.

der agricultural use; forest soils, soils under wetlands, parks and gardens and settlement areas were excluded.

The climate is temperate and humid, and cropping systems prevail in the study area (80%) with small patches of grassland sites (Figure 4.3) (Madlene Nussbaum, 2017). Soils formed mostly after the last glaciation (Würm, approximately until 10000 years ago) and common soil types are Cambisols, Gleysols, Histosols, Luvisols and Fluvisols.

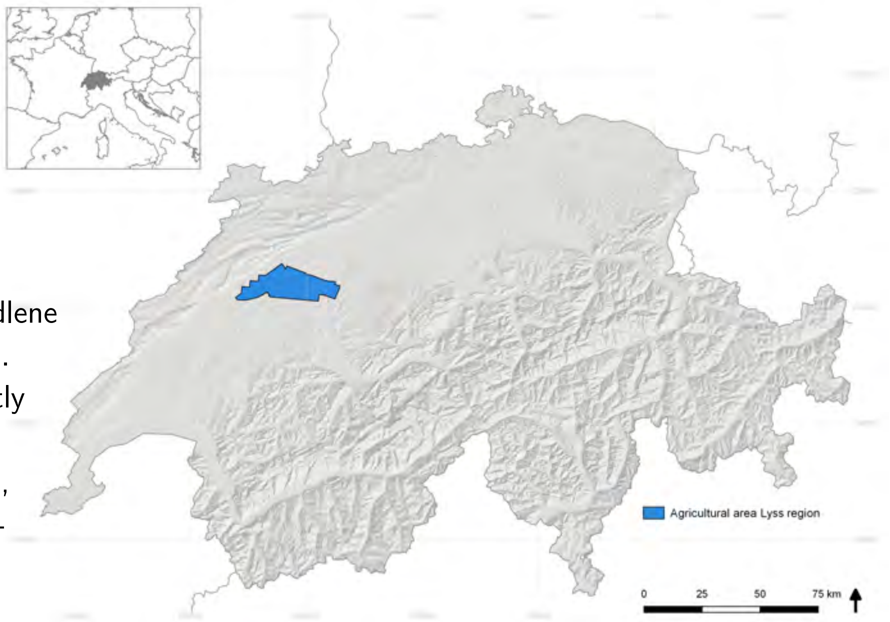

Figure 4.2: Study area Lyss region. (Coordinate Reference System: CHLV1903. Digital elevation model 25 m ©SWISSTOPO. EU administrative boundaries: NUTS 2013, ©EuroGeographics).

4.2.5 Soil data and other environmental data

Soil legacy data were obtained from the Cantonal agencies of Berne and Zürich and harmonized soil profile data were used to predict the spatial variation of soil properties at several soil depths by means of digital soil mapping approaches (Nussbaum et al., 2018). Figure 4.4 shows the spatial variation of some top soil properties of the case

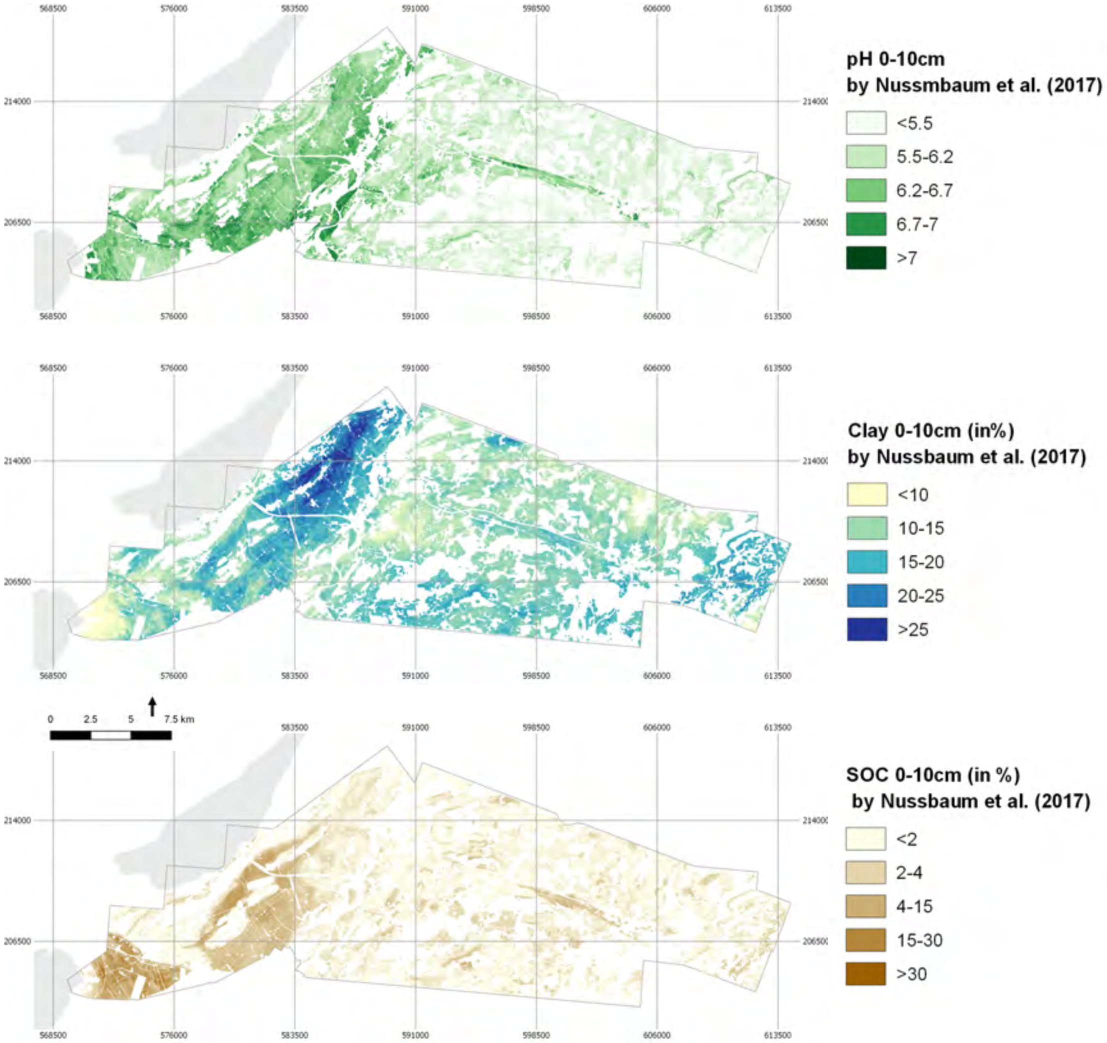

Figure 4.4: Spatial distribution of selected top soil properties in the study area Lyss derived by digital soil mapping (Nussbaum, 2017). The white areas indicate non-agricultural land.

study region. Table 4.1 presents selected summary statistics of basic soil properties for various soil depths. Rooting depths and drainage classes had also been predicted for the nodes of the 20 m grid (Nussbaum et al., 2017). More detailed information on soil legacy data used, soil property predictions and digital soil mapping approaches used can be found in Nussbaum (2017).

The legacy soil data were originally obtained from 1:5000 soil mapping surveys conducted in the 1980s. For evaluation of the reasonableness of the SFA-results with regard to land use, soil type and drainage class a large soil profile dataset was compiled. About 4000 soil profiles from across the Canton of Zurich were processed, about 2400 soil profiles from the Canton of Berne (n = 2409) and 1046 of Swiss forest soils (Walthert et al., 2016). In total, 7578 sets of soil profile data were used to assess the reasonableness of the selected soil function assessment methods. The hydromorphic features of the soils played important roles in most of the SFA methods because soil functions can be restricted if the soil water cycle is disturbed by the presence of stagnic, gleyig, or anoxic soil horizons. Information on hydromorphic features was obtained from the results of soil mapping surveys in which taxonomic data were provided that needed to be transformed into classes suitable for SFA. We grouped the soils into 'drainage classes' taking into account in rough terms whether the water regime in each soil was disturbed or not. The Swiss soil classification system has four hierarchical levels (1 the water regime, 2 the substrate, 3 geochemistry, and 4 percolation) that are used to define a soil type (Baruck et al., 2016). Subtypes can be added to each soil type to account for hydromorphic features. The Swiss soil classification system differentiates between different soil hydromorphic features describing the degree, depth, and source of waterlogging using three main subtypes (stagnic, gleyic, and anoxic soil horizons) and many minor subtypes (FAL, 1997) We decreased the complexity of the soil taxonomy to meet the requirements for SFA to be performed by defining three groups of soils with respect to the hydromorphic featurers of the soils, i.e., three drainage classes (Table 4.1).

Information on soil type as defined by the Swiss soil classification (FAL, 1997) for the soil profile dataset was translated to Reference soil groups of WRB (WRB, 2015). In addition, we used about 100 soil profiles across whole Switzerland of the Swiss soil monitoring network (Gubler et al., 2015), for the calibration of our SFA assessment scales.

4.2.6 Evaluation

We compared the SFA results to soil type and with the Muenchenberg Soil Quality Rating (MSQR, see Mueller et al. (2007)) to evaluate the reasonableness of our results. The MSQR approach is an overall SFA framework based on soil indicators that primarily aims at the evaluation of potential crop yield but also on ranking and controlling agricultural soil quality (Hennings et al., 2016; Mueller et al., 2010, 2013, 2014). In contrast to the three selected SFA-methods the MSQR approach takes into account soil structure, an important factor to soil quality (Bünemann et al., 2018) and has been developed to be applicable either in the field, with measured or modelled data and potentially to soils all over the world (Mueller et al., 2016).

Table 4.1: Soil property grid data and soil property summary statistics Lyss region(Nussbaum, 2017) (N = number of samples used to calibrate the model, Min = minimum, Max = maximum, Std = standard deviation, definition of Rooting depth and Drainage classes in Appendix A.2)

	Unit	Depth (cm)	N	Min	Max	Mean	Median	Std
Soil properties on a standard depth basis								
Clay	% mineral fine earth	0-10	750	0	65.7	17.4	15	7.3
		10-30	771	0	76.2	17.9	15	8.3
		30-50	733	0	76.2	18.4	16.1	9.1
		50-100	741	0	76.2	17.8	16	9.9
Silt	% mineral fine earth	0-10	753	2	75	27.6	25	10.5
		10-30	776	1.8	75	28.5	25	11.5
		30-50	736	2	75	29.8	26	12.6
		50-100	743	2	75	31	27.1	15.2
Soil organic matter	% total fine earth	0-10	788	0.3	61.9	8.5	4	10.2
		10-30	787	0.5	65.4	8.6	2.9	12.8
		30-50	702	0	81.1	10.5	1	18.7
		50-100	480	0	85	15.7	1	25.4
pH	-	0-10	728	4.5	8.5	6.4	6.3	0.8
		10-30	723	4.4	8.5	6.4	6.3	0.8
		30-50	713	4.3	8.7	6.4	6.4	0.8
		50-100	716	3.7	9.1	6.5	6.5	1
Stone content	cm^3 stone content per cm^3 of total soil, in %	0-10	836	0	25	2.7	2	3.2
		10-30	836	0	24	3	2	3.6
		30-50	834	0	40	3.8	2	5.4
		50-100	827	0	45.5	4.8	2	7.4
Soil properties on a grid node basis								
Depth of stagnic, gleyic, or anoxic horizon	cm	-	852	0	260	102	120	47.3
Rooting depth	cm	-	838	13	224	73	70	31.5
Drainage class	Well-drained Moderately well-drained Poorly drained	-	1:540 2:56 3:210					

4.3 Supply of soil functions and evaluation results

Soil function assessment results Contrasting spatial patterns were found for the case study area Lyss for three selected soil functions (Figure 4.5). While the majority of the arable soils show clearly very high fulfilment for P-agri and R-water (soil function fulfillment SFF), the SFF for H-microorg was generally very low. In the western region, where some patterns of drained organic soils emerge, the opposite contrasting pattern was found. This general spatial pattern is slightly superimposed with some intermediate SFF scores for grassland soils. The supply of soil H-microorg, R-water and P-agri is primarily linked to the inherent soil properties, and spatial patterns of basic soil properties (Figure 4.4) are in general agreement with the SFA-results. Overall, about 75% of the soils revealed very low or low SFF scores, while about 70% of the soils supply high and very high SFF for R-water and P-agri (Table 4.2). The arable soils of the region show a high capacity to store water, median value for WSC was 305 mm (Table 4.3). The average value for SHC indicate a relatively high infiltration rate for water at the soil surface. On the other hand, estimated soil microbial biomass in the top soils was in average 577 mg kg^{-1} dry matter for arable soils and 813 mg kg^{-1} dry matter for grassland soils. The former peat soils in the western part of the case study area, that were drained in the last century to enhance agricultural production, revealed very high SFF scores for the habitat functions but low SFF scores for the selected production and regulation function. Overall, the soil function maps clearly reveal the trade-off between H-microorg at the one hand site and R-Water and P-agri at the other hand in the case study area.

Table 4.2: Soil function fulfilment of the three selected soil function assessment methods used (% of the total area of 235 km^2)

Method	Very low (%)	Low (%)	Medium (%)	High (%)	Very high (%)
R-water	0.5	6.6	21.6	2.9	68.4
H-microorg	58.3	17.3	7.3	1.6	15.6
P-agri	0.2	22.1	4.4	2.6	70.7

Comparison to soil type The assessed soil functions discriminate between the main soil types of the study region. Best overall SFF scores are found for Histosols for the habitat function H-microorg, and for Cambisols and Luvisols for P-agri and R-water. Also the other main soil types, Gleysols, Regosols and Fluvisols revealed distinctive patterns for the SFF scores (Table 4.4). Of course, given the rough classification of the WRB and the definition of the reference soil groups, the variation of SFF scores within each main soil type is large, as expressed with the MAD values (Table 4.4). MAD was lowest for SFF scores for P-agri for Histosols, Gleysols and Regosols (¡0.4), but in general high for Cambisols, Regosols and Luvisols indicating the large range of soil property values and of the soil depth within these soil types. MAD was highest

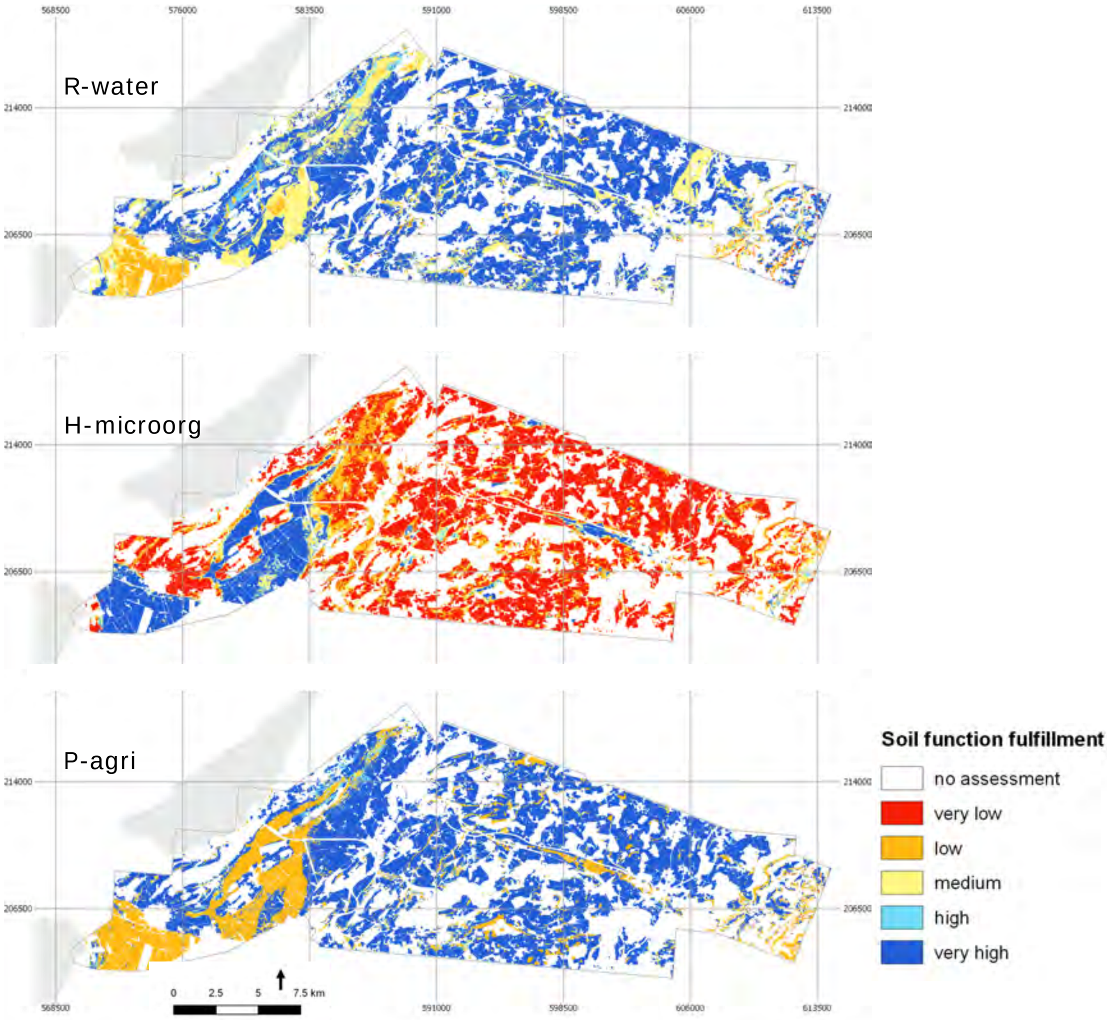

Figure 4.5: Maps for the three selected soil function for the agricultural land in the Berne-Lyss study area (total agricultural area 235 km^2, 20 x 20 m raster data, white areas are urban, forest, and other land-use types)

Table 4.3: Range of physical and biological soil properties for the study area Lyss calculated with the SFA-methods R-water and H-microorg.

		Mean	Median	Q10	Q90	Std
R-water	Water storage capacity (mm)	259	305	120	348	95
	Saturated hydraulic conductivity (cm d^{-1})	88	51	35	214	84
H-microorg	microbial biomass arable land (mg kg^{-1} dried mass), depth: 0-20 cm	577	395	291	1267	455
	microbial biomass grassland (mg kg^{-1} dried mass), depth: 0-30 cm	813	496	346	1932	789

Table 4.4: Comparison of SFA-results between different reference soil groups from World Reference Base of soil Classification (WRB, 2015). Mean, median and mean absolute deviation from median (MAD).

		R-water	H-microorg	P-agri
Cambisol	mean	3.68	2.48	3.71
	median	3	2	4
	MAD	1	0.92	1.15
Gleysol	mean	2.72	3.5	2.25
	median	2	3	2
	MAD	0.79	1.23	0.37
Histosol	mean	3.63	4.74	2.07
	median	3	5	2
	MAD	1.28	0.47	0.14
Regosol	mean	3.8	3.02	2.1
	median	4	3	2
	MAD	1.15	1.11	0.2
Fluvisol	mean	4.24	3.52	2.43
	median	5	4	2
	MAD	0.96	1.3	0.71
Luvisol	mean	3.74	1.86	3.79
	median	3	2	4
	MAD	1.01	0.85	1.13

(> 1.2) for H-microorg in Gleysols and Fluvisols, because these soil types differ largely in soil organic matter (SOM) content. The variability of SOM contents for Histosols was in general large, but overall SOM contents were very large leading to a very high SFF score. MAD was very high (> 1.2) for R-water in Histosols as well due to higher relative variance in water storage capacity. Still, given the large variation of soil properties within main soil type, our analysis clearly show the different capacity of the soil types to fulfil specific soil functions.

Comparison to MSQR The assessment of the production function P-agri agreed well with the MSQR approach (Figure 4.6). Soils with high and very high SFF scores for P-agri revealed also in the MSQR system scores above 25 (MSQR scores range from 1 to 34 for arable soils). This comparison was performed for about 5800 out of the 7500 soil profiles, as for some soil profiles data on the soil structure was missing and thus, the MSQR could not be calculated. In addition, Figure 4.6 shows that low and medium SFF scores for P-agri the MSQR approach results ranged between 15 and 25 indicating that the MSQR approach considers additional limitations for crop growth as P-agri. In summary, the results of the Swiss SFA-method for agricultural production and the international method MSQR confirmed the reasonableness of P-agri.

Comparing the MSQR soil score to SFA-results for R-water shows in general also a positive relationship, except for high SFF scores for R-water. Soils with high SFF scores in water regulation though, do score lower in MSQR because for this class R-water (WSC, 150-180 mm and SHC, 40-164 cm/d) obtain less MSQR-points than profiles with medium SFF score (WSC 110-626 mm, SHC 3-124 cm/d). The relation between MSQR scores and the SFA-results for H-microorg is more pronounced (Figure 4.6). Soils with high SOC content in the top soil rate high in H-microorg, while in the MSQR approach soils with a deep, non-stagnic, non-diluted A-horizon and SOC contents below 30% receive the highest scores. The cross comparison of the SFF results with the MSQR at the ordinal scale indicates that for about 90% of the soil profiles assessed, the SFF scores of P-agri and R-water agreed with the MSQR scores within $\pm$ 1 SFF unit (MSQR scores normalized to the same ordinal scale 1 to 5), while this was only the case for about 50% of the soil profiles for H-microorg.

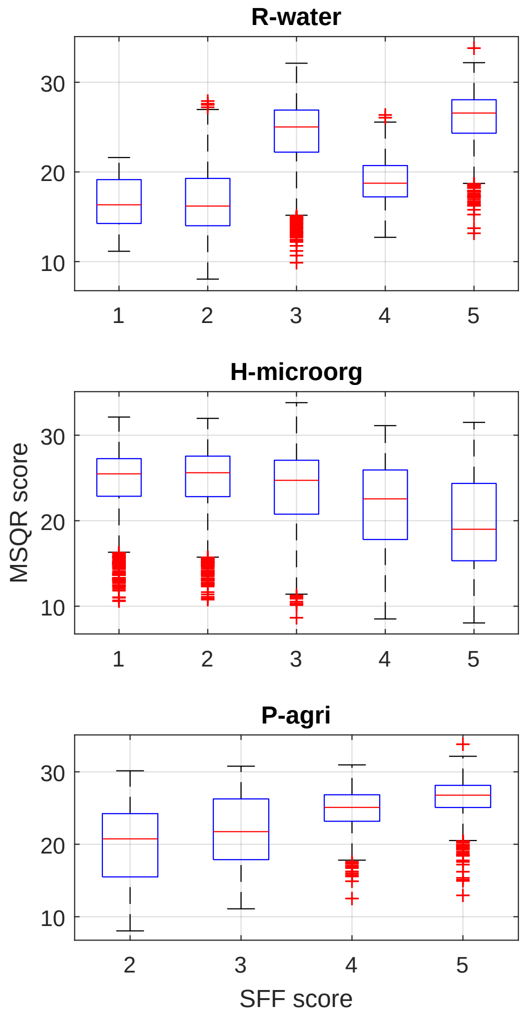

Figure 4.6: MSQR scores for harmonized soil profile data in original scale from 1 (very low) to 34 (very high score) compared to SFA-results for R-water, H-microorg and P-agri in soil function fulfillment (SFF) scores from 1 (very low) to 5 (very high SFF).

4.4 Calibration of SFA assessment scales

The calibration of the assessment scales to transform the physical units of the SFA-results into an easy understandable ordinal scale is a crucial step in the assessment procedure. The results above (Figure 4.5) are visualized with an assessment scales that was derived for about 100 soil profiles across Switzerland that represent a large variety of geology, soil type, altitude, climatic conditions and land use (grassland, arable, special crops, peat soils, forest soils). Therefore, the SFF scores of the case study area are comparable with other regions if the same assessment scales are applied. Alternatively, the assessment scale could be adapted only to the soils within the region (Calzolari et al., 2016). It is a quite simple step in the SFA workflow but an important one that has to be communicated to stakeholders. As an example, we illustrate the effect of applying different assessment scales for R-water using the original assessment scale derived by Danner et al. (2003) for German soils and the assessment scale calibrated to Swiss soils (Figure 4.7). Only 25% of the soil profiles revealed a SHC below 30 cm/d and 25% had a SHC above 70 cm/d applying the orginal assessment scale proposed by Danner et al. (2003). The same was true for the thresholds of the WSC in water storage capacity. In comparison, only 20% of the about 100 soil profiles of the Swiss soil monitoring network showed a WSC below 110 mm and on the other hand, 20% above 270 mm. Calibration of the WSC and SHC assessment scales to Swiss soils revealed a better pronounced spatial pattern of the SFA results (Figure 4.7, right hand side). It is obvious that the calibration of the assessment scales matters for final SFA results and the variation of the results obtained in a study region. However, this crucial step in the assessment of soil functions must be documented to avoid misinterpretation (Calzolari et al., 2016; van Wijnen et al., 2012). With respect to possible decision making and soil policies the interpretation of the assessment scale must be transparent and communicated. In view of consistent SFA studies, widely accepted assessment scales should be established. In addition, political discussion and consensus is needed which level of SFF scores are accepted in the long term (threshold values).

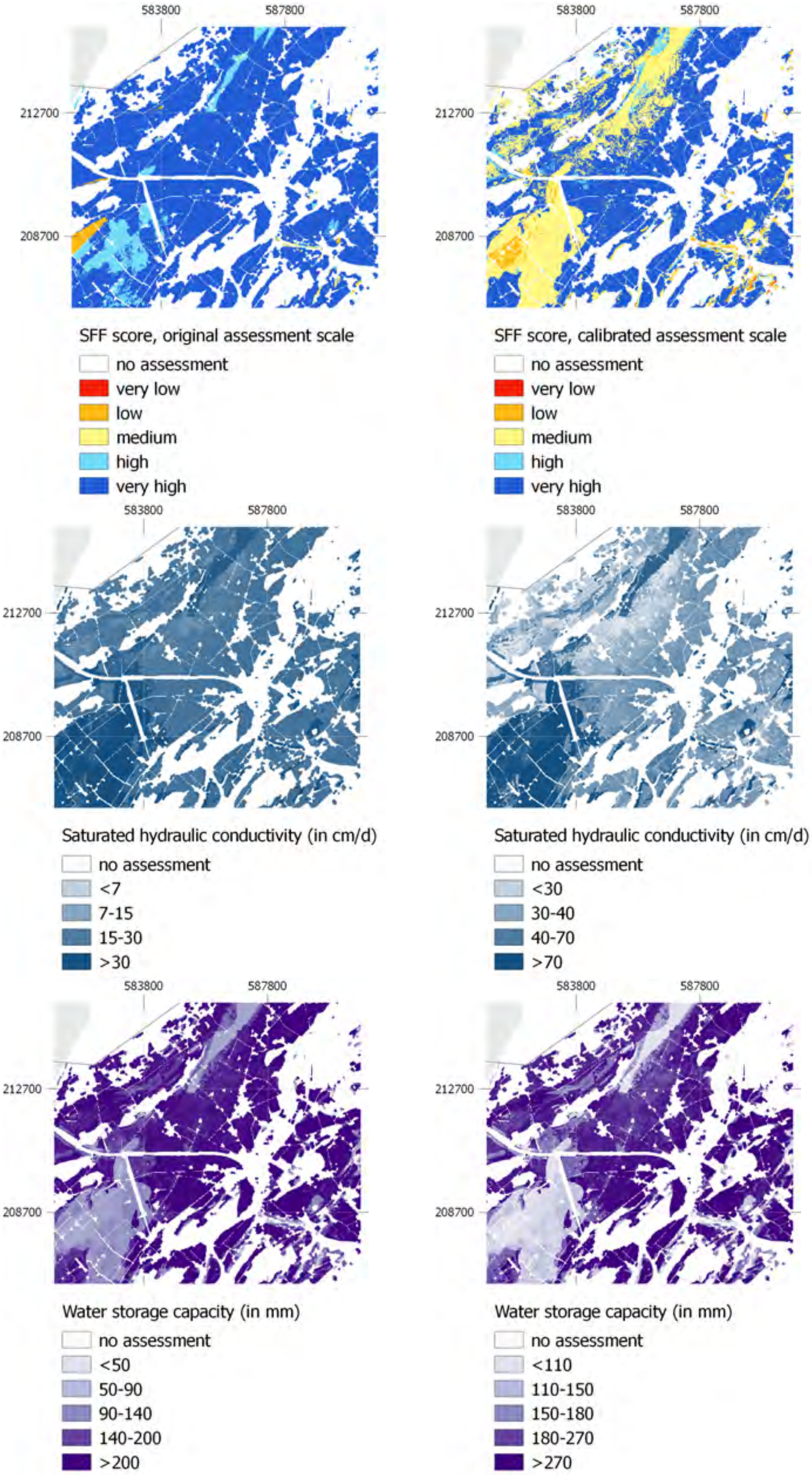

Figure 4.7: Regulation of water cycle assessed with (Danner et al., 2003). Left: original assessment scale for German soils, right: calibrated assessment scale for Swiss soils

4.5 Complexity of SFA methods

The reasonableness of SFA-results depends also on the complexity of the SFA-method. In case of P-agri many environmental variables and soil properties are taken into account by means of look-up tables (see Method section). Thorough analysis for our study area showed that the SFA results for P-agri were highly sensitive to climate, rooting depth and hydrological features. Figure 4.8 illustrate input layers for P-agri and the final results (SFF scores) for a subregion of the Berne-Lyss region. Given the many input variables for P-agri, the local spatial pattern of associated SFF scores is sometimes not easy to interpret. For the sub-region illustrated in Figure 4.8 mainly the rooting depth, soil hydromorphic features (stagnic, gleyic or anoxic conditions), SOC and stone content determine the SFF scores of P-agri.

The development of the P-agri method is related to the soil mapping guideline in Switzerland and reflects experimental and practical observations that were obtained during soil mapping surveys. Practitioners have been using the method P-agri in the field in many soil surveys but the method was not revised with regard to new observations. On the other hand, coupling many environmental and soil data hampers the interpretation and evaluation of the reasonableness of the SFF results.

In the evaluation of its assessment criterion, P-agri faces three linked challenges. 1) Classification happens in every steps of this evaluation even before applying the assessment scale. 2) The relationship between soil properties in the evaluation is not straightforward but convoluted. 3) Adjustment to the evaluation criteria are not easy to make, as the relationship between the soil properties (and climate and terrain) are in a long if/else-form. Method development is hindered.

Figure 4.8: SFA input data and SFA-result for P-agri around the city of Lyss. (Climatic suitability (FOAG, 2012), rooting depth, HydClass, texture, SOC, pH (Nussbaum, 2017), terrain (Swisstopo, 2014), SFF score according to (Jäggli et al., 1998), scales in maps chosen according to thresholds in (Jäggli et al., 1998)).

Chapter 5

Uncertainty indication in soil function maps

Chapter 5 was accepted by SOIL as Greiner, L., Nussbaum, M., Papritz, A., Zimmermann, S., Gubler, A., Grêt-Regamey, A. & Keller, A.. Uncertainty indication in soil function maps –Transparent and easy-to-use information to support sustainable use of soil resources.

Abstract

Spatial information on soil function fulfillment (SFF) is increasingly being used to inform decision-making in spatial planning programs to support sustainable use of soil resources. Soil function maps visualize soils abilities to fulfil their functions, e.g. regulating water and nutrient flows, providing habitats and supporting biomass production based on soil properties. Such information must be reliable for informed and transparent decision-making in spatial planning programs. In this study, we add to the transparency of soil function maps by 1) indicating uncertainties arising from the prediction of soil properties generated by digital soil mapping (DSM) that are used for soil function assessment (SFA) and 2) showing the response of different SFA methods to the propagation of uncertainties through the assessment. For a study area of 170 km^2 in the Swiss Midlands, we map 10 static soil sub-functions for agricultural soils for a spatial resolution of 20 x 20 m together with their uncertainties. Mapping the ten soil sub-functions using simple ordinal assessment scales reveals pronounced spatial patterns with a high variability of SFF scores across the region, linked to the inherent properties of the soils and terrain attributes and climate conditions. Uncertainties in soil properties propagated through SFA methods generally lead to substantial uncertainty in the mapped soil sub-functions. We propose two types of uncertainty maps that can be readily understood by stakeholders. Cumulative distribution functions of SFF scores indicate that SFA methods respond differently to the propagated uncertainty of soil properties. Even where methods are comparable on the level of complexity

and assessment scale, their comparability in view of uncertainty propagation might be different. We conclude that comparable uncertainty indications in soil function maps are relevant to enable informed and transparent decisions on the sustainable use of soil resources.

5.1 Introduction

Human wellbeing relies on soil resources, and soil should therefore be better integrated into ecosystem service frameworks that inform decision-making and environmental policies (Dominati et al., 2010). Soil acts in multi-functional ways, and fulfils many functions in the regulation of the nutrient and water cycle, in carbon sequestration or the filtering of chemical compounds, providing biodiversity and habitats for flora and fauna, and it is essential for the production of food, fibre and biomass (Adhikari and Hartemink, 2016; Haygarth and Ritz, 2009). The capacity of soils to deliver ecosystem services is largely determined by its functions, and each individual soil function can be seen as providing a soil-related contribution to ecosystem services (Bouma, 2014). The concept of soil functions has been increasingly been applied to reveal the role played by soils in sustaining the wellbeing of humans and of society, emphasizing the multi-functionality of soils and their chemical, physical and biological properties. (Dominati et al., 2014; EU, 2006; Haygarth and Ritz, 2009; Makó et al., 2017; Schulte et al., 2014; Schwilch et al., 2016; Tóth et al., 2013). In general, soil function assessment (SFA) entails the rating of soils according to their capacity to fulfill an individual soil function, the so-called soil function fulfillment (SFF). Simplified static SFA methods result in scores that can be integrated into spatial planning procedures (Greiner et al., 2017). Maps that enable visualization of SFF, so-called soil function maps, are well suited to communicating the importance of soils to spatial planners and other disciplines (Haslmayr et al., 2016; Sanchez et al., 2009) and can inform stakeholders on the role of soils for society and the environment (Bouma, 2010; Haygarth and Ritz, 2009; Miller, 2012). In particular, the European soil protection strategy (EU, 2006), even though not adopted, brought the domain of soil functions into public discussions.

In order to allow informed and transparent decision-making in spatial planning programs, however, balancing the social aspects of urbanization and environmental factors (Grêt-Regamey et al., 2017c), not only must the state of soils with regard to their functions be made available, but information on the reliability of the soil function maps is also required. Information on the accuracy of soil function maps facilitates decision-making for environmental policy, increases confidence among stakeholders, thereby helping to avoid poorly informed policy decisions with significant long-term environmental and social consequences (Maxim and van der Sluijs, 2011). At the same time, providing information on the uncertainty of soil function maps might delay decisions (Höllermann and Evers, 2017) or lead to discussions and negotiations in the spatial planning process (Taylor et al., 2015). Nevertheless, the demand for soil information is considerable and stakeholders require not only the state of the soil in terms of soil quality, but also any indication of uncertainties associated with the soil information (Campbell et al., 2017).

Various sources of uncertainty can lead to spatially heterogeneous degrees of reliability in mapping soil functions. In general, the following types of uncertainties can be distinguished in assessing and mapping soil functions (Keller et al., 2002): (i) model uncertainty that might arise from incomplete or incorrect methodological approaches and incomplete process descriptions, (ii) informational uncertainty of input data and model parameters, and (iii) temporal and spatial variation of soil properties. In the case of SFA, informational uncertainties in input data may result for instance from processing soil legacy data (Nussbaum et al., 2018), prediction of soil properties using digital soil mapping approaches (DSM) (e.g., Nussbaum et al., 2018; Sanchez et al., 2009; Vaysse and Lagacherie, 2015) or the application of pedotransfer functions (PTF) (Chirico et al., 2010; Schaap, 2004) to deduce soil parameters from other soil properties.

We distinguish two SFA approaches that differ in their levels of complexity (Greiner et al., 2017). The static approach uses simplified empirical methods to assess the capacity of a soil to fulfil a specific function, neglecting the impacts of land use and land management practices. The static approach is particularly suitable for land-use planning to support the sustainable use of soil resources (Lehmann and Stahr, 2010). The dynamic approach takes into account soil processes and site-specific environmental factors, as well as land use and land management practices. Dynamic models exist for nutrient and water cycling, carbon sequestration, crop production, and other soil sub-functions (Vereecken et al., 2016). The use of dynamic soil models is both data-demanding and time-consuming, but is a powerful means of modelling the impacts of past and future land use and land management practices on soil functions. The assessment of uncertainties in environmental (dynamic) modelling has been demonstrated in numerous studies (Bastin et al., 2013; Brown et al., 2005; Heuvelink et al., 2007, 2010; Krayer von Krauss et al., 2005; Lesschen et al., 2007) and various frameworks have been proposed to take into account sources of uncertainty (Bastin et al., 2013; Heuvelink et al., 2007). Also, uncertainties associated with the spatial prediction of soil properties using DSM approaches are usually quantified (FAO, 2017b). In contrast, uncertainties in the assessment of soil functions and rating of soils according to their function fulfillment have hardly been accounted for at all.

In this study, we propagate prediction uncertainties in soil properties (informational uncertainty) through the calculation of ten static SFAs for a case study area in the Swiss Plateau. The SFA methods used are presented in (Greiner et al., 2017) and were chosen to reveal the breadth of multi-functionality of soils. For SFA, we used soil property maps generated by (Nussbaum et al., 2017). They used a DSM approach that exploits soil legacy data, which has the advantage that the prediction intervals for soil properties are provided. While the study of Nussbaum et al. (2017) focused on the spatial prediction of soil properties, the present study aimed on the assessment of soil functions. The objectives of this paper were to propagate soil property predictions through static SFA, in order to 1) indicate how accurate the SFA results are in response to informational uncertainty and spatial variation of soil properties as quantified by the DSM approach, and 2) to gauge how sensitive the SFA methods are to predictive distribution in soil properties.

5.2 Materials and Methods

5.2.1 Study area

Our study area is located in the Swiss Plateau in the Canton of Zürich around Lake Greifensee, see Figure 5.1. The region is dominated by urban areas and agricultural land (crop production, mixed and dairy farming). We only assessed soils under agricultural use. Urban areas, forest, wetlands, parks, and city gardens are excluded from this study, resulting in a total study area of 170 km^2. Chromic, Calcaric and Eutric Cambisols (63% of study area), Stagnic, Reductigleyic and Calcaric Gleysols (20% of study area), Haptic Luvisols (11% of study area) and Hemic, Drainic Histosol and Calcaric , Eutric Fluvisols or Regosols, have developed in a variable geology, but in general on molasses and moraines. The region lies at about 390-840 metres above sea level, and the growing season amounts to approximately 190 days per year. Slopes greater than 35% can only be found alongside moraines, otherwise the slopes are between 10 and 15% (Jäggli et al., 1998). The shape of the study area is formed by administrative boundaries in the south east and otherwise by APEX spectroscopy flight bands (www.seon.uzh.ch). More details on the region, its soils and its extent are provided in Jäggli et al. (1998) and Nussbaum et al. (2017).

Figure 5.1: Study area in the Swiss Midlands, 672489 - 715769 X, 228156 – 259960 Y, GCS_CH1903 (Orthophotos study area: SWISSIMAGE 2005, ©SWISSTOPO. Administrative boundaries Europe: NUTS 2010, ©EuroGeographics)

5.2.2 Soil function assessment

We assessed regulation, habitat and production functions for 10 soil (sub)-functions (Table 5.1) as proposed in a previous review by Greiner et al. (2017). Each SFA method addresses a certain domain of the soils multi-functionality depicting a specific assessment criterion, e.g., the nutrient storage capacity of soils for the nutrient cycle. The SFA methods require data on soil properties, PTFs, and other environmental data

(Table 5.1).

Regulation functions

We assessed the regulation of the water cycle (R-water) following the method proposed by (Danner et al., 2003), which combines the water storage capacity (WSC in mm/m^2) of soils with their saturated hydraulic conductivity (SHC in cm/day) for a reference soil depth down to 1m. The nutrient storage capacity (NSC in mol$_c$/m^2) of soil is one of its most important parameters, determining the nutrient cycle (R-nutric). We calculated the NSC according to (Lehmann et al., 2013), multiplying the fine earth fraction (mass of clay and silt) and the amount of soil organic matter for each soil layer with its effective cation exchange capacity (CEC$_{eff}$) down to a soil depth of 1 m. The method proposed by Jäggli et al. (1998) evaluates the capacity of soils to prevent the loss of soil nutrients by runoff and percolation to ground and surface water (R-nutril). The SFA method takes into account basic soil properties as well as the hydromorphic properties of soils (waterlogging) and environmental site conditions. The capacity of the soil to filter and buffer trace metals (R-icont) were assessed for cadmium, copper and zinc using a method developed by the German Association of Water, Wastewater and Waste (DVWK, 1988) to prevent groundwater pollution by trace elements. The SFA method evaluates the filtering capacity of topsoils (0- 30 cm) to retain trace metal cations based on sorption sites of organic matter, clay minerals, and sesquioxides in conjunction with soil pH and redox potential (DVWK, 1988). Agricultural soils receive in general fertilizers, e.g. mineral fertilizers, animal manure, compost, waste-derived fertilizers, and pesticides, which contain nutrients but also impurities or by-products such as trace metals. While copper and zinc mainly stem from animal manure, mineral phosphorus fertilizers might contain remarkable amounts of cadmium (Jensen et al., 2016; Six and Smolders, 2014; Keller and Schulin, 2003).

The regulation of organic compounds (R-ocont) is assessed using the method of Litz (1998) for four frequently used herbicides in Switzerland: glyphosate, pendimethalin, metamitron and isoproturon (Franzen et al., 2017). The SFA method assesses the potential sorption and fixation of an organic compound on clay and organic material (binding) and the potential biological activity of a soil to decompose an organic compound (decomposition). In a second step, both assessment criteria are combined to evaluate the retention potential of a soil for a specific chemical compound (retention). To account for the ability of soils to buffer acids (R-acid), we applied the SFA method proposed by (Bechler and Toth, 2010). The method takes into account the amount of clay and organic matter down to a soil depth of 1 m, and soil pH. To address the role of soils in the carbon cycle (R-carbon) we simply calculated the soil carbon stock to 1m depth.

Habitat and production functions

We used the method proposed by Siemer et al. (2014) to assess the capacity of soils to provide niches for rare plant species (H-plant). This is applied to sites with extreme soil properties and shallow soils that lead to relatively dry or wet soil conditions or low nutrient availabilities, which provide niches for rare plant species. As an indicator of the habitat function we estimate soil biological activity based on empirical regression functions to estimate microbial biomass in grassland and arable soils (H-micoorg) (Oberholzer and Scheid, 2007). These PTFs were derived for hundreds of grassland and arable sites across Switzerland.

We assessed the agricultural production function (P-agri) using the method of Jäggli et al. (1998). This SFA method combines basic soil properties, climate data (climate suitability classes depending on temperature, precipitation and length of growing period (FOAG, 2012)), and site conditions (slope, topography) to classify soils into 10 classes according to their suitability for crop growth.

The results of SFA methods are usually given in physical or chemical units and transformed to an ordinal scale, i.e., an SFF score, to facilitate the communication of multifunctionality to stakeholders. In agreement with other studies assessing soil functions (e.g., Miller, 2012; Haslmayr et al., 2016; Lehmann and Stahr, 2010), we applied an ordinal scale with five levels. We adapted the ordinal scale for each SFA method to the range of SFA results obtained from about 100 well-documented soil monitoring sites across Switzerland (Gubler et al., 2015). Thus, the ordinal scale in this study represents a rating of soils capacity to function in relation to a bandwidth of Swiss soils. The five levels of the ordinal scale were: SFF score = 1 (very low/very poor), SFF = 2 (low/poor); SFF=3 (medium), SFF= 4 (high/rich) and SFF=5 (= very high/very rich).

Table 5.1: The ten assessed soil sub-functions for the case study area, their assessment criteria and required input data. For the uncertainty assessment soil properties were treated as fixed (SP_d) or as random variables (SP_d).

Soil (sub-)function Assessment criterion	**Reference**	SP_d[1]				SP_m[1]							
		Clay	SOM[2]	SC	pH	Silt	Depth	WH	DC	PTF[3]	Other environmental data[4]	**Type of method**[5]	**Abbreviation**
Regulation function													
Water cycle													
Water infiltration (cm/d) and storage capacity (mm/m^2) combined in semi-quantitative look-up table	Danner et al. (2003)	x	x	x		x	x	x		BD, SHC, AWC, AAC	Slope, geology, climate	2	R-water
Nutrient cycle													
Nutrient storage capacity of fine earth down to 1 m soil depth (mol$_c$/m^2)	Lehmann et al. (2013)	x	x	x	x	x	x	x		BD, CECeff		1	R-nutric
Nutrient losses													
Retention capacity against nutrient losses, e.g., nitrate (semi-quantitative look-up tables)	Jäggli et al. (1998)	x	x	x		x	x	x	x	BD	Slope, geology, climate	2	R-nutril
Heavy metals													
Sorption capacity for inorganic pollutants (semi-quantitative look-up tables)	DVWK (1988)	x	x	x	x		x			BD		2	R-icont
Organic compounds													
Retention capacity for organic contaminants against percolation into ground water (semi-quantitative look-up tables)	Litz (1998)	x	x	x	x	x	x	x	x	BD, AWC, CECpot, S-value	Properties organic compounds, MAT, MAET, climate	2	R-ocont
Acids and contaminants													
Buffering and binding capacity for acids and contaminants assessed by soil organic matter content (in kg/m^2, clay content (in kg/m^2) and maximum pH in assessment depth combined in a semi-quantitative look-up table	Bechler and Toth (2010)	x	x	x	x		x	x		BD		2	R-acid
Carbon cycle													
Amount of organic matter pool in soil (C-storage) (kg C/m2)	Greiner et al. (unpublished data)		x	x			x			BD		1	R-carbon

Table 5.1: The ten assessed soil sub-functions for the case study area, their assessment criteria and required input data. For the uncertainty assessment soil properties were treated as fixed (SP_d) or as random variables (SP_d).

		SP_d[1]				SP_m[1]							
Soil (sub-)function Assessment criterion	**Reference**	Clay	SOM[2]	SC	pH	Silt	Depth	WH	DC	PTF[3]	Other environmental data[4]	**Type of method**[5]	**Abbreviation**
Habitat function													
Plants													
Soils providing niches for plant species, with very dry, wet or low nutrient properties (assessed by available water capacity in mm, presence of hydromorphic horizon and effective cation exchange capacity in $cmol_c/kg$)	Siemer et al. (2014)	x	x		x	x	x	x		BD, AWC		2	H-plant
Microorganisms													
Amount of microbial biomass (mg/kg dried soil)	Greiner et al. (unpublished data)	x	x		x	x	x			MB	Land use	1	H-microorg
Production function													
Agricultural production													
Suitability for agricultural production (semi-quantitative look up tables)	Jäggli et al. (1998)	x	x	x	x	x	x	x	x	BD	Relief, slope, climate	2	P-agri

[1]SOM: soil organic matter, SC: stone content, WH: presence or absence of waterlogged horizons, DC: Drainage Class

[2] SOM for 50-100 cm depth: SP_m

[3]AAC: available air capacity in mm, AWC: available water capacity, BD: bulk density, CECpot and CECeff: potential and effective cation exchange capacity, MB: microbial biomass, SHC: saturated hydraulic conductivity, S-value: amount of exchangeably bound basic cations

[4] MAT: mean annual temperature, MAET: mean annual evapotranspiration

[5] Type 1: SFA method consists of empirical equations or PTFs, Type 2: SFA method consists of look-up tables

5.2.3 Soil property maps and other data

Nussbaum et al. (2017) generated soil property maps using digital soil mapping (DSM) approaches for the case study area with a spatial resolution of 20 m raster cells. This resulted in a total of about 450 000 raster cells for the agricultural soils. In the DSM approach Nussbaum et al. (2017) used a new boosted geoadditive modelling framework (geoGAM) in which they modelled nonlinear relationships and selected parsimonious models from a large number of covariates. Table 5.2 presents summary statistics of the modelled soil properties in our case study for the four soil layers that were distinguished. The accuracy of the predictions, validated using independent data, was similar to other DSM studies. Independent models were fitted for each soil property and each soil depth (Nussbaum et al., 2017). To predict soil properties, harmonized soil legacy data from about 4000 soil profiles (Walthert et al., 2016) that were investigated during a 1:5000 soil mapping survey between 1988 and 1997 in the Canton of Zurich (Jäggli et al., 1998) were used under a non-public data license. Details are described in publications by Nussbaum et al. (2017, 2018). While these publications were purely focusing on the prediction of soil properties and the choice of DSM approaches, our study aims at the assessment of soil functions based on this soil property data.

In order to apply the SFA methods, PTFs suitable for diverse soil parameters are required (see Table 5.1). To estimate soil bulk density we used the PTF of Nussbaum and Papritz (2015), and for the cation exchange capacity we used the PTF of Gerber et al. (2014). Both PTFs were developed for Swiss soils based on soil legacy data. Available water capacity (AWC) and other soil hydraulic properties were estimated using the German soil mapping guidelines (Goossens et al., 2005). Other environmental data such as slope, relief, climate, geology, geomorphology, properties of organic compounds, and land use were gathered from available databases (BFS, 2010; FOAG, 2012; HADES, 2017; PPDB, 2017; Swisstopo, 2008, 2014).

5.2.4 Indication of uncertainty in mapping soil functions

In this study, we propagated uncertainties for four basic soil properties, i.e., clay content, SOM, pH and stone content, through the calculation of the ten static SFA methods. These four soil properties were treated in the calculations as random variables for each raster cell and soil depths 0-10 cm, 10-30 cm, 30-50 cm and 50-100 cm (Table 5.1). For the soil depth of 50-100 cm, SOM was treated as a fixed input variable *(SP_m)* because its predictive performance was too low (Nussbaum et al., 2017). For SOM at this depth we used the median of the available soil data (n = 418). The probability distributions of these soil properties (SP_d) were derived from the DSM approach mentioned above, performing 1000 simulations for each raster cell and soil depth (Nussbaum et al., 2017). For the calculation of the SFA we drew an independent set of the four SP_d values (drawn and replaced) N=1000 times, and compared range, mean and variance of the generated SP_d set with the original distributions of the four

Table 5.2: Summary statistics of modelled soil properties generated by the DSM approach by Nussbaum et al. (2017) for the Greifensee study area. (SOM: soil organic matter, depths in cm)

	Soil property	**Depths**	**Mean**			**STD**		
			Q0.1	**Q0.5**	**Q0.9**	**Q0.1**	**Q0.5**	**Q0.9**
SP$_d$	Clay (%)	0-10	19.4	24.3	29.4	5.5	5.7	5.8
		10-30	20.4	25.6	31.2	5.5	5.7	5.8
		30-50	20.4	25.4	31.2	6.6	6.8	7.0
		50-100	18.9	24.7	30.3	7.3	7.5	7.7
	SOM (%)	0-10	4.4	5.8	8.2	1.7	2.2	3.1
		10-30	4.3	5.8	8.5	1.9	2.5	3.7
		30-50	1.7	5.9	10.7	6.7	15.5	22.2
	Stone content (%)	0-10	3.1	7.6	12.6	3.5	5.8	7.5
		10-30	3.4	8.3	13.7	3.7	6.0	7.9
		30-50	4.0	9.9	18.1	4.6	7.7	10.5
		50-100	5.4	12.6	21.2	6.4	10.2	13.5
	pH	0-10	6.2	6.5	7.0	0.5	0.5	0.5
		10-30	6.1	6.5	6.9	0.5	0.5	0.5
		30-50	6.1	6.5	7.0	0.6	0.6	0.6
		50-100	6.2	6.6	7.0	0.6	0.6	0.6
SP$_m$	SOM (%)	50-100		1			0	
	Silt (%)	0-10		34.8			2.2	
		10-30		35.5			2.3	
		30-50		32.9			3	
		50-100		33.6			3.1	
	Soil depth (cm)	-		70.1			14.6	

soil properties predicted using the DSM approach.

We restricted the number of random variables to these four soil properties due to the required computation time for such a large number of raster cells (n $= 4x10^5$) with four soil depths. Therefore, for other soil properties such as silt content, soil depth, the presence or absence of waterlogged horizons, and drainage class the mean of the DSM simulations was used (SP_m) (Table 5.1, Table 5.2). The presence of waterlogged soil horizons in the top soil layer (0-30 cm) was found for about 13 % of the case study area, for the 0-50 cm soil depth the figure was 27 %, and for the depth 0-100 cm, it was 40 % of the area. We assumed there was no waterlogging for the 0-10 cm depth because this was rarely observed in the data. About 74% of the agricultural soils were well drained (drainage class 1), 11% were moderately well drained (class 2), and 15% were poorly drained (class 3)(Nussbaum et al., 2017).

For the error propagation and the analysis of the uncertainty assessment results we distinguish two different types of SFA-methods depending on how the chosen random variables are taken into account in the calculation of the SFA methods. In cases where the SFA method consists of empirical equations (e.g., regression functions) or continuous PTFs, the variation of each soil property with probability distribution, SP_d, is fully propagated through these (type 1 equation). In our study this is the case for methods assessing regulation of nutrient cycle, carbon cycle and habitat for microorganisms (R-nutric, R-carbon, and H-microorg). SFA methods assessing soils regulation of water cycle, nutrient losses, acidification, inorganic contaminants, habitat for plants or agricultural production function (R-water, R-nutril, R-acid, R-icont, H-plant, and P-agri) are partly based on look-up tables using a classification of soil properties in the calculation, including PTFs that classify the estimation of secondary soil properties such as available water capacity (type 2 look-up tables). In particular, the method assessing soils regulation of organic contaminants (R-ocont) classifies soil properties at the very beginning and groups the calculation of the retention of organic compounds in soils according to this classification.

We computed a) two measures of uncertainty for SFF scores, b) two types of maps visualizing uncertainties, c) two measures for overall uncertainty per soil sub-function in our study area and show d) uncertainties of SFF scores per soil sub-function in detail.

a) As a measure of uncertainty of the SFF scores for the ten SFA methods, we computed the interquartile range (IQR) for each raster cell, i.e., the difference between the 75% and 25% percentiles, and the ratio of IQR to the mean as an approximation for the coefficient of variation for the ordinal-scaled SFF scores.

b) In order to visualize the uncertainty of the SFF scores in the soil function maps we generated two different map types. We visualized the uncertainty of the SFF scores resulting from the uncertainty of the four SP_d values with the aim of facilitating communication in the decision-making process, and computed the probabilities $<$ 10 %, 10-30% and $>$30% that the SFF score of a raster cell might deviate from the mean SFF score (only SP_m used for SFA) for ± 1 or ± 2 or more SFF units. In this way, stakeholders might gain an overview of the areas of the case study area for which the SFF scores of individual soil sub-functions have more or less confidence, expressed on the ordinal scale. The other type of maps allow visualization of SFF scores in a raster cell only where ≥90% of the 1000 simulated SFF scores were equal (C90), i.e., ≥90% of the simulated SFF scores revealed no variation indicating a high reliability of the result, whereas raster cells that do not meet this criteria are displayed as empty cells in the map. Additionally, 5% and 95% percentiles are displayed.

c) As a measure of the overall uncertainty of a soil function, we calculated for each raster cell the median absolute deviation (MAD) and took the average of the MAD for all raster cells (MMAD).

d) Finally, for more detailed analysis of the resulting uncertainty in the SFF scores for each assessed soil function, we computed the cumulative distribution functions (cdf) of the SFF scores including the mean of the deviations from the mean SFF score of a raster cell (MDM) for the 1000 simulations. The MDM was calculated separately for i) all simulations that were larger or ii) smaller than the mean SFF score.

5.3 Results and Discussion

5.3.1 Mapping uncertainty of soil sub-functions

Mapping the ten soil sub-functions for the study area revealed pronounced spatial patterns, with a high variability of SFF scores across the region, linked to the inherent properties of the soils, terrain attributes, and climate conditions. The propagated uncertainties of soil properties SP_d as produced by the SFA methods generally led to substantial uncertainty in the mapped soil sub-functions, though to a different extent for individual soil sub-functions and for subregions. Figure 5.2 presents the mean SFF scores for three selected soil sub-functions and the associated uncertainties; the same maps for the other soil sub-functions can be found in the Appendix A.3. Figure 5.3 provides a general overview of the range of the SFF scores for the ten mapped soil sub-functions and their uncertainties.

For instance, the regulation function for water (R-water) is in general higher for arable soils in the north-eastern part of the case study area, but is also associated with larger uncertainties. The water storage capacity (WSC) in our study area ranges between 44 mm and 270 mm (10% - 90% quantile, median: 204 mm) and the saturated hydraulic conductivity (SHC) ranges between 17 cm/d and 183 cm/d (median: 32 cm/d). The probability maps indicate that in the north-eastern part, 30% or more of the N= 1000 simulations did not fall in the “very high” SFF score, but scored one or two SFF categories lower, i.e., high or medium (Figure 5.2). Furthermore, the soils between Lakes Greifensee and Zürichsee in the western part of the region with predominantly medium and low SFF scores were quite sensitive to uncertainties in soil properties. For the majority of soils in this subarea there is a relatively high probability that the mean SFF score for R-water might deviate by $\pm$ 1 SFF unit.

As expected, the calculation of the soil carbon pools was very sensitive to uncertainty in soil organic matter and stone content data (Figure 5.2, R-carbon). Carbon pools in agricultural soils are very heterogeneous across the case study area, with low SFF scores mainly in the northern part (< 10 kg/m^2), with medium (13-15 kg/m^2) and high SFF scores (15-21 kg/m^2) in the southern part of the region. Mapping the associated uncertainty of soil carbon pools on an ordinal scale indicated, across almost the whole case study area, high probabilities that the SFF scores might deviate for $\pm$ 1 or even $\pm$ 2 SFF units. In contrast, the agricultural soils of the case study area showed high nutrient storage capacities throughout the region (Figure 5.2, R-nutric) and therefore, SFF scores of R-nutric were not that sensitive to the propagation of uncertainties of SP_d through this SFA method. Only in the north-eastern area did we observe some probabilities that SFF scores for R-nutric might be one SFF unit lower. Overall, the uncertainty of individual soil function maps showed diverse spatial patterns. Mapping their uncertainty in the ordinal scale, as proposed in Figure 5.2, may increase the common understanding of spatially heterogenic uncertainties in SFF in decision-making in spatial planning programs. Uncertainty indication adds information on reliability of the soil function maps used to communicate the value of soils to spatial planners and other disciplines (Haslmayr et al., 2016; Sanchez et al., 2009), thus allowing for more confidence in land use decisions. Moreover, revealing the reliability of soil function maps might support efforts to strengthen the link between soil functions and ecosystem services. This link is important, as ecosystem services are a means of connecting soil functions to the demands and needs of stakeholders to find a balance in land-use planning between economic, social, and environmental aspects, a balance crucial to find (e.g., Bouma, 2014; Grêt-Regamey et al., 2017c; Valujeva et al., 2016).

The responses of the SFF scores for the assessed soil sub-functions to uncertainty in the four simulated soil properties depend not only on the SFA method itself but also on the associated classification of the SFA results into the ordinal scale. In agreement with the very high nutrient storage capacity of the soils, the basic soil properties of the grassland and arable soils are in a range that provides high and very high retention of trace metals (R-icont) as well, while the retention of organic chemical compounds in soil (R-ocont) is very low throughout the region (Figure 5.3) according to the assessment scale proposed in this SFA method (Litz, 1998). Accordingly, the SFF scores for R-nutril, R-icont, and R-ocont are relatively insensitive to uncertainty in soil properties, and the overall coefficient of variation is very small for these soil sub-functions. The highest overall coefficient of variation was found for R-carbon and H-microorg, followed by R-acid and R-water (Figure 5.3). These results raise a question about the appropriate classification of SFA results from physical or chemical units into an ordinal assessment scale, and

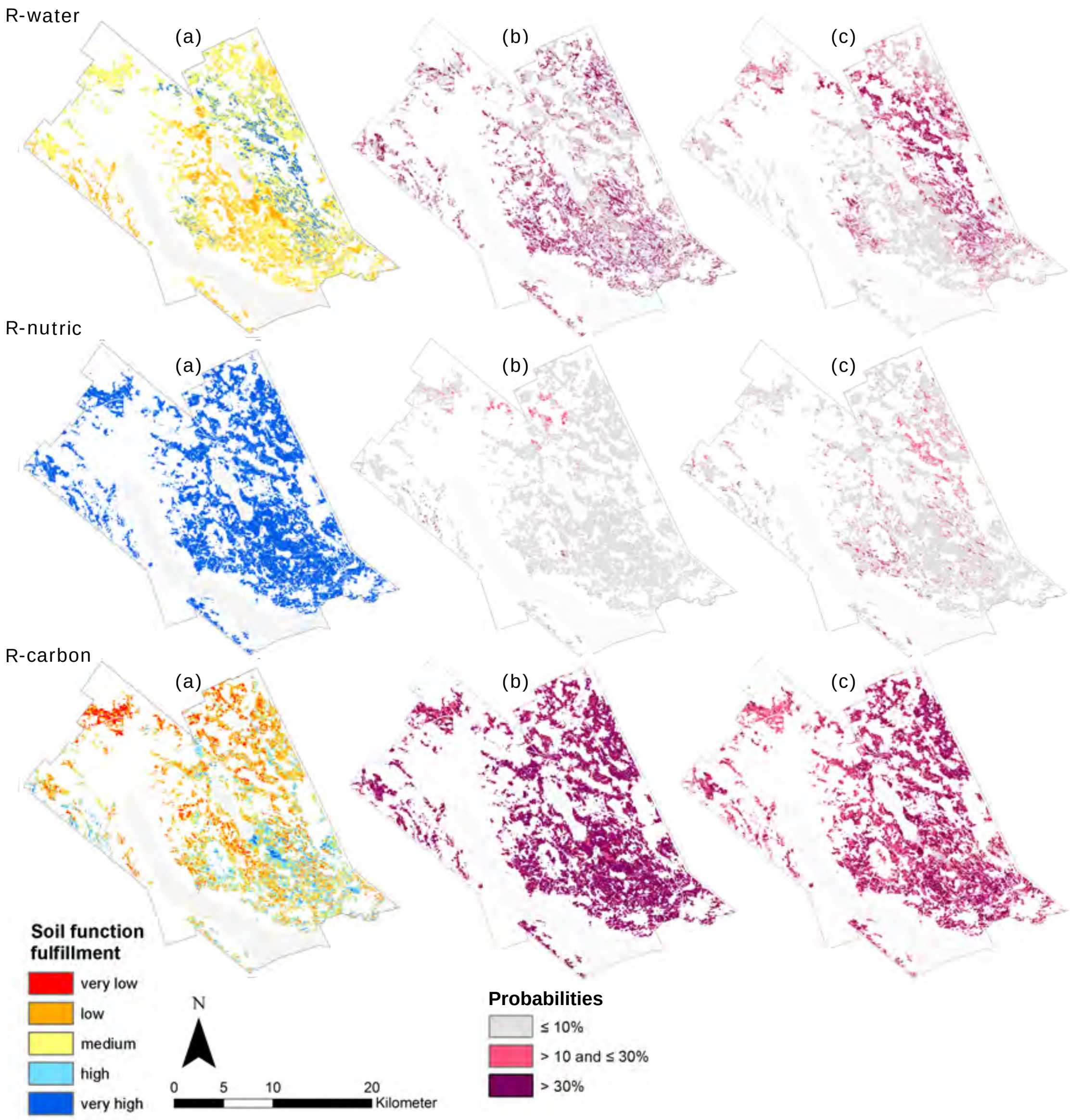

Figure 5.2: Selected soil function maps for the agricultural land of the case study area and indication of their uncertainties in the ordinal scale: a) mean SFF scores (1^{st} column) and b) probability that the mean SFF score of a raster cell deviates in the ordinal scale for $\pm$ 1 (2^{nd} column) or c) $\pm$ 2 or more SFF units (3^{rd} column) (raster cells 20 x 20 m, N=1000 simulations).

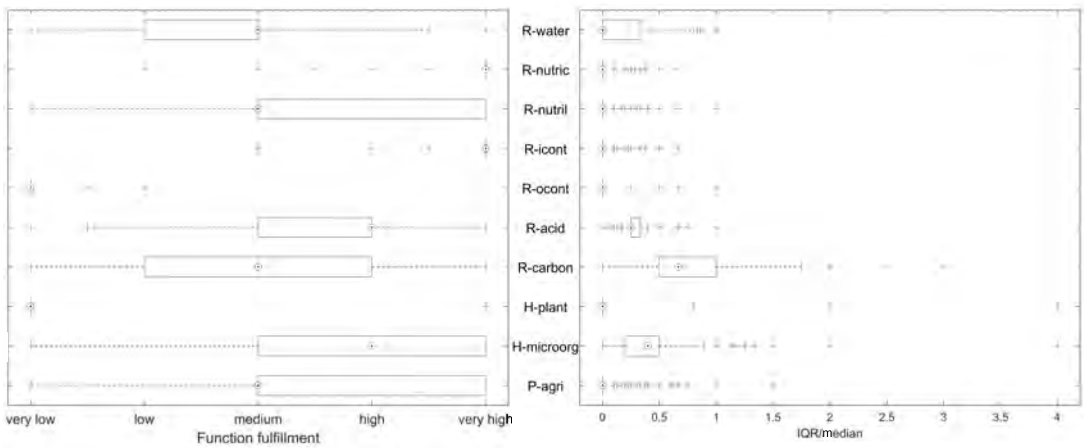

Figure 5.3: General overview of the resulting range of SFF scores for the ten mapped soil functions (left), and of their coefficient of variation (right) expressed as the ratio of the interquartile range (IQR) and the median of the SFF scores for each raster cell. Circles with dots indicate the median coefficient of variation of the SFF scores across the case study area.

the adaption of such a classification for individual soil sub-functions according to the range of soil properties for the case study area of interest or according to national references. Only where the SFF scores on the ordinal scale of a certain soil function show substantial spatial variation can the influence of uncertain soil properties on the SFA results be investigated.

In this regard, H-plant is a special case for the assessment of uncertainties, because the outcome of this SFA method is a binomial variable, i.e., it indicates whether the soil provides niches conditions for rare plant populations or not. The simple SFA revealed that 14% of the soils in the case study area are suitable for providing niches for rare plants in terms of wet or dry soil conditions, low nutrient availability and shallow soils. Such extreme soil conditions are mainly determined by soil depth, soil hydromorphic features, and other soil properties and only to some degree by the considered uncertainty of the soil properties SP_d. Therefore, for a proper uncertainty assessment of the SFA-method H-plant, not only must soil properties be taken into account, but the uncertainty of the aforementioned variables should also be considered.

In addition to the uncertainty maps described above, we generated supplemental information on the uncertainty of soil function maps addressing a given quality assurance criterion (Figure 5.4). We defined the C90 criteria, i.e., mean SFF scores for raster cells are displayed if at least 90% of the SFF score simulations result in the same SFF unit, otherwise the study area is shown as a grey area. In this way, stakeholders can easily gain an overview of those areas for which the soil function maps are reasonably reliable. Figure 5.4 illustrates such supplemental maps and the visual effect of the C90 criteria for three SFA methods with high (R-nutril), medium (R-icont), and low reliability (H-microorg). Independent of the SFF scores, the number of raster cells displayed decreases for these three soil sub-functions, in the same order. In sum, the uncertainty analysis shows that R-nutril and R-nutric fulfil the C90 criteria for most of the assessed agricultural area (85-90%); P-agri, R-water, R-icont, R-ocont fulfil them for about 41-51%; while R-acid, H-microorg and R-carbon apply for less than 5% of the case study area. Accordingly, the average MAD of the SFF scores across the whole region increase noticeably for these three groups in the same order, from < 0.01 for the first group to $0.01 - 0.07$ for the second, and 0.43-0.88 for the third group. For the last group, the range of SFF scores (5% and 95% percentiles for each raster cell) in terms of SFF units varies for large areas from very low to very high, as illustrated for instance for H-microorg in the north-eastern part of the region (see Figure 5.4).

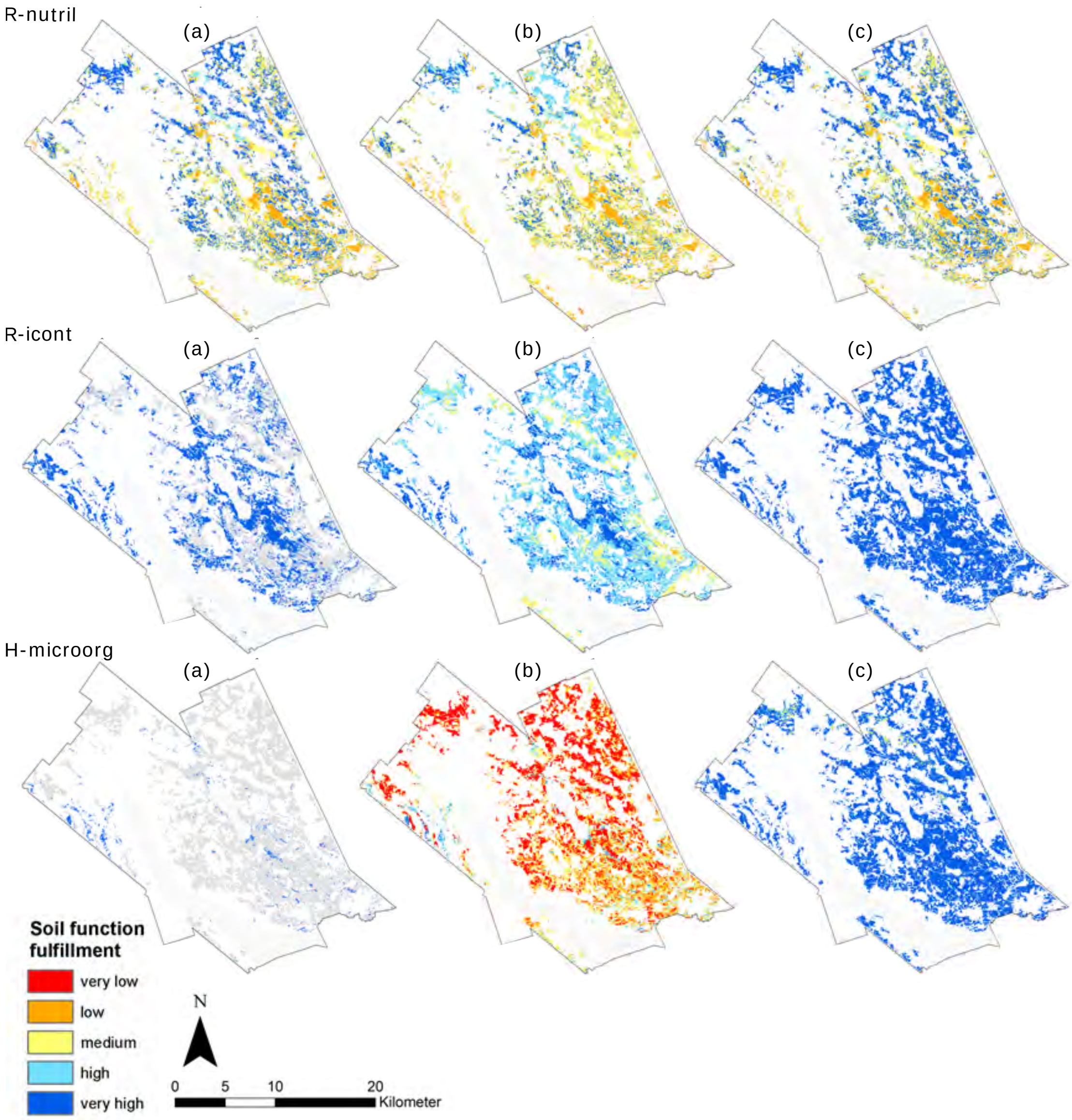

Figure 5.4: Uncertainty indication for soil function maps of R-nutril, R-icont and H-microorg: a) only mean SFF scores for raster cells are displayed if at least 90% of the N= 1000 simulations per raster cell revealed the same SFF score (first column). In addition, the range of SFF scores for each raster cell is shown: b) 5% and c) 95% percentiles of SFF scores, respectively (SFF = soil function fulfillment, grey: not C90 or no assessment, light grey: Lakes, "Arealstatisik" 2009, 72 classes, © BFS 2010, GEOSTAT)

5.3.2 Cumulative distribution functions of SFF scores

Cumulative distribution functions (cdfs) of the SFF scores for all raster cells provided deeper insight into the sensitivity of the SFA methods related to the uncertainty of the basic soil properties SP_d with regard to the uncertainty for each SFF unit for each soil function. In general, we observed two different patterns in the cdfs of the SFF scores for type 1 (equation) and type 2 (look-up table) SFA methods (Figure 5.5 and 5.6).

For type 1 SFA-methods the uncertainty in the soil properties can be propagated entirely through regression functions and deterministic equations, and cdfs of the corresponding SFF scores indicate a smooth pattern of mean SFF scores and their uncertainties from very low to very high SFF scores (Figure 5.5). In contrast, dependent on the classification of soil properties in the look-up tables used in type 2 SFA methods, the cdf for R-nutril and P-agri show pronounced, and for P-water and P-acid less pronounced, step-functions for the mean SFF scores. Both of the first two SFA methods combine information on soils and environmental site conditions (e.g., geology, drainage systems, slope, altitude and climate) using various comprehensive look-up tables, leading to a strong discrimination of the final SFF scores for distinct ranges of soil properties. Therefore, the outcomes of these SFA methods for a given region is not straightforward. For example, R-nutril combines texture, stone and soil organic matter content, bulk density, soil depth, drainage class, and environmental conditions as input data in various look-up tables. Thus, other input parameters including soil properties might also determine the main outcome of R-nutril for certain SFF units. For R-nutril and P-agri, soil depth and drainage class showed strong discrimination between SFF classes.

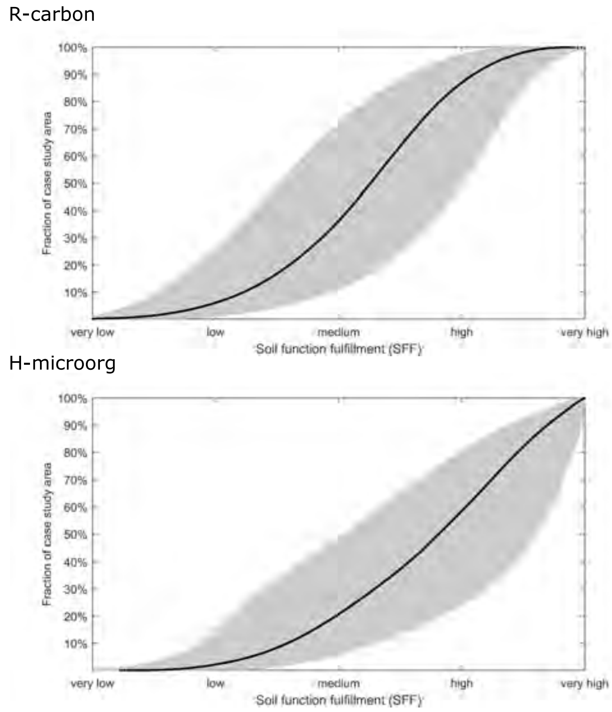

Figure 5.5: Cumulative distribution function (cdf) of SFF scores for type 1 (equation) for R-carbon and) H-microorg for agricultural soils of the case study area and the uncertainty resulting from four basic soil properties. (SFF score 1: very low to 5: very high; black: mean SFF score per raster cell, grey: range ± MDM per raster cell, number of raster cells: about 450 000; total area = 170 km^2).

Figure 5.6 indicates that the SFF scores for R-nutril are only sensitive to some degree to the uncertainty in the soil properties SP_d for high and very high SFF units, while for other SFF units other environmental data are dominant.

Interestingly, we observe that certain SFF units of the type 2 SFA methods are more or less sensitive to the propagated uncertainty of soil properties SP_d (Figure 5.6). This different response in the uncertainty of the SFF scores for the type 2 SFA methods was a priori unexpected and highlights the importance of such an uncertainty analysis of static SFA methods. The analysis provides insight in terms of those SFF units for which uncertainty in soil property data plays an important role. For soils with a low suitability for food production the range of soil properties is not important (see Figure 5.6) given that waterlogging or soil depth might be the dominant factors. However, for soils with medium and high suitability the range of soil organic matter, clay and stone content, and soil pH are decisive.

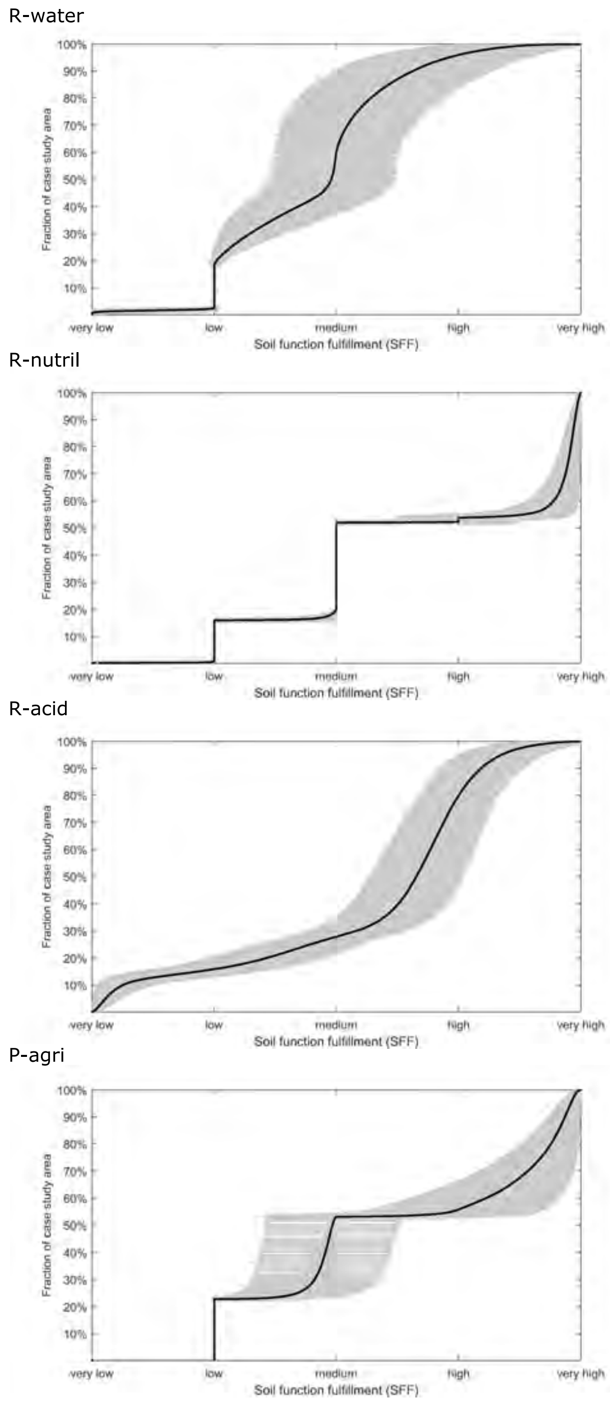

Figure 5.6: Cumulative distribution function (cdf) of SFF scores for type 2 (look-up table) for R-water, R-nutril, R-acid and P-agri for agricultural soils of the case study area and the uncertainty resulting from four basic soil properties. (SFF score 1: very low to 5: very high; black: mean SFF score per raster cell, grey: range ± MDM per raster cell, number of raster cells for these soil functions ranged between 420 000-445 000; total area = 170 km^2).

In line with the analysis of the uncertainty maps discussed above, relatively large uncertainty was found for all raster cells for R-carbon and H-microorg (Figure 5.5). The SFA method H-microorg, for example, links microbial biomass for grassland and arable land use to soil organic matter, pH and clay content through an empirical PTF, and is therefore very sensitive to changes in soil properties. For R-water and P-agri for medium to very high SFF units the uncertainty in the soil properties SP_d also leads to rather less confident

SFF scores. Consequently, the analysis suggests on a specific level that further measurements of basic soil properties are required in the case study area to reduce the uncertainty in the spatial prediction of soil properties obtained from the DSM approach used by Nussbaum et al. (2017).

Moreover, our analysis clearly indicates that SFA results are not comparable between type 1 and type 2 methods and among type 2 methods in view of uncertainty indication. One of the core aspects of the soil function concept is to assess soils multifunctionality and the role soils play for humans and the environment in general and to support land use decisions (e.g., Haygarth and Ritz, 2009; Schulte et al., 2014). However, soil subfunctions are not directly comparable. The valuation of soil is more straightforward and transparent for stakeholders using SFF scores. The comparability of SFA results at the ordinal scale allows to deliberate on the importance of soil functions. Deliberation is seen as a promising tool to value environmental goods or services (Vatn, 2009). Soil function maps including uncertainty indications can also be used in multi-criteria decision analysis (MCDA), for instance in spatial planning programs (Grêt-Regamey et al., 2017c).

5.3.3 Thoughts on uncertainty indication

Uncertainty is usually expressed as a probability of a state or an event, and can be presented numerically, verbally or graphically (IOM, 2013). Its presentation must fit the needs of the audience, the circumstances, and the purpose (IOM, 2013). We argue that the easiest way to interpret and the most suitable way of communicating (un-)certainties to actors in land-use decisions is in the form of maps because this enables the visualization of spatial variability. Clearly, for a general overview of the study area, insight into method behaviour or comparisons between soil function, and information in the form of a table or a plot may also be suitable. In this study, we present readily communicable uncertainty indications for soil function maps. There are many other possibilities as well, of course, including statistically advanced methods to display (un)certainties in soil function maps. Rather than providing statistical measures, however, we advocate provision of simple uncertainty maps such as those illustrated in Figures 5.2 and 5.4 as a means of facilitating the communication of uncertainties with stakeholders who may not be familiar with soil science and the contribution of soils to ecosystem services.

Experience of communicating uncertainty in the context of climate (Budescu, 2016) has shown that the use of simple phrases such as "very likely" combined with a numerical score (e.g., >90%) are of most value because stakeholders understand this kind of message the best. Communication of uncertainty through phrases has the advantage that they capture the attention of stakeholders, although they are also somewhat open to individual interpretations in different contexts. According to (IOM, 2013), although graphical indications can "capture and hold people's attention", the interpretation may vary among individuals. A correspondent option to evaluate in the future would be to communicate a general phrase about the uncertainty of a soil function map, combined with a map that shows the details of the spatial variation of the uncertainty.

Depending on the method used, uncertainties in soil information input in SFA may be more or less disclosed or obvious, and with this in mind the question itself is then what degree of uncertainty in data input in SFA should be transported through the SFA to match the needs of decision-makers in spatial planning processes. The optimal degree of uncertainty indication depends on the stakeholders involved in decision-making and the kind of decisions. The mindsets of the actors involved influence how the decision can profit from good quality soil function maps, including uncertainty indications. Time and resources for decision-making may vary and require a variable quality of information.

5.4 Conclusions

Decision-making in spatial planning programs should be well informed on the role of soils for society and the environment. Mapping of soil functions underpins the contribution of soils to ecosystem services, and is appropriate for communicating the importance of soils to spatial planners and other disciplines. Transparency in mapping of soil functions including their uncertainties adds to the quality of spatial information used for decision-making. In this study, we try to foster transparency in two ways. First, we demonstrate how the reliability of soil function maps can be presented to allow for informed and transparent decisions in spatial planning processes, thereby helping to avoid poorly informed policy decisions with regard to available soil resources. We propose two types of maps for the indication of uncertainties in SFA, which supplement each other. We advocate that uncertainties should be made as transparent as possible and be visualized in easily understandable maps.

Second, taking into account the uncertainty of basic soil properties, the performed uncertainty analysis for SFA provides deeper insight into the sensitivity of the SFA methods. The cumulative distribution functions for the SFF scores of individual soil functions showed different patterns for SFA-methods based on empirical equations and SFA-methods using simplified look-up tables. Indeed, soil data availability for the study area was good in comparison to other areas in Switzerland. To achieve the same degree of detail in applying this approach for larger areas without soil sampling could therefore be challenging.

In this study, we restricted the uncertainty propagation through the SFA methods to four basic soil properties at four depths, mainly because of computational limitations. Other sources of uncertainty such as informational uncertainty of other soil properties, environmental variables, e.g. climate data, and the reliability of PTFs should be considered as well. Furthermore, we presume that model uncertainty arising from methodological simplifications might cause substantial uncertainties in SFA, for instance, with regard to simplification of process descriptions, the reference assessment depth or to the calibration of the ordinal scale. On the other hand, the static SFA approach is in general quite flexible and modular. A general drawback of the SFA approach is that SFA-results can hardly be validated (Calzolari et al., 2016). Although we used established SFA methods, we still consider further development of applicable SFA methods as a future challenge, in particular methods that link soil biology and soil biodiversity to soil functions.

Acknowledgements This study was part of the "Predictive mapping of soil properties for the evaluation of soil functions at regional scale" project (PMSoil; project number 406840-143096) and the "Matching soil functions and soil uses in space and time for sustainable spatial development and land management" project (OPSOL; project number 408640-143092), funded by the Swiss National Science Foundation within the framework of the National Research Programme "Sustainable Use of Soil as a Resource" (NRP 68), www.nrp68.ch. The Swiss Federal Office of the Environment (FOEN) provided additional funding.
Benjamin Seitz supported the translation from soil information in Swiss soil classification to WRB for the description of the study region.

Chapter 6

Conclusions and outlook

6.1 Conclusions

Actors in a spatial planning process should be clearly informed about the roles played by soils in supporting society and the environment, in order to ensure that any decisions made support the sustainable use of soils. Mapping of soil functions underpins the contributions of soils to ESs (Adhikari and Hartemink, 2016) and is appropriate for communicating the importance of soils to spatial planners and other disciplines (Bouma, 2014).

A review of the literature shows that soil-focused ES frameworks exist (e.g., Dominati et al., 2014; Robinson et al., 2012; Schwilch et al., 2016). In 181 publications, the roles of soils in supplying ESs are considered, and in 83 of these publications at least one method or proxy indicator derived from soil properties for quantifying soil-related ESs is presented. About a quarter of these publications take four or more soil functions into consideration (e.g., Dominati and Mackay, 2013; Dominati et al., 2014; Rutgers et al., 2012; Schulte et al., 2014), and Calzolari et al. (2016) present a particularly broad study. Haygarth and Ritz (2009) state that the multi-functional roles of soils in ESs are generally not well assessed. Bouma (2014) arrived at the same conclusion, and the present findings also indicate that soil could be better integrated in ES mapping. A set of well documented and potentially transferable SFA methods and a minimal dataset for SFA are presented, and, because a lack of data is often blamed for soil not being considered (e.g., Adhikari and Hartemink, 2016; Liekens et al., 2013; Maes et al., 2012), some indication of possible sources of soil properties and PTFs are given in Chapter 2 to facilitate the integration of soil into methods for quantifying the soil-related supply of ESs.

In collaboration with partners in the PMSoil and OPSOL projects, some clarification is given of the soil function concept for statically assessing soil functions and possibly integrating the concept into the ES approach that is frequently used to support spatial planning decisions (Grêt-Regamey et al., 2015). A set of soil functions is defined, relevant to protecting soil and covering a broad range of soil functions and demands for soil information made by stakeholders in different organisations. The generally mapped and possibly predictable soil properties are matched with the requirements of SFA methods.

By means of a case study, SFA methods were adapted and applied to regulation (i.e., the regulation of water, nutrients, heavy metals, organic compounds, acids, and contaminants, and the buffering of acidity), habitats (plants and microorganisms), and production (agriculture) using harmonised legacy soil data published by Walthert et al. (2016) and soil property maps from a digital soil mapping exercise performed by Nussbaum et al. (2018, 2017), in an attempt to capture the multi-functionality of soil. Existing international SFA methods were transferred to Swiss soils by focusing on SFA methods that use few ordinal data, and the SFA methods were adapted to the Swiss soil classification system where necessary (mainly for hydromorphic features and rooting depth). The assessment scales were also calibrated to the variability in Swiss soil. Assessment was made of how reasonable the soil function maps were by comparing the SFA results for the profile data with land use, drainage class, and soil type data.

The soil function maps were mostly reasonable and showed pronounced and variable spatial patterns. The exceptions were the soil function maps for the regulation of inorganic and organic contaminants, which were similar for all study areas.

Static SFA requires a strong methodological basis. Methods for production and regulation functions based on chemical and physical soil properties are already quite well developed (Ad-hoc-AG Boden, 2007; Blaser et al., 2008; Calzolari et al., 2016; Makó et al., 2017; Müller and Waldeck, 2011), but methods for SFA of habitat functions and SFAs including the effects of biological parameters on regulation and production functions are still being considered (Aksoy et al., 2017; Bünemann et al., 2018; Griffiths et al., 2016; Keesstra et al., 2016; ÖNORM, 2013).

An SFA depends strongly on the availability of soil mapping survey-data and PTFs. Soil properties and PTFs are important to the reliability of the soil function map produced, but SFA methods contribute to the quality of each soil function map produced because they require appropriate assessment criteria to be used, appropriate soil properties for evaluating the criteria to be chosen, sensible assessment scales, and soil functions to be simplified to an appropriate degree.

We evaluated the use of four options (Miller, 2012; Haslmayr et al., 2016) with two stakeholder weightings to aggregate different soil function maps into one "soil index" map because further simplification could make it easier for stakeholders to use the soil information. The soil index maps for our study area contained variations for some options and were close to the average soil function fulfilment score for other options. No general tendencies were found for the four options, and we found no reasons to favour a certain aggregation from the viewpoint of soil protection.

Bünemann et al. (2018) reviewed other approaches to aggregating different indicators into one soil quality index and found that soil functions may have very different importance ranks and weightings at different sites.

In the case study, two types of maps were proposed for indicating uncertainties in the SFA. These maps complemented each other and showed that the SFA methods have different sensitivities to uncertainties in the soil property input data. As is required by stakeholders, particularly those involved in policy (Campbell et al., 2017), uncertainties in soil function maps should be made as transparent as possible, be communicated verbally, and be shown in easy-to-understand maps that help avoid poorly informed policy decisions relating to available soil resources (Budescu, 2016; Maxim and van der Sluijs, 2011).

Interpreting soil information using SFAs allow actors in land-use decision-making to understand the multi-functionality of soil and allow soil information to be integrated when quantifying the supply of ESs (Drobnik et al., 2018).

Having all these features in mind, this thesis is a practical contribution to soil protection in Switzerland that will help bridge the gap between soil information and the users of soil information in spatial planning processes and possibly stakeholders in other fields, such as water management and climate change, who use static and interpreted soil information.

6.2 Outlook

Having established a process chain for generating soil function maps for Swiss conditions, the process was then tested in a case study. Static SFAs are increasingly being established and used in Germany and Austria (Ad-hoc-AG Boden, 2007; Haslmayr et al., 2016), but SFAs for Switzerland are only starting to be developed, and further work is required to implement SFA in terms of soil data (see Section 6.2.1) and the method used (see Section 6.2.2). Further work is required to link the soil function concept directly with practical problems or approaches aimed at putting values to ecosystems, such as the ES approach (see Section 6.2.3).

6.2.1 Data for SFAs

The minimum dataset required to assess soil functions was defined based on the data requirements of SFA methods, i.e., soil texture, organic matter content, stone content, pH, soil depth, presence or absence of a gleyic or anoxic horizon, and drainage.

This minimum dataset could be challenged but matches the soil properties that are generally measured (van Leeuwen et al., 2017). It is not possible to perform an SFA without soil data, so SFA methods can only be developed to use available data.

There is little doubt that SFA methods for assessing the habitat functions of soils need to be developed further. This is also because few biological data for soil are available, as shown for soil monitoring networks by van Leeuwen et al. (2017). A larger minimum dataset is required for some adaptations of the habitat SFA method and possibly other SFA methods. Several options for including soil biology into the SFA or soil quality indicators and the corresponding data requirements have been presented, for example by Bünemann et al. (2018); Griffiths et al. (2016).

In addition to the minimum dataset, PTFs appropriate to the study region are required to allow secondary soil properties to be derived for use in SFAs. Bulk density, saturated hydraulic conductivity, and cation exchange capacity are examples of such secondary properties. These are time-consuming and expensive to measure (Bouma, 1989). PTFs are only partially available for Swiss soils (e.g., Nussbaum and Papritz, 2015; Nussbaum et al., 2016), and PTFs for soil hydraulic properties in particular are required (Carrizoni et al., 2017).

We used a simplified version of the soil subtypes (subtypes I, G, and R (FAL, 1997)) to describe drainage in three classes for two of the SFAs. Soil properties are classified in several SFA methods, often according to local soil classification schemes (e.g., Danner et al., 2003; Jäggli et al., 1998; Litz, 1998). A combination of continuous soil properties and soil properties in ordinal classes may cause implicit weighting of SFA input data and mask uncertainties in the input data, decreasing transparency and making it harder to interpret the resulting soil function fulfilment score. Properties such as soil subtypes on drainage seem to be open to interpretation to a certain degree. It is suggested that SFA methods using fewer ordinal soil taxonomic data should be developed, together with methodological approaches that support the translation of soil taxonomic data into continuous soil parameters.

6.2.2 SFA methods

A number of SFA methods for assessing production functions for soils have been developed and have been established for a long time (Brevik et al., 2016), but others are quite new and less well established. The Swiss SFA method for agricultural production (P-agri) could be easier to interpret, and other SFA methods clearly need to be evaluated better and have stronger bases. In particular, SFA methods for representing biodiversity in soils should be developed more quickly than at present. This is challenging because many factors determine biodiversity patterns in soils, and the contributions of different factors are poorly understood (Keesstra et al., 2016), although several indicators have been proposed (Bünemann et al., 2018; Griffiths et al., 2016). The results of ongoing research should be integrated into practical approaches as soon as possible. Methods probably need to be adapted to include forest soils properly and to include the strongly varying acidity buffering capacities of forest soils (Blaser et al., 2008). The set of methods would need to be expanded.

Non-soil properties are mostly used in SFA methods for assessing the production functions of soils. This is also the case for other SFAs. As stated in Chapter 3, this could weaken soil as a resource. It would be possible to explore the effects of removing non-soil-properties from established SFA methods.

The established methods have certain assessment depths, but data are often only available for topsoil, which is a problem when assessing soil functions (van Leeuwen et al., 2017). Explicit justification for the selected assessment depth is not given. Assessment depths are selected based on expert knowledge and probably on the data available. van Leeuwen et al. (2017) found that in many cases only topsoil samples are taken. The quality of an SFA would improve if we could show that the assessment depth is functionally relevant. It would be sensible to indicate the loss of variation between different soils if a SFA is restricted to a certain depth instead of considering the soil to its parent material. Torres-Sallan et al. (2017) state that the ability of soil to act as a carbon sink may vary with depth because soil organic carbon may be stored in the long term below 30 cm deep, depending on the clay fraction.

To the best of our knowledge, SFA methods have not been compared with biophysical models of soil functions, which are not used to assess soil functions but to quantify soil functions through the flow or the transformation of materials or energy (Banwart et al., 2017). Such a comparison could help to indicate whether important aspects of a soil function are taken into consideration in a SFA method and whether certain benchmarks in a SFA are sensible compared with the variability of a given unit.

A comparison of static SFA methods with dynamic soil function modelling approaches could also provide insights into the required complexity of a soil function description. Until now, SFA methods have varied in the degree of complexity with which they describe a soil function because of the different states of development of different SFA methods. It may be sensible to strive for comparable complexities in all SFA methods used to describe the multi-functionality of soil. The amount of complexity that needs to be considered to answer spatial planning questions also needs to be determined.

The interdependence of SFA methods needs to be investigated further. One can of course compare SFA results, but the degree to which similar soil property inputs affect the final results is not well understood. The interdependence of soil function maps being merged may be seen in the aggregated "soil index map" produced. Building a meaningful "soil index map" requires an awareness of and ability to quantify these interdependencies.

We used 100 Soil Monitoring Network profile sites in Switzerland to calibrate the assessment scales of our SFA methods. Many measured soil properties were available for the sites, but hydraulic conductivity and available water capacity were not available and were deduced using PTFs. Measuring desorption curves for the profile sites, for example, would allow variability in the roles of the Swiss soils in the water cycle to be represented better than was otherwise possible. The water cycle regulation function of soil is crucial today and may be even more important in the future considering potential climate change. Knowledge about soil function fulfillment may allow to better adapt to drought periods or more pronounced rainfall events (NIR, 2017).

It was shown here that different types of SFA method (direct assessment of data, combined look-up tables, and methods with various classifications) propagate uncertain input data to different degrees. Harmonising the methods in this regard would make different soil function maps more comparable and make it possible to aggregate functions to give a more reasonable soil index map than can currently be drawn. Depending on the method type, the complexity of a soil function could be preserved, but increasing complexity could make it more difficult to interpret the results.

In summary, the SFA process should be transparent and is most useful if the methods used

a) simplify soil functions but still represent the core of soil functions with appropriate assessment criteria, evaluation measures, and reference values (Bünemann et al., 2018),

b) are comparable in terms of complexity,

c) deal in comparable ways with uncertainty in the data input,

d) have sensibly calibrated assessment scales, and

e) have resulting soil function fulfilment scores that can easily and clearly be interpreted (Bünemann et al., 2018).

The SFA approach is generally flexible and modular, and SFA methods can be improved or exchanged. However, the SFA approach suffers because it is almost impossible to validate an assessment result (Calzolari et al., 2016). The results of a SFA will be useful, however, if the points mentioned above are taken into consideration. The challenge is either to meet requirements a–e or agree when they are met.

6.2.3 SFAs for practical use

Soil information may be used directly or interpreted to produce soil function maps, and soil function maps can be weighted and aggregated to give an overall soil indicator (e.g., for spatial planning Haslmayr et al., 2016; Wolff and Blümlein, 2017). Alternatively, soil information can be integrated into an ecosystem valuation approach (Robinson et al., 2012).

Which of these four options is the most appropriate depends on the issue being addressed. Direct use of soil information or soil function maps may be appropriate for technical questions such as questions about irrigation, flood protection or manuring. Indicators and ecosystem valuation approaches may be useful for spatial planning processes or for increasing awareness of the value of soil in general. However, various valuation approaches are available for linking soil systems to socioeconomic factors, and there remains debate about which are the most appropriate (Vogel et al., 2018). Bünemann et al. (2018) suggest that unavoidable trade-offs between various soil uses mean that stakeholder involvement in the valuation process is important. Schulte et al. (2014) for example, developed a conceptual framework to provide soil function information to meet the demand made by soil policies. This functional land management concept was aimed at optimizing the agronomic and environmental return from land based on soil multi-functionality (O'Sullivan et al., 2015). Five key soil functions were selected for use in the framework, three of them regulation functions (water purification, soil carbon storage, and nutrient cycling), one the habitat for biodiversity function, and the other the food production function. The soil function set chosen should capture as far as possible the whole spectrum of soil multi-functionality (Haygarth and Ritz, 2009; Bouma et al., 2012). The set of five key soil functions - used by other authors as well, e.g.Techen and Helming (2017) and shown to be of interest in Greiner et al. (2017)) - should be complemented by other regulation functions mainly.

Soil protection is currently on the political agenda in Switzerland (FOEN, 2017). This means it is appropriate to communicate the need for soil information (soil mapping), discuss interpretations of this information from the soil science perspective (i.e., SFA), and find useful ways of valuing (potentially interpreted) soil information for different applications using ecosystem approaches and involving stakeholders. These questions have been addressed for Switzerland by a thematic synthesis of NRP68 (Keller et al., 2018), Nussbaum (2017), and Carrizoni et al. (2017).

Bouma (2014) propose that soil scientists should actively acquire soil information for use in the decision-making process. In a future project (a pilot study organized by the "Sanu Durabilitas" foundation (www.sanudurabilitas.ch)) the aim will be to test the use of soil function maps by directly collaborating with local administrators in Switzerland. This is expected to improve SFA methods to make them of more practical use in the decision-making process.

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Appendix A

A.1 Appendix Chapter 2

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187	Willemen, L., Hein, L., van Mensvoort, M. E.,Verburg, P. H. (2010). Space for people, plants, and livestock? Quantifying interactions among multiple landscape functions in a Dutch rural region. Ecological Indicators, 10(1), 62-73. doi:10.1016/j.ecolind.2009.02.015
188	Willemen, L., Veldkamp, A., Verburg, P., Hein, L., Leemans, R. (2012). A multi-scale modelling approach for analysing landscape service dynamics. Journal of Environmental Management, 100, 86-95. http://dx.doi.org/10.1016/j.jenvman.2012.01.022

Table A.1: References ecosystem services literature

No.	Author(s) or project
189	Willemen, L., Verburg, P. H., Hein, L., van Mensvoort, M. E. (2008). Spatial characterization of landscape functions. Landscape and Urban Planning, 88(1), 34-43. http://dx.doi.org/10.1016/j.landurbplan.2008.08.004
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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
1	Adhikari, Kabindra	2016	s	x		x	x		SOC, texture, pH, soil depth, bulk density, AWC, CEC, electrical conductivity, porosity and air, saturated hydraulic conductivity, soil biota, structure, temperature, clay mineralogy, subsoil pans	Provisioning (food, fuel, fibre, raw materials, gene pool, water), regulating (climate and gas, water, erosion and flood control, pollination, seed dispersal, pest and disease, C sequestration, water purification), Cultural (recreation/ecotourism, aesthetic, knowledge, cultural heritage), supporting (soil formation, nutrient cycling, provisioning of habitat)
2	Altwegg, Jürg	2014	w				x	x	soil suitability map ("BEK"), expert knowledge on soils	Provisioning(food, drinking water, wood, fibre, genetic resources), Regulating (climate, water), Supporting (soil formation, element cycling, primary production)
3	Anderson, Barbara	2009	w					x	SOC, bulk density, stone content (from UK National Soil Resources Institute, until 1m soil depth)	C storage, Agriculture value
4	Antle, John	2006			x				SOC	
5	ARIES, Villa, Ferdinando,Bagstad, Kenneth	2009, 2011, 2014	w					x	Soil C:N ratio, SOC, pH, soil oxygen, infiltration, soil texture, hydrological soil group	C sequestration and storage, flood regulation, water supply, nutrient regulation (under development), sediment regulation
6	Ausseil, Anne-Gaelle	2013	w					x	total WC and AWC available water, soil type (from Fundamental Soil, Layers database, used for water flow and water quality)	regulation of climate, regulation of water flow (quantity), provision of clean water (quality), provision of food and fibre, and provision of natural habitat
7	Swiss Federal Office for the Environment (FOEN)	2011	w			x			SOC, perhaps biodiversity monitoring (BDM) data, land suitability classes	Final ES: health, security (CO2 sink, water retention), natural biodiversity, economic services (fertile soil, filtering and buffering of residuals, filtering of drinking water)
8	Bagstad, Kenneth	2013	w						SOC	C sequestration, C-storage
9	Bagstad, Kenneth	2013								
10	Bai, Yang	2011	w					x	SOC, soil depth, plant available water content	carbon sequestration, water quality, water yield
11	Banzhaf, Spencer	2005			x	x		x		

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
12	Barbier, Edward B.	2007			x	x				Puts what elsewhere is titled with 'ES' under the category ' ES function' (eg. Regulatory functions, habitat functions). Examples for ES (soil related): maintenance of productivity on arable land, Flood mitigation, drainage and natural irigation
13	Barrios, Edmundo	2007	w							Provisioning (agri, prod.) Regulating (Nutrient cycling, N-fixation, pest and desease control) 'ecosystem services of soil erosion cpntrpö and C sequestration' (S. 280)
14	Bastian, Olaf	2013	w					x	natural yield potential (out of AWC, capillary moisture, CEC and base saturation. Data from the Soil Atlas of Saxony)	potential of food crop provision
15	Bastian, Olaf	2012				x		x		climate regulation, c sequestration
16	Bateman, Ian, J.	2013	w		x			x	physical soil properties for agriculture (not specified), soil depth, stone content, texture, SOC (European soil data base)	agricultural production, greenhouse gases
17	Batker, David	2010	w					x	hydrological soil group (NRSC soil survey, 30X30m)	flood protection
18	Birch, Jennifer	2014	w					x	litter and soil carbon (form IPCC tier 1)	global climate change mitigation, water quality and provision, cultivated goods
19	Blouin, Manuel	2013	w	x						
20	Boumans, Roelof	2002	w		x		x		N, decomposition rate of organic material, SOC	soil formation, nutrient cycling, climate regulation, gas regulation
21	Boyanova, Kremena (same focus: Nedkov and Burkhard 2012, Stürck et al. 2014)	2014	w					x	digital soil map data (FAO), USDA soil data set	
22	Boyd, James	2007			x	x				soil quality (one ES under the benefit 'harvest')
23	Braat, L.	2008			x	x				
24	Brandt, Patric	2014	w					x	percent of organic content in upper 2mm of the soil (?)	regulating (organic matter in soil)
25	Breure, Anton M.	2005	w			x				

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
26	Breure, Anton M.	2012	s	x	x	x		x		Regulating services (water purification, nutrient cycling, ...), Provisioning services (water, food, ..), Societal services (biodiversity, recreation, ..)
27	Brevik, Eric C.	2016	s	x		x	x		long list of soil properties but not in connection with ES	Supporting (habitat for plants, humans and infrastructure, soil organims), Provisioning (food, wood fibre, raw materials), Regulating (water storage, water runoff, nutrient and pollutatnt retention and release, natural attenuation of pollutants, C storage and GHG regulation), Cultural (spiritual value, esthetic, knowledge)
28	Broekx, Steven	2013	w					x	moisture, texture, drainage, SOC, (N- and P-content is derived from SOC)	regulation (nutrient retention, climate regulation)
29	Burkhard, Benjamin	2012	w					x	soil type, SOC	
30	Burkhard, Benjamin	2013						x		
31	Burkhard, Benjamin	2013				x				
32	Calzolari, Costanza	2016	s	x				x	texture, SOC, stone content, bulk density, carbon stock, CEC, air entry potential, saturated hydraulic conductivity, soil water content at different tensions, available water capacity, shallow water table depth	Habitat for soil organims, nutrient and pollutants retention, natural attenuation, contribution to microclimate regulation, carbon sequestration potential, food provision, support to human instrastructure, water regulation - flood control, water storage
33	Carpenter, Stephen R.	2009	w			x				
34	**Castro, Antonio**	2014	w		x			x	SOC (for climate regulation)	cultivation of crops, climate regulation
35	Chan, Kai M. A.	2006						x	(soil indirectly represented with vegetation, crop reports, hydrology unis, physiografic units)	carbon storage, flood control, forage production, water provision
36	CICES (see also Haines-Young and Potschin 2013)	2013	w			x				provisioning (no soil relation), regulating and maintenance(mediation of waste/toxics/other nuisances, mediation of flows-flood regulation, soil formation and composition)
37	Clec'h, Le, Solen	2016	s					x	texture, SOC, saturated saturated hydraulic conductivity, bulk density, soil biota (earthworms, other macrovertrebrates, CEC, pH, echangeable NH4+ and P	Climate regulation, soil fertility, water cycle regulation and erosion control, suppor to production, biodiversity, support to productiona and pollination
38	Conte, Marc	2011	w		x			x	SOC and additionally soil properties affecting land use	climate regulation via C storage and sequestration

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
39	Costanza, Robert	1997	w		x	x				climate regulation, water regulation, soil formation, nutrient cycling, waste treatment, food production, raw materials
40	Costanza, Robert	2008				x				
41	Crossman, Neville D	2013						x		Provisioning (food, water, raw materials), Regulating (climate, moderation of extreme events (mostly flooding), water flows, maintenance soil fertility), Habitat (live cycle maintenance, genetic diversity)
42	Daily, Gretchen C.	2009			x	x		x		
43	Daily, Gretchen C.	1997	w		x	x				S. 3 Purification of air and water, mitigation of floods and droughts, detoxification and decomposition of wastes, generation and renewal of soil and soil fertility, pollination of crops and natural vegetation, control of potential agricult. Pests: dispersals of seeds and translocation of nutrients, maintenance of biodiversity, partial stabilization of climate, moderation of temperature and the force of wind and waves, p. 117-125 (explicitly soil ES). Buffering and moderation of the hydrological cycle, physical support of plants, Retention and delivery of nutrients to plants, Dead organic matter and waste (decomposition), Renewal of soil fertility, Regulation of major element cycles
44	de Groot, Rudolf	2002	w		x				Soil formation, Soil retention	(more focussed on ecosystem functions: regulation, habitat, production, information function) A lot of ES follow from these functions
45	de Groot, Rudolf	2011	w		x	x		x	water storage capacity, water retention capacity, bioturbation (Kenngrösse hier?)	Provisioning services(food, freshwater, raw materials, genetic resources) Regulating services (air quality maintenance, climate regulation, moderation of extreme events, water regulation, waste treatment, erosion control, maintenance of soil fertility pollination, biological control) habitat or supporting services (maintenance of life cicles of migratory species and of genetic diversity)
46	de Groot, Rudolf	2006	w					x		In difference to de Groots articel from 2011 here the same ES are named as "Functions" : regulation functions, habitat functions,production functions, information functions, carrier functions. There are just example for possible goods and services

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
47	de Groot, Rudolf	2010	w			x			water storage capacity (for natural hazard mitigation, soil not named explicitely) , water retention capacity in soils, ect or at the surface (for water regulation), Amount of topsoil (re)generated per year (for soil formation and regeneration)	provisioning (food, water, raw materials), regulating (climate, natural hazard, water, erosion protection, soil formation and regeneration), habitat (genepool protection)
48	De Meyer, Annelies	2013	w					x	SOC	none explicitely named (? Apporach seems a bit irritating because of this, there don't seem to be predefined es which will then be assessed? Did i get that right?)
49	Dominati, Estelle	2010	s			x			depth, clay types, texture, stoniness, size of aggregates, subsoil wetness class, SOC, pH.... (S. 1863)	Provisioning (food, wood, fibre, physical support, raw materials) Regulating (flodd mitigation, filtering of nutrients, Biological control of pests and diseases, Recycling of wastes and detoxification, C storage and regulation of N2O and CH4 emissions) Cultural services (soil supporting vegetation, ...)
50	Dominati, Estelle	2013	s		x		x	x	trace-elements deficiency, bulk density, compaction OB, slope, (for flood mitigation: annual rainfall and runoff), N and P losses, Soil water content, macroporosity, PWP, FK, texture	Provision (forage, support, raw materials), Flood Mitigation, Filtering of Nutrients and contaminants, Detoxification and Recycling of Wastes, Carbon storage and Greenhouse Gases Regulation, Regulation of Pest and Disease Populations
51	Dominati, Estelle	2014	s		x	x		x	trace elements in the soil, field capacity, soil water saturation days, nFK, wilting point, depht, structure, texture, strength (?), stone content, clay content, frangipane, drainage class, mineral contents, biodiversity, organic matter, DOC, AAK, KAK, pH, porosity, bulk density, nutrient status	provision (food, physical support), flood mitigation, filtering of nutrients and contaminants, detoxification and recycling of wastes, C-storage and regulation on N2O and CH4, biological control of pests and diseases
52	Egoh, Benis	2012	w						belowground biomass, SOC (climate regulation), soil characteristics (?) (used for Erosion prevention, maintenace of soil fertility, regulation of water flow, food provision, water provision, climate regulation), Nutrient retention (soil fertility maintenance, regulation of water flow)	Provisioning (food, water, and other resources), Regulating (climate, soil quality, carbon sequestration, erosion prevention) , Habitat or Supporting (habitats for species and maintenance of genetic diversity)
53	Egoh, Benis	2008	w				x	x	soil depth	"five ecosystem services in South Africa: surface water supply, water flow regulation, soil accumulation, soil retention, and carbon storage." (p. 135)
54	Eigenbrod, Felix	2010	w				x		SOC (DEFRA study)	agricultural production, carbon storage
55	El Serafy, Salah	1998,2013			x					

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
56	Emmet, Bridget A.	2016	s					×	soil type	productivity, water quality, carbon storage and biodiversity
57	esp-mapping.net	2014	w					×		
58	Felipe-Lucia, Maria	2015	w					×	SOC	Regulating (gas regulation, soil formation, nutrient regulation), Supporting (habitat provision, food, raw material), Cultural (recreation, education)
59	Fisher, Brendan	2011	w		×	×		×		not really clear (mentioned: carbon, timber, water, biodiversity and "all")
60	Fisher, Brendan	2009				×				
61	Fu, B.	2014	w		×			×	soil depth, plant available water content, bulk density, texture, SOM, soil particle composition (?)	water retention
62	Gao, Yang	2014	w					×	soil depht, soil available water content (deduced out of these two: plant available water content..)	freshwater supply
63	Gascoinge, William	2011	w		×			×	SOC (estimated), SOC samples for 0-15cm to estimate C flow depending on land cover ..?	C sequestration, reduction in sedimentation (= soil erosion reduction)
64	Gret-Regamey, Adrienne	2013			×	×	×	×		
65	Gret-Regamey, Adrienne	2013			×	×		×		
66	Gret-Regamey, Adrienne	2007						×		avalanche protection, biomass production, carbon storage
67	Gret-Regamey, Adrienne	2008						×		
68	Grunewald, Karsten	2013				×				
69	Grunewald, Karsten	2013				×				
70	Guo, Zhongwei	2002	w					×	five soil types (yellow, yellow-brown, lime, purple, rice)	water retention

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
71	Haines-Young, Roy	2008			x	x	x	x	no soil data mentionned (for fertility score, pH score and soil moisture score plant indices used)	(in habitat approach, considered best by authors:) Production (fibre,food, freshwater, genetic, medicinal, other) Regulation (buffer, climate, disease, erosion (??), pest, water quality and flow regulation (assessed depending on landuse)) Supporting (nutrient cycling, primary production, sediment, soil formation)
72	Harmackova, Zuzana	2015	w					x	SOC, Soil depth ,AWC , Root depth, Nitrogen export coefficients	Climate regualtion, water quality improvement
73	Haygarth, Philip M.	2009	w	x		x			texture, bulk density, hydrological properties	Supporting services(primary production, soil formation, nutrient cycling), Provisioning (regugia, water storage, platform, food, biomaterials, raw materials, biodiversity and genetic resources), Regulating (water quality, water supply, gas, climate, erosion control)
74	Hewitt, Allan	2015	s			x		x	AWC, hydromorphic properties, fine earth, horizon thikness	nitrate filtering (= nitrate storage service and nitrate reduction service), P filtering service
75	Huo, Ying	2014	w					x		organic carbon density (?), (+ food crop output per unit sown area and per fertilizer input, also agricultural labour productivity)
76	InVEST		w		x			x	belowground biomass, C stored in soil, PNG, nFK, (+ nutrient loading coefficients, LAND USE)	Carbon storage/sequestration, nutrient retention/water purification
77	Jackson, Bethanna	2013	w					x	soil data/hydraulic capacity, SOC, soil information (not specified for agricultural valuation, no information on soil fertility available for case study, but for waterlogging)	flood mitigation
78	Jonsson, Jon Örvar	2016	s	x	x	x				Support functions (biodiversity, nutrient cycling, soil formation, water cycling), Regulating services (biological control of pests and diseases, climate and gas regulation, hydrological control, filtering of nutrients and contaminants, recycling of wastes and detoxification), Provisioning services (biomass production, clean water provision, raw material, physical envirionment), Cultural services(heritage, cognitive services, recreation)
79	Jopke, Cornelius	2015	w					x	SOC (soil fertility and c-storage)	provision (crop, timber, water, livestock), regulation (climate, water, soil fertility)

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
80	Lamarque, Pénélope	2011	w			x		x		
81	Landuyt, Dries	2015	w					x	soil type, texture, drainage class, soil moisture content	Wood production, agricultural production, climate regulation (through C sequestration), clean water provision (through infiltration), biodiversity potential
82	Laterra, Pedro	2012	s					x	SOC (by soil type and corrected by land-use factor), Soil Conservation Service curvenumber (to estimate water infiltration, soil input there: maximum potential soil moisture retention in Liter), productivity index (wetness, drainage, effective depth, texture and structure, alkalinity, soluble salt concentration, SOC, CEC, mineral reserves, soil erodability)	(functional ecosystem capacity), soil carbon storage, water infiltration capacity, productivity index
83	Lautenbach, Sven	2011	w					x	soil fertility classes (from soil fertility maps Sachsen,based on "Bodenschätzung"), yield	Water purification, food production
84	Lautenbach, Sven	2012	w					x	soil type, SOC	risk reduction of pesticides in ecological habitats, N-retention
85	Lavelle, Patrick	2006	w							Water supply, nutrient cycling, primary production, Soil formation, climate regulation
86	Lavelle, Patrick	2014	s					x	macro invertebrates, C storage in soil 0-20cm and GHG emission, AWC, porosity, moisture content, bulk density, resistance to vertical penetration, shear strength resistance, texture, pH, Al-saturation, content of N, Ca, Mg, P, K, Fe,Mn, Cu, Zn, B, S, C:N, stoniness, aggregate diameter (mean), type of macro aggregates (root, faunal, plant, physical), CEC	soil biodiversity, climate regulation, hydrological functions, soil stability, nutrient provision potential
87	Layke, Christian	2012	w				x		soil water infiltration, soil water storage	provisioning (food, biological raw materials, freshwater), regulating (climate, water, erosion, soil quality, water purification), supporting (primary production, nutrient cycling, soil formation, water cycling)
88	Li, Jing	2006	w		x			x	amount of water in the soil (es: water conservation)	vegetation's primary productivity, soil and fertility conservation, water conservation, carbon fixation and oxygen supply
89	Liekens, Inge	2013	w				x	x	texture, soil moisture	Provisioning (agri, wood prod.), Regulating (clima regulation by storage of SOC, nutrient retention, air quality, nois mitigation), Cultural ES

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90	Luck, Gary	2009	w					×	SOC	water provision, flood mitigation, carbon storage
91	Mace, Georgina M.	2012				×				
92	MAES	2014	w			×			chemical properties, water storage capacity, SOC, pollutants in soil, nutrients in soil, water retention capacity, CEC, pH of topsoil, presence of hydromorphic soils	
93	Maes, Joachim	2011	w			×	×	×	infiltration water, N and P-flux model (used to assess water purification serive), SOC (for soil quality)	crop services, water regulating services, water purification service, climate regulation service/carbon storage, soil quality regulation
94	Maes, Joachim	2013				×				
95	Maes, Joachim	2012				×	×	×		
96	Maes, Joachim	2012						×		
97	Martínez-Harms, María José	2012	w							
98	MEA	2005				×				Supporting (nutrient cycling, soil formation, primary production) Provisioning (food, fresh water, wood and fibre) Regulating (climate regualtion, flood regulation, disease regulation, water purification)
99	Metzger, Marc (closely related to Schröer et al. 2005)	2008	w					×	SOC (for both ES)	soil fertility maintenance, climate protection
100	MIMES	2010						×		
101	Muradian, Roldan	2010			×	×				
102	Naidoo, Robin	2008					×	×		C sequestration, C storage, Grassland production of livestock, water provision
103	Nelson, Erik	2009	w		×			×	soil depth, hydraulic connectivity, USLE	water quality soil conservation c sequestration
104	Nelson, Erik	2011	w		×			×	US soil capability class, GAEZ maps and other examples form expected yield maps	agricultural productivity (es processes contributing to productivity and therefore being ES: soil retention, nutrient cycling in the soil, water capture)

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
105	Nelson, Erik	2010								
106	O'Farrell, P.J.	2010	w					x	soil type (for grazing potential according to Schole et al. 1998s approach)	grazing potential, water supply, water flow regulation
107	O'Sullivan, L.	2015	w		x			x	soil drainage	productivity, carbon storage
108	Pagella, Timothy	2014				x				
109	Palm, Cheryl	2007	s	x		x			depht, texture, SOC, mineralogy, soil biota, CEC, AEC, Al-saturation, electrical conductivity, exchangeable Na, surface macroporosity, saturated hydraulic conductivity, aggregation, bulk density, root restricting layer	physical support for plants (soil formation), provision of nutrients (mineral weathering,soil organic matter mineralization,decomposition of organic additions,ion retention and exchange,toxicities), provision of water (infiltration, storage in soil, drainage) not in brackets: ES, in brackets: soil process
110	Petz, Katalin	2014	w					x	soil depth, soil available water, rooting depht	forage production, fuel wood provision, water supply, c-sequestration
111	Plieninger,Tobias	2014				x				
112	Portela, Rosimeiry	2012	w					x	soil C:N-ratio, pH, soil oxygene conditions (all three used to deduce SOC)	carbon storage, c-sequestration, water supply
113	Porter, John	2009	w		x		x	x	soil microorganisms (experiment on N-mineralisation), earthworm density (as indicator for soil formation)	N-regulation, Soil formation, Food production, Raw Material Production Carbon Accumulation (aber nur by crop and roots), Hydrological Flows
114	Posthumus, Helena	2010	w					x	SOC stock (indicator for soil quality), drainable porosity of the soil (indicator for floodwater storage), soil type (for GHG emission, peats),	Production (agricultural production, soil quality) Regulation (flood water storage, water quality, GHG balance) Habitat (habitat provision, wildlife)
115	Power, Alison	2010	w			x				water quality and quantity, soil structure and fertility (services to agriculture)
116	Raudsepp-Hearne, C.	2010	w					x	Phosphorus saturation Index and SOC in agrigultural soils (both from provincial soil data base), (for provisioning: Agricultural cencus and water quality form provincial water database, for C-sequestration: Remote sensing)	Provisioning (crops, drinking water, maple syrup, pork), Regulating (c-sequestration, soil phosphorus retention, SOC)

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
117	Raymond, Christopher M.	2009			x	x				Provisioning (food, fibre, water), Regulating (climate regulation, erosion regulation, water purification, natural hazard regulation), Supporting (soil formation, water cycling, nutrient cyclilng, primary production)
118	Remme, Roy	2014	w					x	soil type (clay soil/sandy soil, for crop prod., clay/peat/wet sand/dry sand for fodder production)	crop production, fodder production
119	Reyers, Belinda	2009						x	soil texture	potential water-flow regulation, potential carbon storage (soil not considered), potential forage production (soil not considered)
120	Robinson, D. A.	2012	s		x				SOC	
121	Robinson, D. A.	2013	s	x		x			texture, depht, mineralogy, nutrient content, SOC, redox status, pH, soil water content, soil temperature, structure	soil mass stock (minerals, nutrients, OC, organisms, water content, gas content), soil energy stock (temperature, OC), soil structure of stocks (abiotic and biotic structure, spatio-temporal structure) (for each stock, the matching Defra soil function is mentioned)
122	Rodriguez, N.	2015	w					x	SOC (from Colombian SOC-map, IDEAM 2001)	water provision, regulation of water flow, climate regulation-C-storage in soil
123	Rodriguez-Loinaz, Gloria	2015	w		x	x		x	SOC (for soil fertility and climate regulation), water storage capacity, soil water infiltration capacity (for water flow regulation)	maintenance of soil fertility, climate regulation, water flow regulation
124	Ruckelshaus, Mary	2013			x					
125	Ruijs, A.	2013	w		x			x	soil (for potential yield...)	Agricultural production, c-sequestration, potential yield
126	Rutgers, M.	2012	s	x				x	biological, chemical and physical soil paramters (see appendix!)	provisioning (soil agricultural capacity), regulation functions (c-pool, natural attenuation, water regulation, climate regulation..), habitat (soil as reservoir for biodiversity)
127	Sandhu, Harpinder S.	2010	w		x			x	earthworm population (for soil assessment of economic value of soil formation), mineralisation of organic matter (field experiment)	biological control of pests, soil formation, mineralisation of plant nutrients

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
128	Sandhu, Harpinder S.	2008	w		x			x	earthworm population, TOC, (rainfall and wateruse of crops for assessing hydrological flow), estimated crop and root residue, estimated N available to crop	biological control of pests, soil formation, mineralisation of plant nutrients, pollination services provided by shelterbelts and hedges, hydrological flow aesthetics, food, raw material, carbon accumulation, nitrogen fixation, soil fertility
129	Schägner, Jan Philipp	2013	w		x					
130	Schröter, Dagmar	2005	w					x	SOC, various soil properties (not specified) in tree-growth model and modelling of forest fires	food production, carbon storage, biodiversity, tree growth, bio fuel crops, hydrology
131	Schröter, Matthias	2014	w					x	soil respiration (for forest carbon storage)	forest carbon storage
132	Schulp, Catharina	2012	w			x		x	texture, rooting depht, bulk density (from Harmonized World Soil Database)	food crop yield, C-sequestration, flood protection, erosion protection
133	Schulte, Rogier P.O.	2014	s	x		x		x	maxiumum soil carrying capacity stocking rate (for production function, as in ireland mostly grasland), capacity of soil to remediate ntirate leaching through nitrification and capacpity to absorb excess phosphate (for water purification, therefor drainage state of soil needed)	(soil functions) production of food, fibre, (biofuel), water purification, carbon sequestration, habitat for biodiversity, recycling (of external) nutrients/agro-chemicals
134	Schweppe-Kraft, Burkhard	2013			x					
135	Schwilch, Gudrun	2016	s	x	x	x			soil texture, clay types, depth, structure (subsoil), stone content, subsoil wetness class, subsoil pan, soluble P, mineral N, pH, macroporosity, bulk density, temperature, SOC, soil organisms	Provisioning, regulating and maintenance, cultural ES (all of them only with examples)
136	Seppelt, Ralf	2012				x				
137	**Seppelt, Ralf**	2011				x				
138	Serna-Chaver, H.M.	2014	w					x	top-soil SOC, below-ground carbon density	water provision, climate regulation
139	Shaw, Rebecca	2011	w		x		x	x	soil moisture (out of biogeochemistry module of dynamic vegetation model), soil data (for forage production, not further specified which data, source: STATSGO)	C sequestration, forage production
140	Shiferaw, B.	2005	w		x				soil depth, soil type, soil moisture, fertility, rooting depth, water-holding capacity, SOC, soil erosion	soil retention, soil formation (mentionned)

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
141	Shoyama, Kikuko	2014	w					x	SOC, soil depht, plant available water content, rooting depht	c-storage, water yield
142	Sherrouse, Benson C.	2011								
143	Soussan, John	2011	w		x			x		Supporting (nutrient cycling, soil formation, primary production) Provisioning (food, fresh water, wood and fibre) , Regulating (climate regualtion, flood regulation, disease regulation, water purification), (as MEA)
144	Sumarga, Elham	2014	w					x	soil type, depth peat layer	carbon storage
145	Swallow, Brent M.	2009	w		x			x	Soil information for SWAT (from Kenya Soil Survey KSS), (for agricultural production: aerial photos)	Regulation, Supporting, Agricultural Production
146	Swinton, Scott M.	2007	w		x				SOC, soil structure	Supporting services (Maintenance of soil fertility), Regulating services (regulate the population dynamics of pollinators, pests, pathogens and wildlife, as well as fluctuations in levels of soil loss, water quality and supply, and greenhouse gas emissions and carbon sequestration)
147	Syrbe, Ralf-Uwe	2012								
148	Tallis, Heather(see also Tallis and Polaski 2009)	2011				x				
149	Tallis, Heather (see also Goldman, R. et al. 2008)	2009	w			x				
150	Tardieu, Léa	2013	w		x			x	SOC (provided by InfoSol GISSOL, deduced by soil coverage, climate data and soil moisture regime)	carbon sequestration and storage
151	Tardieu, Léa	2015	w		x			x	SOC	global climate regualtino, flood protection, water flow regulation
152	TEEB	2010			x	x				
153	TEEB	2010				x				
154	Terrado, M.	2014	w					x	soil depth, (for provisioning) nutrient filtration efficency (?, not specified) (for provisioning and purification)	Provisioning (water) Regulation (water purification/N-retention, erosion control)

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
155	Troy, Austin	2006			x					soil formation and retention
156	Tsonkova, Penka	2014	w					x	SOC (0-30cm), texture, nFK, bulk density, thikness	carbon sequestration, soil fertility, water regulation, and water quality
157	Turner, Katrine Grace	2014	w					x	amount of humus in A-horizon (national soil cover map)	regulating (soil organic carbon storage)
158	UK National Ecosystem Assessment	2014			x	x				
159	van den Belt, Marjan	2014	w							
160	Van der Biest, Katrien	2013	w				x	x	SOC	Provisioning (agri, wood prod.) Regulating (clima regulation by storage of SOC)
161	Van Eekeren, Nick	2010	s					x	"Hence, for soil quality assessment of grassland on sandy soils, the focus should be on abiotic parameters such as soil moisture content, SOM and total N. On other soil types these findings could be different." (S. 1502)	soil structure maintenance, water regulation, nutrient supply, grass production
162	van Jaarsveld, A.S.	2005	w					x	water storing capacity, N-availability, soil structure	provisioning (food, freshwater, wood-fuel)
163	van Oudenhoven, Alexander	2012	w			x		x	soil porosity, moisture content (?), SOC, soil water holding capacity	regulation (c storage, water storage)
164	van Wijnen, H.J	2012	s					x	pH, SOM, soil type, P-Gehalt, functional microbial activiy (FMA, amount of soil sample required to reach 50% activity in the Biolog multiwell plates), C-Mineralization, N-Mineralization (from Dutch national soil survey)	natural attenuation of pollutants (capacity of soils)
165	Vigerstol, Kari, L.	2011	w							water retention, water yield (?), natural water infiltration, sediment regulation (?)
166	Vihervaara, Petteri	2010	w				x	x	accumulation of organic materials in soils (is mentioned as indicator for soil formation, but no indication, if this indicator is actually used?)	Provisioning(food, fibre, water, genetic resources, fodder) Regulating(C sequestration, nutrient sequestration, local and regional climate) Supporting (soil formation, nutrient cycling)

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
167	Volchko, Yevheniya	2013	w	x					soil type, particle size distribution, soil structure, texture, water holding capacity, SOC temperature, pH, CEC, total C, total N	(not so clear, here: example of soil services such as source of raw material, for biomass production, archive of geology and history, acting as carbon pool etc. Same as soil functions in soil thematic strategy from EU 2006)
168	Waage, Sissel	2011						x		
169	Wainger, Lisa	2011			x	x				
170	Wales, Countryside Council	2010	w					x	soil type (soil map of wales, deep peat highest sore, middle score: shallow peat, humic gley, ranker, podzol)	carbon storage, water regulation, food, energy, fibre, biodiversity
171	Wallace, Ken J.	2007				x				Food, Water(potable), Protection from disease and parasites, Benign environmental regimes of temperature, moisture, light, chemical, Genetic resources
172	Wallace, Ken J.	2008				x				
173	Wang, Chongyun	2009	w					x	soil type (distinction dark forest soil, alluvial soil, other soils, because these 3 differ in SOC- important for soil quality, distinction needed for all three ES)	protection (canopy coverage, vegetation density, erosion intensity) , biodiversity (species richness, structural diversity), production (crop biomass)
174	Wang, Meie	2015	s					x	clay, SOC, bulk density, pH, total Nitrogen content (all for 0-10cm soil depth)	Natural attenuation capacity for pollutants in urban soils
175	Weber, Jean-Louis	2007	w		x	x				
176	Willamette Ecosystem Marketplace	2014						x		
177	Willemen, Louise	2010	w			x		x	soil texture/humus content (sandy soil, sandy clay soil, peat soil, only yes or no)	(here called 'landscape' functions) plant habitat, arable production
178	Willemen, Louise	2012	w			x		x	soil texture/humus content (sandy soil, sandy clay soil, peat soil, only yes or no)	(here called 'landscape' service) plant habitat, arable production
179	Willemen, Louise	2013	w					x	soil type (food production)	food production, c-storage, timbre and fuel wood production
180	Winowiecki, Leigh	2016	s					x		C sequestration

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No.	First author/project	Year	SC	ISF	EF	CS	ELD	EP	Soil properties considered[1]	Soil-related ES considered
181	Zhang,Wie	2007	w							Soil fertility and formation, nutrient cycling, Soil retention, Pollination, Pest control, Water provision and purification, genetic diveristy, climate regulation

Table A.3: Reviews ecosystem services literature.(SC = soil considered. Soil is the main topic (s = strongly considered), soil is one of several topics with no special focus (w= weakly considered). ISF = Integrating soil functions.EF = Economic focus.CS = Conceptual study.ELD = Emphasize lack of data. EP = Example provided, presentation of an example or a method to quantify ES, not (only) in monetary value.) [1] If there is a quantification of ES supply, the soil properties used for the quantifications are listed. If it is a publication without quantification, soil properties mentioned are named.

No.	First author / project	Year	Title	SC	ISF	EF	CS	ELD	EP	Soil properties considered[3]	Soil-related ES considered
1	Adhikari, Kabindra	2016	Linking soils to ecosystem services - A global review	s	×		×	×		SOC, texture, pH, soil depth, bulk density, AWC, CEC, electrical conductivity, porosity and air, saturated hydraulic conductivity, soil biota, structure, temperature, clay mineralogy, subsoil pans	Provisioning (food, fuel, fibre, raw materials, gene pool, water), regulating (climate and gas, water, erosion and flood control, pollination, seed dispersal, pest and disease, C sequestration, water purification), Cultural (recreation/ecotourism, aesthetic, knowledge, cultural heritage), supporting (soil formation, nutrient cycling, provisioning of habitat)
2	Bagstad, Kenneth	2013	A comparative assessment of decision-support tools for ecosystem services quantification and valuation	w							
3	Crossman, Neville D.	2013	A blueprint for mapping and modelling ecosystem services						×		Provisioning (food, water, raw materials) Regulating (climate, moderation of extreme events (mostly flooding), water flows, maintenance soil fertility), Habitat (live cycle maintenance, genetic diversity)
4	Egoh, Benis	2012	Indicators for mapping ecosystem services: a review	w						below ground biomass, SOC (climate regulation),soil characteristics (?) (used for Erosion prevention, maintenance of soil fertility, regulation of water flow, food provision, water provision, climate regulation), Nutrient retention (soil fertility maintenance, regulation of water flow)	Provisioning (food, water, and other resources) , Regulating (climate, soil quality, carbon sequestration, erosion prevention), Habitat or Supporting (habitats for species and maintenance of genetic diversity)
5	Jonsson, Jon Örvar	2016	Classification and valuation of soil ecosystem services	s	×	×	×				Support functions (biodiversity, nutrient cycling, soil formation, water cycling), Regulating services (biological control of pests and diseases, climate and gas regulation, hydrological control, filtering of nutrients and contaminants, recycling of wastes and detoxification), Provisioning services (biomass production, clean water provision, raw material, physical environment), Cultural services(heritage, cognitive services, recreation)

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No.	First author / project	Year	Title	SC	ISF	EF	CS	ELD	EP	Soil properties considered[3]	Soil-related ES considered
6	Layke, Christian	2012	Indicators from the global and sub-global Millennium Ecosystem Assessments: An analysis and next steps	w				×		soil water infiltration, soil water storage (both with no indication of unit, all other indicators with unit, used as indicator for water regulation), ev. C-stock (within climate regulation, soil here not mentioned)	provisioning (food, biological raw materials, freshwater), regulating (climate, water, erosion, soil quality, water purification), supporting (primary production, nutrient cycling, soil formation, water cycling)
7	Maes, Joachim	2012	Mapping ecosystem services for policy support and decision making in the European Union				×	×	×		
8	Martínez-Harms, María José	2012	Methods for mapping ecosystem service supply: a review	w							
9	Nelson, Erik	2010	Modelling ecosystem services in terrestrial systems								
10	Pagella, Timothy	2014	Development and use of a typology of mapping tools to assess their fitness for supporting management of ecosystem service provision				×				
11	Schägner, Jan Philipp	2013	Mapping ecosystem services' values: Current practice and future prospects	w		×					
12	Schwilch, Gudrun	2016	Operationalizing ecosystem services for the mitigation of soil threats: A proposed framework Gudrun	s	×	×	×			soil texture, clay types, depth, structure (subsoil), stone content, subsoil wetness class, subsoil pan, soluble P, mineral N, pH, macroporosity, bulk density, temperature, SOC, soil organisms	Provisioning, regulating and maintenance, cultural ES (all of them only with examples)
13	van den Belt, Marjan	2014	Ecosystem services in new Zealand agro-ecosystems: A literature review	w							
14	Vigerstol, Kari, L.	2011	A comparison of tools for modeling freshwater ecosystem services	w							water retention, water yield (?), natural water infiltration, sediment regulation (?)

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No.	First author / project	Year	Title	SC	ISF	EF	CS	ELD	EP	Soil properties considered[3]	Soil-related ES considered
15	Waage, Sissel	2011	New Business Decision-Making Aids in an Era of Complexity, Scrutiny, and Uncertainty. Tools for Identifying, Assessing, and Valuing Ecosystem Services						×		

Table A.4: Mapping studies ecoystem services literature I. (HP = Hydromorphic properties, SOC = soil organic carbon, CEC = Cation exchange capacity, BS = base saturation, AWC = available water capacity, AC = Air capacity, SHC = saturated hydraulic conductivity, PRM = provides reprodrucible method, FandB = Filter and Buffer)

No.	First author/project	Year	Texture	Humus	pH	HP	Horizon depths	Stone content	Soil depth	Soil Structure	Soil type	Bulk density	SOC	CEC	BS	AWC	AC	SHC	Percolation rate	Other soil data	**PRM**	Water cycling	Nutrient cycling	FanB org.	FanB inorg.	Acidity buffering	C storing	Habitat for plants	Agricultural prod.	Other soil-relevant ES
1	Altwegg, Jürg	2014																		×	×	×					×		×	×
2	Anderson, Barbara	2009						×				×	×								×						×		×	
3	ARIES (Villa, Ferdinando,Bagstad, Kenneth)	2009, 2011, 2014	×		×	×							×					×		×		×	×				×			
4	Ausseil, Anne-Gaelle	2013									×					×						×		×	×			×	×	
5	Bai, Yang	2011							×				×			×						×		×	×		×			
6	Bastian, Olaf	2013												×	×	×		×											×	
7	Bateman, Ian, J.	2013	×					×	×				×								×						×		×	
8	Batker, David	2010				×																×								
9	Birch, Jennifer	2014											×							×		×		×	×		×		×	
10	Boumans, Roelof	2002											×							×			×				×			
11	Boyanova, Kremena, (same focus: Nedkov and Burkhard 2012, Stürck et al. 2014)	2014																×		×		×								
12	Brandt, Patric	2014		×																	×						×			
13	Broekx, Steven	2013	×			×							×			×							×				×			
14	Calzolari, Costanza	2016	×	×	×	×		×	×		×	×	×	×		×	×	×		×	×	×	×	×	×		×	×	×	×
15	Castro, Antonio	2014	×				×	×			×	×	×								×						×		×	
16	Clec'h, Le, Solen	2016	×		×		×					×	×	×				×		×		×					×		×	×

Table A.4: Mapping studies ecosystem services literature I. (HP = Hydromorphic properties, SOC = soil organic carbon, CEC = Cation exchange capacity, BS = base saturation, AWC = available water capacity, AC = Air capacity, SHC = saturated hydraulic conductivity, PRM = provides reprodrucible method, FandB = Filter and Buffer)

No.	First author/project	Year	Texture	Humus	pH	HP	Horizon depths	Stone content	Soil depth	Soil Structure	Soil type	Bulk density	SOC	CEC	BS	AWC	AC	SHC	Percolation rate	Other soil data	**PRM**	Water cycling	Nutrient cycling	FanB org.	FanB inorg.	Acidity buffering	C storing	Habitat for plants	Agricultural prod.	Other soil-relevant ES
17	Conte, Marc	2011											×														×			
18	de Groot, Rudolf	2011														×				×		×	×				×	×	×	×
19	de Groot, Rudolf	2006																				×		×	×				×	×
20	De Meyer, Annelies	2013											×													×	×		×	
21	Dominati, Estelle	2014	×	×	×	×		×	×			×				×						×	×	×	×		×		×	×
22	Egoh, Benis	2008							×													×					×			×
23	Emmet, Bridget A.	2016									×											×					×		×	×
24	esp-mapping.net	2014																									×			
25	Felipe-Lucia, Maria	2015											×										×					×	×	×
26	Fu, B.	2014	×						×	×		×	×			×						×								
27	Gao, Yang	2014							×							×						×								
28	Gascoinge, William	2011											×														×			
29	Guo, Zhongwei	2002									×										×	×								
30	Harmackova, Zuzana	2015							×				×			×				×	×		×				×			
31	Hewitt, Allan	2015	×			×	×					×				×							×							
32	Huo, Ying	2014											×																×	
33	InVEST								×				×			×				×	×	×	×				×			
34	Jackson, Bethanna	2013				×							×			×		×				×					×		×	
35	Jopke, Cornelius	2015											×									×					×		×	

Table A.4: Mapping studies ecosystem services literature I. (HP = Hydromorphic properties, SOC = soil organic carbon, CEC = Cation exchange capacity, BS = base saturation, AWC = available water capacity, AC = Air capacity, SHC = saturated hydraulic conductivity, PRM = provides reprodrucible method, FandB = Filter and Buffer)

No.	First author/project	Year	Texture	Humus	pH	HP	Horizon depths	Stone content	Soil depth	Soil Structure	Soil type	Bulk density	SOC	CEC	BS	AWC	AC	SHC	Percolation rate	Other soil data	**PRM**	Water cycling	Nutrient cycling	FanB org.	FanB inorg.	Acidity buffering	C storing	Habitat for plants	Agricultural prod.	Other soil-relevant ES
36	Landuyt, Dries	2015	×			×					×											×					×		×	×
37	Laterra, Pedro	2012	×	×		×	×			×	×		×	×		×				×	×	×					×		×	
38	Lautenbach, Sven	2011																		×	×		×	×	×				×	
39	Lautenbach, Sven	2012									×		×										×					×		×
40	Lavelle, Patrick	2014	×		×			×				×	×	×		×				×		×	×				×			×
41	Li, Jing	2006																		×							×		×	×
42	Liekens, Inge	2013	×			×							×			×							×				×		×	
43	Luck, Gary	2009											×									×					×			
44	Maes, Joachim	2011											×					×				×		×	×		×		×	×
45	Metzger, Marc (closely related to Schröter et al. 2005)	2008											×														×		×	
46	Nelson, Erik	2009							×									×			×						×			×
47	O'Farrell, P.J.	2010									×											×							×	
48	O'Sullivan, L.	2015				×																					×		×	
49	Petz, Katalin	2014							×							×					×	×					×		×	
50	Portela, Rosimeiry	2012			×															×							×			
51	Posthumus, Helena	2010									×		×			×					×	×					×	×	×	
52	Raudsepp-Hearne, C.	2010											×							×	×		×				×		×	
53	Remme, Roy	2014									×																		×	

Table A.4: Mapping studies ecoystem services literature I. (HP = Hydromorphic properties, SOC = soil organic carbon, CEC = Cation exchange capacity, BS = base saturation, AWC = available water capacity, AC = Air capacity, SHC = saturated hydraulic conductivity, PRM = provides reprodrucible method, FandB = Filter and Buffer)

No.	First author/project	Year	Texture	Humus	pH	HP	Horizon depths	Stone content	Soil depth	Soil Structure	Soil type	Bulk density	SOC	CEC	BS	AWC	AC	SHC	Percolation rate	Other soil data	**PRM**	Water cycling	Nutrient cycling	FanB org.	FanB inorg.	Acidity buffering	C storing	Habitat for plants	Agricultural prod.	Other soil-relevant ES
54	Rodriguez, N.	2015											×									×					×			
55	Rodriguez-Loinaz, Gloria	2015											×			×		×				×					×			×
56	Rutgers, M.	2012	×	×	×	×						×				×	×		×	×	×	×		×	×	×	×	×	×	
57	Sandhu, Harpinder S.	2010																		×										×
58	Sandhu, Harpinder S.	2008			×							×								×							×	×	×	×
59	Schröter, Dagmar	2005											×									×					×		×	
60	Schulp, Catharina	2012	×						×			×									×	×					×		×	
61	Schulte, Rogier P.O.	2014				×														×				×	×		×	×	×	
62	Serna-Chavez, H.M.	2014											×									×					×			
63	Shaw, Rebecca	2011														×											×		×	
64	Shoyama, Kikuko	2014							×				×			×											×			
65	Sumarga, Elham	2014					×				×										×						×			
66	Swallow, Brent M.	2009																		×		×								
67	Tardieu, Léa	2013					×						×														×			
68	Tardieu, Léa	2015											×									×					×			
69	Terrado, M.	2014							×											×	×	×								
70	Tsonkova, Penka	2014	×				×					×	×			×					×	×					×			×
71	Turner, Katrine Grace	2014		×																							×			

Table A.4: Mapping studies ecoystem services literature I. (HP = Hydromorphic properties, SOC = soil organic carbon, CEC = Cation exchange capacity, BS = base saturation, AWC = available water capacity, AC = Air capacity, SHC = saturated hydraulic conductivity, PRM = provides reprodrucible method, FandB = Filter and Buffer)

No.	First author/project	Year	Texture	Humus	pH	HP	Horizon depths	Stone content	Soil depth	Soil Structure	Soil type	Bulk density	SOC	CEC	BS	AWC	AC	SHC	Percolation rate	Other soil data	**PRM**	Water cycling	Nutrient cycling	FanB org.	FanB inorg.	Acidity buffering	C storing	Habitat for plants	Agricultural prod.	Other soil-relevant ES
72	Van der Biest, Katrien	2013	×										×							×							×		×	
73	Van Eekeren, Nick	2010	×	×								×						×		×	×	×	×						×	
74	van Oudenhoven, Alexander	2012											×			×				×		×					×			
75	van Wijnen, H.J	2012		×	×						×									×	×			×	×					
76	Vihervaara, Petteri	2010		×																			×				×		×	
77	Wales, No.ryside Council	2010									×											×					×	×	×	
78	Wang, Chongyun	2009									×																	×	×	
79	Wang, Meie	2015	×		×							×	×							×	×			×	×					
80	Willemen, Louise	2010	×	×																								×	×	
81	Willemen, Louise	2012	×	×		×																						×	×	
82	Willemen, Louise	2013									×																×		×	
83	Winowiecki, Leigh	2016	×		×		×						×		×					×							×			

Table A.5: Mapping studies ecoystem services literature II. (AP1 = static assessment approach, AP2 = (semi-)dynamic assessment approach, AP3 = not clear or combined assessment approach)

No.	First author / Project name	Year	Source of soil data	Data source reference	AP1	AP1	AP3	Spatial scale	Documentation	Method reference
1	Altwegg, Jürg	2014	soil database	Soil suitability map Switzerland ("Bodeneignungskarte), expert knowledge	x			Local/Regional	yes	
2	Anderson, Barbara	2009	soil database	UK National Soil Resources Institute, until 1m soil depth	x			National	yes	
3	ARIES. Villa, Ferdinando, Bagstad, Kenneth (+ Homepage)	2009, 2011, 2014	not specified				x		partially	(see website)
4	Ausseil, Anne-Gaelle	2013	soil database	Fundamental Soil Layers soil database (New Zealand)		x		National	no	WATYIELD, Overseer
5	Bai, Yang	2011	not specified			x		Regional	partially	InVEST
6	Bastian, Olaf	2013	soil database	Soil Atlas of Saxony	x			Regional	no	LfULG
7	Bateman, Ian, J.	2013	soil database	www.naturalengland.org.uk and European Soil database		x		National	yes	
8	Batker, David	2010	soil database	NRSC soil survey			x	Regional	no	ARIES
9	Birch, Jennifer	2014	other publication(s)	IPCC 2006	x			Regional	no	TESSA
10	Boumans, Roelof	2002	soil database	not specified		x		Global	no	GUMBO (indicated URL not found)
11	Boyanova, Kremena (same focus: Nedkov and Burkhard 2012, Stürck et al. 2014)	2014	soil database	USDA	x			Regional	no	KINEROS, AGWA
12	Brandt, Patric	2014	soil database	United States Environmental Protection Agency	x			Regional	yes	
13	Broekx, Steven	2013	not specified			x		Regional	no	Flemish documentation on the web
14	Calzolari, Costanza	2016	soil database	Regional soil survey and soil map of Emilia Romagna Region	x			Regional	partially	Parisi et al. 2005 (Biodiversity index), Guermandi 2000 (Land capability classification)
15	Castro, Antonio	2014	soil database	soil map (LUCDEME, 2003)	x			Regional	partially	ALPIS (Mintegui and Robredo1993)
16	Le Clec'h, Solen	2016	soil survey				x	Local		

Table A.5: Mapping studies ecoystem services literature II. (AP1 = static assessment approach, AP2 = (semi-)dynamic assessment approach, AP3 = not clear or combined assessment approach)

No.	First author / Project name	Year	Source of soil data	Data source reference	AP1	AP1	AP3	Spatial scale	Docu-mentation	Method reference
17	Conte, Marc	2011	soil database	LULC-maps with estimates (?) from, Makundi 2001 and IPCC 2006		x		Regional	no	Glenday 2006 and Ruesch and Gibbs 2008, IPCC, Makundi
18	de Groot, Rudolf	2011	not specified		x					
19	de Groot, Rudolf	2006	other publications	European Post Graduate Course on Environmental Management, 1997 and 2000	x			Regional	no	probably out of the Graduate Course?
20	De Meyer, Annelies	2013	soil database	digitised soil association map at a source scale of 1:500.000 (Tavernier and Maréchal, 1972)		x		Regional	partially	Van Orshoven et al. (1992), Lettens et al. (2005), OSMOSE
21	Dominati, Estelle	2014	soil survey			x		Point	no	SPASMO
22	**Egoh, Benis**	2008	soil database, other publication(s)	Groundwater recharge data from the Department of Water Affaires and Forestry 2005, South Africa, Schoeman et al., 2002; Tekle, 2004 (for soil depth)	x			National	partially	
23	Emmet, Bridget A.	2016	soil database	NATMAP of England and Wales	x			Regional	partially	Milne and Brown 1997
24	esp-mapping.net	2014					x	EU	no	C-fix-model
25	Felipe-Lucia, Maria	2015	soil survey		x			Local	partially	
26	Fu, B.	2014	not specified				x	Regional	partially	InVEST
27	Gao, Yang	2014	soil database	Environmental and Ecological Science Data Centre for West China		x		Regional	partially	InVEST
28	Gascoigne, William	2011	other publications	Gleason et al. 2008 and Reynolds et al. 2007		x		Regional	partially	Gleason et al. 2008
29	**Guo, Zhongwei**	2002	soil database	Xinshang County	x			Regional	yes	
30	Harmackova, Zuzana	2015	other publications	De Simon et al.,2012; IFER, 2010; Joyce,2001;Lindsay,2010;O'Halloran et al.,2013; NIR, 2012; Schumacher and Roscher, 2009; Truus,2011		x		Regional	partially	InVEST
31	Hewitt, Allan	2015	soil database	Soil Survey New Zealand 1999	x			Point	no	Webb et al. 2010
32	Huo, Ying	2014	soil database	Land use change survey data of Jiangsu			x	Regional	no	
33	InVEST		special case: needs user input			x		various	yes	

Table A.5: Mapping studies ecoystem services literature II. (AP1 = static assessment approach, AP2 = (semi-)dynamic assessment approach, AP3 = not clear or combined assessment approach)

No.	First author / Project name	Year	Source of soil data	Data source reference	AP1	AP1	AP3	Spatial scale	Docu-mentation	Method reference
34	Jackson, Bethanna	2013	other publications	not specified	x			Regional	no	(indicated URL not found)
35	Jopke, Cornelius	2015	not specified	(maybe Eurostat?)	x			EU	no	Maes et al. 2011
36	Landuyt, Dries	2015	soil database	AGIV 2001	x			Regional	partially	Meersman et al. 2008, Kirschbaum et al. 2001
37	Laterra, Pedro	2012	soil database	INTA Balcarce	x			Regional	partially	Riquier et al. 1970 (Productivity)
38	Lautenbach, Sven	2011	soil database	Soil fertility maps Sachsen (Bodenschätzung)		x		Regional	yes	
39	Lautenbach, Sven	2012	not specified		x			various	partially	MONERIS, SWAT, GREAT ER
40	Lavelle, Patrick	2014	soil survey			x		Regional	no	Velazquez et al. 2007
41	Li, Jing	2006	soil database	not specified	x			Regional	partially	
42	Liekens, Inge	2013	other publications	Pinay et al. 2007 (water quality, denitrification) Meersman et al. 2008 (SOC), Koerselman et al. 1996 (water quality, C:N:P ratio)			x	Regional	partially	Meersman et al. 2008, Seitzinger et al. 2006
43	Luck, Gary	2009	soil database	global dataset for SOC (not further specified)	x			Global	yes	
44	Maes, Joachim	2011	soil database, other publications	CDIAC website (SOC), Pistocchi et al. 2010 (Water regulation), JRC's European Soil Data Centre (for soil quality and soil erosion regulation)	x			EU	partially	GREEN (Grizetti et al. 2008, N-retention)
45	Metzger, Marc (Closely related to Schröter et al. 2005)	2008	not specified			x		EU	no	Smith et al. 1996 (SUNDIAL) and Coleman et al. 1997 (ROTHC) to model agriculture, Sitch et al. 2003 (C-storage)
46	Nelson, Erik	2009	not specified	(URL indicated for Appendix not working)		x		Regional	partially	InVEST for SOC accounting: Adams et al. 1999, Plantinga et al. 1999, Feng 2005, Lubowski et al. 2006

Table A.5: Mapping studies ecoystem services literature II. (AP1 = static assessment approach, AP2 = (semi-)dynamic assessment approach, AP3 = not clear or combined assessment approach)

No.	First author / Project name	Year	Source of soil data	Data source reference	AP1	AP1	AP3	Spatial scale	Docu-mentation	Method reference
47	O'Farrell, P.J.	2010	soil database, other publications	South African 1:250,000 maps of areas of homogeneous grazing potential (Scholes 1998)		x		Regional	no	Water regulation: Braune and Wessels 1980; Görgens and Hughes 1982, 1986; Midgley et al. 1994b; DWAF 2003a, b, 2004a, b, 2005; DWAF GRA2 2005) Grazing potential: Scholes 1998
48	O'Sullivan, L.	2015	other publications	Schulte et al. (submitted)		x		National	partially	Schulte et al. 2005, 2012
49	Petz, Katalin	2014	other publication(s)	Schulze, R.E., Horan, M.J.C., 2007	x			Regional	partially	InVEST (for water supply, other soil relevant ES did not use soil data)
50	Portela, Rosimeiry	2012	not specified			x		Regional	partially	ARIES
51	Posthumus, Helena	2010	other publication(s), not specified	Adger et al. 1992 (SOC), Kasimir-Klemedtsson et al., 1997 (GHG emission from peat soil)		x		National	partially	Adger et al. 1992 (SOC), Kasimir-Klemedtsson et al., 1997 (GHG emission from peat soil)
52	Raudsepp-Hearne, C.	2010	soil database	provincial soil data base Quebec	x			Regional	yes	
53	Remme, Roy	2014	soil database	Soil map of the Netherlands (Alterra 2006)			x	Regional		
54	Rodriguez, N.	2015	soil database	Colombian SOC-map (IDEAM 2001)	x			National	partially	IDEAM 2010 and IDEAM 2001
55	Rodriguez-Loinaz, Gloria	2015	not specified		x			Regional	partially	(deduction of ES- indicators not found)
56	Rutgers, M.	2012	soil survey			x		Local	yes	
57	Sandhu, Harpinder S.	2010	soil survey		x			Regional	yes	
58	Sandhu, Harpinder S.	2008	soil survey		x			Regional	yes	
59	Schröter, Dagmar	2005	soil database	European Soils soil database		x		EU	partially	Rothamsted Carbon model (SOC)
60	Schulp, Catharina	2012	soil database	Harmonized World Soil database	x			Multi-National	partially	Bouwman et al. 2006 (crop yield)
61	Schulte, Rogier P.O.	2014	not specified			x		National	no	
62	Serna-Chavez, H.M.	2014	soil database, other publication(s)	Hiderer and Köchi 2012; estimates from World harmonized Soil database, Ruesch and Gibbs 2008, (IPCC))		x		Global	partially	Hiderer and Köchi 2012, Ruesch and Gibbs 2008, Sitch et al. 2003

Table A.5: Mapping studies ecoystem services literature II. (AP1 = static assessment approach, AP2 = (semi-)dynamic assessment approach, AP3 = not clear or combined assessment approach)

No.	First author / Project name	Year	Source of soil data	Data source reference	AP1	AP1	AP3	Spatial scale	Docu-mentation	Method reference
63	Shaw, Rebecca	2011	soil database	STATSGO		×		Regional	partially	MC1-Model (C-Sequestration), NRCS Ecological Site Description website (http://esis.sc.egov.usda.gov) (forage production)
64	Shoyama, Kikuko	2014	soil database	National Land Numerical Information		×		Regional	partially	InVEST
65	Sumarga, Elham	2014	other publications	Van der Kamp et al. (2009), Murdiyarso et al. (2009), Wetland International (2004)		×		Regional	yes	
66	Swallow, Brent M.	2009	soil database	Kenya Soil Survey KSS		×		Regional	no	SWAT
67	Tardieu, Léa	2013	soil database	InfoSol GISSOL	×			Regional	no	InfoSol GISSOL (INRA)
68	Tardieu, Léa	2015	other publications	Tardieu et al. 2013			×	Regional	no	Tardieu et al. 2013
69	Terrado, M.	2014	not specified			×		Regional	partially	InVEST
70	Tsonkova, Penka	2014	soil database, other publication(s)	soil map of Germany (BGR 2007), BMELV, 2010; DVWK, 1984; Hall, 2003; IPCC,2006; Jankiewicz et al., 2004; Kort et al., 1998; KTBL, 2005; Müllerand Wal-deck, 2011; Schwertmann et al., 1989; USDA-SCS, 1972;VDLUFA, 2004; Wend-land et al., 2011	×			National	yes	Batjes 1996, VDLUFA 2004
71	Turner, Katrine Grace	2014	soil database	Denmark National Soil Cover (?) Map	×			National	yes	(Proxy use)
72	Van der Biest, Katrien	2013	soil database	Digital Soil Map of Antwerpen (Antwerpen 1998)		×		Regional	partially	Meersman et al. 2008, Post et al. 1987, Adhikari et al. 2009 (all for SOC)
73	Van Eekeren, Nick	2010	soil survey		×			Local	yes	
74	van Oudenhoven, Alex-ander	2012	other publications	De Vries and Camarasa (2009), Querner et al. (2008), Kuikman et al. (2003), Layke (2009), Schulp and Verburg (2009), Pulle-man et al. (2000)		×		Regional	partially	
75	van Wijnen, H.J	2012	soil database	Dutch National Soil Survey	×			National	yes	
76	Vihervaara, Petteri	2010	soil database	Finnish National Land Survey (peatland mask)		×		Regional		

Table A.5: Mapping studies ecoystem services literature II. (AP1 = static assessment approach, AP2 = (semi-)dynamic assessment approach, AP3 = not clear or combined assessment approach)

No.	First author / Project name	Year	Source of soil data	Data source reference	AP1	AP1	AP3	Spatial scale	Docu-mentation	Method reference
77	Wales, Countryside Council	2010	soil database	Soil Map of Wales	x			Regional	yes	
78	Wang, Chongyun	2009	soil database	Soil Map (1: 100'000)		x		Regional	yes	
79	Wang, Meie	2015	soil survey		x			Local	partially	van Wijnen et al. 2012
80	Willemen, Louise	2010	not specified		x			Regional	no	Weitkamp et al. 2007
81	Willemen, Louise	2012	soil database	Soil Map of the Netherlands (Alterra 2006)		x		Regional	partially	Hertog and Rijken 1996; Rijken, 2000, Willemen et al . 2008
82	Willemen, Louise	2013	not specified			x		National	partially	
83	Winowiecki, Leigh	2016	soil survey			x		Regional	yes	

Table A.6: References soil function (assessment) literature

No.	Author(s) or project	SFA-methods
1	Ad-hoc-AG Boden (2007). Methodenkatalog zur Bewertung natürlicher Bodenfunktionen, der Archivfunktion des Bodens, der Nutzungsfunktion "Rohstofflagerstätte" nach BBodSchG sowie der Empfindlichkeit des Bodens gegenüber Erosion und Verdichtung.	
2	Amsler, J., Biedermann, A., Calörtscher, M., Nievergelt, J., Ryf, K., Valli, C. (2004). Grundlagen zur Bewertung von Kulturland und naturnahen Flächen bei Landumlegungen.	x
3	BAFU. (2011). Integrale Bodenpolitik: Boden brauchen wir alle. Bundesamt für Umwelt (BAFU): http://www.bafu.admin.ch/bodenschutz/13513/13530/13533/index.html?lang=de, last accessed 03.04.2017	
4	Bechler, K., Toth, O. (2010). Bewertung von Böden nach ihrer Leistungsfähigkeit. Leitfaden für Planungen und Gestattungsverfahren. LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg. http://www4.lubw.baden-wuerttemberg.de/servlet/is/74536/bewertung_von_boeden_nach_leistungsfaehigkeit.pdf?command=downloadContent&filename=bewertung_von_boeden_nach_leistungsfaehigkeit.pdf,last accessed 03.04.2017	x
5	BGR (2013). Schematische übersicht der Methodenbank im FISBo BGR. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR).	
6	Blaser, P., L. Walthert, Zimmermann, S., Graf Pannatier, E., Luster, J. (2008). "Classification schemes for the acidity, base saturation, and acidification status of forest soils in Switzerland." Journal of Plant Nutrition and Soil Science 171(2): 163-170. https://doi.org/10.1002/jpln.200700008	x
7	Bouma, J. (2014). Soil science contributions towards Sustainable Development Goals and their implementation: linking soil functions with ecosystem services. Journal of Plant Nutrition and Soil Science, 177(2), 111-120. https://doi.org/10.1002/jpln.201300646	
8	Bouma J., G. Broll, T. Crane, O. Dewitte, C. Gardi, R. Schulte, W. Towers. (2012). Soil information in support of policy making and awareness raising. Current Opinion in Environmental Sustainability 2012, 4:552-558. https://doi.org/10.1016/j.cosust.2012.07.001	
9	Bouma, J. (2010). Implications of the Knowledge Paradox for Soil Science. Advances in Agronomy, 106, 143-171. https://doi.org/10.1016/S0065-2113(10)06004-9	
10	Bouma, J. (2009). Soils are back on the global agenda: Now what? Geoderma, 150, 224-225. https://doi.org/10.1016/j.geoderma.2009.01.015	
11	Bouma, J. (1989). Using soil survey data for quantitative land evaluation. Advances in Soil Science 9, 177-213.	
12	Danner, C., Hensold, C., Blum, P., Weidenhammer, S., Aussendorf, M., ... Kölling, C. (2003). Das Schutzgut Boden in der Planung. Bewertung natürlicher Bodenfunktionen und Umsetzung in Planungs- und Genehmigungsverfahren, Bayerisches Landesamt für Umweltschutz, Bayerisches Geologisches Landesamt. http://www.lfu.bayern.de/boden/bodenfunktionen/ertragsfaehigkeit/doc/arbeitshilfe_boden.pdf, last accessed 03.04.2017.	x
13	FAL (1997). Kartieren und Beurteilen von Landwirtschaftsböden. Eidgenössische Forschungsanstalt für Agrarökologie und Landbau, Zürich-Reckenholz (FAL).	x
14	BUWAL. (2001). Erläuterungen zur Verordnung vom 1. Juli 1998 über Belastungen des Bodens (VBBo). Bundesamt für Umwelt, Wald und Landschaft (BUWAL).	
15	Calzolari, C., F. Ungaro, Filippi, N., Guermandi, M., Malucelli, F., Marchi, N., Staffilani, F., Tarocco, P. (2016). "A methodological framework to assess the multiple contributions of soils to ecosystem services delivery at regional scale." Geoderma 261: 190-203. https://doi.org/10.1016/j.geoderma.2015.07.013	x
16	Carré, F., McBratney, A. B., Mayr, T., Montanarella, L. (2007). Digital soil assessments: Beyond DSM. Geoderma, 142(1-2), 69-79. https://doi.org/10.1016/j.geoderma.2007.08.015	
17	Dobos, E., Carré, F., Hengl, T., Reuter, H. I., Tóth, G. (2006). Digital Soil Mapping as a support to production of functional maps. (EUR 22123 EN). Luxemburg: Office for Official Publications of the European Communities.	
18	DVWK, Deutscher Verband für Wasserwirtschaft und Kulturbau. (1988). Filtereigenschaften des Bodens gegenüber Schadstoffen. Teil I: Beurteilung der Fähigkeit von Böden, zugeführte Schwermetalle zu immobilisieren. Merkblätter zur Wasserwirtschaft.	x
19	DVWK, Deutscher Verband für Wasserwirtschaft und Kulturbau. (1994). Bodenkundliche Untersuchungen im Felde zur Ermittlung von Kennwerten zur Standortcharakterisierung. Teil I: Ansprache der Böden Regeln zur Wasserwirtschaft.	x
20	European Commission (2012a). Die Umsetzung der Thematischen Strategie für den Bodenschutz und laufende Massnahmen (COM 2012, 46 final). http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2012:0046:FIN:DE:PDF, last accessed 03.04.2017.	
21	European Commission (2012b). Soil - The decision-making process. http://ec.europa.eu/environment/soil/process_en.htm, last accessed 03.04.2017.	
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23	European Commission (2006b). Thematic Strategy for Soil Protection (COM 2006, 231 final). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52006DC0231&from=EN, last accessed 03.04.2017.	
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Table A.6: References soil function (assessment) literature

No.	Author(s) or project	SFA-methods
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Table A.6: References soil function (assessment) literature

No.	Author(s) or project	SFA-methods
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A.2 Appendix Chapter 3 and 4

Methods established in this paper

Regulation of carbon cycle

This methods considers soils as carbon pools and assesses the amount stored in a soil.

Soil data input: soil organic matter, stone content, horizon depths, bulk density, rooting depth

Assessment depth: 100cm

Table A.7: lookup table R-carbon (C_{org} in kg/m^2)

$> C_{org}$	$\leq Corg$	Rating
0	10	1
10	13	2
13	15	3
15	21	4
21		5

Habitat for microorganims

Microbial biomass can be used to quantify the amount of life and activity in a soil. The amount of microbial biomass indicates metabolising capacity, microbes are a pool for quickly metabolisable nutrients.

Soil data input: Clay, silt, organic carbon, pH, stone content, horizon depths, depth gg/r-horizons, Drainage class, bulk density, rooting depth

Deduced soil data: microbial biomass via PTF by Oberholzer and Scheid (2007)

Other data input: Land use (input for PTF)

Assessment depth: 0-10cm for arable land, 0-20cm for grasland and others.

Table A.8: lookup table H-microorg (microbial biomass in mg/kgdriedsoilsample)

$> Microbialbiomass$	$\leq Microbialbiomass$	Rating
0	460	1
460	620	2
620	890	3
890	1160	4
1160		5

Soil property for a given depth

Some methods require clay, silt or soil organic matter (in %) content for a given depth (R-nutric1, R-nutril, R-icont, R-ocont, R-acid, R-carbon, H-microorg, P-agri). We used the amount of fine earth (FE in g/cm^2, mineral or organic part, respectively, deduced by horizon depth, HD in cm, stone content, SC in cm/cm, and bulk density, BD in g/cm^3) to weigh the amounts of the property for a given depth.

$$FE = HD * (1 - SC) * BD \tag{A.1}$$

$$FE_{org} = FE * H \tag{A.2}$$

$$FE_{min} = FE - FE_{org} \tag{A.3}$$

If pH is required for a certain depth, we weighed it by HD.

Definitions SFA input data

Rooting depth

Rooting depth (RD, in cm) is used based on Swiss soil classification (FAL, 1997). RD is defined by stone content of a soil (SC), its horizon depths (HD), indication of hydromorphic horizons if they exist (gg =1 or r =1) and would use a weighing factor for this hydromorphic horizons. Instead of a flexible weighing of the hydromorphic horizons, we use a fixed weighing commonly used in Swiss soil mapping practice.

$$RD = \sum HD_i * (1 - \frac{SC_i}{100}) * gg_i * \frac{1}{3} * r_i * \frac{1}{10} \tag{A.4}$$

Drainage Class

We aggregated the soil subtypes (I, G, R) from Swiss Soil classifications on soils water regimes FAL (1997) into three groups from well-drained (1), to moderately well drained (2), to poorly drained (3). Definitions of Drainage Classes are not not trivial:

- Subtype I: Stagnant water, additionally defined by depth and upper boundary (UB) of g or gg horizon (I1 and I2: depth AND UB of g OR(inclusive) gg)
- subtype G: Ground or slope water, alternating, additionally defined by upper boundary of g or gg horizon (G1: g and eventually gg, G2 and G3: g or gg)
- subtype R: Ground or slope water, permanent, additionally defined by upper boundary of r horizon

We defined the three classes on a soils water regime the following way:

- Drainage Class 1: nor I, G or R; I1, I2, G1, G2, G3, R1
- Drainage Class 2: I3, I4, G4
- Drainage Class 3: G5, G6, R2, R3, R4, R5

Slope

Besides many other calculations, M. Fraefel calculated from the SwissAlti3D altitude data (2m resolution) (Swisstopo, 2014) the slope with a 8 pixel neighbourhood and then applied a weighed smoothing (Gaussian filter) over a radius of 15 pixel $..slope_{2m_s15}$. We decide on using this slope-layer as the soil data we worked with was mostly taken to produce a map of a 1:5'000 scale. For such a scale, the soil surveyor aims at a polygon size of 20-30m perimeter.

Relief

Relief ("Geländeform", originally) is a ordinal class from Swiss Soil Classification (FAL, 1997) used to describe the relief for a polygon on a soil map. The class is based on **1) slope** - we used the slope-layer mentioned above - and on four **2) types of relief**, even, convex, concave and uneven. We used two layers to define these four types: 1) A curvature layer (curvature from ArcGIS) smoothed (weighed and with a Gaussian filter) for a (pixel) radius of 30m - $curv_{2ms15}$ and 2) the standard deviation of the curvature for a 5 pixel (10m radius) neighbourhood- $curv_{2mstd5}$.

- even, if $0.3 >= curv_{2ms15} >= -0.3$
- convex, if $-0.3 > curv_{2ms15}$
- concave, if $curv_{2ms15} > 0.3$
- uneven, if $curv_{2mstd5} > 11$

We defined the threshold values above by checking examples with an experienced soil surveyor from the Swiss soil monitoring network on aerial images and a digital elevation model.

A.3 Appendix Chapter 5

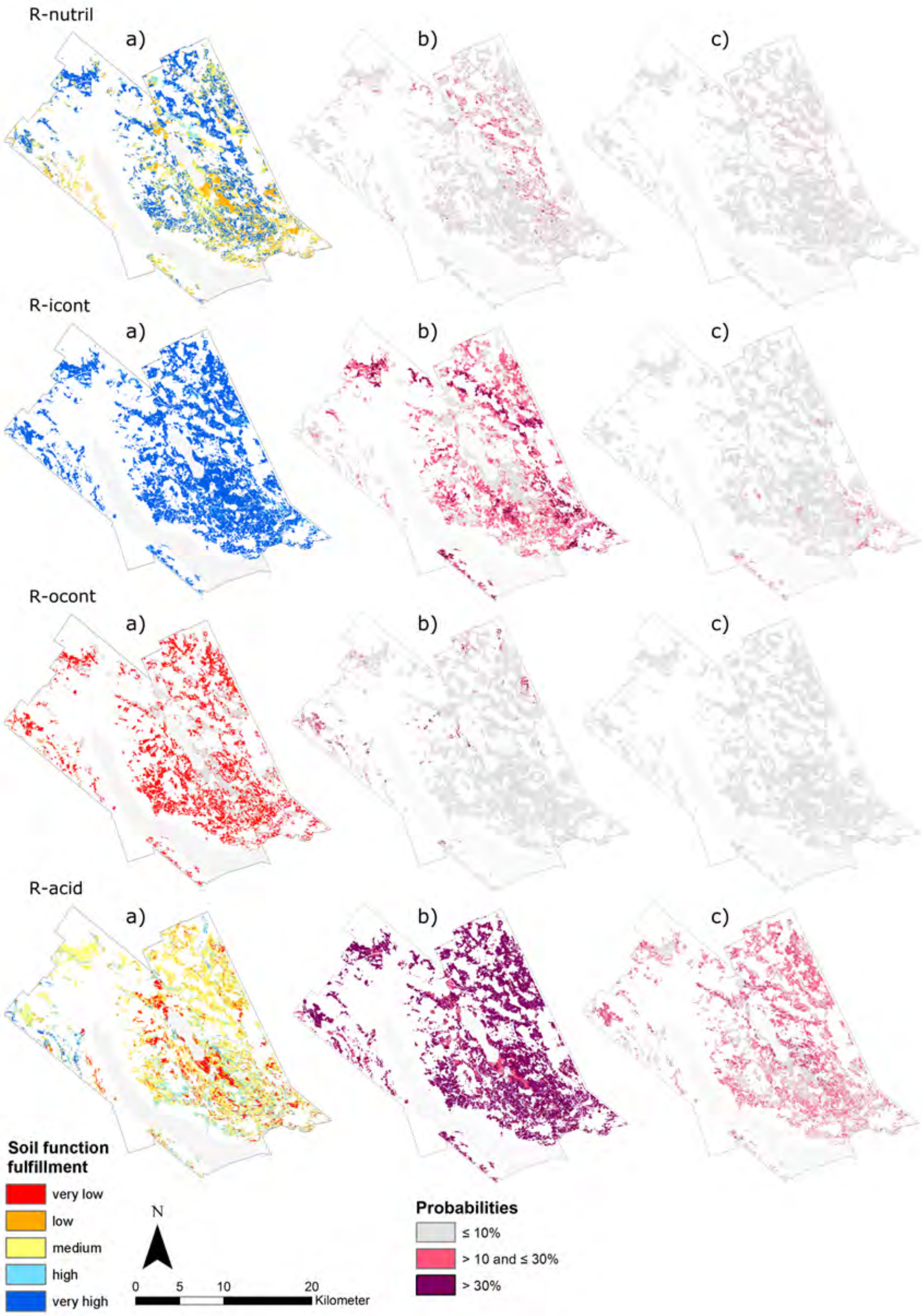

Figure A.1: Regulation functions maps for the agricultural land of the case study area and indication of their uncertainties in the ordinal scale: a) mean SFF scores and b) probability that the mean SFF score of a raster cell deviates in the ordinal scale for ± 1 or c) ± 2 or more SFF units (raster cells $20x20m$, $N = 1000$ simulations)

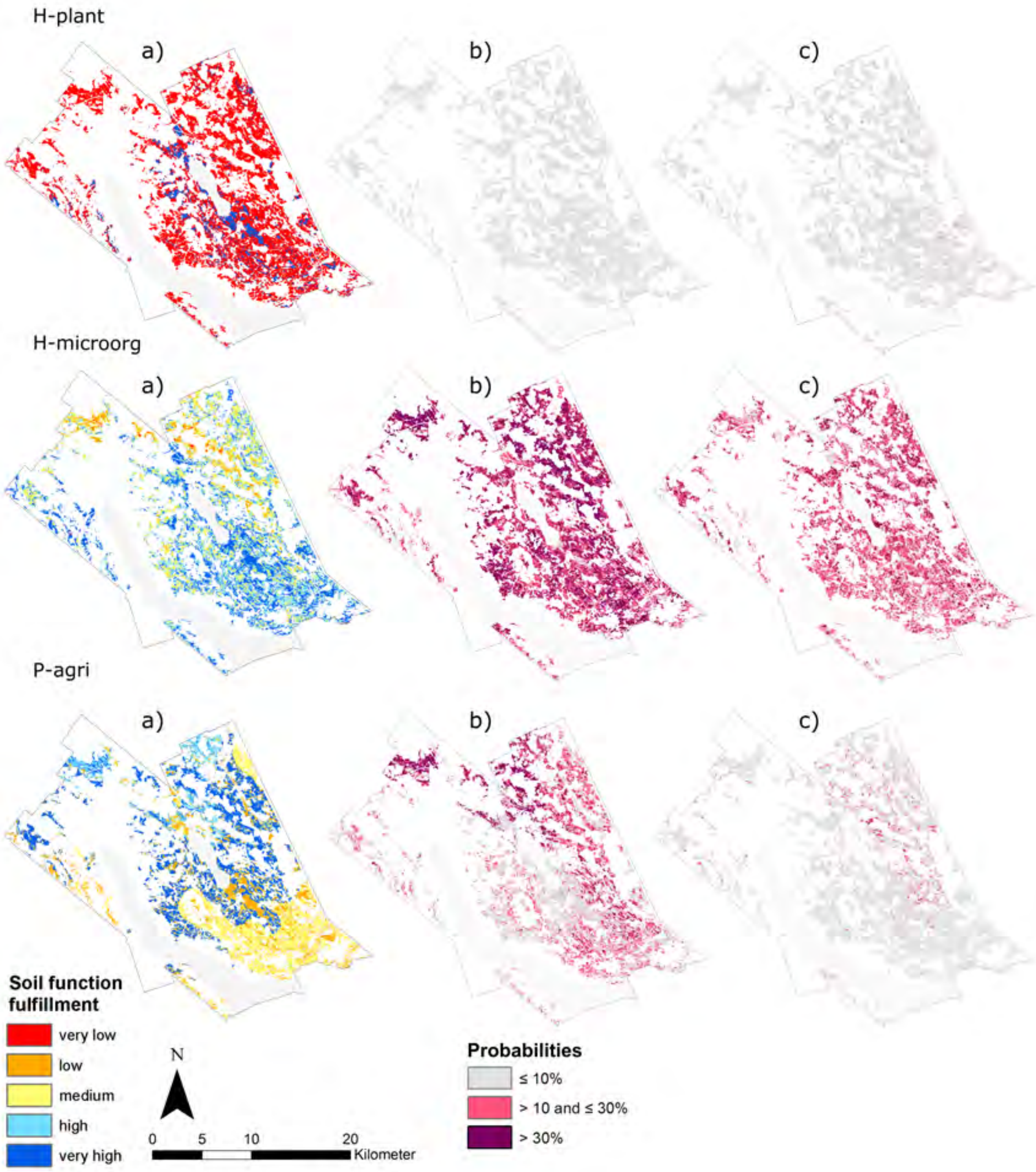

Figure A.2: Habitat functions and production function maps for the agricultural land of the case study area and indication of their uncertainties in the ordinal scale: a) mean SFF scores and b) probability that the mean SFF score of a raster cell deviates in the ordinal scale for ± 1 or c) ± 2 or more SFF units (raster cells $20x20m$, $N = 1000$ simulations).

A.4 List of publications

Articles in peer-reviewed journals

Greiner, L., Keller, A. Grêt-Regamey, A. & Papritz, A. (2017). Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services. Land Use Policy, 69, 224-237. DOI: 10.1016/jlandusepol.2017.06.025

Greiner, L., Nussbaum, M., Papritz, A., Zimmermann, S., Fraefel, M., Schwab, P., Grêt-Regamey, A. & Keller, A.. Assessment of soil multi-functionality to support the sustainable use of soil resources on the Swiss Plateau. *Submitted to Geoderma Regional, in revision.*

Greiner, L., Nussbaum, M., Papritz, A., Zimmermann, S., Gubler, A., Grêt-Regamey, A. & Keller, A.. Uncertainty indication in soil function maps –Transparent and easy-to-use information to support sustainable use of soil resources. *Accepted for publication by SOIL.*

Oral presentations

Greiner, L., Keller, A., Nussbaum, M., Zimmermann, S., and Papritz, A. (2018). Uncertainties in soil function maps. Oral presentation at the BONARES conference 'Soil as a Sustainable Resource', Berlin, Germany.

Greiner, L. and Keller, A. (2016). Bodenfunktionen bewerten: Anwendungsbeispiel fur Wasserhaushalt und landwirtschaftliche Produktion. Oral presentation at Annual Meeting of Swiss Soil Science Society.

Greiner, L. (2016). WP D Bodenfunktionen. Oral Presentation at PMSoil Stakeholder Meeting at ETH Zurich.

Greiner, L. and Keller, A. (2015). Die Bewertung von Bodenfunktionen in der Ecosystem Service Community - eine Literaturstudie. Oral presentation at the workshop of the Working Group Digital Soil Mapping of the German Soil Science Society, Tubingen, Germany.

Greiner, L., Keller, A., Zimmermann, S., and Papritz, A. (2015). Assessement and mapping of soil services for spatial planning procedures. Oral presentation at the Wageningen Soil Conference 'Soil in a Changing World', Wageningen, The Netherlands.

Greiner, L., Keller, A., Zimmermann, S., and Papritz, A. (2014). Bodenfunktionsbewertung: Die Rolle des Bodens anderen Fachdisziplinen kommunizieren. In BGS Bulletin, volume 35, pages 23-28, Changins. Bodenkundliche Gesellschaft der Schweiz.

Grêt-Regamey, A., Greiner, L., Keller, A., Siegrist, D., and Diggelmann, H. (2014).Project OPSOL operationalizing cross-scale interactions of soil functions, soil uses,spatial development and land management spatially explicit in a decision support system. Vortrag Tagung Aussprache Bodenschutz in der Schweiz; Bodenmonitoring: Heute und Morgen - In der Schweiz und im Ausland, Bern.

Keller, A., Greiner, L., Papritz, A., and Grêt-Regamey, A. (2013). Towards soil function assessment methods for Switzerland. Oral presentation at the International Conference Protection of soil functions — challenges for the future, IUNG Institute for Soil Science and Plant Cultivation, Pulawi, Poland.

Keller, A., Greiner, L., Zimmermann, S., Nussbaum, M. & Papritz, A. (2015). Integration of assessment methods for soil services in ecosystem service frameworks. Oral presentation at Pedometrics 2015 Conference, Cordoba, Spain.

Poster presentations

Greiner, L., Keller, A., Nussbaum, M., Zimmermann, S., and Papritz, A. (2018). Uncertainty of soil function maps - Improving transparency for decision-making in spatial planning. Poster presentation at the BONARES conference 'Soil as a Sustainable Resource', Berlin, Germany.

Greiner, L. (2015). Awareness rising and communication means: soil function maps for spatial planning. Poster presentation the Annual Meeting of the Swiss Soil Science Society, Basel, Switzerland.

Greiner, L. and Keller, A. (2013a). Towards soil function assessment methods for Switzerland. Poster presentation at the International Conference Protection of soil functions — challenges for the future, IUNG Institute for Soil Science and Plant Cultivation, Pulawi, Poland.

Greiner, L. and Keller, A. (2013b). Bewertungsmethoden für Bodenfunktionen in der Schweiz? Poster presentation at the Annual Meeting of the German Soil Science Society, Rostock, Germany.

Greiner, L., Keller, A., Zimmermann, S., and Papritz, A. (2014). Towards soil function assessment for Switzerland. Poster presentation at the 12th Swiss Geoscience Meeting, Fribourg, Switzerland.

Papritz, A., Baltensweiler, A., Carizzoni, M. De Jong, R., Diek, S., Fraefel, M., Greiner, L., Grét-Regamey, A., Grob, U., Keller, A., Nussbaum, M., Schaepman, M. E., Walthert, L., and Zimmermann, S. (2014b). NRP68 project PMSoil: Spatial prediction of soil properties and soil function potentials from legacy soil data and environmental covariates. Poster presentation at the 12th Swiss Geoscience Meeting, Fribourg, Switzerland.

Other publications

Greiner, L. and Keller, A. (2015). Indexpunkte gegen den Landverbrauch. TEC21, 41, 24-26.

Grêt-Regamey, A., Drobnik, T., Greiner, L., Keller, A., and Papritz (2017). Factsheet Soil and Ecosystem Services: Soils and their contribution to ecosystem services. White Paper, Swiss National Research Programme 'Sustainable Use of Soil as a Resource' (NRP 68), Berne, Switzerland.

Keller, A. and Greiner, L. (2017). Bodenfunktionen. In: Bodenschutz in der Praxis. R. Krebs, M. Egli, R. Schulin, S. Tobias (Eds.), Haupt Verlag, Göttingen.

Greiner, L. and Keller, A. (2017). Bodenfunktionsbewertung und Bodenindexpunkte. Konzept und Wege zur Umsetzung. Report for the Federal Office of Spatial Development (ARE).

A.5 Curriculum vitae

of Lucie Greiner, 21.11.1985, of Basel (BS), Switzerland

Education

2010: Master of Science in Geography, University of Bern

2009: Bachelor of Science in Geography, University of Bern

2006: Erasmus term at University of Zaragoza

2004: Matura (High school certificate), Gymnasium Thun-Schadau

Work experience

2013-2017: PhD at Agroscope and ETH ZÃ¼rich

2013-2013: Employed at Agroscope

2011-2013: Employed at Mundi consulting AG

2011-2011: Employed at Leuenberger consulting, University of Bern, Swisstraffic AG

2005-2010: Employed at Swiss register of testaments

2003-2010: Various employments (sales; service; teaching (children 7-15); hospital internship)

Skills

Languages: German (mothertongue), French (good), English (good), Spanish (basics)

Softwares: MATLAB, ArcGIS, Inkscape, MS Windows and OpenOffice