Check for updates

European Journal of Soil Science

WILEY

SPECIAL ISSUE EJP SOIL Special Issue - Climate-Smart Sustainable Agricultural Soil Management for the Future - III

REVIEW ARTICLE OPEN ACCESS

Opportunities and Challenges for Sustainable Agricultural Soil Management in Switzerland

Klaus A. Jarosch[1] | Nicole Bütikofer[1] | Olivier Heller[1] | Juliane Hirte[1] | Luca Bragazza[2] | Thomas D. Bucheli[3] | Nikolas Hagemann[3] | Isabel Hilber[3] | Annelie Holzkämper[1] | Shiva Ghiasi[1] | Sonja G. Keel[1] | Thomas Keller[1,4] | John Koestel[1] | Jens Leifeld[1] | Frank Liebisch[1] | Jochen Mayer[1] | Muhammad Mehran Anjum[1] | Konrad Metzger[2] | Ferran Romero[1,5,6] | Alejandro Romero-Ruiz[1,7] | Gudrun Schwilch[8] | Michael Simmler[9] | Marcel van der Heijden[1] | Florian Walder[1] | Michael Zimmermann[10] | Lutz Merbold[1]

[1]Agroscope, Agroecology and Environment, Zurich, Switzerland | [2]Agroscope, Field Crop Systems and Plant Nutrition, Nyon, Switzerland | [3]Agroscope, Method Development and Analytics, Zurich, Switzerland | [4]Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden | [5]Department of Plant and Microbial Biology, University of Zurich, Zurich, Switzerland | [6]Department of Agroecology, Aarhus University, Slagelse, Denmark | [7]Centre for Hydrogeology and Geothermics, University of Neuchâtel, Neuchâtel, Switzerland | [8]Federal Office for the Environment, Bern, Switzerland | [9]Agroscope, Sustainability Assessment and Agricultural Management, Ettenhausen, Switzerland | [10]Federal Office for Agriculture, Bern, Switzerland

Correspondence: Klaus A. Jarosch (klaus.jarosch@agroscope.admin.ch)

Received: 31 October 2025 | **Revised:** 12 May 2026 | **Accepted:** 15 May 2026

Keywords: EJP SOIL | soil challenges | sustainable soil management | Switzerland

ABSTRACT

Switzerland has a wide diversity of soil types that are subject to pressures of varying intensity and scale. Localised pressures such as compaction, sealing or heavy metal accumulation threaten both short- and long-term soil fertility and food production. Large-scale trends such as the intensive use of fertilisers or continued cultivation of organic soils can have effects on the ecosystem functioning of an entire region. Many of these pressures are concentrated on the Swiss plateau, which covers only about one third of the country and contains both the densest population and the most productive soils. We here review the main soil challenges of Switzerland and examine to which extent these challenges are addressed by different legal frameworks. Soil erosion, contamination as well as nutrient availability and use efficiency are all best described in the scientific literature and regulated by policies. In contrast, for several pressing soil challenges such as soil organic carbon loss, biodiversity loss or soil compaction only limited policy instruments are in place. We also report on the key findings of the 5-year EJP SOIL project that aimed to address several of these soil challenges in research projects of different scale. We discuss the key findings relevant for Switzerland, and outline their implications for various stakeholder groups, including researchers, policy makers, farmers, land managers and advisors. This not only enhances the value of the research outputs for stakeholders but also demonstrates how a research programme of this scale can directly benefit different national stakeholder groups.

1 | Introduction

Soils provide a variety of ecosystem services including the possibility for food, feed and fibre production, water filtration, carbon (C) storage and habitat provision (Greiner et al. 2017; Drobnik et al. 2018). Given their finite availability, there are conflicts of interest in using soil, especially because the provision of specific functions can impede the provision of another function. For example, land for construction competes with land for food production or nutrient-loaded agricultural soil often exhibits reduced water filtration efficiency (Reyes-Rojas et al. 2025).

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *European Journal of Soil Science* published by John Wiley & Sons Ltd on behalf of British Society of Soil Science.

Highlights

1. Diverse Swiss soils face localised and large-scale environmental pressures.
2. Legal and management tools address soil degradation and protection needs.
3. EJP SOIL advanced climate-smart farming research across Switzerland.
4. Findings guide researchers, policymakers and practitioners in soil management.

The critical role of soils is increasingly acknowledged in policy making. This is reflected in legislative initiatives such as the recently adopted EU directive on soil monitoring and resilience (Soil Monitoring Law) or in different national legislations. Simultaneously, there is still a paucity of information on how to quantify soil functioning to be applicable and comparable across different scales, timeframes and countries. One main challenge is the intrinsically strong heterogeneity of soils, making it often difficult to adequately down-scale general findings to specific locations or to account for the full complexity of soils while developing a simple metric for soil functioning (Feeney et al. 2023; Hollis et al. 2025).

A good example for this conundrum is Switzerland, located in Central Europe. The country is dominated by two mountain ranges that limit the area available for providing key ecosystem services in relation to agriculture to about one third of the country's surface where population density is the highest. With population expected to grow, pressures on soils will likely increase further. Consequently, better process understanding and targeted stakeholder communication are essential to maintain soil functions for future generations, which is however challenged by several constraints. This review article thus has two major aims. First, we provide a comprehensive overview on the soil challenges of Switzerland, identify knowledge gaps and how specific soil challenges are addressed in legislation. This is done to enable an international benchmarking and for aiding future projects for setting priorities on the most urgent research questions. Second, we provide a concrete example of a 5-year European Joint Programme (EJP SOIL) that aimed to address some of these challenges with a special focus on agricultural soils. We discuss the key findings relevant for Switzerland, and outline their implications for various stakeholder groups, including researchers, policy makers, farmers, land managers and advisors. This not only enhances the value of the research outputs for stakeholders but also demonstrates how a research programme of this scale can directly benefit different national stakeholder groups.

2 | Material and Methods

2.1 | Identification of Major Soil Challenges in Switzerland

The major soil challenges in Switzerland were identified by screening the Swiss soil strategy (FOEN 2020b), as well as the project reports of the Swiss National Research Programme NRP 68 'Soil as a Resource' (Steiger et al. 2018) that analysed sustainable soil use in Switzerland between 2013 and 2017. We synthesised the main challenges in six topics and provided information on active legislation on specific topics. 'Soil sealing and land-use conflicts' were excluded from the current study because they cannot be tackled directly by agricultural soil management, but only by spatial planning policies that were beyond the scope of EJP SOIL. For the visualisation of regions where specific soil challenges are particularly imminent, we created maps by using various indicators such as sealed surface area for the challenge of soil sealing or nitrogen (N) and phosphorus (P) losses for the challenge of high nutrient loads. All maps were created using the QGIS 3.36 software. A comprehensive list of available soil databases, monitoring schemes and soil monitoring networks from Switzerland was compiled, including information on the start of the observations, the number of sites or entries and the considered soil data.

2.2 | Case Study EJP SOIL: Design, Aims and Synthesis of Swiss Projects

From January 2020 to January 2025, EJP SOIL brought together 26 partner organisations in 24 European countries to perform coordinated research on climate-smart, sustainable management of agricultural soils. Agroscope, the Swiss centre of excellence for agricultural research, participated in EJP SOIL activities as one of the partner organisations. The respective research objectives were defined in close collaboration with Swiss national stakeholders to align scientific work with local knowledge gaps and needs. The EJP SOIL consortium conducted a series of pan-European stocktakes and surveys. Each inquiry was performed at the national level and later synthesised into European reports. Depending on the topic, national stocktakes comprised stakeholder and expert consultations, analyses of current and future soil policies, or reviews of peer-reviewed and grey literature. The topics addressed various aspects of sustainable land use, knowledge and data availability, as well as policy requirements (Table S1). Beyond the reports, peer-reviewed studies originated from the stocktakes, covering soil science knowledge and education (Vanino et al. 2023; Veenstra et al. 2024; Walter et al. 2024), sustainable soil management (Thorsøe et al. 2023; Keesstra et al. 2024; Paz et al. 2024; Weninger et al. 2024), fertiliser recommendations (Higgins et al. 2023; Jordan-Meille et al. 2023), soil structure and soil hydrological functioning (Blanchy, Bragato, et al. 2023; Blanchy, Albrecht, Bragato, et al. 2023; Blanchy et al. 2024), achievable soil organic carbon (SOC) sequestration potential (Rodrigues et al. 2021) and soil monitoring networks (Froger et al. 2024; Mason et al. 2025). The Swiss contribution to the stocktakes—covering soil challenge prevalence, management strategies, the capacity of the agricultural knowledge information system (AKIS) and policy analyses of current and future soil policies—were summarised by Heller et al. (2021). This report included a stakeholder consultation-based ranking of soil challenges and a policy gap analysis for Switzerland.

Based on the pan-European stocktakes, knowledge gaps and research needs were identified, leading to a research roadmap for EJP SOIL (Keesstra et al. 2021) and, subsequently, calls for research projects (Adamczyk et al. 2024; Stangl, Briefer, et al. 2024; Stangl, Minixhofer, et al. 2024) that were launched. As a result, 26 research projects across six topics (Borchard, Leppälä, et al. 2024; Borchard, Rodríguez, et al. 2024; Leppälä et al. 2024) were conducted. Researchers from Switzerland

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 1 | Overview on the research activities conducted with EJP SOIL with Swiss contribution.

#	Project acronym	Project title	Relative contribution (%)
1	MaxRoot-C	Optimising C inputs in annual cropping systems	14.3
2	SoilX	Soil management to mitigate climate change-related precipitation eXtremes	11.6
3	CarboSeq	Soil organic carbon sequestration potential of agricultural soils in Europe	8.9
4	SIMPLE	Scenario modelling for assessing impacts of policy changes and socio-economic effects on ecosystem services of soils	8.9
5	ARTEMIS	Agro-ecological strategies for promoting climate change Mitigation and Adaptation by enhancing soil ecosystem services and sustainable crop production	8.9
6	ROAD4SCHEMES	Roadmap for carbon farming schemes	8.3
7	ProbeField	A novel protocol for in-field monitoring of soil carbon stock, based on proximal sensors and soil spectral libraries	7.7
8	SoilCompaC	Mapping and alleviating soil compaction in a climate change context	7.1
9	INSURE	Wet management of cultivated peatlands a sustainable land use option for peat soils	6.6
10	TRACE-Soils	Trade-offs between soil carbon sequestration, greenhouse gas emissions and nutrient losses in agricultural soils across Europe: mechanisms and management options	6.3
11	STEROPES	Stimulating novel Technologies from Earth Remote Observation to Predict European Soil carbon	2.4
12	MINOTAUR	Modelling and mapping soil biodiversity patterns and functions across Europe	2.3
13	EJP SOIL working package 6	Supporting harmonised soil information & reporting	1.8
14	i-SoMPE	Innovative Soil Management Practices across Europe	1.6
15	EOM4SOIL	External organic matters for climate mitigation and soil health	1.5
16	CLIMASOMA	CLIMAte change adaptation through SOil and crop MAnagement: synthesis and ways forward	1.2
17	SIREN	Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values	0.3
18	PRAC2LIV	Fostering soil management PRACtices and uptake and developing decision support TOols through LIVing labs in EU	0.1

Note: The relative contribution estimates the resource-allocation to specific topics, based on the person-months dedicated to each activity (sum = 100% = the total amount of research time invested from Swiss partners to the project).

contributed to 18 projects, coordinated three, and were also involved in studies that addressed national soil monitoring and information systems. An overview of these projects is provided in Table 1, including the allocated resources per project.

2.3 | Synthesis of Switzerland-Related Research Activities Within EJP SOIL

At the end of EJP SOIL in January 2025, each lead scientist from Switzerland involved in at least one project (Table 1) completed a survey identifying outputs most relevant to national stakeholders. The survey covered:

1. Key outputs and findings—including stocktakes with Swiss participation, experimental research findings conducted on Swiss soils samples or long-term field experiments as well as modelling studies relevant to national conditions.
2. Details for each output, including a short description, scientific conclusions and suggested next steps.
3. Stakeholder implications for: (i) Swiss farmers, advisors and companies, (ii) legislations and administrations and (iii) scientists and researchers on a national and international level.

Responses of the survey were reviewed by a core team to identify overarching themes that coherently cover the large diversity

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

of projects and therein addressed topics. This resulted in six themes that represent the key output of the project with direct relevance for different Swiss stakeholders. After summarising these six main themes we discussed these themes and their potential impact on three different stakeholder groups, namely researchers, legislators and practitioners in the field.

We further revisited the initial demands of the Swiss stakeholders and evaluated to which extend the soil challenges they had named were addressed within the EJP SOIL research activities. For this, we grouped the stakeholder perception of soil challenge relevance (Heller et al. 2021) in categories ranging from irrelevant (e.g., salinisation) to highly important (e.g., compaction). For each of the soil challenges we also evaluated to what extent it was addressed by the accumulated scientific literature of the last 15 years by using a scientific literature search engine screening for articles that name the combination of the keywords in their abstracts (details in Table S2). Lastly, we evaluated the internal resource allocation from the Swiss project partner to each of the soil challenges. For that we allocated each of the research activities listed in Table 1 to the soil challenges that they addressed. We then divided the total number of dedicated person-months by the number of personal months dedicated to each soil challenge to identify where most resources were invested in.

3 | Results

3.1 | Switzerland's Geography and Soil Information

Switzerland covers about 41,000 km^2 and is divided into three regions: (1) the alpine region (63%), dominated by mountain ranges and harsh climatic conditions; (2) the Jura-mountain ridge (10%); and (3) the Swiss Plateau (27%) in between hosting most of Switzerland's population (FSO 2021a) and croplands (Figure 1a). About half of the country lies at altitudes higher than 1,000 m above sea level. The continental and alpine environmental zones dominate (Metzger et al. 2005), with the mean annual temperatures on the Swiss Plateau ranging from 8°C to 12°C and precipitation ranging from 550 to 2,000 mm (MeteoSwiss, n.d.).

Land use is 35% agriculture, 32% forestry, 8% housing and infrastructure and 25% are declared as 'unproductive' area, with either no or no productive vegetation, including water bodies and glaciers (FDFA 2023). Pedoclimatic conditions determine regional agricultural land use. Shallow, nutrient poor alpine soils are predominantly used as grasslands, while lowland mineral and organic soils, the latter often drained, support crop and vegetable production (Steiger et al. 2018). Switzerland relies on food imports (Ritzel et al. 2024), with 56% of consumed food produced abroad (Agrarbericht 2024c).

Due to Switzerland's diverse geology, topography, climate and varying time periods available for soil formation since the last glacial maximum (~24,000 years), a large diversity of soil types (Sprafke et al. 2025) can be found in close proximity (Figure 1b). Shallow Leptosols and Regosols dominate the Alps, while calcareous Leptosols dominate in the Jura, and Cambisols, Luvisols, Gleysols and Histosols are predominant in the Swiss plateau. Although a large-scale national soil suitability map for agricultural land use exists (Frei et al. 1980), digitalised by FSO (2000) (Figure 1b), 81% of the agricultural land lacked detailed soil maps in 2019 (Rehbein et al. 2019). Following the transfer of soil mapping responsibilities from the federal service to the 26 cantons in 1996 (FOEN 2017; Steiger et al. 2018), soil mapping intensity varied. Some cantons have completed soil mapping at a nominal scale of 1:5,000, while others are still expanding coverage, using heterogeneous methods that affect comparability. To address this issue, a harmonisation and revision of the Swiss soil classification system has recently been conducted and will be published in 2026.

The Competence Centre for Soil (KOBO/CCS), established in 2019, currently harmonises and develops methods for field and lab soil evaluation, and supports the national soil mapping efforts, which are planned between 2029 and 2050. Although nationwide soil mapping requires significant investment, recently developed techniques such as digital soil mapping make it possible to produce soil maps tailored to diverse stakeholders needs, generating a projected net economic benefit for society (Steiger et al. 2018).

Complementary to the soil mapping activities, several soil monitoring programmes are in place to assess soil quality and its development at varying temporal and spatial scales (Table 2). The nation-wide Swiss Soil Monitoring Network (NABO), established in 1984, monitors heavy metals concentrations, organic pollutants, SOC, nutrients, as well as key soil biological and physical properties (Desaules 1993; VBBo 1998).

3.2 | Specific Soil Challenges in Switzerland

3.2.1 | Soil Sealing and Land-Use Conflicts

Sealed areas (i.e., land permanently covered by impermeable materials) have in Switzerland increased by 40% over the last 30 years (Figure 1c), affecting most often former grassland or arable soils (FSO 2021b, 2024). Soil sealing progresses at approximately 18 km^2 per year (FOEN 2020b), equivalent to 0.044% of Switzerland's surface. Protecting fertile soils for food production is especially critical as agricultural land is already scarce (Charles et al. 2018) and the population of 9 million continues to grow by about 1% annually (FSO 2026). Soil sealing is addressed by three spatial planning instruments: The Federal Act on Spatial Planning that defines agricultural and building zones, the Sectoral Plan of Cropland Protection, preserving 438,460 ha of prime cropland (ARE 2020) and regulations concerning construction activities outside building zones (Leuthard et al. 2016). However, these instruments are not legally binding at the lower administrative levels and consequently lead to a net loss of soil for agricultural production. Furthermore, planning authorities are not necessarily required to compensate for the loss of the most fertile soils (Oliveira et al. 2019). Research on restoring soils (including unsealing) remains limited, and the capacity of restored soils to provide services requires further study (Tobias et al. 2018). Generally, the loss of agricultural land increases the pressure and use intensity on the remaining farmland to sustain

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

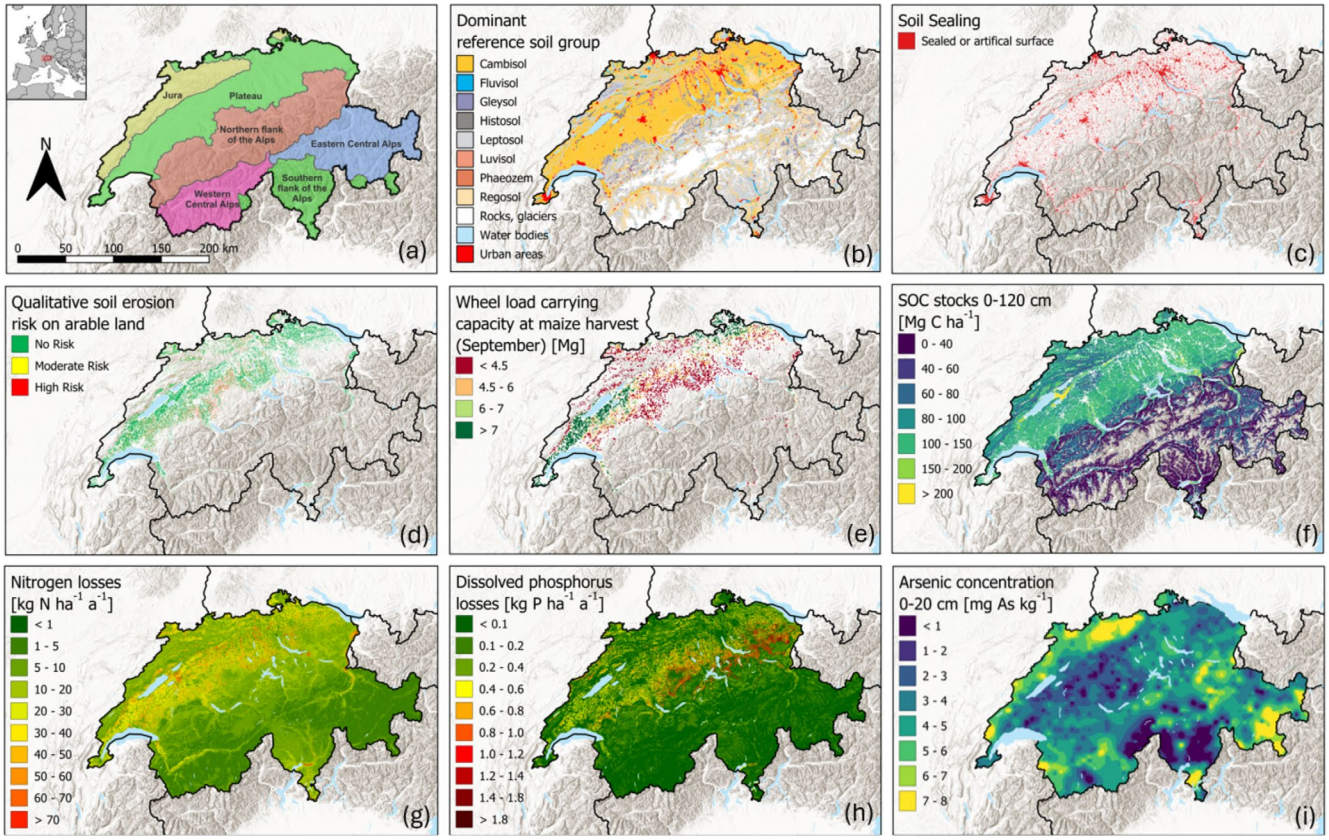

FIGURE 1 | Biogeographical regions of Switzerland (a) according to FOEN (2020b) and FSO (2021a) and (b) dominant reference soil groups in Switzerland according to WRB classification (Frei et al. 1980; digitalised by FSO 2000). Sealed and artificial (c) soils according to the Swiss land use statistics 2018 (FSO 2021b). Qualitative soil erosion risk of arable soils (d) modelled with RUSLE (Bircher et al. 2019). Wheel load carrying capacity (e) at maize harvest in September modelled with SaSCia (Agrarbericht 2024b; Weiss and Keller 2024). Soil organic carbon (f) stocks to a depth of 1.2 m (Stumpf et al. 2026). Diffuse N (g) and P (h) losses modelled with MODIFFUS (Hutchings et al. 2023). (i) Topsoil Arsenic concentration taken from Reusser et al. (2023).

food security (FOEN 2020b). The Swiss Soil Strategy aims to reduce the loss of soil functions by requiring restoration or compensation measures when construction projects impair local soil functioning (FOEN 2020b).

3.2.2 | Soil Erosion

Erosion—the translocation of soil particles—is largely driven by inadequate soil management, such as insufficient soil cover or tillage at unsuitable location or time (Blanchy, Bragato, et al. 2023). It threatens soil fertility since topsoil, rich in organic C and nutrients, is most affected. The Ordinance of soil protection (VBBo 1998) sets the legally tolerable soil loss at $2\,t\,ha^{-1}\,y^{-1}$ for soils with a profile depth of 0.7 m, and $4\,t\,ha^{-1}\,y^{-1}$ for deeper soils. The nation-wide soil erosion risk maps for arable lands (Bircher et al. 2019) and grasslands (Schmidt et al. 2019) support local authorities and farmers to identify erosion prone areas (Figure 1d). Appropriate local measures are required in these areas (FOEN and FOAG 2013; Prasuhn et al. 2017). The farmer-to-farmer-extension model has shown to be effective in the dissemination and adaptation of soil protection practices (Schneider et al. 2009). A 20-year on-farm soil erosion monitoring network programme across 203 fields in the Canton of Bern showed erosion rates decreasing from $0.74\,t\,ha^{-1}\,y^{-1}$ (1997–2007) to $0.20\,t\,ha^{-1}\,y^{-1}$ (2007–2017) (Prasuhn 2020) by a wider use of conservation tillage driven by improved financial incentives (Prasuhn 2012, 2020; Charles et al. 2018). In 2017, conservation tillage covered 70,000 ha, that is, a quarter of Switzerland's arable land (Prasuhn 2020).

3.2.3 | Soil Compaction

Soil compaction, an unintended result of soil management, affects the multifunctionality of soils by degrading soil structure, disrupting C and nutrient dynamics and decreasing water infiltration and storage capacity (Horn et al. 1995; Colombi and Keller 2019).

High agricultural mechanisation with increasing machine weight and a humid climate have led to substantial soil compaction risks across Switzerland (Figure 1e; Weiss and Keller 2024). Although soil compaction being part of legal directives (Ordinance Relating to Pollutants; VBBo 1998; PEP [Proof of Ecological Performance]), enforcement tools are still lacking (Charles et al. 2018). Federal authorities and farmers advisors provide guidelines to assess and reduce compaction risk in agriculture, including the web-based Terranimo model (Stettler et al. 2014; FOEN 2017) and a national compaction risk map

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 2 | List of major monitoring systems, soil sample archives and data viewers addressing soil properties at different spatial and temporal scales in Switzerland.

Type	Name	Sites/data entries	Data since	Properties considered
Monitoring system and sample archive	Swiss Soil Monitoring Network (NABO)	105	1984	Basic soil physical parameters, SOC, pollutants (heavy metals, pesticides, PFAS), nutrients, acidity, soil biology
Monitoring system and sample archive	Topsoil grid sampling within the Biodiversity Monitoring Switzerland (BDM)	~1,200	2010	Basic soil physical parameters, SOC, 53 chemical elements
Monitoring system and sample archive	Cantonal soil monitoring networks (KABOs)	~820	Varying (earliest in the 1980s)	Varying, with emphasis on pollutants
Monitoring system	Soil moisture network operated by 11 out of 26 cantons	65	1996	Soil moisture, soil water tension
Monitoring system	Sensor network for the Irrigation Network	~250	2016	Soil moisture, soil water tension, soil temperature
Monitoring system	Soil moisture measurement network within the Swiss Soil Moisture EXperiment (SwissSMEX)	19	2008	Soil moisture, soil temperature
Monitoring system	National Soil Moisture Monitoring Network (subproject of the National Drought Program)	> 20	Upcoming (2027)	Soil moisture
Monitoring system	SOMOMOUNT—soil moisture in mountainous terrain	6	2013	Soil moisture, soil temperature
Monitoring system	Long-term forest monitoring plots of the Federal Institute for Forest, Snow and Landscape Research WSL	17	1997	Soil solution chemistry, soil moisture, soil water tension
Monitoring system	Soil analyses within the framework of the subsidy scheme Proof of Ecological Performance (PEP)	~30,000 per year	2010, suspension currently discussed	Nutrients, acidity (only in agricultural topsoils)
Sample archive	Soil library at the University of Neuchâtel	> 4,000	1983	SOC, TC, N, C/N, acidity

(Continues)

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 2 | (Continued)

Type	Name	Sites/data entries	Data since	Properties considered
Sample archive	Forest soil archive of the Swiss Federal Institute for Forest, Snow and Landscape Research WSL	> 2,000 soil profiles, ca. 12,000 topsoil and 1,850 subsoil samples	1975	Physical, chemical, morphological properties per horizon
Data repository	Soil database of soil profiles of the Swiss Federal Institute for Forest, Snow and Landscape Research WSL	~1,400		Morphological, physical, chemical properties
Data repository	National soil information system (NABODAT)—shared soil data platform mainly for cantonal and federal authorities; available on request: Swiss Soil Dataset	~42,000	1955	Profile description, basic soil physical parameters, SOC, pollutants, nutrients, acidity
Data repository	WSL Soil database (Bodendatenbank). Data available on request.	> 2,000 soil profiles	2009	Physical, chemical, morphological properties per horizon of forest soils in the WSL Soil library
Data viewer	geo.admin.ch: Swiss federal geoportal including many soil-related maps, such as the maps of the Geochemical Atlas of Switzerland and the Soil Suitability Maps of Switzerland			
Data viewer	Soil portal of the Competence Centre for Soil: maps covering national and regional soil information, e.g., compaction, soil organic carbon, pollutants, acidification, etc.			
Data viewer	High-resolution soil maps for the Swiss forest			

Note: References to each monitoring type are provided in Table S3.

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

(1:200,000 scale; Peyer 1988). An inter-cantonal network also provides real-time soil moisture data to guide agricultural field traffic and construction activities (Meteotest and Kantonale Fachstellen, 2025).

Beyond agriculture, major infrastructure projects—such as roads, pipelines or buildings—can cause severe soil compaction. Switzerland addressed these issues by introducing the pipeline construction soil protection guidelines in 1997 (FSKB 2021; FOEN 2022, 2024).

3.2.4 | Climate Change and Related Loss of Soil Organic Carbon

Soils store more C than the atmosphere and vegetation combined, making them a key global C pool (Schils et al. 2008). Maintaining or increasing SOC supports both climate change mitigation and adaptation, for example by enhancing soil water retention (Sanderman et al. 2017).

In Switzerland, agricultural soils emit substantial amounts of nitrous oxide (N_2O) and carbon dioxide (CO_2) (FOEN 2025b). About 10% of agricultural emissions stem from peat oxidation of organic soils drained for agriculture. Climate change is expected to intensify summer droughts and heavy rainfall (Scherrer et al. 2016). By 2060, major soil-related risks include altered hydrology and composition of soils, thawing permafrost and greater soil erosion caused by extreme precipitation (FOEN 2025a). Faster organic matter decomposition may further impair soil fertility (Volk et al. 2022).

Data from the Swiss Soil Monitoring Network NABO (> 100 sites) showed mostly stable SOC concentrations in mineral soils from 1985 to 2019, with average values ranging from 30.8 to 96.6 g C kg^{-1} soil for 0–0.2 m soil depth (Gubler et al. 2019; Moll-Mielewczik et al. 2023). Remaining organic soils (32,700 ha or 30% of the original area), store about 30 Mt of C (Wüst-Galley et al. 2020; Wüst-Galley and Leifeld 2025). Organic soils and their C stocks are still threatened by peat mineralisation, soil subsidence and compaction due to loss of organic matter driven by continued drainage (Hagedorn et al. 2018). Continued soil degradation could emit up to 100 Mt CO_2-eq (Wüst-Galley et al. 2015). Rewetting drained organic soils is the most effective mitigation pathway, reducing CO_2 emissions and enhancing biodiversity (Tiemeyer et al. 2020; Darusman et al. 2023; Paul et al. 2024). However, peatland rewetting faces economic barriers (Hagedorn et al. 2018) since C credit revenues rarely offset lost agricultural income (Ferré et al. 2019). In the next decades, large parts of Switzerland's drainage infrastructure is reaching the end of its lifetime, and the need for its renovation has led to a debate on whether drainages should be renovated or peatlands restored (Béguin and Smola 2010; Weber et al. 2019). Alternatives to peatland rewetting include covering organic soils with mineral soil and concurrently increasing water table depth, or converting them to wet production, for example, rice (Paul et al. 2024; Widmer et al. 2026).

Non-agricultural bogs, often dominated by organic soils, are strongly protected after a popular petition ('Rothenthurm-Initiative') in 1987, which includes the prohibition of peat mining. However, until today about 500,000 m^3 of peat are annually imported, used mainly for the production of vegetable seedlings. In 2010, the Federal Council started evaluating options to reduce the import of peat (The Swiss Federal Assembly 2010).

Carbon sequestration in mineral agricultural soils remains a core climate change mitigation strategy (Roe et al. 2019; Walker et al. 2022). Guidelines and tools support farmers in maintaining and increasing SOC (Zihlmann et al. 2019; Oberholzer et al. 2025). Carbon farming initiatives—private and cantonal (e.g., Solothurn, Basel-Country and Grisons)—provide financial incentives for climate-smart practices through result-based, action-based, or hybrid models (Huber et al. 2022). These require reliable quantification and certification of SOC and CO_2 removal.

3.2.5 | Unbalanced Fertilisation and Contaminant Inputs

Excessive nutrient loading from intensive agriculture can cause eutrophication and introduce pollutants such as plant protection products (PPPs) and antibiotics into the food chain (Bucheli et al. 2023).

Despite reductions, between 2020 and 2022, Swiss farmland still received average nutrient surpluses of 86 kg N ha^{-1} y^{-1} and 4 kg P ha^{-1} y^{-1} (Spiess and Liebisch 2024). In livestock-dense regions, this contributes to nitrate contamination and P-driven eutrophication of soil and water bodies (Binderheim 2018; FOEN 2019, 2020b; Tu et al. 2019). Farmyard manure remains the main fertiliser in Switzerland (Carlen et al. 2017). National nutrient reduction targets align with the EU farm to fork (F2F) strategy (EC 2020), but are more modest and attainable (Harder and Liebisch 2025).

In some management systems PPP use has led to widespread pesticide residues persisting in soils decades after applications (Bucheli et al. 2023; Riedo et al. 2023; Barmettler et al. 2025). The Swiss Government's 2017 action plan on sustainable application of PPPs includes over 50 measures, including the establishment of a multi-residue analysis method in soils (Rösch et al. 2023), bioindicators for soil fertility, soil protection values and long-term monitoring (Agrarbericht 2024a).

External organic matter (EOM) such as compost, digestates and formerly sewage sludge (banned from application in 2006) can introduce contaminants into the soil and food system. Repeated application of such material to soils can increase their concentrations beyond levels considered as safe by current legislation. Few compounds, such as heavy metals or polycyclic aromatic hydrocarbons (PAHs), are regulated in Europe and Switzerland. While concentrations of these contaminants remain mostly lower than guide values (Brändli et al. 2007), other contaminants, such as microplastics, are known to be excessively found in EOM, such as sewage sludge (Corradini et al. 2019) or compost (Braun et al. 2021). Annual plastic input into soil via compost and digestate is estimated to be 50 t yr^{-1} (Kalberer et al. 2019).

Biochar application has expanded as a strategy to improve soil quality and to increase SOC. Switzerland was the first

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

country to regulate biochar production in 2012 (Bachmann Jr et al. 2016) and aligned in 2024 its regulations with EU standards (EU 2019/1009) while maintaining strict application limits (Hagemann 2025).

Sites with heavy metal contamination are managed under the Contaminated Sites Ordinance (2025), with major sources including shooting ranges and chemical industry pollution. Several cantons (e.g., Zurich) have mapped potential hotspots of contaminated soils to prevent untraceable spreading of contaminated soils (Schulin et al. 2018), including sites with high arsenic concentrations of geogenic origin (Figure 1i), leading to restrictions of agricultural land use (Schmutz et al. 2018). Future risks can be reduced by using low cadmium (Cd) and low uranium (U) fertilisers (Bigalke et al. 2017), and uncontaminated manure and slurry (Gubler et al. 2015).

3.2.6 | Soil Biodiversity Decline

Soil biodiversity plays a vital role in ecosystem functioning, yet many studies report that land-use intensification leads to homogenisation and overall reductions in soil biological diversity (Peng et al. 2024; Eisenhauer et al. 2026). For example, pesticide presence in soils has recently been linked to declines in the diversity of beneficial organisms, such as arbuscular mycorrhizal fungi (Köninger et al. 2026). At the same time, some researchers have observed higher microbial taxonomic diversity in intensively managed arable soils compared to grasslands or forests. However, these increases are often driven by the proliferation of opportunistic or undesired taxa, such as plant pathogens, rather than by functionally beneficial communities (Labouyrie et al. 2023). This highlights that taxonomic diversity alone does not necessarily reflect improved ecosystem functioning, and that both taxonomic and functional dimensions of soil biodiversity must be considered. Long-term trends nevertheless remain unclear due to the lack of consistent soil biodiversity monitoring (Gschwend, Hartmann, Hug, et al. 2021; Campiche 2025).

Indicators and protocols for assessing landscape-scale biodiversity exist, including standardised approaches to quantify microorganisms, soil fauna and biological activity. This covers metrics such as microbial biomass and community composition, functional groups identified through metabarcoding, soil enzyme activities and the abundance and diversity of nematodes, micro-arthropods and earthworms (Herzog et al. 2017; Martin et al. 2019). However, economically viable, site-specific practices for promoting soil as a habitat and enhancing soil biodiversity are still needed (Riggi et al. 2025; Romero et al. 2025).

3.3 | EJP SOIL Findings, Addressing Specific Swiss Soil Challenges

3.3.1 | Resilience Against Climate Change: Mitigation and Adaptation

A review of 127 meta-analyses showed that organic soil amendments and continuous soil cover significantly enhance the soil water regulation function (Blanchy, Bragato, et al. 2023). In Switzerland, increasing SOC by 1% in the top 60 cm of soil could reduce drought-related induced potato yield losses in the Broye region from 16% to 7% (Heinz et al. 2025), while a 2% SOC rise to a soil depth of 65 cm could cut maize transpiration deficits by 40 mm (Turek et al. 2023).

Gains in SOC can be achieved through various methods, though with varying efficiency. Model simulations from a Swiss long-term experiment showed that 16% of plant-derived C remained in the soil after 40 years, compared with 3%–5% for manure or digestate, or 10% with compost amendments (Keel et al. 2025). Biochar retains the most C due to its high stability (Rodrigues et al. 2023), but its sequestration potential depends on the availability of biomass for biochar production. Optimising the use of biomass is therefore key to contribute to net zero strategies, while minimising negative effects on soil fauna (FOEN 2023). In cool regions rewetting organic soils can reduce emissions without yield losses under grassland management (Lång et al. 2024; Nielsen et al. 2024).

Conservation agriculture—reduced tillage, permanent soil cover, diversified crop rotations—can improve the resilience of these production systems against various stressors. A European meta-analysis found only a 3% cereal yield gap compared to the conventional systems, while yield stability, often used as an indicator for resilience in a production system, was reduced to 9%. The major moderators impacting the yield gap were the tillage depth in conservation agriculture systems, clay content of the soils, amount of applied mineral N fertiliser and the type of cereals. The meta-analysis further revealed no overall effect of conservation agriculture on N_2O emissions compared to conventional agriculture. However, N_2O emissions from conservation agriculture increased with increasing soil clay contents (Ceriani et al. 2026; Valkama et al. 2026).

Carbon farming schemes can encourage the adoption of such practices but are not yet widely endorsed by Swiss authorities (FOEN 2023). A review of 160 European carbon farming schemes, including 11 Swiss, highlighted the need to combine financial and technical support (Thorsøe et al. 2025). Result-based schemes offer transparency but are costly due to intensive soil sampling, where C storage change is quantified directly. As this approach is very laborious and expensive, it is ideally supplemented with modelling, also to optimise sampling numbers.

Distinguishing biochar derived C from native SOC remains difficult, posing challenges for certification and C accounting. When using biochar together with other C farming activities, there is also a risk of double counting if the biochar has already been certified for C sink, but its C quantified again as SOC (Lotz et al. 2024; Rathnayake et al. 2024). Centralised systems, such as the Swiss-hosted Global C-Sink Registry can prevent double-counting risks (Rathnayake et al. 2024). Another challenge with biochar amendments is the increased spatial heterogeneity of SOC (e.g., in furrows), complicating field sampling campaigns (Lotz et al. 2024).

Selecting crop varieties with deeper root systems enables plants to access otherwise unavailable water and nutrients while facilitating C input into deep soil layers. However, environmental

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

factors often outweigh genetic influences. At two Swiss sites (Eschikon, ZH and Changins, VD), root biomass of 10 winter wheat varieties varied twofold between sites but did not always increase yields (Heinemann et al. 2025). Across 11 European sites, temperature was the dominant factor shaping subsoil traits; the Swiss variety *Montalbano* displayed strong root plasticity that sustained yields under variable conditions (Durand-Maniclas et al. 2025).

3.3.2 | Soil Assessment and Monitoring

Accurate soil assessment supports sustainable soil management. Field spectroscopy has gained interest in recent years due to the prospect of a high sample throughput, and thus offers rapid, low-cost alternatives to lab analyses and reliably measures SOC, total N, cation exchange capacity (CEC) and clay content (Metzger, Liebisch, Herrera, Guillaume, Walder, and Bragazza 2024; Piccini et al. 2024) when tested with soils from three different locations in Switzerland (Changins, Reckenholz, Tänikon). A hands-on field protocol with calibration links to soil spectral libraries was developed (Fondón et al. 2024; Stenberg et al. 2024; Castaldi et al. 2025).

Satellite remote sensing has the potential to assess soil properties at a high temporal and spatial resolution. It allows observation of in-field variability, while simultaneously covering entire regions. Including auxiliary data often improves performance of models that estimate soil properties from satellite information. This was shown for including soil texture information in estimation of SOC from multispectral satellite data, but the effect was found to vary strongly across 34 local-scale study areas in 10 European countries, including Switzerland (Wetterlind et al. 2025). Combining satellite information with terrain, climate and coarse-scale soil data, alongside support sampling (i.e., soil sampling guided by satellite information), enabled the development of performant models for estimating SOC (Yuzugullu, Fajraoui, Don, and Liebisch 2024), soil texture and pH (Yuzugullu, Fajraoui, and Liebisch 2024), which were validated also in Switzerland (Lotz et al. 2024; Rathnayake et al. 2024; Yuzugullu, Fajraoui, Don, and Liebisch 2024; Yuzugullu, Fajraoui, and Liebisch 2024; Wetterlind et al. 2025).

Switzerland's soil monitoring system meets many core requirements of the EU's Soil Monitoring and Resilience Directive—such as stratified random sampling based on soil units defined by soil type and land use and GPS tracking (European Commission 2023). Still, the current system lags in sampling depth (20 vs. 30 cm), ISO compliance and public data accessibility (Mason et al. 2025).

3.3.3 | Soil Management and Socio-Economic Framework

Farmer behaviour directly affects soil properties. Interviews with 26 Swiss farmers revealed three archetypes of Swiss farmers: (a) the 'sustainable farmer', (b) the 'pragmatic farmer' and (c) the 'market-focused traditionalist', differing in decision making on soil management options (long-term vs. short-term effects), implementation of up-to-date scientific knowledge and orientation on legal restrictions and economic considerations (Bütikofer et al. 2024; Lötscher 2024). Consequently, policy measures must reflect this diversity to ensure acceptance.

For carbon farming and its certification, a focus group in June 2023 found that Swiss farmers favour regenerative practices such as grass in rotation, cover crops and forage legumes as beneficial for soil health. In contrast, rewetting organic soils or setting aside productive land was rejected due to concerns over reduced food production in an import-dependent country. Many were sceptical of carbon markets, stressing the need to reward SOC maintenance and ensure transparent, farmer-oriented schemes.

Switzerland shows high adoption levels for crop rotations, cover cropping, organic fertilisers, integrated pest management, liming and the installation and maintenance of drainage systems many of those being supported by financial incentives (Heller et al. 2024). Practices with great potential for higher adoption include conservation tillage, residue retention, agroforestry and paludiculture. Major barriers for the adoption of sustainable soil management practices include limited knowledge and machinery to farmers, high investments, climatic constraints and socio-cultural resistance to changing current farming practices (Thorsøe et al. 2023; Heller et al. 2024). Furthermore, digital decision support tools remain underused compared to other EU countries (Herrmann et al. 2025; Warren Raffa et al. 2025).

3.3.4 | Soil Fertilisation, Amelioration and Introduction of New Compounds

Fertiliser input reduction not only affects productivity but could also lead to reduced SOC storage. In a modelling simulation study, averaged over European countries, a 20% reduction in mineral N fertiliser application showed a 9%–10% decrease in yields for six main crops, while SOC losses were 0.9 t ha^{-1} of agricultural land over 30 years. Emissions of N_2O were 15% lower and N leaching and runoff were reduced by 24% (Keel et al. 2025).

Organic and mineral fertilisers are main sources of C and nutrient inputs into soils. Two stocktake studies summarised the methods used to determine fertilisation demand for N (Jordan-Meille et al. 2023) and P, potassium, magnesium and calcium (Higgins et al. 2023). The results call for greater harmonisation within Europe, allowing better use of knowledge, research and operational synergies across borders. While Switzerland has well-established methods and field specific recommendations (Carlen et al. 2017), they are underutilised in legislations and practice. Going more into detail, a 35-year-long Swiss field experiment showed that maintaining or increasing N soil stocks requires a positive soil surface N budget (Oberson et al. 2024), indicating a trade-off between preserving soil quality (maintaining stable N stocks) and minimising N losses due to N oversupply.

Fertilisers can introduce other undesired compounds into the soil system. For instance, plastic can enter soils via EOM and subsequently migrate to the subsoil (Heinze et al. 2024). As of today, Switzerland enforces stricter limit values for both organic and inorganic contaminants in biochar than the EU (Hagemann 2025) and Swiss producers comply with these

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

requirements. Biochar production in Switzerland is currently still wood-based but may include untreated plant biomass and secondary biomass. Neither EU regulations nor Swiss regulations allow biochar production from sewage sludge, although there is a potential of co-pyrolysis of sewage sludge with lignocellulosic biomass (e.g., wood) for P recycling. Within Europe only a few national regulations allow this, for example, Finland.

3.3.5 | Soil Structure

Soil management strongly affects soil structure. Soil cover, organic amendments and reduced soil compaction are key for a functional soil structure (Blanchy, Bragato, et al. 2023; Blanchy, Albrecht, Bragato, et al. 2023). Modelling revealed the highest compaction risks in Switzerland during primary tillage, slurry spreading and autumn harvest (Kuhwald et al. 2018; Weiss and Keller 2024). Compaction risks were largely controlled by soil moisture (Weiss and Keller 2024).

Single compaction events can reduce crop yields by ~20% and simultaneously increase N_2O emissions by ~150%, and N leaching by ~17% (Romero-Ruiz et al. 2026). Several Swiss long-term field experiments demonstrated that adding organic matter via compost or farmyard manure had no significant effect on the penetration resistance or soil water holding capacity, neither in topsoil nor in subsoil below 30 cm. At the same time, another long-term field experiment confirmed that conventional tillage effectively decreased the penetration resistance compared to the no-till system (Holzkämper et al. 2024).

Mapping soil hydraulic conductivities is needed to mitigate risks of erosion and flooding and remains challenging due to poor predictors such as soil texture or SOC (Weber et al. 2024). Better structural data are crucially needed for reliable modelling efforts (Garré et al. 2022; Blanchy, Albrecht, Bragato, et al. 2023).

3.3.6 | Soil Biota and Multifunctionality

Soil biota underpin many soil functions. Six Swiss field studies showed that double cover cropping enhanced microbial activity and nutrient availability in comparison to a permanent soil cover that instead increased SOC, exemplifying differences in soil processes also between rather similar soil conservational approaches (Oberholzer, Jarosch, et al. 2024).

The Swiss National Soil Monitoring Network NABO monitors 30 sites using environmental DNA (eDNA) sequencing, revealing land-use–specific microbial communities. Results showed that soil microbial community structures were site- and land-use type specific (Gschwend, Hartmann, Mayerhofer, et al. 2021), and that soil bacterial and fungal communities remained stable over 5 years, enabling the definition of a set of core taxa representing entire communities (Gschwend, Hartmann, Hug, et al. 2021; Gschwend, Hartmann, Mayerhofer, et al. 2021). Switzerland leads in soil biodiversity monitoring. Expanding the Swiss National Soil Monitoring Network NABO to alpine sites and including other indicators such as soil enzymatic activity and nematode could further strengthen assessments (Romero et al. 2024; Riggi et al. 2025).

Across seven European long-term trials, including the Swiss p29c trial at Agroscope-Nyon, we observed that no-till practices increased arbuscular mycorrhizal fungi (AMF) diversity. In a similar field study with 10 winter wheat varieties at four European sites, AMF colonisation varied mainly by environmental factors. Yet, differences in mycorrhizal colonisation did not translate into grain yield, highlighting the dominant role of soil and climate as main drivers (Veršulienė et al. 2024; Durand-Maniclas et al. 2025).

4 | Discussion

4.1 | Implications for Research

4.1.1 | Need to Improve Understanding of Soil Processes

Increases in SOC can improve soil water dynamics and offer additional benefits to crop productivity and yield stability by fostering beneficial microbial communities such as rhizobacteria, N-fixing bacteria and mycorrhizal fungi (Kallenbach and Grandy 2011; Renwick et al. 2021; Coban et al. 2022). Future field experiments should investigate the multiple benefits of SOC increases on soil functioning. In this context, long-term field experiments remain a valuable research infrastructure for studying soil processes in situ. Yet, the previously postulated positive effects of organic amendments on soil water regulation (Blanchy, Bragato, et al. 2023) were not consistently observed in the long-term field experiments (examined in EJP SOIL) (Holzkämper et al. 2024; Skadell et al. 2025). While this does not negate the effect, it highlights the need for broader and more representative datasets to draw general conclusions. The meta-analysis of Blanchy, Bragato, et al. (2023) could not be conducted in a fully quantitative fashion due to the vast number (> 2,800) of publications on this subject. Advances in large language models will soon enable detailed quantitative data extraction from large scientific literature corpuses (Blanchy, Albrecht, Koestel, and Garré 2023).

Soil biota strongly influences soil multifunctionality, yet detailed process understanding remains limited. For instance, mycorrhizal root colonisation may be more beneficial for wheat cultivation in resource-limited than resource-rich sites in terms of nutrient and water availability. Research should particularly focus on how AMF affect crop yields and soil functioning under such conditions in Switzerland. Studies should also investigate management practices that promote high earthworm densities—such as reduced tillage, cover cropping and organic amendments—and examine how microbial patterns relate to ecosystem functions such as C cycling, nutrient availability and climate resilience. Expanding the Swiss National Soil Monitoring Network NABO's soil biodiversity monitoring to alpine regions and integrating additional bioindicators could strengthen Swiss and European soil policies and legislation.

Lastly, it is important to keep in mind that an improved understanding of soil processes does not guarantee practical solutions, as socio-economic barriers often hinder the adoption of sustainable practices. For example, while decision support tools such as Terranimo (e.g., www.terranimo.world; Stettler et al. 2014)

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

can help prevent soil compaction by ensuring applied stresses remain below soil strength (Horn et al. 1995), the push for high efficiency machinery (Schjønning et al. 2015) creates economic and operational pressures that hamper the implementation of the recommendations.

4.1.2 | Improving Methods for Soil Evaluation

Greater harmonisation of field sampling and laboratory analyses remains essential, as methodological differences limit results comparability (Higgins et al. 2023). The same applies to in-field soil evaluation techniques such as the 'spade test' (Johannes et al. 2023), spectroscopic analyses (Metzger, Liebisch, Herrera, Guillaume, and Bragazza 2024; Piccini et al. 2024; Castaldi et al. 2025) and soil biological parameters (Marín et al. 2025).

Understanding emerging contaminants in EOM—including (micro-)plastics—requires further analytical development. In Switzerland, manure should also be considered as EOM as it is often transported beyond production sites. The pollutant content of EOM remains largely understudied, yet it is critical for mass flow analysis of contaminants to soils, and corresponding soil risk assessments. Both are needed for the development of regulatory guide values.

Biochar production and quality control are now sufficiently advanced for safe use in practice. Future research should focus on long-term field experiments across different climatic zones, including alpine and temperate regions as found in Switzerland to better understand its effects on soils and organisms. Analytical refinements such as x-ray spectroscopy (Keiluweit et al. 2010), time-domain near-mid infrared (Conte 2018), thermal analysis (Hardy et al. 2022) and hydropyrolysis (Rombola et al. 2016; Eurofins Umwelt-Ost 2023; Sanei et al. 2024; Hagemann et al. 2025) are needed to quantify the stable C fraction of biochar.

Model-based approaches also require improvement. Simulations assessing soil compaction risks and their impacts on soil functions should better integrate new data and emphasise accessibility and usability for agriculture and environmental decision making. Future field- and model-based research should evaluate trade-offs and synergies involving SOC, supporting management strategies related to other soil ecosystem services such as nitrate leaching, soil erosion and runoff, to support sustainable agricultural management (Bonfante et al. 2019).

Estimating SOC requires the integration of diverse data sources. Estimations of crop root C input to soil C modelling would benefit from variety- and region-specific root-shoot ratios, as these depend on genotype, soil and climate (Heinemann et al. 2025). Root data of individual varieties should be centrally managed and made freely available to users, for example, as part of the CarboSeq database (Ruysschaert et al. 2023), while existing soil and climate datasets should be geospatially explicit and easily linkable, for example, accessible via the linked data services such as the Linked Data Day LINDAS (lindas.admin.ch) and the federal geoportal (geo.admin.ch). This integration would improve national SOC modelling accuracy.

To align with the EU Soil Monitoring Law, Switzerland should conduct a feasibility study defining national stakeholder requirements, analytical standards and open data policies, similar to a previous survey (FOEN 2020a). Method comparison studies are essential before modifying long-term monitoring protocols to ensure continuity in data usability.

4.2 | Implications for Swiss Legislation for Promoting Sustainable Land Use

4.2.1 | Development and Refinement of Reference Values

Although Switzerland is not part of the EU, new European soil evaluation or monitoring standards will likely have direct or indirect effects on Swiss legislations. Methodological harmonisation—sampling depths, analytical methods and data accessibility—would enable cross country comparisons. Data sharing can be improved through protection policies and enhanced open-access data platforms such as the Linked Data Day (LINDAS: lindas.admin.ch). The legal frameworks affecting soil use should be adjusted to align with current scientific knowledge. While biochar regulations are well-established and robust, EOM and soil ordinances should incorporate reference values for emerging contaminants. The (co-)pyrolysis of heavy metal-poor sewage sludge with lignocellulosic biomass could be approved for P recycling.

Carbon farming policies such as laid down in the Swiss CO_2 Ordinance for biological C storage (FOEN 2025c) should become less restrictive and more cost-effective, with direct payments rewarding practices that enhance SOC and disincentivise agriculture that induces strong SOC losses such as for drained peatland cultivation. Farmers also called for public knowledge-sharing platforms and practical soil assessment tools.

Given Switzerland's high mechanisation and a relatively high mean annual precipitation, soil compaction remains a major threat to soil functioning. Prevention should take priority, supported by monitoring systems and legislative measures (Blanchy, Bragato, et al. 2023; Blanchy, Albrecht, Bragato, et al. 2023).

4.2.2 | Methods and Approaches for Implementing Sustainable Land Use

Adoption of sustainable soil management practices can be improved by supporting farmer-advisor-researcher networks focused on sustainable soil management, as well as the provision of developing site-specific guidelines, and offering technical support and financial incentives for their adoption support. The Swiss 'Thematic Network Soil', involving EJP SOIL partners, is one example leading to tools such as the Visual Evaluation of Soil Structure (VESS) tool in close collaboration between science and practice (Johannes et al. 2023).

Effective policies should consider farmers' contexts (Bütikofer et al. 2024). Combining knowledge exchange, social networks and targeted incentives can enhance adoption. Moreover, financial incentives such as sustainability-linked markets or

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

subsidies for conservation practices should be considered (Kittinger et al. 2025).

Additional barriers—including cultural norms, economic constraints and risk aversion—require context aware measures. Education and awareness campaigns can shift perceptions, changing common perceptions of what it means to have well-taken care of tidy fields, while insurance or subsidies can buffer transitional risks. Given similar needs across Europe, coordinated policy frameworks could effectively maintain soil ecosystem services losses as low as possible (Drobnik et al. 2020).

4.2.3 | Regulatory Framework Towards Site-Specific Recommendations

To effectively address issues such as soil erosion, contamination, compaction and loss of organic matter from organic soils, their assessments should be conducted at a regional level, considering prevalent soils, topography, climate and agricultural structures. Administrative boundaries (such as cantons) may not reflect the natural soil system. On the European level, such assessments are often performed based on environmental stratifications (e.g., *soil districts, soil regions, environmental zones*). Possible spatial units for a Swiss assessment are the Swiss Environmental Domains (Lehmann et al. 2010), a qualified grouping of the soil reference units of one of the Swiss soil maps (Frei et al. 1980) or the European Soil Regions (EUSR5000 2005).

Existing data sources, such as world overview of conservation approaches and technologies (WOCAT: www.wocat.net) inventories or structural survey datasets could help map current management practices (Vanwindekens and Heller 2024; Rees et al. 2025; Schievano et al. 2025). Remote sensing and soil spectroscopy tools can complement these efforts, for legislation applications and ecological performance verification. However, standardisation of methods and quality control is crucial (see Section 4.2.2).

Swiss legislation should continue promoting European collaboration and support knowledge integration as outlined in the Swiss Soil Strategy (FOEN 2020b). Delivering accessible maps and decision support tools would enable society to leverage high-quality digital soil data across sectors.

4.3 | Implications for Practitioners

Various soil-improving products are available, but compliance with the required quality standards must always be verified. For example, EOM should originate from certified producers, following recommendations from relevant associations (e.g., Biomasse Suisse) and authorities (Swiss EPA). Biochar Certificate (EBC) ensures safe use under the current application restrictions. Carbon certification systems should recognise both SOC maintenance and increases. Managing the soil microbiome remains challenging and expectations should therefore remain realistic—despite the strong interest among some farmers in these approaches (Oberholzer, Herrmann, et al. 2024). Certain soil management, for example, as with intensive tillage can disrupt beneficial AM fungi (Säle et al. 2015; Banerjee et al. 2019). Crop breeding programmes could prioritise wheat varieties with high root biomass enhancing soil C input. Advisors and seed companies could label varieties by root C input potentials, such as the Swiss variety Montalbano.

Region-specific assessment of soil challenges and tailored management practices to tackle them would provide clear guidelines and would help farmers and farm advisors on a regional scale to optimise productivity and sustainability. Adoption requires addressing both socio-technical as well as economic barriers particularly for issues such as soil compaction or soil erosion. Reliable soil maps are essential for decision making, but soil map products targeted to stakeholder needs still need further development. Advisors, planners and authorities increasingly rely on soil spectroscopy, which is becoming closer to being a standard tool for extension services and agricultural laboratories in Switzerland. Open access to spectral libraries through the Competence Centre for Soil (KOBO/CCS) would further advance this approach.

4.4 | International Context and Critical Outcome Evaluation

Addressing complex agricultural soil threats requires collaboration among stakeholders, both directly and indirectly affected (Pulido-Moncada et al. 2025; Winowiecki et al. 2025). The EJP SOIL programme was one such initiative, providing a strategic soil research agenda for the upcoming decade (Keesstra et al. 2025). With soil-related ecosystem services gaining recognition at multiple political levels (Reyes-Rojas et al. 2025), the need for comparable soil quality indicators for international benchmarking is growing. The recently adopted EU Soil Monitoring Law and related efforts towards sustainable soil management (Panagos et al. 2022) offer a framework for such benchmarking, one that will likely affect Switzerland at least indirectly. Switzerland's continued participation in international research collaborations remains essential, given that several soil degradation challenges are shared with neighbouring countries (Arrouays et al. 2022; Vanino et al. 2022).

Participatory research has become an increasingly valuable approach to bridging scientific expertise and practical stakeholders' knowledge in a co-creational process. The research priorities identified as most urgent for Switzerland (Table 3) were corroborated at the last Swiss congress on Soil Health (Hitzfeld et al. 2024) where soil erosion, loss of SOC, loss of soil biodiversity and soil compaction were similarly named as top threats. The EJP SOIL project invested considerable resources in making outputs openly accessible (Larooche et al. 2025), as is standard practice for Horizon Europe projects. Among the soil challenges identified by Swiss stakeholders, loss of SOC has received the most research attention in EJP SOIL, with 6 of 18 projects directly addressing it. By contrast, soil erosion—equally ranked as a top priority—was not addressed by any project with Swiss participation, despite an extensive body of scientific literature on the topic. The largest gap between stakeholders' priorities and research action, however, concerned soil sealing. The EJP SOIL project's focus on agricultural soils meant that spatial planning was largely excluded from project design (see Section 2.2, Table 1). Yet, closer collaboration between soil scientists and spatial or urban planners appears a promising avenue for

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 3 | Overview on soil challenges and perceived importance, reflectance of the topic in scientific publications, status of policies and addressing within EJP SOIL.

Soil challenge, identified by Swiss stakeholders ($n = 29$)	Importance according stakeholders	Number of publications in last 15 years	Taken into account by policy	Resource allocation within EJP SOIL, Swiss contribution	Project #
Soil compaction	!!!	##	(§)	€	13, 8, 14, 17
Soil sealing	!!!	#	(§)		
Soil erosion	!!!	###	§	€	13, 14, 17
Soil organic carbon loss	!!!	###	(§)	€€€	1, 3, 4, 5, 6, 7, 10, 11, 13, 14, 17, 18
Soil biodiversity loss	!!!	##	(§)	€	12, 13, 14, 17
Soil contamination	!!!	###	§	€	7, 11, 13, 14, 15, 17
Low nutrient use efficiency	!-!!!	###	§	€	7, 10, 11, 13, 14, 17, 18
Soil acidification	!-!!!	#	§	€	13, 14, 17
Peat degradation	!	#	§	€	9, 13, 14, 17
Nitrous oxide and methane emissions	!	#	§	€	5, 14, 17
Low water retention	!	#		€€	2, 13, 14, 16, 17, 18
Soil salinisation	—	#		€	13, 14, 17

Note: Soil challenges identified by Swiss stakeholder survey at the beginning of the EJP SOIL project (Heller et al. 2021). Number of publications on specific soil challenges in Switzerland derived from survey (Table S2). Consideration in policy making is based on the policy analysis reported in Heller et al. (2021) and the literature review conducted in this study. Resource allocation from Swiss project partners estimated from personal months dedicated to specific soil challenges. Project # refers to projects listed in Table 1, projects in brackets covered several soil challenges. *Importance according to stakeholders*: !!!: «important» or «rather important» for majority of stakeholders. !: «important» or «rather important» for several stakeholders. !-!!!: varying assessment by different stakeholders. —: 'unimportant' or 'rather unimportant' for majority of stakeholders. *Number of publications*: ###: > 300 publication. ##: 100–300 publications. #: < 10 publications. *Policy*: §: measures and/or reference values available. (§): fundamentals in place. No entry: no measures found. *Resource allocation*: €€€: > 50%. €€: 10%–50%. €: < 10%. No entry: not addressed.

reconciling current demands for housing and infrastructure with the long-term safeguarding of multifunctional soils for future generations (Aust et al. 2013).

5 | Conclusions

Switzerland's soils are under growing pressure from soil sealing, intensive land use and climate change. With only one-third of the country's surface suitable for agricultural use, safeguarding soil functions demands improved understanding of soil processes, coordinated monitoring, spatial planning and active stakeholder engagement. The Swiss contribution to the European Joint Programme (EJP) SOIL helped identify key challenges—climate-driven carbon loss, nutrient surpluses, contamination from organic amendments and declining soil biodiversity—while generating valuable insights through 18 research projects focused on soil carbon, structure, nutrient management and monitoring strategies.

Continuous attention to international soil-related development remains essential to benchmark national approaches against global standards. The recently adopted EU Soil Monitoring Law exemplifies this process. Future activities should continue to link scientific knowledge with policy and practice. Incentive systems that reward carbon-positive and biodiversity-friendly farming, preventive measures against soil compaction and rationalised soil assessments are key elements of sustainable soil management.

Author Contributions

Klaus A. Jarosch: conceptualization, investigation, writing – original draft, writing – review and editing, visualization, project administration. **Nicole Bütikofer:** conceptualization, investigation, writing – original draft, writing – review and editing, visualization. **Olivier Heller:** conceptualization, investigation, writing – original draft, writing – review and editing, visualization. **Juliane Hirte:** conceptualization, writing – original draft, writing – review and editing. **Luca Bragazza:** writing – review and editing, investigation. **Thomas D. Bucheli:** investigation, writing – original draft, writing – review and editing. **Nikolas Hagemann:** investigation, writing – original draft, writing – review and editing. **Isabel Hilber:** investigation, writing – review and editing. **Annelie Holzkämper:** investigation, writing – original draft, writing – review and editing. **Shiva Ghiasi:** investigation, data curation, writing – review and editing, visualization. **Sonja G. Keel:** investigation, writing – original draft, writing – review and editing. **Thomas Keller:** investigation, writing – original draft, writing – review and editing. **John Koestel:** investigation, writing – original draft, writing – review and editing. **Jens Leifeld:** investigation, writing – original draft, writing – review and editing. **Frank Liebisch:** investigation, writing – original draft, writing – review and editing. **Jochen Mayer:** investigation, writing – review and editing. **Muhammad Mehran Anjum:** investigation, writing – review and editing. **Konrad Metzger:** investigation, writing – review and editing. **Ferran Romero:** investigation, writing

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

– review and editing, writing – original draft. **Alejandro Romero-Ruiz:** investigation, writing – review and editing. **Gudrun Schwilch:** investigation, writing – review and editing. **Michael Simmler:** investigation, writing – review and editing. **Marcel van der Heijden:** investigation, writing – original draft, writing – review and editing. **Florian Walder:** investigation, writing – original draft, writing – review and editing. **Michael Zimmermann:** investigation, writing – review and editing. **Lutz Merbold:** investigation, writing – original draft, writing – review and editing, funding acquisition, project administration.

Acknowledgements

This work was developed in the framework of the European Joint Program on Agricultural Soil Management 'Towards climate-smart sustainable management of agricultural soils' (EJP SOIL) project (Grant agreement No. 862695) under the European Union's Horizon Programme. The authors want to thank all stakeholders involved in the Swiss National Hub and as well as those participating in the survey on Swiss National research needs. Special thanks go to Claire Chenu, Raisa Gerasina-Chaix, Saskia Visser, Anna Besse-Lototskaya and all other individuals and institutions that were critically involved in the development and performance of this project. F.R. acknowledges funding from the Novo Nordisk Foundation through grant number NNF24OC0094454 and the Swiss National Science Foundation through the Spark programme (CRSK-3_237492). We thank the three anonymous reviewers and the handling editors for the critical evaluation and their constructive feedback that helped to improve this manuscript. Open access publishing facilitated by Agroscope, as part of the Wiley - Agroscope agreement via the Consortium Of Swiss Academic Libraries.

Funding

This work was supported by the European Commission (862695); Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung (CRSK-3_237492); Novo Nordisk Fonden (NNF24OC0094454).

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Adamczyk, B., R. Stangl, P. Minixhofer, and E. Rodríguez. 2024. *EJP SOIL Call Text of the 1st Internal Call (2020)*. Zenodo. https://doi.org/10.5281/zenodo.11102920.

Agrarbericht. 2024a. "Nachweisliche Verminderung der Risiken Durch den Einsatz von Pflanzenschutzmitteln." https://www.agrarbericht.ch/de/produktion/produktionsmittel/aktionsplan-pflanzenschutzmittel?highlight=pflanzenschutzmittel.

Agrarbericht. 2024b. "Übersichtskarten Helfen Bodenverdichtungen Vermeiden." https://agrarbericht.ch/de/produktion/standortangepasste-produktion/bodenverdichtungskarte.

Agrarbericht. 2024c. "Selbstversorgungsgrad." https://www.agrarbericht.ch/de/markt/marktentwicklungen/selbstversorgungsgrad.

ARE. 2020. *Sectoral Plan Prime Cropland (FFF)*. Federal Office for Spatial Development.

Arrouays, D., P. Hinsinger, and S. Pellerin. 2022. "Research and Management Priorities for Mainland France Soils." *Geoderma Regional* 29: e00493.

Aust, G., A. Baumgartner, A. Freudenschuss, et al. 2013. *Bodenfunktionsbewertung: Methodische Umsetzung der ÖNORM L 1076. Gemeinsame Arbeitsgruppe Des Fachbeirats Für Bodenfruchtbarkeit und Bodenschutz Im Lebensministerium und des Österreichischen Normungsinstituts*. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (Hrsg.).

Bachmann, H., Jr., T. D. Bucheli, A. Dieguez-Alonso, et al. 2016. "Toward the Standardization of Biochar Analysis: The COST Action TD1107 Interlaboratory Comparison." *Journal of Agricultural and Food Chemistry* 64: 513–527.

Banerjee, S., F. Walder, L. Büchi, et al. 2019. "Agricultural Intensification Reduces Microbial Network Complexity and the Abundance of Keystone Taxa in Roots." *ISME Journal* 13: 1722–1736.

Barmettler, E., M. G. van der Heijden, A. Rösch, et al. 2025. "Double the Trouble: High Levels of Both Synthetic Pesticides and Copper in Vineyard Soils." *Environmental Pollution* 375: 126356.

Béguin, J., and S. Smola. 2010. *Stand der Drainagen in der Schweiz Bilanz der Umfrage 2008*. Bundesamt für Landwirtschaft BLW, Fachbereich Meliorationen.

Bigalke, M., A. Ulrich, A. Rehmus, and A. Keller. 2017. "Accumulation of Cadmium and Uranium in Arable Soils in Switzerland." *Environmental Pollution* 221: 85–93.

Binderheim, E. 2018. "Wie Steht Es Um Die Schweizer Kleinseen?" *Aqua & Gas* 6: 60–65.

Bircher, P., H. P. Liniger, and V. Prasuhn. 2019. *Aktualisierung und Optimierung der Erosionsrisikokarte (ERK2): Die Neue ERK2 (2019) Für Das Ackerland der Schweiz: Schlussbericht*, 61. Agroscope.

Blanchy, G., L. Albrecht, G. Bragato, S. Garré, N. Jarvis, and J. Koestel. 2023. "Impacts of Soil Management and Climate on Saturated and Near-Saturated Hydraulic Conductivity: Analyses of the Open Tension-Disk Infiltrometer Meta-Database (OTIM)." *Hydrology and Earth System Sciences* 27: 2703–2724.

Blanchy, G., L. Albrecht, J. Koestel, and S. Garré. 2023. "Potential of Natural Language Processing for Metadata Extraction From Environmental Scientific Publications." *Soil* 9: 155–168.

Blanchy, G., G. Bragato, C. Di Bene, et al. 2023. "Soil and Crop Management Practices and the Water Regulation Functions of Soils: A Qualitative Synthesis of Meta-Analyses Relevant to European Agriculture." *Soil* 9: 1–20.

Blanchy, G., T. d'Hose, C. Donmez, et al. 2024. "An Open-Source Metadataset of Running European Mid- and Long-Term Agricultural Field Experiments." *Soil Use and Management* 40: e12978.

Bonfante, A., F. Terribile, and J. Bouma. 2019. "Refining Physical Aspects of Soil Quality and Soil Health When Exploring the Effects of Soil Degradation and Climate Change on Biomass Production: An Italian Case Study." *Soil* 5: 1–14.

Borchard, N., J. Leppälä, M. Kujala, et al. 2024. *EJP SOIL List of Selected Proposals of 2nd Internal Call (1.1)*. Zenodo. https://doi.org/10.5281/Zenodo.11103268.

Borchard, N., E. Rodríguez, V. Carrasco, P. Minixhofer, and R. Stangl. 2024. *EJP SOIL List of Selected Proposals of 1st Internal Call (1.0)*. Zenodo. https://doi.org/10.5281/Zenodo.11103758.

Brändli, R. C., T. D. Bucheli, T. Kupper, et al. 2007. "Organic Pollutants in Compost and Digestate. Part 1. Polychlorinated Biphenyls, Polycyclic Aromatic Hydrocarbons and Molecular Markers." *Journal of Environmental Monitoring* 9: 456–464.

Braun, M., M. Mail, R. Heyse, and W. Amelung. 2021. "Plastic in Compost: Prevalence and Potential Input Into Agricultural and Horticultural Soils." *Science of the Total Environment* 760: 143335.

Bucheli, T. D., E. Barmettler, N. Bartolomé, et al. 2023. "Pesticides in Agricultural Soils: Major Findings From Various Monitoring Campaigns in Switzerland." *Chimia* 77: 750–757.

Bütikofer, N., M. Hacek, O. Heller, H. Leonhardt, and A. Holzkämper. 2024. "Ansichten von Schweizer Landwirtinnen und Landwirten Zum Thema Bodenbearbeitung." *Agrarforschung Schweiz* 15: 279–287.

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Campiche, S. 2025. "Soil Biodiversity in Switzerland, Synthesis Report."

Carlen, C., R. Flisch, C. Gilli, et al. 2017. "Principles of Fertilization of Agricultural Crops in Switzerland."

Castaldi, F., B. Stenberg, F. Liebisch, et al. 2025. "Estimating Soil Organic Carbon Using Field VNIR-SWIR Spectroscopy and Existing Soil Spectral Libraries: Mitigating Heterogeneity, Roughness and Moisture Effects." *Smart Agricultural Technology* 12: 101353.

Ceriani, R., J. Fohrafellner, P. Maenhout, et al. 2026. "Cereal Yield, Yield Stability, and Nitrous Oxide Release in European Conservation Agriculture: A Meta-Analysis." *Field Crops Research* 341: 110386.

Charles, R., M. Wendling, and S. Burgos. 2018. *Boden und Nahrungsmittelproduktion: Thematische Synthese TS1 Des Nationalen Forschungsprogramms "Nachhaltige Nutzung der Ressource Boden" (NFP 68)*. Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung.

Coban, O., G. B. De Deyn, and M. van der Ploeg. 2022. "Soil Microbiota as Game-Changers in Restoration of Degraded Lands." *Science* 375: abe0725.

Colombi, T., and T. Keller. 2019. "Developing Strategies to Recover Crop Productivity After Soil Compaction—A Plant Eco-Physiological Perspective." *Soil and Tillage Research* 191: 156–161.

Contaminated Sites Ordinance. 2025. *Contaminate Sites Ordinance (CSO). 1998, SR814.680-Ordinance of 26 August 1998 on the Remediation of Polluted Sites, Fedlex*. Swiss Federal Council.

Conte, P. 2018. "Environmental Applications of Fast Field-Cycling NMR Relaxometry." In *Field-Cycling NMR Relaxometry: Instrumentation, Model Theories and Applications*, edited by R. Kimmich. Royal Society of Chemistry.

Corradini, F., P. Meza, R. Eguiluz, F. Casado, E. Huerta-Lwanga, and V. Geissen. 2019. "Evidence of Microplastic Accumulation in Agricultural Soils From Sewage Sludge Disposal." *Science of the Total Environment* 671: 411–420.

Darusman, T., D. Murdiyarso, Impron, and I. Anas. 2023. "Effect of Rewetting Degraded Peatlands on Carbon Fluxes: A Meta-Analysis." *Mitigation and Adaptation Strategies for Global Change* 28: 10.

Desaules, A. 1993. "Soil Monitoring in Switzerland by the NABO-Network: Objectives, Experiences and Problems." In *Soil Monitoring: Early Detection and Surveying of Soil Contamination and Degradation*, 7–24. Springer.

Drobnik, T., L. Greiner, A. Keller, and A. Grêt-Regamey. 2018. "Soil Quality Indicators—From Soil Functions to Ecosystem Services." *Ecological Indicators* 94: 151–169.

Drobnik, T., J. Schwaab, and A. Grêt-Regamey. 2020. "Moving Towards Integrating Soil Into Spatial Planning: No Net Loss of Soil-Based Ecosystem Services." *Journal of Environmental Management* 263: 110406.

Durand-Maniclas, F., H. Heinemann, F. Seidel, et al. 2025. "Linking Root Length and Surface Area to Yield: Variety-Specific Root Plasticity in Winter Wheat Across Contrasting European Environments." *Annals of Botany* 136: mcaf155.

EC. 2020. "A Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System."

Eisenhauer, N., M. Sünnemann, M. M. Pollierer, et al. 2026. "Soil Biodiversity Effects on Ecosystems." *Nature Reviews Biodiversity* 2: 1–16.

Eurofins Umwelt-Ost. 2023. *Conductivity Meter Black Gauss I*. Zenodo.

European Commission. 2023. "Impact Assessment Accompanying the Proposal for a Directive on Soil Monitoring and Resilience [COM(2023) 416 final]." Publications Office of the European Union.

EUSR5000. 2005. "Soil Regions of the European Union and Adjacent Countries 1:5,000,000."

FDFA. 2023. "Geography—Facts and Figures."

Feeney, C. J., D. A. Robinson, A. M. Keith, et al. 2023. "Development of Soil Health Benchmarks for Managed and Semi-Natural Landscapes." *Science of the Total Environment* 886: 163973.

Ferré, M., A. Muller, J. Leifeld, et al. 2019. "Sustainable Management of Cultivated Peatlands in Switzerland: Insights, Challenges, and Opportunities." *Land Use Policy* 87: 104019.

FOEN. 2017. *Boden in der Schweiz. Zustand und Entwicklung. Stand 2017. Umwelt-Zustand Nr. 1721: 86 S*. Bundesamt für Umwelt.

FOEN. 2019. *BAFU (Hrsg.), Zustand und Entwicklung Grundwasser Schweiz. Ergebnisse der Nationalen Grundwasserbeobachtung NAQUA, Stand 2016*. BAFU, Bundesamt für Umwelt.

FOEN. 2020a. *Bedürfnisse der Kantone und Des Bundes Rund Um Ein Monitoring der Ressource Boden, Erfassung und Beurteilung von Risiko, Zustand und Zeitlicher Entwicklung Durch Flächenhafte Erhebungen (Kartierung) und Langfristige Beobachtung*. Bundesamt für Umwelt (BAFU), Abteilung Boden und Biotechnologie.

FOEN. 2020b. "Swiss National Soil Strategy for Sustainable Soil Management." In *Environmental Info*. Swiss Federal Council.

FOEN. 2022. "Sachgerechter Umgang Mit Boden Beim Bauen." Bodenschutzmassnahmen Auf Baustellen. Ein Modul der Vollzugshilfe Bodenschutz Beim Bauen. Umwelt-Vollzug Nr. 2112: 36 S.

FOEN. 2023. "Pflanzenkohle in der Schweizer Landwirtschaft Risiken und Chancen Für Boden und Klima." Fact Sheet.

FOEN. 2024. *Terrainveränderungen Zum Zweck der Bodenaufwertung Aufwertung von Ökologischen Bodenfunktionen. Ein Modul der Vollzugshilfe «Bodenschutz Beim Bauen»*. Herausgegeben vom Bundesamt für Umwelt BAFU.

FOEN. 2025a. "Climate Risk Analysis for Switzerland."

FOEN. 2025b. "Kenngrössen Zur Entwicklung der Treibhausgasemissionen in der Schweiz 1990-2023."

FOEN. 2025c. *Verordnung Über Die Reduktion der CO_2-Emissionen (CO_2-Verordnung)*. Der Schweizerische Bundesrat.

FOEN, and FOAG. 2013. *Bodenschutz in der Landwirtschaft. Ein Modul der Vollzugshilfe Umweltschutz in der Landwirtschaft. Umwelt-Vollzug Nr. 1313: 59 S*. Bundesamt für Umwelt.

Fondón, C. L., M. Fantappiè, R. Barbetti, et al. 2024. "A Fieldwork Protocol and Procedures for Cost-Benefit Estimation for Using Proximal Soil Sensing Methods."

Frei, E., U. Vögt, R. Flückiger, H. Brunner, F. Schai, and R. Häberli. 1980. *Bodeneignungskarte der Schweiz (Massstab 1: 200'000), Grundlagen Für Die Raumplanung*, edited by Eidg. Forschungsanstalt für landwirtschaftlichen Pflanzenbau und Eidgenössische Forschungsanstalt WSL. Eidg. Drucksachen-und Materialzentrale.

Froger, C., E. Tondini, D. Arrouays, et al. 2024. "Comparing LUCAS Soil and National Systems: Towards a Harmonized European Soil Monitoring Network." *Geoderma* 449: 117027.

FSKB. 2021. *FSKB—Rekultivierungsrichtlinie. Richtlinie Für Den Sachgerechten Umgang Mit Boden*. FSKB Fachverband der Schweizerischen Kies- und Betonindustrie.

FSO. 2000. *Bodeneignungskarte der Schweiz*. Geodaten.

FSO. 2021a. *Biogeographic Regions of Switzerland and Their Surface Area*. Federal Statistical Office.

FSO. 2021b. *Land Use in Switzerland. Results of the Swiss Land Use Statistics 2018*. Federal Statistical Office FSO.

FSO. 2024. "Arealstatistik der Schweiz—Erhebung der Bodennutzung und der Bodenbedeckung."

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

FSO. 2026. *Current Situation and Change, Sex, Age, Civil Status, Population Change, Spatial Distribution*. Federal Statistical Office.

Garré, S., G. Blanchy, N. Jarvis, et al. 2022. *Climasoma: Climate Change Adaptation Through Soil and Crop Management: Synthesis and Ways Forward: Deliverable WP5. D1: CLIMASOMA Final Report*. Institute for Agricultural and Fisheries Research (ILVO).

Greiner, L., A. Keller, A. Grêt-Regamey, and A. Papritz. 2017. "Soil Function Assessment: Review of Methods for Quantifying the Contributions of Soils to Ecosystem Services." *Land Use Policy* 69: 224–237.

Gschwend, F., M. Hartmann, A. S. Hug, et al. 2021. "Long-Term Stability of Soil Bacterial and Fungal Community Structures Revealed in Their Abundant and Rare Fractions." *Molecular Ecology* 30: 4305–4320.

Gschwend, F., M. Hartmann, J. Mayerhofer, et al. 2021. "Site and Land-Use Associations of Soil Bacteria and Fungi Define Core and Indicative Taxa." *FEMS Microbiology Ecology* 97: fiab165.

Gubler, A., P. Schwab, D. Wächter, R. G. Meuli, and A. Keller. 2015. *Ergebnisse der Nationalen Bodenbeobachtung (NABO) 1985-2009: Zustand und Veränderungen der Anorganischen Schadstoffe und Bodenbegleitparameter*. Bundesamt für Umwelt BAFU.

Gubler, A., D. Wächter, P. Schwab, M. Müller, and A. Keller. 2019. "Twenty-Five Years of Observations of Soil Organic Carbon in Swiss Croplands Showing Stability Overall but With Some Divergent Trends." *Environmental Monitoring and Assessment* 191: 277.

Hagedorn, F., H.-M. Krause, M. Studer, A. Schellenberger, and A. Gattinger. 2018. *Boden und Umwelt: Organische Bodensubstanz, Treibhausgasemissionen und Physikalische Belastung von Schweizer Böden: Thematische Synthese TS2 Des Nationalen Forschungsprogramms "Nachhaltige Nutzung der Ressource Boden" (NFP 68)*. Schweizer Nationalfonds.

Hagemann, N. 2025. "Zulassung von Pflanzenkohle in der Schweiz." *Ithaka-Journal*: 450–454. https://doi.org/10.5281/zenodo.15387328.

Hagemann, N., H.-P. Schmidt, T. D. Bucheli, et al. 2025. "Proxies for Use in Biochar Decay Models: Hydropyrolysis, Electric Conductivity, and H/C Org Molar Ratio." *PLoS One* 20: e0330206.

Harder, R., and F. Liebisch. 2025. "Exploring the Strategic Potential for Switzerland to Reduce Nitrogen and Phosphorus Surplus in Agriculture." *Resources, Conservation and Recycling* 218: 108239.

Hardy, B., N. Borchard, and J. Leifeld. 2022. "Identification of Thermal Signature and Quantification of Charcoal in Soil Using Differential Scanning Calorimetry and Benzene Polycarboxylic Acid (BPCA) Markers." *Soil* 8: 451–466.

Heinemann, H., F. Durand-Maniclas, F. Seidel, et al. 2025. "Optimising Root and Grain Yield Through Variety Selection in Winter Wheat Across a European Climate Gradient." *European Journal of Soil Science* 76: e70077.

Heinz, M., M. E. Turek, B. Schaefli, A. Keiser, and A. Holzkämper. 2025. "Can Adaptations of Crop and Soil Management Prevent Yield Losses During Water Scarcity? A Modeling Study." *Hydrology and Earth System Sciences* 29: 1807–1827.

Heinze, W. M., Z. Steinmetz, N. D. R. Klemmensen, J. Vollertsen, and G. Cornelis. 2024. "Vertical Distribution of Microplastics in an Agricultural Soil After Long-Term Treatment With Sewage Sludge and Mineral Fertiliser." *Environmental Pollution* 356: 124343.

Heller, O., C. D. Bene, P. Nino, et al. 2024. "Towards Enhanced Adoption of Soil-Improving Management Practices in Europe." *European Journal of Soil Science* 75: e13483.

Heller, O., N. Peter, G. Garland, and P. Weisskopf. 2021. "Switzerland's EJP SOIL Stocktake: Tasks 2.1, 2.2 and 2.3." *Agroscope Science* 117: 1–31. https://doi.org/10.34776/as117e.

Herrmann, A. M., G. Miaris, A. Gonzalez-Martinez, G. Mack, and U. Djanibekov. 2025. *EJP SOIL SIMPLE: Deliverable 2.1: Impact of Fertiliser Use Reduction: The Case of the European Union*. Zenodo.

Herzog, F., G. Lüscher, M. Arndorfer, et al. 2017. "European Farm Scale Habitat Descriptors for the Evaluation of Biodiversity." *Ecological Indicators* 77: 205–217.

Higgins, S., S. D. Keesstra, Ž. Kadziuliene, et al. 2023. "Stocktake Study of Current Fertilisation Recommendations Across Europe and Discussion Towards a More Harmonised Approach." *European Journal of Soil Science* 74: e13422.

Hitzfeld, B., N. Rodríguez Eugenio, and A. H. Wissemeier. 2024. "Soil Health—From Practical Issues to Indicators: A Workshop at the 1st European Healthy Soils Conference." *European Journal of Soil Science* 75: e13504.

Hollis, J., A. Lilly, P. Bellamy, M. Kibblewhite, K. Ritz, and R. Corstanje. 2025. "Response to the Paper 'The Development of Soil Health Benchmarks for Managed and Semi Natural Landscapes' by Feeney et al. 2023." *Science of the Total Environment* 965: 178619.

Holzkämper, A., L. ten Damme, T. D'Hose, et al. 2024. *EJPSOIL-SoilX: Final Project Report*. Zenodo.

Horn, R., H. Domżżał, A. Słowińska-Jurkiewicz, and C. Van Ouwerkerk. 1995. "Soil Compaction Processes and Their Effects on the Structure of Arable Soils and the Environment." *Soil and Tillage Research* 35: 23–36.

Huber, S., F. Baumann, and C. Gilli. 2022. *Treibhausgase Aus der Bündner Landwirtschaft, Resultate und Erkenntnisse Aus der Klimabilanzierung von 52 Pilotbetrieben*. Klimaneutrale Landwirtschaft Graubünden.

Hutchings, C., E. Spiess, and V. Prasuhn. 2023. "Abschätzung Diffuser Stickstoff- und Phosphoreinträge in Die Gewässer der Schweiz Mit MODIFFUS 3.1, Stand 2020." *Agroscope Science* 155: 161.

Johannes, A., L. A. Kellermann, and P. Weisskopf. 2023. "Weiterentwicklung der Spatenproben-Methoden BodenDok, VESS2020 und SpadeSubVESS in der Schweiz." *Agrarforschung Schweiz* 14: 197–206.

Jordan-Meille, L., P. Denoroy, K. Dittert, et al. 2023. "Comparison of Nitrogen Fertilisation Recommendations of West European Countries." *European Journal of Soil Science* 74: e13436.

Kalberer, A., D. Kawecki-Wenger, and T. D. Bucheli. 2019. "Plastikströme in der Schweizer Landwirtschaft und Ihr Risikopotenzial Für Böden." *Agrarforschung Schweiz* 10: 416–423.

Kallenbach, C., and A. S. Grandy. 2011. "Controls Over Soil Microbial Biomass Responses to Carbon Amendments in Agricultural Systems: A Meta-Analysis." *Agriculture, Ecosystems & Environment* 144: 241–252.

Keel, S. G., A. Budai, L. Elsgaard, et al. 2025. "Efficiency of Plant Biomass Processing Pathways for Long-Term Soil Carbon Storage." *European Journal of Soil Science* 76: e70074.

Keesstra, S., C. Chenu, L. Munkholm, et al. 2024. "European Agricultural Soil Management: Towards Climate-Smart and Sustainability, Knowledge Needs and Research Approaches." *European Journal of Soil Science* 75: e13437.

Keesstra, S., L. Munkholm, S. Cornu, et al. 2021. "Towards Climate-Smart Sustainable Management of Agricultural Soils: Deliverable 2.4 Roadmap for the European Joint Programme SOIL."

Keesstra, S. D., S. Cornu, L. J. Munkholm, et al. 2025. "Towards Climate-Smart Sustainable Management of Agricultural Soils, Deliverable 2.11, Provisional Strategic Research Agenda (2025–2035) for Agricultural Soil Research in Europe."

Keiluweit, M., P. S. Nico, M. G. Johnson, and M. Kleber. 2010. "Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)." *Environmental Science & Technology* 44: 1247–1253.

Kittinger, M., A. Spiegel, T. Sandén, O. Heller, and F. Vanwindekens. 2025. "Fostering Sustainable Soil Management Practices Across Europe." EJP SOIL Policy Brief.

Köninger, J., M. Labouyrie, C. Ballabio, et al. 2026. "Pesticide Residues Alter Taxonomic and Functional Biodiversity in Soils." *Nature* 650: 1–7.

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Kuhwald, M., K. Dörnhöfer, N. Oppelt, and R. Duttmann. 2018. "Spatially Explicit Soil Compaction Risk Assessment of Arable Soils at Regional Scale: The SaSCiA-Model." *Sustainability* 10: 1618.

Labouyrie, M., C. Ballabio, F. Romero, et al. 2023. "Patterns in Soil Microbial Diversity Across Europe." *Nature Communications* 14: 3311.

Lång, K., H. Honkanen, J. Heikkinen, S. Saarnio, T. Larmola, and H. Kekkonen. 2024. "Impact of Crop Type on the Greenhouse Gas (GHG) Emissions of a Rewetted Cultivated Peatland." *Soil* 10: 827–841.

Larooche, L., C. Hachem-Majdalani, A. Besse-Lototskaya, R. Gerasina, and C. Chenu. 2025. "Towards Climate-Smart Sustainable Management of Agricultural Soil: Outputs of the European Co-Fund Research Programme EJP SOIL."

Lehmann, A., K. Allenbach, R. Maggini, J.-P. Richard, J. Jacquet, and H. Dao. 2010. *Swiss Environmental Domains: A New Spatial Framework for Reporting on the Environment*. Environment. Federal Office for the Environment FOEN, Environmental Studies.

Leppälä, J., M. Kujala, M. Kytö, et al. 2024. *EJP SOIL List of Selected Proposals of 3rd Internal Call (1.0)*. Zenodo. https://doi.org/10.5281/Zenodo.11102048.

Leuthard, J., S. Tobias, and N. Backhaus. 2016. *Kulturlandschutz in der Schweiz: Eine Qualitative Untersuchung der Politischen Steuerungsinstrumente*. Geographisches Institut der Universität Zürich.

Lötscher, J. 2024. *Swiss Farmers' Views on Cover Crop Practice and Climate Change*. Zenodo.

Lotz, S., T. D. Bucheli, H.-P. Schmidt, and N. Hagemann. 2024. "Quantification of Soil Organic Carbon: The Challenge of Biochar-Induced Spatial Heterogeneity." *Frontiers in Climate* 6: 1344524.

Marín, C., C. Barreto, B. K. Singh, et al. 2025. "Open Letter: A Global Call to Strengthen National Soil Biodiversity Action Through Coordination and Harmonization." *Plants, People, Planet* 8: 8–13. https://doi.org/10.1002/ppp3.70121.

Martin, E. A., M. Dainese, Y. Clough, et al. 2019. "The Interplay of Landscape Composition and Configuration: New Pathways to Manage Functional Biodiversity and Agroecosystem Services Across Europe." *Ecology Letters* 22: 1083–1094.

Mason, E., S. Cornu, D. Arrouays, et al. 2025. "Monitoring Systems of Agricultural Soils Across Europe Regarding the Upcoming European Soil Monitoring Law." *European Journal of Soil Science* 76: e70163.

MeteoSwiss. n.d. "The Climate of Switzerland." https://www.meteoswiss.admin.ch/climate/the-climate-of-switzerland.html.

Meteotest, and B. Kantonale Fachstellen. 2025. *Bodenmessnetz Nordwestschweiz*. Meteotest AG. https://www.bodenmessnetz.ch.

Metzger, K., F. Liebisch, J. M. Herrera, T. Guillaume, and L. Bragazza. 2024. "Prediction Accuracy of Soil Chemical Parameters by Field- and Laboratory-Obtained Vis-NIR Spectra After External Parameter Orthogonalization." *Sensors* 24: 3556.

Metzger, K., F. Liebisch, J. M. Herrera, T. Guillaume, F. Walder, and L. Bragazza. 2024. "The Use of Visible and Near-Infrared Spectroscopy for In-Situ Characterization of Agricultural Soil Fertility: A Proposition of Best Practice by Comparing Scanning Positions and Spectrometers." *Soil Use and Management* 40: e12952.

Metzger, M. J., R. G. H. Bunce, R. H. Jongman, C. A. Mücher, and J. W. Watkins. 2005. "A Climatic Stratification of the Environment of Europe." *Global Ecology and Biogeography* 14: 549–563.

Moll-Mielewczik, J., S. G. Keel, and A. Gubler. 2023. "Organic Carbon Contents of Mineral Grassland Soils in Switzerland Over the Last 30 Years." *Agriculture, Ecosystems & Environment* 342: 108258.

Nielsen, C. K., W. Liu, M. Koppelgaard, and P. E. Laerke. 2024. "To Harvest or Not to Harvest: Management Intensity Did Not Affect Greenhouse Gas Balances of Phalaris Arundinacea Paludiculture." *Wetlands* 44: 79.

Oberholzer, H. R., P. Weisskopf, and J. Meier. 2025. "Humusbilanz Agroscope."

Oberholzer, S., C. Herrmann, N. Bodenhausen, et al. 2024. "No Effect on Biological or Chemical Soil Properties When Amended With Effective Microorganisms for Improved Cover Crop Decomposition." *Applied Soil Ecology* 197: 105358.

Oberholzer, S., K. A. Jarosch, N. Harder, M. Steffens, and C. I. Speranza. 2024. "Cover Cropping in Organic Reduced Tillage Systems: Maximizing Soil Cover or Plant Above Ground Biomass Input?" *European Journal of Soil Science* 75: e70012.

Oberson, A., K. A. Jarosch, E. Frossard, et al. 2024. "Higher Than Expected: Nitrogen Flows, Budgets, and Use Efficiencies Over 35 Years of Organic and Conventional Cropping." *Agriculture, Ecosystems & Environment* 362: 108802.

Oliveira, E., J. Leuthard, and S. Tobias. 2019. "Spatial Planning Instruments for Cropland Protection in Western European Countries." *Land Use Policy* 87: 104031.

Panagos, P., L. Montanarella, M. Barbero, A. Schneegans, L. Aguglia, and A. Jones. 2022. "Soil Priorities in the European Union." *Geoderma Regional* 29: e00510.

Paul, S., C. Ammann, Y. Wang, C. Alewell, and J. Leifeld. 2024. "Can Mineral Soil Coverage Be a Suitable Option to Mitigate Greenhouse Gas Emissions From Agriculturally Managed Peatlands? Agriculture." *Ecosystems & Environment* 375: 109197.

Paz, A. M., N. Castanheira, J. Miloczki, et al. 2024. "Collected Knowledge on the Impacts of Agricultural Soil Management Practices in Europe." *European Journal of Soil Science* 75: e13468.

Peng, Z., X. Qian, Y. Liu, et al. 2024. "Land Conversion to Agriculture Induces Taxonomic Homogenization of Soil Microbial Communities Globally." *Nature Communications* 15: 3624.

Peyer, K. 1988. "Potentielle Verdichtungsgefährdung Schweizer Ackerböden." Nationales Forschungsprogramm "Nutzung der Schweizer Böden", Map, 1000.

Piccini, C., K. Metzger, G. Debaene, et al. 2024. "In-Field Soil Spectroscopy in Vis–NIR Range for Fast and Reliable Soil Analysis: A Review." *European Journal of Soil Science* 75: e13481.

Prasuhn, V. 2012. "On-Farm Effects of Tillage and Crops on Soil Erosion Measured Over 10 Years in Switzerland." *Soil and Tillage Research* 120: 137–146.

Prasuhn, V. 2020. "Twenty Years of Soil Erosion on-Farm Measurement: Annual Variation, Spatial Distribution and the Impact of Conservation Programmes for Soil Loss Rates in Switzerland." *Earth Surface Processes and Landforms* 45: 1539–1554.

Prasuhn, V., T. Lemann, G. Schwilch, et al. 2017. "Der Einfluss von Lochstern und Querdammhäufler Auf Erosion und Staunässe Im Kartoffelanbau." *BGS Bulletin* 38: 27–37.

Pulido-Moncada, M., T. F. Stone, J. L. Bach, et al. 2025. "Stakeholders' Perspectives on the Current State and Transition to Sustainable Soil Management Across Europe." *European Journal of Soil Science* 76: e70214.

Rathnayake, D., H.-P. Schmidt, J. Leifeld, D. Bürge, T. D. Bucheli, and N. Hagemann. 2024. "Quantifying Soil Organic Carbon After Biochar Application: How to Avoid (The Risk of) Counting CDR Twice?" *Frontiers in Climate* 6: 1343516.

Rees, C., L. Ineichen, R. Finger, and C. Grovermann. 2025. "Data Covering Soil Management Practices and Farm Characteristics on Swiss Arable Farms." *Scientific Data* 12: 1471.

Rehbein, K., C. Sprecher, and A. Keller. 2019. *Übersicht Stand BodenkartierunginderSchweiz–ErgänzungDesBodenkartierungskataloges Schweiz Um Bodeninformationen Aus Meliorationsprojekten*. Agroscope, Servicestelle NABODAT, Zürich.

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Renwick, L. L., W. Deen, L. Silva, et al. 2021. "Long-Term Crop Rotation Diversification Enhances Maize Drought Resistance Through Soil Organic Matter." *Environmental Research Letters* 16: 084067.

Reusser, J., M. Siegenthaler, L. H. Winkel, D. Wächter, R. Kretzschmar, and R. G. Meuli. 2023. "Geochemical Soil Atlas of Switzerland-Distribution of Toxic Elements." *Chimia* 77: 758–763.

Reyes-Rojas, J., D. Montagne, N. P. Saby, et al. 2025. "Review of Soil Threats and Soil-Related Ecosystem Services European Maps: Can we Use Them to Study Their Relationships?" *European Journal of Soil Science* 76: e70215.

Riedo, J., D. Wächter, A. Gubler, F. E. Wettstein, R. G. Meuli, and T. D. Bucheli. 2023. "Pesticide Residues in Agricultural Soils in Light of Their On-Farm Application History." *Environmental Pollution* 331: 121892.

Riggi, L., G. Pérès, C. Aponte, et al. 2025. "Establishing Assessment Criteria for Soil Bioindicators: Insights From Case Studies in Europe." *Ecological Indicators* 178: 114063.

Ritzel, C., A. Möhring, and A. von Ow. 2024. "Vulnerability Assessment of Food Imports—Conceptual Framework and Empirical Application to the Case of Switzerland." *Heliyon* 10: e27058.

Rodrigues, L., A. Budai, L. Elsgaard, et al. 2023. "The Importance of Biochar Quality and Pyrolysis Yield for Soil Carbon Sequestration in Practice." *European Journal of Soil Science* 74: e13396.

Rodrigues, L., B. Hardy, B. Huyghebeart, et al. 2021. "Achievable Agricultural Soil Carbon Sequestration Across Europe From Country-Specific Estimates." *Global Change Biology* 27: 6363–6380.

Roe, S., C. Streck, M. Obersteiner, et al. 2019. "Contribution of the Land Sector to a 1.5 C World." *Nature Climate Change* 9: 817–828.

Rombola, A. G., D. Fabbri, W. Meredith, C. E. Snape, and A. Dieguez-Alonso. 2016. "Molecular Characterization of the Thermally Labile Fraction of Biochar by Hydropyrolysis and Pyrolysis-GC/MS." *Journal of Analytical and Applied Pyrolysis* 121: 230–239.

Romero, F., M. Labouyrie, A. Orgiazzi, et al. 2024. "Soil Health Is Associated With Higher Primary Productivity Across Europe." *Nature Ecology & Evolution* 8: 1847–1855.

Romero, F., M. Labouyrie, A. Orgiazzi, et al. 2025. "The Soil Microbiome as an Indicator of Ecosystem Multifunctionality in European Soils." *Nature Communications* 17: 705.

Romero-Ruiz, A., A. Chargas Torres, M. Lamandé, M. Kuhwald, and T. Keller. 2026. "Modelling Long-Term Effects of Soil Compaction on Crop Yield, Soil Organic Carbon Stocks and Nitrogen Losses From Soil." *European Journal of Soil Science* 77: e70314. https://doi.org/10.1111/ejss.70314.

Rösch, A., F. E. Wettstein, D. Wächter, V. Reininger, R. G. Meuli, and T. D. Bucheli. 2023. "A Multi-Residue Method for Trace Analysis of Pesticides in Soils With Special Emphasis on Rigorous Quality Control." *Analytical and Bioanalytical Chemistry* 415: 6009–6025.

Ruysschaert, G., I. Panagea, G. Blanchy, et al. 2023. "EJPSOIL CarboSeq Crop and Soil Management Database."

Säle, V., P. Aguilera, E. Laczko, et al. 2015. "Impact of Conservation Tillage and Organic Farming on the Diversity of Arbuscular Mycorrhizal Fungi." *Soil Biology and Biochemistry* 84: 38–52.

Sanderman, J., T. Hengl, and G. J. Fiske. 2017. "Soil Carbon Debt of 12,000 Years of Human Land Use." *Proceedings of the National Academy of Sciences* 114: 9575–9580.

Sanei, H., A. Rudra, Z. M. M. Przyswitt, et al. 2024. "Assessing Biochar's Permanence: An Inertinite Benchmark." *International Journal of Coal Geology* 281: 104409.

Scherrer, S. C., E. M. Fischer, R. Posselt, M. A. Liniger, M. Croci-Maspoli, and R. Knutti. 2016. "Emerging Trends in Heavy Precipitation and Hot Temperature Extremes in Switzerland." *Journal of Geophysical Research: Atmospheres* 121: 2626–2637.

Schievano, A., S. Bosco, J.-M. Terres, et al. 2025. "The JRC Farming Practices Evidence Library."

Schils, R., P. Kuikman, J. Liski, et al. 2008. "Review of Existing Information on the Interrelations Between Soil and Climate Change."

Schjønning, P., M. Stettler, T. Keller, P. Lassen, and M. Lamandé. 2015. "Predicted Tyre–Soil Interface Area and Vertical Stress Distribution Based on Loading Characteristics." *Soil and Tillage Research* 152: 52–66.

Schmidt, S., C. Alewell, and K. Meusburger. 2019. "Monthly RUSLE Soil Erosion Risk of Swiss Grasslands." *Journal of Maps* 15: 247–256.

Schmutz, D., D. Utinger, and R. Bono. 2018. "Bodenbelastungen Natürlichen Ursprungs, Umgang Mit Geogen Vorliegenden Schadstoffen in Baselbieter Böden." *Regio BASILIENSIS* 59: 129–138.

Schneider, F., P. Fry, T. Ledermann, and S. Rist. 2009. "Social Learning Processes in Swiss Soil Protection—The 'From Farmer-to Farmer' Project." *Human Ecology* 37: 475–489.

Schulin, R., A. Keller, and M. Evangelou. 2018. "Treatment and Management of Contaminated Soils in Switzerland." In *SMSER Conference Sustainable Management of Soil and Environment Resources*, 1–7. University of Kerman – National Iranian Copper Industries Co.

Skadell, L. E., U. Dettmann, G. Guggenberger, and A. Don. 2025. "Effects of Agricultural Management on Water Retention via Changes in Organic Carbon in Topsoil and Subsoil." *Journal of Plant Nutrition and Soil Science* 188: 949–963.

Spiess, E., and F. Liebisch. 2024. "Nährstoffbilanz der Schweizerischen Landwirtschaft für die Jahre 1975 Bis 2022." *Agroscope Science* 198: 1–29.

Sprafke, T., S. Tanner, S. Oechslin, et al. 2025. *Bodenlandschaften Im Kanton Bern*. Geographischen Instituts der Universität Bern.

Stangl, R., A. Briefer, E. Rodríguez-Valín, V. Carrasco, and M. Kujala. 2024. *EJP SOIL Call Text of the 3rd Internal Call (1.0)*. Zenodo. https://doi.org/10.5281/Zenodo.11102613.

Stangl, R., P. Minixhofer, E. Rodríguez-Valín, V. Carrasco, and E. Karjalainen. 2024. *EJP SOIL Call Text of the 2nd Internal Call (1.0)*. Zenodo. https://doi.org/10.5281/Zenodo.11091560.

Steiger, U., P. Knüsel, and L. Rey. 2018. *Die Ressource Boden Nachhaltig Nutzen. Gesamtsynthese Des Nationalen Forschungsprogramms «Nachhaltige Nutzung der Ressource Boden» (nfp 68)*. Hrsg.: Leitungsgruppe des nfp 68.

Stenberg, B., T. Koganti, F. Castaldi, et al. 2024. "Best Practice Protocol for Field Spectroscopy and Assessment by Soil Spectral Library Based Calibrations: Deliverable D5.1."

Stettler, M., T. Keller, P. Weisskopf, M. Lamandé, P. Lassen, and P. Schjønning. 2014. "Terranimo—A Web-Based Tool for Evaluating Soil Compaction." *Landtechnik* 69: 132–137.

Stumpf, F., T. Behrens, K. Schmidt, and A. Keller. 2026. *Hinweiskarten: Bodenkohlenstoffvorrat – Räumlich-Zeitliche Modellierung Des Bodenkohlenstoffvorrats der Schweiz in Drei Tiefenstufen Seit 1985*. Vol. 13. KOBO-Bericht.

The Swiss Federal Assembly. 2010. "Plan D'abandon De La Tourbe."

Thorsøe, M. H., E. Facq, I. Criscuoli, et al. 2025. "Carbon Farming: The Foundation for Carbon Farming Schemes–Lessons Learned From 160 European Schemes [Agriculture Carbone: Les Fondements Des Programmes D'agriculture Carbone–Enseignements Tirés De 160 Programmes Européens]."

Thorsøe, M. H., S. Keesstra, M. De Boever, et al. 2023. "Sustainable Soil Management: Soil Knowledge Use and Gaps in Europe." *European Journal of Soil Science* 74: e13439.

Tiemeyer, B., A. Freibauer, E. A. Borraz, et al. 2020. "A New Methodology for Organic Soils in National Greenhouse Gas Inventories:

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Data Synthesis, Derivation and Application." *Ecological Indicators* 109: 105838.

Tobias, S., F. Conen, A. Duss, L. M. Wenzel, C. Buser, and C. Alewell. 2018. "Soil Sealing and Unsealing: State of the Art and Examples." *Land Degradation & Development* 29: 2015–2024.

Tu, L., K. A. Jarosch, T. Schneider, and M. Grosjean. 2019. "Phosphorus Fractions in Sediments and Their Relevance for Historical Lake Eutrophication in the Ponte Tresa Basin (Lake Lugano, Switzerland) Since 1959." *Science of the Total Environment* 685: 806–817.

Turek, M. E., A. Nemes, and A. Holzkämper. 2023. "Sequestering Carbon in the Subsoil Benefits Crop Transpiration at the Onset of Drought." *Soil* 9: 545–560.

Valkama, E., R. Ceriani, J. Fohrafellner, et al. 2026. *Dataset to: Cereal Yield, Yield Stability, and Nitrous Oxide Release in European Conservation Agriculture: A Meta-Analysis*. Vol. 341, 110386. Zenodo.

Vanino, S., R. Farina, T. Pirelli, et al. 2022. "Soil Priorities for Italy. A Multi-Stakeholder Consultation, Barriers and Opportunities for Research System." *Geoderma Regional* 29: e00528.

Vanino, S., T. Pirelli, C. Di Bene, et al. 2023. "Barriers and Opportunities of Soil Knowledge to Address Soil Challenges: Stakeholders' Perspectives Across Europe." *Journal of Environmental Management* 325: 116581.

Vanwindekens, F., and O. Heller. 2024. *A Web-App for Exploring the Inventory of Innovative Soil Management Practices*. Zenodo.

VBBo. 1998. *Verordnung Über Belastungen Des Bodens*. Der Schweizerische Bundesrat.

Veenstra, J., Y. Coquet, R. Melot, and C. Walter. 2024. "A European Stakeholder Survey on Soil Science Skills for Sustainable Agriculture." *European Journal of Soil Science* 75: e13449.

Veršulienė, A., J. Hirte, F. Ciulla, et al. 2024. "Wheat Varieties Show Consistent Differences in Root Colonization by Mycorrhiza Across a European Pedoclimatic Gradient." *European Journal of Soil Science* 75: e13543.

Volk, M., M. Suter, A.-L. Wahl, and S. Bassin. 2022. "Massive Warming-Induced Carbon Loss From Subalpine Grassland Soils in an Altitudinal Transplantation Experiment." *Biogeosciences* 19: 2921–2937.

Walker, W. S., S. R. Gorelik, S. C. Cook-Patton, et al. 2022. "The Global Potential for Increased Storage of Carbon on Land." *Proceedings of the National Academy of Sciences* 119: e2111312119.

Walter, C., J. Veenstra, R. Melot, and Y. Coquet. 2024. "Identification of Soil-Related Professional Profiles for the Future From a Survey of European Stakeholders." *European Journal of Soil Science* 75: e13469.

Warren Raffa, D., T. A. Räsänen, A. Trinchera, et al. 2025. "Agricultural Decision Support Tools in Europe: What Kind of Tools Are Needed to Foster Soil Health?" *European Journal of Soil Science* 76: e70097.

Weber, P., K. Zirfass, U. Bollens, T. Egloff, and A. Hofmann. 2019. *Innovationsprojekt «Umgang Mit Drainierten Böden»–Schlussbericht*, 75. Kantone Aargau.

Weber, T. K. D., L. Weihermüller, A. Nemes, et al. 2024. "Hydro-Pedotransfer Functions: A Roadmap for Future Development." *Hydrology and Earth System Sciences* 28: 3391–3433.

Weiss, L., and T. Keller. 2024. *Potenzielle Verdichtungsgefährdung Schweizer Ackerland. Schlussbericht 2024. Unpublished Report*. Agroscope.

Weninger, T., D. Ramler, G. Bondi, et al. 2024. "Do We Speak One Language on the Way to Sustainable Soil Management in Europe? A Terminology Check via an EU-Wide Survey." *European Journal of Soil Science* 75: e13476.

Wetterlind, J., M. Simmler, F. Castaldi, et al. 2025. "Influence of Soil Texture on the Estimation of Soil Organic Carbon From Sentinel-2 Temporal Mosaics at 34 European Sites." *European Journal of Soil Science* 76: e70054.

Widmer, A., L. Tamagni, C. Wüst-Galley, et al. 2026. "Mitigating Greenhouse Gas Emissions of a Managed Organic Soil by Paddy Rice Cultivation in the Cool Temperate Zone." *Agriculture, Ecosystems & Environment* 399: 110146.

Winowiecki, L. A., H. Linden, S. Alexander, et al. 2025. "Multistakeholder Engagement to Scale Soil Health Globally: The Coalition of Action 4 Soil Health." *European Journal of Soil Science* 76: e70128.

Wüst-Galley, C., A. Grünig, and J. Leifeld. 2015. "Locating Organic Soils for the Swiss Greenhouse Gas Inventory." *Agroscope Science* 26: 1–100.

Wüst-Galley, C., A. Grünig, and J. Leifeld. 2020. "Land Use-Driven Historical Soil Carbon Losses in Swiss Peatlands." *Landscape Ecology* 35: 173–187.

Wüst-Galley, C., and J. Leifeld. 2025. "The Distribution and (Future) Use of Switzerland's Organic Soils." *Mires and Peat* 32: 4.

Yuzugullu, O., N. Fajraoui, A. Don, and F. Liebisch. 2024. "Satellite-Based Soil Organic Carbon Mapping on European Soils Using Available Datasets and Support Sampling." *Science of Remote Sensing* 9: 100118.

Yuzugullu, O., N. Fajraoui, and F. Liebisch. 2024. "Soil Texture and pH Mapping Using Remote Sensing and Support Sampling." *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 17: 12685–12705.

Zihlmann, U., P. Weisskopf, A. Chervet, and B. Seitz. 2019. *Humus in Ackerböden–Vermehren Statt Verzehren*. Agridea, Merkblatt, Lindau-Eschikon.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Overview on stocktakes conducted in the frame of EJP SOIL. **Table S2:** Overview on the research activities on specific soil challenges in Switzerland and related policies in place. **Table S3:** List and references of databases, monitoring schemes and soil monitoring networks addressing specific soil properties at different spatial and temporal scales.

13652389, 2026, 3, Downloaded from https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/ejss.70355 by Schweizerische Akademie Der, Wiley Online Library on [31/05/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License