Executive Stakeholder Summary

Project number	406840_143023
Project title	Sentinels of Soil Organic Matter Vulnerability in Swiss Soils
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Contribution(s) to thematic synthesis:

☐ Soils and Food Production	☒ Soils and Environment	☐ Spatial Development	☐ Soil Data, Methods and Tools	☐ Soil Governance

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Background

Dealing with ongoing climate change calls for improved understanding of the dynamics of the carbon cycle and its relationship with the global climate. More precise recordings of carbon sources and sinks helps us to evaluate the extent and rate of climate change and thus to contribute to climate protection and adaptation efforts. Soils form the largest terrestrial reservoir of organic carbon, containing roughly twice as much as carbon as the atmosphere (in the form of CO_2). Beside carbon storage, soil organic matter (SOM) plays a key role in physical and chemical processes in soils and constitutes the essential nutrient reservoir that soil ecosystems (plants and micro-organisms) depend on. Furthermore, SOM also contributes to the filtering of water and retention of pollutants. However, there is currently no consensus on the net effect that climate change and land use change will have on these large soil carbon stocks. The complex nature of SOM and the multitude of drivers that govern SOM stability and vulnerability confound attempts to parameterize and predict SOM behaviour. By improving knowledge of SOM dynamics, the understanding of the multitude of functions can be advanced. Radiocarbon (^{14}C) measurements are increasingly used in studies of SOM as they constitute a uniquely powerful means to derive estimates of carbon turnover rates, ranging from decadal to millennial timescales. Due to the heterogeneity and complexity of SOM, comprehensive understanding of SOM storage and vulnerability requires an investigative approach that encompasses a range spatial and temporal scales and spans different climatic and environmental gradients. Additionally, in order to disentangle underlying processes that shape the composition and fate of SOM, specific carbon pools that are characterized by different stabilization mechanisms require investigation.

Aim

The ”vulnerability indicators” project was aimed at improving our understanding of how SOM dynamics vary across different spatial scales and over time, and identifying which SOM components may be particularly vunerable or resistant to environmental changes. In this context the following questions were raised:

1. How does soil carbon age (expressed via radiocarbon signatures) vary over different spatial scales and across climatic and geological gradients?
2. How do soil radiocarbon signatures in various ecosystems change over time, and what does this imply for the stability and dynamics of soil carbon?
3. What role does SOM play in the context of carbon accumulation and loss? Is SOM particularly vulnerable to climate-change induced perturbations?
4. What insights do source-specific compounds (plant lipids) provide into the stability and potential vulnerability of soil carbon?

The investigations were based on legacy and newly-collected samples obtained from the long-term monitoring sites of the WSL Langfristige Waldökosystem-Forschung (LWF) programme, in combination with state-of-the-art ETH laboratory facilities. The large, naturally-occurring climatic and geological gradients within Switzerland provide an ideal setting for examining these research questions.

Results

The key results emanating from the project can be divided into two main groups: the behaviour of SOM in different climatic settings and over time (research goals 1 & 2) and the dynamics of specific SOM pools – vulnerable (dissolved organic matter) and stable (plant wax lipids) (research goals 3 & 4). The latter were identified as *sentinels* in terms of stability or vulnerability of different SOM pools.

Climatic and geological gradients

Spatial scales of variability in ^{14}C

The magnitude and controlling factors in SOM variability (stocks, dynamics and fluxes) across different spatial scales are poorly understood. Our results show that plot-scale variability in the multi-meter scale is significant, and of the same order of magnitude as that observed across different geographic regions (multi-km scale). With the exception of weak correlations with mean annual temperature (MAT) and mean annual precipitation (MAP) (Fig. 1), no clear correlations between ^{14}C signatures and climatological factors or soil textural factors were identified. Furthermore, the radiocarbon signature of deep soils is found to be surprisingly homogeneous despite strongly contrasting climatological settings. These results emphasize the importance of representative (grid-based) sampling campaigns in accounting for small-scale spatial variability in examination of carbon-cycle processes in soils.

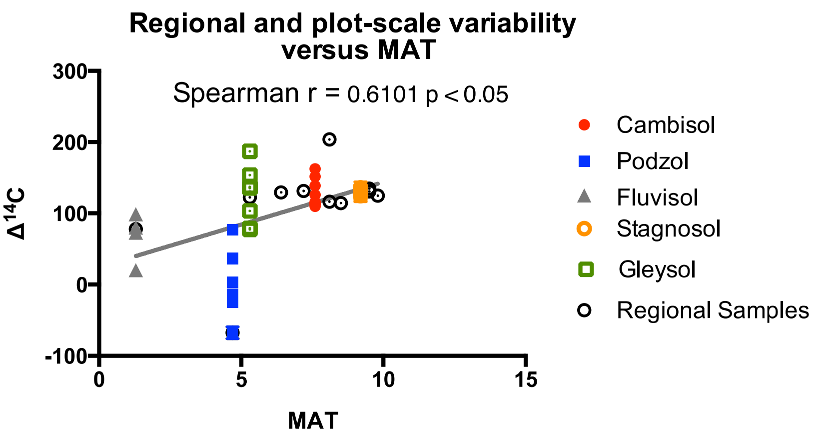

Fig 1. Variability on plot and regional-scale. MAT stands for mean annual temperature (°C) Results indicate major plot-scale variability that equals region-scale variability for both singular and mixed samples.

Time-series radiocarbon analysis of soils spanning a forest ecosystem gradient.

Radiocarbon measurements of soil samples taken in the 1990s and in 2014 provided an opportunity to analyse short-term ^{14}C variations. This shed further light on carbon dynamics (stocks, turnover, fluxes). A novel modeling approach was used to estimate carbon turnover times in both the top and deep soils for a variety of ecosystems (temperate to alpine). In all non-waterlogged soils, turnover times increase, while fluxes decrease exponentially with depth in all soils. This implies that although substantial amounts of carbon stocks reside in deep soils, this deep soil C pool does not significantly contribute to overall fluxes. Nor did these measurements reveal any clear correlation between carbon turnover (or fluxes) and environmental drivers (mean annual temperature, mean annual precipitation, net primary production) or soil texture, implying that no single factor dominates SOM processing. Mathematical modelling of soil carbon profiles did reveal a significant contribution of bedrock-derived carbon to the deep soil C pool, blurring the interface between the actively cycling and passive (sedimentary) components of the carbon cycle.

Carbon pools and resilience under global climate change

In order to further understand the dynamics and vulnerability of different components of the complex SOM pool, two approaches were followed (i) analysis of dissolved organic carbon (DOC) and (ii) examination of operationally-defined density fractions and specific compounds (lipids) isolated from bulk SOM.

Dissolved organic carbon as a dynamic and potentially vulnerable carbon pool

Changes in concentration and radiocarbon characteristics of dissolved organic carbon (DOC) collected during a summer drought (2015) from two Swiss sites implies either a net loss of stabilized carbon or changing carbon source. Given predictions for increased droughts by the mid-21st century, this process could potentially lead to increased loss of older (stabilized) carbon. Furthermore, DOC radiocarbon measurements suggest that DOC may be a key factor in rapid (decadal-scale) changes in the SOM pool. And finally, radiocarbon evidence was found for continuous interactions between deep bulk SOM and DOC throughout the soil profile.

Hydrophobic plant wax lipids as proxies for an immobile and potentially resilient carbon pool

Radiocarbon analyses of specific lipid compounds isolated from soil profiles indicate that they trace the most stable, mineral-associated pool of carbon, which appears relatively impervious to environmental change. The large spread in ^{14}C ages among individual lipid marker compounds implies that the spectrum of carbon dynamics among SOM pools is most fully expressed at the molecular level. Lastly, biomarker isotopic values unequivocally reveal contributions of bedrock (geogenic) carbon to SOM. Overall, compound-specific analyses yield significantly improved insights into SOM carbon dynamics as compared to those derived from examination of operationally-defined (e.g., density) fractions, which are susceptible to interference from other carbon pools. Therefore, the specific organic compounds (lipid markers) serve as novel, molecular sentinels of SOM stability.

Importance for research

Controlling variables in soil carbon dynamics

The combination of comprehensive radiocarbon measurements and mathematical modelling approaches applied to Swiss soils sheds new light on the dynamics of soil carbon across a range of spatial and temporal scales and over strong environmental gradients. The key data for the study sites (climate, soil texture, soil minerology) also yielded insights into factors that co-vary with soil carbon turnover. The small- (plot-)scale variability of SOM is of the same order as regional-scale variability. Temperature was found to influence topsoil carbon dynamics only weakly, whereas at greater soil depth soil texture and precipitation emerge as more important factors. Radiocarbon measurements on top- and deep soils spanning a range of forest sites also provide a comprehensive dataset that provides a foundation for future assessment of spatial temporal variability on SOM in Swiss soils. Results reveal highly similar carbon dynamics in non-waterlogged soils despite diverse environmental settings. Furthermore, deep soils were found to be hosting old, currently stable carbon stocks.

Vulnerable and recalcitrant carbon pools in the context of climatic and environmental change
Dissolved organic carbon (DOC) constitutes one of the most dynamic pools for SOM and is therefore of great interest in the context of soil formation, soil carbon turnover and responses to climate change. As part of this project, a novel time-series radiocarbon dataset for DOC dataset during a summer drought was collected. Droughts are projected to increase sharply in Switzerland and elsewhere as a result of climate change. Thus it is important to understand their effects on soil carbon dynamics. Our findings provide strong evidence for a corresponding increase in DOC age, suggesting that aged carbon pools are destabilized in response to drought. This loss of carbon via transfer to the DOC pool therefore serves as a sentinel for climate-driven changes in soil carbon.

In contrast to DOC, plant-derived lipid compounds are found to be a highly stabilized portion of soil carbon. We attribute this to their hydrophobic nature and close association with mineral surfaces. Traditionally, operationally-defined [density] fractions are used to deconvolve different sub-pools of soil carbon. However, this approach has a number of limitations. Our exploratory results using compound-specific radiocarbon analyses on soil lipids reveal that they serve as more effective tracers of different soil carbon pools, and encompass a broad spectrum of carbon turnover times. In particular, plant wax lipids appear to trace the least vulnerable (i.e., stable) SOM, and therefore may serve as a sentinel for highly stabilized carbon pools.

Implication for practice

This research project was designed to improve understanding at a fundamental level of the factors that govern carbon dynamics in Swiss soils. Because of the fundamental nature of this research, the scientific findings are not readily translatable to every-day practice but help to advance our overall understanding of how potential soil C losses can be mitigated in the longer-term through changing land-use practices in response to climate and environmental change. The results of this research have general implications for practitioners and stakeholders:

1. Regarding Swiss soil carbon stocks

   Swiss forests hold large carbon stocks in both the top and deep soils. These stocks presently appear stable, but could potentially be vulnerable to future perturbations (drought). Carbon stocks and stability are found to positively correlate with precipitation or soil moisture. Hence the importance of preventing the drying-out of forest soil.

2. Regarding the extrapolation of data for soil carbon inventories

   The unexpected homogeneity in soil carbon dynamics in surface and deeper layers of non-waterlogged soils provides justification for broader-scale extrapolation of parameters in large-scale soil carbon models.

3. Fossil carbon as an additional carbon source & soil carbon inventories

   When taking into account soil carbon stocks in Switzerland, contributions not only from overlying vegetation but also from underlying bedrock should be considered. The relative portions of these carbon inputs, determined using radiocarbon measurements, has carbon cycle implications, with metabolization of fossil (previously stabilized) carbon constituting an additional source of carbon in the atmosphere. This fossil C pool is not presently incorporated in soil carbon cycle models (e.g. Yasso model).

Recommendations

1. Carbon stocks
   The large carbon stocks in Swiss soils may be sensitive to hydrological changes, suggesting that drying, particularly of waterlogged soils should be avoided.
2. Agricultural sites
   This work has focused on forested sites, providing new insights into the stability of soil carbon in forested ecosystems. However, since large parts of Switzerland are used for agricultural purposes, the application of similar approaches, including assessing specific carbon pools at the molecular level on farmed or grazed land, is warranted.
3. Strength and potential long-term monitoring sites
   Long-term ecosystem monitoring programs (WSL LWF sites) enable us to examine soil stability and vulnerability. Short-term laboratory-based experiments cannot achieve this goal. Given projected on-going changes to regional and global climate, maintaining a long-term commitment to these programs is crucial. They can be expected to have a positive multiplier effect for the scientific community. This could improve the usage of natural (national) resources and thereby also benefit the Swiss public.