

Review on the techniques and requirements for monitoring stock changes of soil organic carbon

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I. Introduction

Soil organic matter (SOM) is the organic component of soil, providing numerous benefits to the physical, chemical and biological properties of soil and the soil's capacity to support regulatory ecosystem services. SOM is often expressed as soil organic carbon (SOC) and more informally as humus. SOM is most often calculated from the measured SOC (see chapter 2.3). SOM contains other elements in addition to carbon and is important for soil functions and soil quality, as it provides stability and structure to soils and thus builds the adaptive capacity of a soil towards environmental stressors and climate change related hazards and is closely linked to the human civilisation (Lal, 2007; Montgomery, 2012).

Besides the involvement of SOM in numerous soil functions and complex interactions of organisms with the non-living mineral matrix, it represents one of the largest carbon pools on Earth and thus plays a significant role in climate change mitigation and adaptation. The dynamics of SOC and the capacity of soils to provide the ecosystem service of carbon sequestration on large land surfaces in exchange with the atmosphere are debated intensely. In a recent review, Fuss *et al.* (2018) estimate that all soils worldwide can technically sequester 2-5 Gt CO₂ per year, while the competition to crop production and economic constraints push it to the lower end (Smith *et al.*, 2020). In the exchange with the atmosphere the SOC bound in the whole soil volume below the soil surface – the carbon stock – needs to be considered.

In the light of this potential, the 4per1000 initiative launched at the COP21 in Paris has reached the public and ever since landowners and -users are raising expectations to participate in carbon trade and compensation mechanisms. SOM, however, is a natural phenomenon and ever since humans tilled the soil to grow crops, it has been used as a source of nutrients while it mineralized. Building SOM is an inherent goal of organic and sustainable farmers, who know how difficult and elusive this goal is. Although the managers of soils practice the usage of SOC so constantly, we poorly manage to maintain the current level and even less to increase it. In addition the effects of climate change may lead to a decrease in SOC due to the rising temperature level (Riggers *et al.*, 2021).

In addition to just building up SOC stocks, five main conditions to high-quality carbon offsets are defined:

1. **Additionality:** Would the effect occur anyway, without this initiative because (a) it is economically interesting or (b) because it will be regulated out of other reasons?
2. **Precision:** How can the baseline and the effect be measured?
3. **Permanence:** Are the benefits reversible as e.g. trees can be harvested as firewood and SOM gains can be decomposed again.
4. **Leakage:** Does the sequestration of carbon in one area cause emissions elsewhere?
5. **Co-benefits:** Does the implementation of carbon sequestration technology provide other benefits?

While each of the five points is difficult to achieve, **measurability** and **precision** is a difficult task due to the soil formation over millennia, the diverse landscapes and the opacity of the soils. The question of **permanence** is closely related to the question how carbon stocks and their change over time can be maintained, and what the fate of the new SOM that has been built will be. If an improved soil management increases SOC stocks, a change back to business as usual would involve the risk of a SOC decline. So, the permanence in agricultural systems is unsure as long as the farmer is free in his or her decisions to change the soil management, when it will provide a higher profit. With respect to **additionality**, subsidy programs aiming at improving agricultural sustainability (e.g. ÖLN) and including a measure to build SOM are in place already and therefore it is questionable if an initiative for carbon offsets would be additional.

The requirements for a carbon offset imply the focus on SOC stocks that are stabilized/protected against decomposition for long periods of time (> 30 years). This is most often a fraction of SOM, which is defined through analytical methodologies. Including well defined labile and stable fractions in what we define as carbon sequestration may help to achieve the goal of permanence. The concept of SOM stabilisation through sorption to charged surfaces of clay minerals or the occlusion within soil aggregates has been taken up by several authors (Hassink, 1997; Dexter *et al.*, 2008; Johannes *et al.*, 2017; Lehmann *et al.*, 2020). On the other hand, the labile fraction of SOM is often defined by a high turnover and good accessibility to microbial decomposition and also the soil microbial biomass is considered a fraction of SOM which is highly dynamic. The turnover of SOM is an important component of models for the simulation of SOC dynamics (Jenkinson and Rayner, 1977; Parton *et al.*, 1996; Zimmermann *et al.*, 2006). Even though the search on this active/stabile pool of SOM is elusive, there are numerous attempts to measure it (Magid *et al.*, 1996; Magid *et al.*, 1997; Smith *et al.*, 1997; Smith, 2004; Smith *et al.*, 2020).

In the following chapters we will explain the methodology to measure SOC, SOC stocks and their changes over time. Quite important to mention is the difference between the gravimetric content [g kg^{-1} soil] and the area-based stock [kg ha^{-1}] of SOC. We are not considering the various fractions of SOM that are conceptually or analytically separated (active *vs.* passive; stable *vs.* labile; soluble *vs.* bound *vs.* particulate; protected). We will evaluate the current standard techniques, their potentials and limitations and new ways to account for the immanent spatial variability of soils by remote sensing and spectroscopic analyses. This report explains, what is currently possible and what can be done within the next ten years, if spectroscopic methods are used in the laboratory and attached to the agricultural machinery to combine them with remote sensing data.

2. Analytical assessment of SOC sequestration

The assessment of carbon sequestration starts with the precise measurement of SOC stocks of a given area or soil volume. This assessment consists of three main steps:

1. Sampling of representative soil masses,

2. the quantitative analyses of bulk density and organic carbon content of the soil sample, and
3. the calculation of stocks using the measured parameters.

We critically present the current state-of-the-art in all three steps and introduce spectroscopic methods and their promising use in combination with remote sensing or as an accessory to soil tillage machinery to improve the assessment of SOC stocks in future.

2.1 Soil sampling strategies

Traditionally, soil analyses are destructive and based on a soil sample that is aimed at representing the area of the field of interest. Soil sampling strategies vary widely according to the studied objectives. They contain reflections on the frequency and season of sampling, sampling depth and increments and on how the sample is representing the total area of the field under investigation. The measurement frequency depends on the dynamics at which a change is expected: biologically driven processes may vary quickly within hours and a few days, but changes in total SOM are taking place slowly over a couple of years to show a detectable change. The smallest unit in the sampling strategy is a soil core that is taken from a particular soil layer at a specific time. Due to the geological processes that shaped our soils the variability along horizontal and vertical gradients must be taken in consideration, too. Agriculture often uses fixed sampling depths linked to the tillage depth (Ap-horizon) or soil volumes reached by the annual or perennial crops and their roots (e.g. N_{\min} 0-30-60-90 cm). Natural and forest soils are often sampled down to the bedrock, considering diagnostic soil horizons to subdivide the soil profile into increments.

Horizontally, soils are varying according to topography, geological origin of their parent material, and the historic and current land use and management. Soils in the landscape often show inhomogeneities that are relicts of former vegetation, aquifers, roads and erosion channels. Even though the land area is highly variable, spatially resolved data is needed to address the role of soils in climate change, where the soil surface divides atmosphere and pedosphere. Wiesmeier *et al.* (2020) and Leifeld *et al.* (2019) explain the criteria and requirements for certifying carbon sinks in agricultural soil. FAO (2020) describes the protocol for measuring, reporting and verification while Smith *et al.* (2020) are explaining the scientific background. Soil quality is under observation in many countries and each of these observation programmes is following a well-defined strategy, but hardly two are identical. In the following, we will present the various sampling strategies used in soil observation programmes in Switzerland and some neighbouring countries.

2.1.1 Certificate of ecological performance (ÖLN)

All farmers who apply for direct subsidies according to ÖLN have to analyse the soils of their fields (1-5 ha) in a certified lab every 10 years if fertilizers are applied. The analyses need to include pH, P, K, soil texture (tactile), SOM (colour code). It is foreseen to measure SOM more reliably with analytical methods in the near future. A composite sample is made of 20 soil cores of the top 20 cm on arable fields and 0-10 cm on permanent grassland. The procedures for ÖLN are poorly defined but recommend a composite sample representative for the field (KIP c/o AGRIDEA, 2019), often in form of a cross pattern or two parallel



Fig. 1: Soil sampling according to ÖLN methodology. 20 samples are taken (blue: along two crossing lines, or yellow: randomly distributed).

lines along which the cores of a composite sample are to be taken. A video shows how a mixed sample of a field for ÖLN can be taken (Deluz, 2019), however a uniform methodology is missing for the sampling as well as for the analysis, which limits the usefulness of this control measure for direct subsidies. If the field is larger than 5 ha or if it is not homogenous, separate samples have to be taken, e.g. from a slope and from the plain areas. Similar random sampling designs are reported for many studies of farmers' fields (Reijneveld *et al.*, 2009; Taghizadeh-Toosi *et al.*, 2014).

The Swiss ÖLN programme can be seen as exemplary for subsidizing sustainable agriculture. Most Swiss farmers take part in it. It could serve as a model for the accounting of carbon sequestration if it was carried out consequently based on analytical measures and if the reporting was correctly done. Currently the potential of this programme, is not fully exploitable since the data are considered private and are therefore protected in most cantons. A serious accounting of sequestered CO₂ would need more than just changing the management and entering the management into field books. The proven positive effect of a certain management change in a field trial has not always come true in practice.

2.1.2 Swiss Soil Monitoring Networks

The Swiss soil monitoring network NABO operates more than 100 long-term monitoring sites throughout Switzerland (Gubler *et al.*, 2015; Gubler *et al.*, 2019), 30 of which are used as permanent cropland or cropland-meadow. Topsoil samples (0–20 cm) are taken in

five-year intervals, usually in spring. At each sampling time, four replicate samples (stratified random sampling design: composite sample of soil cores taken from 25 subplots of 1 m²) were collected from the same precisely located area of 10 × 10 m (Fig. 2). From 2005 on, subsoil samples (75-100cm) were taken using the HUMAX system including bulk density, skeleton and water content (Gubler *et al.*, 2019).

A uniform sampling scheme for the analysis of soil contamination has been developed by Hämman and Desales (2003) based on their long-term experiences and is used by most of the cantons in their procedures.

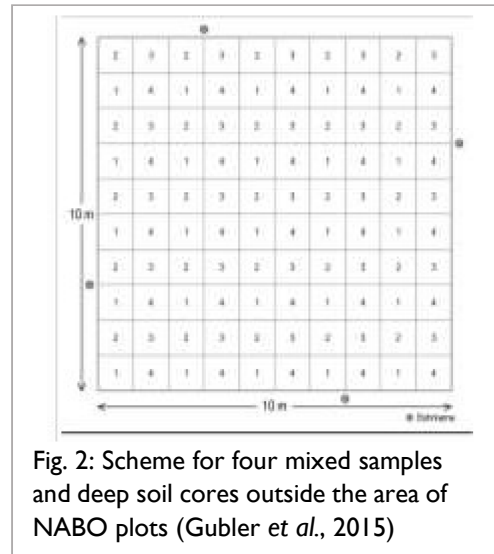


Fig. 2: Scheme for four mixed samples and deep soil cores outside the area of NABO plots (Gubler *et al.*, 2015)

In addition, there are several long-term cantonal soil monitoring networks (KABO) including pasture, cropland (Maurer-Troxler *et al.*, 2005; Maurer *et al.*, 2016) and forest soils (Braun *et al.*, 2018) or urban soils (Levasseur *et al.*, 2019) (see VBBio - BioSA (2015)).

2.1.3 German national soil inventory (BZE)

A nationwide soil survey of forest (BZE I 1987-1992, BZE II 2006-2008) and agricultural soils (BZE LW 2011-2017) is established in Germany. Both sampling strategies are based on a systematic standardised point sampling based on an 8 × 8 km grid and central soil profiles (Jacobs *et al.*, 2018) (Fig. 3). In the case of BZE LW, the sampling was carried out with the active support of local farmers including information on soil management strategies. The total number of soil sampling sites was 3104, with soil sampling depths of 0-10, 10-30, 30-50, 50-70 and 70-100 cm and additional soil sampling according to the soil horizons if the differences between the predefined soil sampling depths and the soil horizons were more than 4 cm (Jacobs *et al.*, 2018). Deep peat soils were sampled below the excavated soil profile of 2 m depth with pile-driving cores (Rammkernsonde).

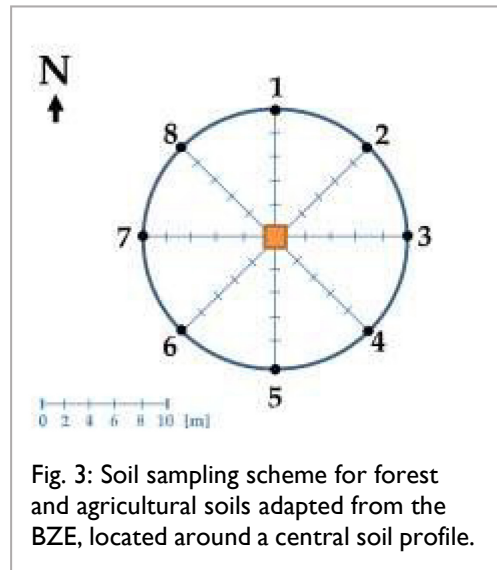


Fig. 3: Soil sampling scheme for forest and agricultural soils adapted from the BZE, located around a central soil profile.

The soil sampling strategy on the approximately 2000 forest sites in the BZE I and II were sampled in a slightly different way, with soil sampling increments of 0-5, 5-10, 10-30, 30-60, 60-90, 90-140 and 140-200 cm wherever possible. In the second soil inventory (BZE II), special emphasis was placed on the division of all horizons of the uppermost organic soil layer (Wellbrock *et al.*, 2016).

2.1.4 Soil observation Bavaria

For the Bavarian SOM monitoring program, soil samples were taken during spring time (February-April) before the first soil management or fertiliser application (e.g. slurry or fertilizers). Each field consisted of five replicate sampling sites which were positioned with GPS and magnetically marked (Capriel, 2010). Another five replicate soil cores were sampled in each sampling site resulting in $5 \times 5 = 25$ samples per field. The author

highlighted that soil sampling sites especially for the sampling of soil humus should be divided into small sampling sites (e.g. with a radius of 1.5 m, Fig.4) and contain a known position for future monitoring.

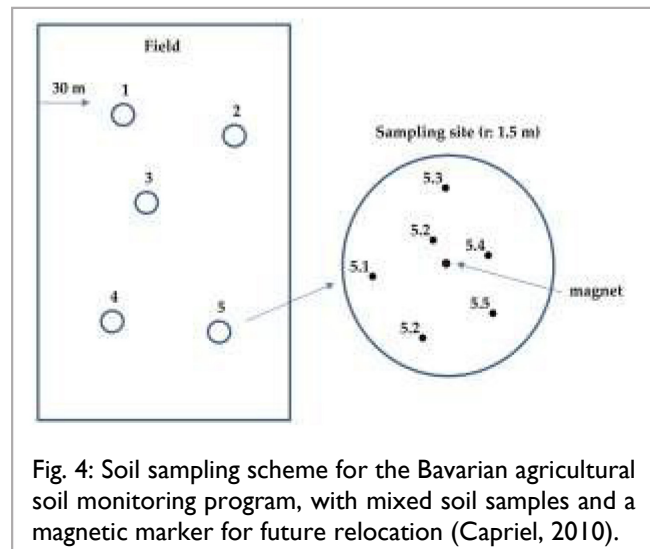


Fig. 4: Soil sampling scheme for the Bavarian agricultural soil monitoring program, with mixed soil samples and a magnetic marker for future relocation (Capriel, 2010).

2.2 Reference sites and reference samples

Spatial-temporal monitoring of SOC is done in order to deliver analytical data that prove the efficacy of a change in soil management. The question what a site specific SOC content and SOC stock may be, needs cautious considerations and comparison to other sites and samples that can serve as controls (Fliessbach *et al.*, 2020). A control site or reference site may be a defined area, where the “business as usual” is continued and documented, or an area where no change is expected because a climax situation has been reached. Reference sites are thought to remain constant with respect to the parameters in question and this may also include a continuous and constant management. Of course, constancy is based on theory and assumption, since the soil quality parameters will change due to a change in geoclimatic conditions that cause background variation. A reference site may just help to identify this background noise, if the sampling, the sample treatment and the analysis are done in the same way. The selection of reference sites is of crucial importance and needs expert knowledge. The well-documented network of sites under long-term observation from the national soil observation programme (NABO) or from field trials are safe and controlled areas and they are independent from personal interests and spontaneous decisions. These sites deliver the information needed to evaluate time-bound changes and provide information on what changes will be expectable upon a change in management. They probably cover most of the abiotic environmental conditions that shape the soils such as the geological origin, climate, altitude, particle sizes, pH, hydrology, etc., but it may be necessary to enlarge the network according to needs.

Reference samples are used to show that the analytical procedure in the lab is reliably producing constant results (accuracy) and that the analytical errors are relatively small (precision). Often a series of reference samples covers the analytical range from low to high concentrations. They need to be available in sufficient quantity and have to be stored under appropriate conditions (dry, cold, in appropriate portions). The reference sample has to be included in each batch of analysis to ensure analytical and instrument stability (see Tab 2.). Reference material should be stored in a trusted soil archive and be available for any comparison and analytical testing.

2.3 Analytical measures to determine SOC

Soils contain three basic forms of carbon: elemental C, inorganic C, and organic C. **Elemental** carbon includes charcoal, soot, graphite and coal, the origin of which is incomplete combustion or geological transformation of organic matter. **Inorganic** carbon forms are often remainder of the parent geological material. Typically, they are present as carbonates. The two most common carbonate minerals found in soils are calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$), among others such as siderite (FeCO_3). Agricultural soils may contain calcite and dolomite from liming practices. A steady state equilibrium is established between carbonates, bicarbonates, dissolved and gaseous carbon dioxide, depending among others on pH and temperature.

Organic carbon forms derive from primary (plants) and secondary (e.g. animals) production. Various organic forms are present in soils from freshly deposited plant litter to highly aggregated and transformed forms. Generally, the analysis is based on SOC. Often SOM is calculated from SOC using a fixed conversion factor of 1.725, since the average carbon content of SOM is 58%. However, there is no universal conversion factor, the values may range from 1.7 to 2.5 (Schumacher, 2002). Nevertheless, the farmer usually receives the analytical data as percent SOM or humus of the soil dry mass. The analysis is generally based on the fine particle fraction (<2 mm) of a soil material.

It is important to distinguish between organic and inorganic carbon in soils:

$$\text{Total SOC} = C_{\text{org}} + C_{\text{inorg}} \text{ or } C_{\text{org}} = \text{Total SOC} - C_{\text{inorg}}$$

Generally, the methods for soil organic carbon analysis are destructive, but non-destructive measurements are developing.

2.3.1 Semi-quantitative methods

Loss on Ignition (LoI): Organic matter in soil can be thermally removed by heating a sample to temperatures between 350 and 500 °C (Nelson and Sommers, 1996). If a sample is heated to >450 °C, inorganic C can disintegrate and produce false results. After cooling the sample in a desiccator, it is weighed and compared to its original dry weight in order to obtain the weight loss, which corresponds to the weight of SOM. Potential errors stem from mineral-bound water, which would produce higher values of weight loss. This method is only suitable for soils with high content of organic matter and relatively low clay content.

The **hydrogen peroxide oxidation** method is not recommended and should only be applied as sample pre-treatment for removing SOM for further analyses. Here, H₂O₂ is added to the sample until the frothing ceases. The sample can be heated to increase the speed and completeness of the oxidation. After drying, the weight loss is determined as mentioned before.

In the field, **tactile tests and colour cards** are used to vaguely obtain an approximate of the SOM level. The values obtained are neither precise nor reliable, therefore the tactile test will be taken out of the official Swiss methodologies.

2.3.2 Quantitative methods

The most often used techniques to measure soil carbon are either based on wet oxidation with K₂Cr₂O₇ – a technique that is applicable in many labs – or based on dry combustion with excess oxygen in element analysers – a technique that requires investments and standard lab conditions.

Destructive methods for the quantification of SOC can be subdivided into

1. wet oxidation followed by photometric determination of Cr³⁺ or titration with ferrous ammonium sulphate (Walkley and Black, 1934),
2. wet oxidation followed by the collection and measurement of evolved CO₂,
3. dry combustion at high temperatures in a furnace with the collection and detection of evolved CO₂ (Tiessen and Moir, 1993), effective measure C_{tot} (DIN EN 15936:2012-11)
4. dry combustion at high temperature in a furnace after previous combustion of organic carbon at 500 °C, effective measure C_{inorg}
5. dry combustion at high temperature in a furnace with previous removal of carbonates by adding HCl, effective measure C_{org}
6. consecutive combination of 3 and 4: dry combustion at 500 °C and then at 900 °C, effective measures C_{org} and C_{inorg}.

Wet oxidation of SOC using K₂Cr₂O₇ and H₂SO₄

At present this method is still the standard procedure for analysing SOC in agricultural soils in Switzerland (Agroscope, 1996-2018). In the official method 2 ml potassium dichromate (80 g K₂Cr₂O₇ l⁻¹) and 3 ml concentrated H₂SO₄ are added to between 0.5 g and 1.0 g finely ground soil. The solution is shaken and allowed to cool down prior to adding water to halt the reaction.



The method is widely used because it is simple, rapid and needs only basic equipment (Nelson and Sommers, 1996). Environmental concerns with respect to the disposal of acid waste containing chromium and the safety risks associated with the concentrated

H₂SO₄ favour the use of alternative techniques (Kerven *et al.*, 2000). However, the oxidation of organic carbon, in particular elemental carbon, is incomplete, with a mean recovery of 76% (Walkley and Black, 1934). To overcome this problem, the Agroscope method includes a heating procedure of the sample during digestion. The sample in the extraction solutions is gently boiled at 150 °C for 7 minutes in a sandbed or oilbath, allowed to cool, and then water is added to halt the reaction. The temperature of this method must be strictly controlled because the acid dichromate solution decomposes at temperatures above 150 °C. This does not lead to a complete digestion of the organic C in the sample but increases the recovery to 88%. A prolonged heating phase of 30 min as proposed by Heanes (1984) results in a complete recovery of the soil carbon. Long-term soil observation is struggling to harmonise data from wet oxidation and dry combustion in concluding that site specific conversion factors are needed (Gubler *et al.*, 2018) that are based on several years of measuring samples with both methods.

In the reaction equation, the three measurable products of the acid dichromate digestion process are Cr₂O₇²⁻, Cr³⁺ and CO₂. Cr₂O₇²⁻ and Cr³⁺ remain in solution and can be measured titrimetrically or colorimetrically, while the evolved CO₂, in its gaseous state, is less common to be measured with appropriate techniques (Nelson and Sommers, 1996).

For the titration, 1.5 g sodiumfluoride (NaF) and 4 drops of a diphenylamine solution are added to the digestate. The titration with an Fe(II) titration solution is then done to an endpoint at the change from blue to green. Instead of the titration procedure, the remaining Cr³⁺ can be measured photometrically at 585 nm after filtering the digestate.

Element analysis by dry combustion

The element analysis is based on the complete combustion of all C to gaseous CO₂, which is then quantitated by one out of various methods depending on the manufacturer of the apparatus. The major differences between the approaches are i) the way how inorganic and organic carbon are separated and ii) the mass of the sample to be combusted, which ranges between a 1 mg and 2 g of dry soil. The evolved CO₂ is either measured by spectroscopic or thermal conductivity detectors. The possibility to use large sample masses simplifies the preparatory work as grinding is not mandatory. The combustion >900 °C completely oxidizes all carbon compounds in the sample including carbonates. Hence, the machine reports the total carbon content and the separation of organic and inorganic carbon is not possible. Several protocols exist to separate these fractions: An acidification of the sample before the combustion removes all inorganic carbon = carbonates. Some manufacturers include this step in the automated routines of the instruments where the acidification is done automatically. However, the halogen remainders of the acids reduce the life expectancy of certain components of the apparatus.

The new reference method for SOC in Switzerland will be based on DIN 19'539 that defines the measurement in an element analyser (Diane Bürge, pers. communication). The decision will probably be taken in Feb. 2021. Total organic carbon (TOC) is then

defined as the CO₂ evolving at 400°C, residual oxidizable carbon (ROC) at 650°C and total inorganic carbon at 900°C. ROC is considered elementary C. An alternative to this approach is using N₂ instead of O₂ as a carrier gas for the ROC peak that allows for a better peak separation.

The method currently used in the FiBL laboratories is making use of a Vario Max Cube CHN (Elementar Analysensysteme Hanau GmbH), which uses a fixed combustion temperature of 900 °C and is equipped with an autosampler for steel crucibles that may carry about 5 ml of sample volume. The large crucibles are useful, since there is no need to grind the sample finely, because up to 2 g of soil can be used. The FiBL method measures the organic C as the difference between total C and inorganic C. 1 g of air-dried soil is weighed in two crucibles each. If SOC is expected to be higher than 5% the weight is reduced. These subsamples are dried for 12 h at 105 °C. One of the samples is placed in a muffle furnace at 500 °C for 5 hours to remove all organic carbon compounds. Afterwards the inorganic carbon that remains in the sample is measured in the element analyser. In the other sample the total carbon content (organic and inorganic carbon) is measured at 900 °C directly.

Infrared spectroscopy

Many scientific and some commercial labs already use infrared (IR) spectroscopy to measure the OC content of various natural materials including soil. The technique records the reflection of a sample in the infrared part of the electromagnetic spectrum. By correlating the recorded spectra to reference samples that were characterised with classic analytical techniques the content of organic carbon (and many other parameters) can be estimated. The advantages of IR spectroscopy are that it is a non-destructive, rapid, cheap and precise, if comparable soils with a wide range of SOC contents are considered in the regression. More details can be found in the chapter 2.7.

2.3.3 Qualitative methods

Chemical fractions

Humic acids, fulvic acids and humates were part of a sequential chemical extraction protocol. They were analysed in earlier times because they were thought to represent a large part of the SOM and can be extracted from the soil matrix. The main deficiency of this method is the production of extraction artefacts. Today the value of these fractions for interpreting SOM quality is rejected since novel approaches are better suited for this objective, as explained in the following.

Soluble carbon or **dissolved organic carbon** (DOC) represent organic molecules that are dissolved or dispersed in the soil water or the water extract.

Solid state ¹³C nuclear magnetic resonance spectroscopy (NMR) is used on soil samples to characterize the molecular structure of SOM. It is a semi-quantitative technique that identifies the functional groups of carbon in a sample with a very high information

density. It is not applicable as a standard method because of costs, challenging data interpretation and lack of standardisation.

Infrared (IR) spectroscopy is an analytical technique that acquires information on many soil properties. Besides quantitative analyses on the SOC content, the spectra can be analysed considering the quality of SOM, too. It even offers the potential to derive information on important co-variables of carbon sequestration and stabilisation like clay content and mineralogy, but no information on bulk density. More detail can be found in chapter 2.8.

Physical fractionation of SOM by density and particle size

SOM fractions associated or bound to the mineral fraction of a soil are often measured in order to identify fractions with different turnover times (Lehmann *et al.*, 2020). SOM is often closely bound to the charged surfaces of clay minerals and fine silt. SOM bound to clay minerals is considered a very stable SOM fraction, whilst SOM occluded inside aggregates is considered less stable and accessible to decomposer organisms and their enzymes. Physical SOM fractions are obtained by wet sieving after aggregate disruption. Particulate organic matter (POM) is free of mineral particles but it can be stabilized by the chemical nature of the material itself (recalcitrance). SOM in the sand-sized fraction is often considered as POM. The fractionation technique to separate POM from sand is often based on flotation and centrifugation steps with poly-tungstate solutions of defined density. Other techniques are identifying light and heavy POM, where light often means that the material still has air filled voids that show the plant origin.

The coverage of the charged surfaces of the soil fraction smaller than 20 μm , i.e. the fine silt and clay fraction, with SOM was developed as a guiding principle for what a good quality soil is. A SOC/clay ratio of 1/10 was often found in soils all around the world (Hassink, 1997; Dexter *et al.*, 2008), which was then defined as the capacity of soils to preserve SOC. Johannes *et al.* (2017) used this principle in combination with an improved spade diagnosis to define optimal SOM levels for soil structure quality of arable soils.

Biological fractions

The concept of the microbial biomass arose in the 1970ies and allowed to measure the amount of carbon bound in living microbial cells within a given soil. Jenkinson (1976) and Jenkinson and Powlson (1976) developed this method on the search for compounds that sterilise the soil. They realised a flush of C-mineralization after the sterilisation procedure with CHCl_3 vapour and when counting and measuring the number of microbes in the soil they found that the figures were corresponding. The approach that developed hereof was called the holistic or black box approach, which took the microbial biomass as an active fraction of the SOM which “is the eye of the needle that all organic material entering the soil has to go through”. This idea paved the way to develop the Roth-C model for carbon turnover in soils.

Rock-Eval pyrolysis

This thermal analysis performs a stepwise heating of a sample, releasing CO and CO₂ gases monitored by a flame ionisation detector (FID) for pyrolysis in oxygen free carrier gas and an infrared detector (IR) for combustion under an artificial air supply. Compounds of organic and inorganic matter are identified according to their thermal stability, providing quantitative measurements of C_{tot} and C_{inorg} as well as indices of different OM sourcing and stability (Sebag *et al.*, 2016). Although it does not require any previous sample treatments, additional information about other elemental concentrations such as N_{tot} are lacking. The method is destructive and gives only limited information on the composition of the original SOM since the temperature is changing the material and together with oxygen it will be completely oxidized to CO₂. The additional value of this technique compared to the element analyser is the temporal resolution, which provides the peak times for CO₂-development.

Thermogravimetry

The same difficulty in data interpretation as for the Rock-Eval technique can be criticized here. Simple weight loss measures on heating a soil sample is used for rapid screening of soil properties (Siewert, 2004). The author recommends this technique for organic C, total N, clay and carbonate content of soils. However, it has not been used widely.

2.4 Calculation of carbon stocks and their change

Accurate estimates of SOC stock changes rely strongly on baseline SOC values, which are determined by physical sampling and soil C content measurements. This approach traditionally involves the quantification of (a) fine earth (<2 mm) and coarse mineral (>2 mm) fractions of the soil; (b) organic carbon (OC) concentration (%) of the fine earth fraction; and (c) soil bulk density or fine earth mass (FAO, 2020; Smith *et al.*, 2020). The determination of soil bulk density, the dry mass of the investigated soil volume, requires a standardised volumetric and undisturbed soil sampling. Bulk density measurements need a lot of manual handling and it is not yet possible to derive bulk density information from other sources such as remote sensing. Usually the method is done by inserting volumetric cylinders into the soil, that are taken to the lab without disturbance. The dry weight of the defined soil volume will be determined and corrected by the amount of coarse (> 2mm) particles (see the comment of Hobley *et al.* (2018b) to Poeplau *et al.* (2017)). This can be a challenging task in soils with a high proportion of large roots, stones or on steep slopes (Jurgensen *et al.*, 2017), as is the case for many Swiss forest soils in particular.

Alternatively, volumetric soil sampling using the HUMAX system (<https://www.greenground.ch/>) offers the opportunity for manual and machine-based sampling of volumetric samples. This procedure may be limited to the number of parallel soil cores taken, but they may serve as a detailed measure to calibrate NIR & mid-IR Spectra in the lab and the field.

2.5 Expenses and costs for measuring, reporting and verification

Measurement costs vary depending on the considered method, which include different sampling pre-treatment, but also between laboratories. Table 1 shows a collection of estimated analytical costs of accredited Swiss soil laboratories, indicating that sample preparation including drying and sieving of the soil is almost as costly as the measurement itself, due to the time required. We expect that the estimated costs of CHN analysis will decrease as more certified laboratories will offer this analytical service once this method becomes the new Swiss standard procedure, which will be based on DIN19539, which is currently under evaluation. Furthermore, costs can be lowered by combining analytical sample measurements with IR spectroscopy.

Table 1 Costs for measurements (in CHF/sample) in accredited Swiss soil laboratories, based on a list of approved laboratories (Agroscope, 2020b, a). Mean costs are averaged for all given laboratories (No. labs). ¹Including drying (40°C, sieving < 2mm). ² Wet oxidation of SOC using K₂Cr₂O₇ and H₂SO₄.

Measurement	Method	Mean	Min	Max	No labs
Sample preparation ¹	BAFU VU-4814-D	28	10	60	4
Dry weight	Gravimetrically	29	20	50	4
C _{org}	Swiss standard method ²	57	25	85	7
C _{org} and N _{tot}	CHN Elementar Analyser	105	60	150	2
Grinding sample	BAFU VU-4814-D	37	20	60	3

Bulk density determination requires the presence of expert personnel in the field, who prepare the cylinder samples, transport them to the lab and determine the dry weight on analytical balances. To our information, none of the Swiss laboratories offers bulk density measurement according to the standard methodology (Agroscope, 1996-2018).

2.6 Sensitivity and Reproducibility

The organic carbon content of a homogenized soil sample can be measured at high precision. Repeated measurements with the element analyser in the FiBL labs showed an average coefficient of variation of 1-2% at contents between 0.7 to 2.6% C. Towards low carbon values, approaching the detection limits, the error is increasing (Tab. 2). Reference material in form of soils as quality standards are to be included in each of the series. These quality standards need to be chosen carefully to cover the expected range of the values. They should also include samples with high SOC including carbonates.

Table 2 Mean values of three reference soils with low, medium and high SOC, where the high SOC is a soil with carbonates. CV: coefficient of variation (%) of the analytical procedure at FiBL laboratories (CHN Vario Max Cube (Elementar Analysensysteme Hanau GmbH)).

Reference soil (n)	Low	CV(%)	Medium	CV(%)	High	CV(%)
Total carbon [%] c.v.	0.73	1	1.383	1	2.604	2
Inorganic carbon [%] c.v.	0.012	58	0.006	117	0.483	6
organic carbon [%]	0.718		1.378		2.121	

The minimum detectable difference is a function of the variability in the field and the number of replicate samples (Ellert *et al.*, 2008). Changes in SOC stocks rely on the measurement method but also on appropriate sampling design, because the spatial variability in a field can be very high (Minasny *et al.*, 2017). Temporal variation within a year may follow the geoclimatic changes and the vegetation in particular. Reducing the signal to noise ratio is the challenge when changes are to be measured. Within the NABO, the seasonal variation of heavy metal loads was measured over several years to detect reasons for unexplained variability. The seasonal changes were found to be crucial for SOM (A. Keller, pers. comm.) due to the changing amounts of roots and plant residues present. This effect can be minimised by sampling at the same time of the year and in relation to the crop or vegetation growth and the management of a field.

Large scale spatial variability (e.g. at catchment level) is easier to detect than small scale spatial variability. The latter can result from soil management, drainage, erosion, biological activity, historical structures (field paths, hedges, ponds included in the field) and historical use, differential lithology and weathering intensities. This is especially the case for forest soils, where for instance litterfall can add high small-scale spatial variability (Vanguelova *et al.*, 2016). To reduce potential errors in SOC stock estimation sufficient sampling depth is also required (Smith *et al.*, 2020). In conclusion the horizontal and vertical variability remains largely unknown. The sampling density can hardly cover the infield variability, but solutions to resolve this difficulty may develop from remote sensing or from IR sensors attached to soil tillage machinery and also from the increasing data collection verified by classical analysis if they are stored in a common database.

Using the long-term data set of the DOK trial, the average coefficient of variation in the annual C-stock measurements was 7.7%. The stocks have been calculated with plot wise bulk density averages of the first seven years (1st crop rotation) (Fliessbach *et al.*, in preparation). The measurements show a clear trend for each of the farming systems. The first significant difference between any farming system in the trial appeared in 1984, six years after the start of the experiment in 1978. The difference in SOC stocks between the two system was 3.7 Mg ha⁻¹. It took another eight years until two farming systems using animal manure at the same stocking density showed this difference. This difference stabilised in the annual analyses from the 22nd year on. Based on 30 monitoring sites under crops in the Swiss NABO, Gubler *et al.* (2019) state a minimum detectable change of 0.35% annually with respect to SOC content. In the DOK trial the corresponding changes in SOC content are much lower but they are based on a large number of replicates and compare systems with and without manure (Fliessbach *et al.*, in preparation).

Part of the field variability was due to a clay gradient and also the block structure of the field trial accounted for some of the variability. By taking a mixed sample over the whole field this variability would not be detectable. If we want to measure the SOC stock change of a farmer's field with confidence, we need to measure with high precision and accuracy to account for the changes due to the change in soil management before the

background of the potential variability in the field. The DOK trial provides the opportunity to look at each of the four blocks (replicates) or each of the three subplots individually. The field was chosen for the trial, because of its relatively homogenous appearance in terms of crop yield distribution. SOC stock change in the system with highest sequestration rates (BIODYN) range from 41 to 203 kg C per hectare and year, if the four blocks are calculated separately, or from 68 to 135 kg C per hectare and year if the calculation is based on the subplot structure. This supports the importance of a sampling strategy that is equally considering the area coverage and its variability. Expert personnel are needed to decide upon the sampling design, depending on a previously determined homogeneity test. In the DOK trial the blocks and subplots are both replicate structures in the trial: 4 blocks are the field replicate with 3 (nested) subplots; in the 3 subplots the crop rotation is temporally shifted. If we would only look at the farming systems within one block or one subplot, we would come to different conclusions, which may vary by the factor 2.

If the dynamics of change were the same on a farm with business as usual (IP, crop rotation with a grass-clover ley and 1.4 LU per hectare) as in the DOK trial, a management change to composted manure instead of mineral fertiliser would become detectable only 14 years later. Therefore, early indicators to quantify and evaluate C-sequestration more efficiently are needed to prove a change, justify any payments, and to motivate the farmer to continue (Smith, 2004).

2.7 IR spectroscopy

Infrared spectroscopy is a technique that is established, accepted and widely applied for qualitative and quantitative analyses of soil samples. During the last two decades IR spectroscopy has been picked up by commercial companies and is frequently applied in business solutions. We will shortly introduce the basics of both techniques and present the current state-of-the-art of their application and precision in the context of assessing soil organic carbon.

2.7.1 Basics of IR spectroscopy

Spectroscopic methods make use of the property of elements and molecules of simple to complex structure to absorb or reflect electromagnetic radiation. For opaque media such as soil, only reflectance spectroscopy can be applied and due to the surface roughness diffuse reflectance is mostly measured. In general, all spectroscopic methods are non-destructive and the actual signal acquisition is a fast, robust and easily standardisable process, however, the interpretation of the data is not trivial and needs expert knowledge and experience. The obtained spectra are either compared to spectral libraries or calibrated to analytical data using various statistical approaches. Comprehensive spectral libraries that reliably represent the heterogeneity of Swiss or European soils are far from being complete. Hence, precise analyses of SOC for calibrating IR spectra will be needed in the next 20 years at least. Once spectral libraries are widely available, SOC analyses will still be needed for validation. Spectroscopy alone

does not allow for SOC content determination, now and in the foreseeable future. Nevertheless, IR spectroscopy is the most promising technique, inevitable to improve the assessment of soil properties and to support farmers, foresters and extension services striving for optimising soil management and opening new avenues for sustainable land-use systems

IR spectroscopy can be classified according to the measured wavelengths. In the visual light (400-700 nm = Vis) and near infrared domain (700-2500 nm = NIR), the identification of materials is more complex because the signals of elements and molecules are superimposed. In the mid-infrared domain (2500-25000 nm = MIR), the signals of specific functional groups and elements can be clearly distinguished, but the measurement is more sensitive to water absorption and surface roughness. Two principles are applied in IR spectroscopy: (a) most VisNIR instruments measure the reflected light after refraction in a prism or diffraction by a diffraction grating; and (b) many NIR and MIR instruments make use of an interferometer to identify the specific absorption bands of a sample after performing a Fourier transformation (diffuse reflectance infrared fourier transform spectroscopy, DRIFT). The latter is faster, has a better signal to noise ratio but requires a more complex sample preparation.

Reeves (2010) compares the performances of VisNIR, NIR and MIR for soil analyses with a special focus on soil organic carbon. The author concludes that DRIFT is often more accurate and produces more robust calibrations than VisNIR when analysing ground, dry soils under laboratory conditions. However, MIR spectra are known to be more affected by moisture and sample preparation than NIR. While both techniques offer the potential for the analysis of soils on-site, and even in situ, many questions remain to be answered.

2.7.2 Lab spectroscopy and the global spectral library

In soil sciences, IR spectroscopy has become a standard analytical method for various parameters related to SOM and other mineralogical and chemical parameters (Tab. 3).

Based on the European soil database LUCAS, a spectral database for Europe is currently being compiled (Stevens *et al.*, 2013; Nocita *et al.*, 2015; Orgiazzi *et al.*, 2018). Viscarra Rossel and Webster (2012) assessed the prediction power of an Australian VisNIR spectral library. Viscarra Rossel and Hicks (2015) assessed the potential of VisNIR spectroscopy to estimate total SOC content and stocks as well as specific carbon fractions. They conclude that measurements in the VisNIR range need little sample preparation and therefore they are rapid, practical and cheap. A further advantage is that the technique can be used directly in the field. Wijewardane *et al.* (2016) evaluated the potential of VisNIR to predict soil carbon, while Sanderman *et al.* (2020) used MIR for the prediction of soil health indicators in the United States. They describe a very high precision for a wide range of soil quality indicators including SOM content and various SOM fractions. In parallel, similar spectral databases are being developed on the global scale (Brown *et al.*, 2006; Terhoeven-Urselmans *et al.*, 2010; Viscarra Rossel *et al.*, 2016).

Table 3 Spectroscopic approaches applied in studies on SOM and related soil quality parameters

Soil parameter	IR methodology	Reference
Various soil properties		Stenberg et al. (2010) Soriano-Disla et al. (2017) Nocita et al. (2015) Mouazen et al. (2016) Viscarra Rossel and Bouma (2016)
SOM or SOC content		Gholizadeh et al. (2013)
Soil texture		Hermansen et al. (2017)
SOM fractions	MIR VisNIR + MIR	Zimmermann et al. (2007) Madhavan et al. (2017)
SOM chemical composition	VisNIR VisNIR MIR	Terhoeven-Urselmans et al. (2006) St. Luce et al. (2014) Margenot et al. (2020)
Mineralogy	VisNIR	Fang et al. (2018)
Aggregate stability	VisNIR + MIR VisNIR	Cañasveras et al. (2010) Shi et al. (2020b)
SOC-to-clay ratio	VisNIR	Hermansen et al. (2016)
Particle size distribution, SOC	commercially available NIR spectrometers	Jaconi et al. (2017) Jaconi et al. (2019)
SOC, pH and various metals	VisNIR and MIR	Riedel et al. (2018) Clairotte et al. (2016)
SOC and other soil properties	MIR	Baumann et al. (2021)

In Switzerland, Baumann *et al.* (2021) assessed approx. 4000 soil samples from NABO and BDM sites analytically and by MID IR with high conformity ($r^2 > 0.9$). Ludwig *et al.* (2019) underline the large potential of partial least square regressions based on R that outperform commercial chemometric software. This adds to the applicability of MIR spectroscopy as a cheap and powerful tool for the assessment of soil quality and especially organic carbon. Several authors analysed costs and benefits of IR spectroscopy and compared it to the classic analysis for soil organic carbon (O'Rourke and Holden, 2011; Nocita *et al.*, 2015).

2.7.3 Field IR spectroscopy

Besides the application under clean laboratory conditions, IR spectroscopy is developed further as a field method. There are three main approaches for IR spectroscopy in the field:

1. hand-held spectrometers that acquire spectra of soil samples or surfaces under field conditions,
2. IR spectrometers connected to other analytical and management instruments in the field that enable the assessment of a whole suite of soil properties, and

3. imaging IR spectroscopy, an application of hyperspectral cameras promising high resolution assessment of soil properties on the soil core or soil profile scale.

Barthes and Chotte (2020) reviewed the current literature on field application of IR spectroscopy and conclude a strong potential for the fast assessment of soil organic carbon in the field enabling the evaluation of soil and land degradation. Cambou *et al.* (2016) and Soriano-Disla *et al.* (2017) compared the performance of four different portable infrared spectrometers. They found that both the full range VisNIR and the MIR spectrometers could estimate many classic soil properties with high precision. Tang *et al.* (2020) and Barthes *et al.* (2019) compared different low-cost spectrometers and found different performances depending on the spectral range covered.

In the last years portable mid-IR spectrometers have been developed and are applied in soil science. Hutengs *et al.* (2019) compared spectrometers in the field and conclude that “handheld MIR and VisNIR spectrometers have a potential to facilitate quantitative applications in proximal soil sensing, although with less accuracy than in the laboratory”. Poggio *et al.* (2008) developed an instrument that combines a penetrometer with a VisNIR spectrometer to estimate various properties along a soil profile (Poggio and Vrščaj, 2009). Ackerson *et al.* (2017) developed an algorithm to consider the detrimental effects of soil moisture on the VisNIR spectra collected with this instrument, and Wijewardane *et al.* (2020) improved the performance of the penetrometer-mounted spectrometer to automatically measure *in situ* soil VisNIR reflectance spectra, penetration resistance, and insertion depth along a soil profile.

Nawar and Mouazen (2019) used a spectrometer attached to plough-like subsoiler chisel to measure the reflectance from the soil on the bottom of the trench opened by the proceeded chisel (Mouazen *et al.*, 2005). They conclude that field application is possible without significantly lower precision when taking care during the statistical model development. Viscarra Rossel *et al.* (2017) developed the Soil Condition Analysis System (SCANS) that combines several instruments to measure bulk density, volumetric water content, available water capacity, clay content and mineralogy, cation exchange capacity, pH, total, particulate, humus, and resistant SOC, and the uncertainties of all properties. Viscarra Rossel and Brus (2018) concluded that IR spectroscopy using their SCANS system was overall 1.2 to 2.1 times more cost-efficient than pooling of samples for classic analyses. Currently we do not know of any activity to develop, establish and promote this technology in Switzerland, and thus call for a coordinated approach. The HAFL research group Bodennutzung und Bodenschutz uses a drilling system for sampling organic soils. It is capable of taking intact cores of a length of up to 2m and record RGB-NIR images subsequently. The Competence Center for Soils (CCSols) evaluated handheld NIR devices for the field and currently develops a protocol for NIR field application to be conducted 2021 and 2022 in the frame of soil mapping surveys.

To conclude, field IR spectroscopy offers an enormous potential for improving the assessment of SOC quantity and quality in the area of land management and policy. In

particular, the possibility to assess SOC dynamics in the field with a high spatial and temporal resolution is promising.

2.7.4 Imaging IR spectroscopy

Imaging IR spectroscopy is a new application where hyperspectral cameras are used to acquire spatially resolved IR spectra. They can be used to measure the VisNIR reflectance of soil cores up to 1 m length. The information is used to calculate high resolution maps ($50 \times 50 \mu\text{m}^2 \times \text{pixel}^{-1}$) of various soil properties, e.g. quality and quantity of total SOC and specific fractions or total N (Buddenbaum and Steffens, 2011, 2012; O'Rourke and Holden, 2012; Steffens and Buddenbaum, 2013; Steffens *et al.*, 2014; Schreiner *et al.*, 2015; Askari *et al.*, 2018; Hobley *et al.*, 2018a; Mueller *et al.*, 2019; Lucas *et al.*, 2020). Until today, only VisNIR cameras were used under laboratory conditions in imaging IR spectroscopy. MIR cameras are available, too, but data interpretation is much more challenging. O'Rourke and Holden (2012) compare the cost efficiency of five techniques (Wet oxidation (Walkley and Black, 1934), dry combustion, laboratory IR spectrometer, portable IR spectrometer, and imaging IR spectrometer) to measure the SOC content of soil samples. They conclude that imaging IR spectroscopy is "the most rapid technique with a potential to scan about 720 samples per day at 90% less cost than the Walkley-Black method. The opportunity cost of hyperspectral imaging is to forfeit some analytical accuracy associated with the dry combustion method."

2.7.5 Summary on IR spectroscopy

In conclusion, IR spectroscopy is an established technique for the qualitative and quantitative analysis of various soil properties, especially the SOC content. The current approaches to standardise measurement process and data (pre-)treatment together with the continuous improvements in statistical data analyses will enable the application in commercial labs within the next decade. Spectral libraries will benefit from this additional information and enable much more frequent and precise estimations of the quality and quantity of SOC in soil samples. In combination with estimations of important co-variables of carbon sequestration (e.g. texture, clay mineralogy, carbonate content, specific fractions of SOM) IR spectroscopy will open new avenues in the assessment of carbon sequestration and soil management.

2.8 Remote sensing

2.8.1 Basics of remote sensing

Remote sensing is the acquisition of information about an object without making physical contact with the object. In most cases remote sensing is an imaging technique that produces a georeferenced image during acquisition. Remote sensing is used in numerous fields, including geography, land surveying and most Earth science disciplines. In contrast to proximal sensing, remote sensing requires a more complex pre-treatment of the data, such as geographic and radiometric corrections (Minu *et al.*, 2017).

These corrections may contain topographic corrections and corrections of the movement of the sensor platform. However, many remote sensing products already offer corrected products. Older satellite missions produced only raw data where users had to apply all corrections by themselves.

Remote sensing can be differentiated by the type of sensor and platform as well as the information acquisition. Sensor types can be categorized as active or passive. Passive sensors use the reflected sunlight to gather information on the object. In contrast, active sensors (e.g. RADAR = RADio Detection And Ranging) emit a signal (either Radio or microwaves) and record the reflected signal. The main advantage of active systems is that the acquisition is in most cases not obstructed by clouds and not dependent on sunlight. This means that information can be gathered more frequently than with reflected sunlight. In current usage, the term "remote sensing" generally refers to the use of unmanned aerial vehicle (UAV), also named drones, air- or spaceborne sensor technologies to detect and classify objects on Earth. The type of platform is decisive for the spatial resolution of the product and the revisit time or acquisition interval. While drones are characterised by high spatial resolutions in the range $<10 \times 10 \text{ cm}^2 \times \text{pixel}^{-1}$, airplanes and satellites have generally lower spatial resolutions $>10 \times 10 \text{ cm}^2 \times \text{pixel}^{-1}$. Despite its high spatial resolution, UAV and airplane missions are mostly single events and time series are not possible without extensive investment. Satellite missions are characterised by a lower spatial resolution but enable time series analyses because the satellite is on a constant orbit with defined revisit intervals. Most important current and freely-available satellite missions are the European Copernicus (Sentinel 1-3) and the US Landsat Program. Many satellite missions are still operating multispectral sensors that acquire information in relatively few and broad spectral bands (Sentinel and Landsat missions). The information acquired can be used in many disciplines but more for qualitative than quantitative analyses. During the last decade hyperspectral satellite missions established, producing data that enable high resolution quantitative earth observation. Especially the free Copernicus Program with two RADAR and two multispectral tandem satellites opened new avenues for spatially and temporally highly-resolved qualitative and quantitative earth observations (Gholizadeh *et al.*, 2018; Segarra *et al.*, 2020). At least five satellites equipped with hyperspectral imagers have already started or are envisaged to be launched in the near future: the German Environmental Mapping and Analysis Program (EnMap), the Italian PRecursores IperSpettrale della Missione Applicativa (PRISMA), the U.S. NASA Hyperspectral Infrared Imager (HypSI), the Japanese Hyperspectral Imager Suite (HISUI), the Israeli Hyperspectral imager (SHALOM), and the China Commercial Remote-sensing Satellite System (CCRSS). All studies presented here focus on VisNIR spectroscopy and eventual RADAR.

2.8.2 Prediction of soil organic carbon using remote sensing

Stevens *et al.* (2006) describe some problems when predicting SOC contents using an airborne hyperspectral scanner. The main hindering factors were that there are no universal calibrations due to different soil textures and water contents. Since 2006,

sensors and data analyses have improved, but soil cover, especially crop residues, is still an important limitation, which can lead to overestimations of SOC. Dvorakova *et al.* (2020) assessed the power of various indices to identify pixels covered by crop residues in airborne hyperspectral images. They describe satisfactory results for airborne data but identified new problems when transferring the method to Sentinel 2 data. Shi *et al.* (2020a) used airborne data to estimate SOC content and aggregate stability in agricultural plots in Belgium and describe satisfactorily predictions for both parameters and great potential of hyperspectral remote sensing to capture both the fine-scale, in-field as well as between-field variability of these soil properties. Zhou *et al.* (2020) used a data fusion between Sentinel 1, 2 and derivatives of high-resolution digital elevation models to predict SOC content of Slovenia. Paul *et al.* (2020) used Landsat images and digital elevation models to predict SOC and clay content and combine them in a high-resolution map of the soil workability in Canada. They were able to estimate the gravimetric soil water content above which soil may be degraded with any mechanical operation. Castaldi *et al.* (2018) pushed the limits when evaluating the power of an airborne hyperspectral scanner in combination with the European topsoil database LUCAS to estimate SOC content along two flight paths in Belgium and Luxembourg. They showed that the spectral information in the LUCAS dataset is already sufficient to estimate the SOC content from hyperspectral data without analysing actually sampled soil material from the corresponding plots. Castaldi *et al.* (2019) compared the accuracy of Sentinel 2 and airborne APEX (Airborne Prism Experiment = airborne imaging spectrometer) data to estimate SOC content of three regions in Luxembourg, Germany and Belgium. They conclude that despite slightly lower accuracies Sentinel 2 data is adequate to describe SOC variability within field and at regional scale. Diek *et al.* (2017) showed that 5 years of Landsat data were required to cover most of the bare soil area in the Swiss midlands. Clay content and SOM could be derived from this data.

By contrast Yuzugullu *et al.* (2020) aim at using Sentinel 2 and 3 data to identify homogenous subplots in agricultural fields solely based on remote sensing data. This approach can enable a targeted sampling design for agricultural plots. We assume this approach to be promising to identify the ideal amount and location for soil sampling locations to represent a plot inheriting heterogeneity.

2.9 Nationally coordinated programme on soil carbon: an example from Australia

Several Australian groups developed an innovative and comprehensive carbon accounting framework that relies on VisNIR spectroscopy, remote sensing and statistical data management (Rose, 2020). Viscarra Rossel *et al.* (2014) used data from three different sources including a classic soil sampling campaign, the Australian VisNIR spectral library and the Australian soil information system to develop a baseline map of organic carbon for Australia. In a next step, Viscarra Rossel and Hicks (2015) developed a routine to estimate total SOC and particulate, humic and resistant organic carbon fractions using a hand-held VisNIR spectrometer. Lobsey and Viscarra Rossel (2016) developed a technique that combines γ -ray attenuation and VisNIR spectroscopy to measure *ex situ*

the bulk density of soil cores to 1m depth under field conditions. This construction enables the assessment of SOC stocks in the field. The authors improved this system by adding an automated soil corer and digital cameras (Viscarra Rossel *et al.*, 2017). The soil condition analysis system (SCANS) allows to automatically estimate total SOC, particulate, humus, and resistant organic C, clay content, cation exchange capacity, pH, volumetric water content, available water capacity, and their uncertainties. Based on the large potentials of this instrument, England and Viscarra Rossel (2018) discuss the requirements for new SOC accounting methods based on proximal sensing. Baldock *et al.* (2018) showed the potential to predict stocks, composition and vulnerability to loss of SOC using MIR spectroscopy. Based on the information available, Viscarra Rossel *et al.* (2019) improved their baseline map of SOC for Australia by considering SOC composition and vulnerability. They conclude that more local parametrizations of models are needed but postulate a large potential for region-specific strategies for effective carbon management and climate change mitigation.

3. Interpreting the measurable changes in the view of the demands for certification and compensation

Soils contain more carbon than the atmosphere and biomass combined and cover the large terrestrial surfaces in exchange with the atmosphere. Upon soil cultivation they have lost a large part of their SOC and for these reasons it seems reasonable to consider SOC sequestration as the reverse process to be a viable way for the mitigation of climate change. In addition, SOM build-up has advantages for many ecosystem services related to the soil functions. SOM is playing a major role for all the biological soil functions habitat, regulation and production (Fliessbach *et al.*, 2020). On the other hand, soils provide a large variability from micro- to macroscale – they provide microhabitats within soil aggregates and these differ from outside the aggregate and they are part of the various geologically formed landscapes. So, apart from many things, soils have in common, they provide variability and diversity. This means a major challenge for the standardisation of a protocol for measuring C-sequestration. If we pledge to stick strictly to the protocols and never change them we can exclude a major factor that often impedes the comparability of measures.

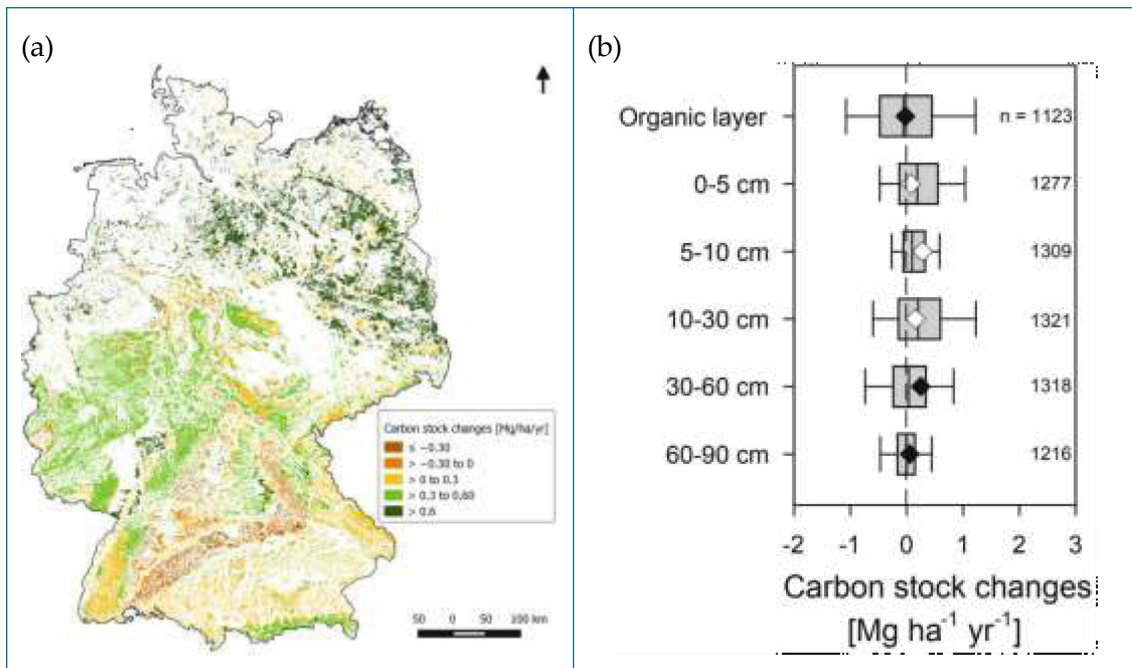


Fig 5: Soil carbon stock changes in the top 30 cm at forest sites in approx. 15 years between BZE I and BZE II (a) and the average stock changes (b). Box plots with white diamonds indicate significant differences (Grüneberg *et al.*, 2019).

Any measurement of a change needs to be related to a well-defined baseline. Switzerland is getting ready for mapping their soils and may at the same time collect the respective data for SOC content and stocks. Germany has just finalised a point based data collection of forest (Fig 5a) and agricultural soils (Fig. 6) in the BZE including soil profiles (Flessa *et al.*, 2019). The forest sites had been analysed previously 15 years before, which allowed for an estimate of soil carbon stock change (Fig. 5b). The Swiss NABO sites were selected to represent natural background loads of environmental pollution, unlike the sites for biodiversity monitoring (BDM) that are arranged along regular grids similar to the BZE. The NABO sites are revisited every five years and provide a very detailed dataset, but additional sites may be considered useful to complete their potential to serve as reference sites for the diversity of arable fields and forests in Switzerland. This data set, like the German BZE, are based on point-based samples, so they lack the variability measure needed for the carbon accounting of a field, but it is a major achievement in the contribution to a national SOC inventory and represent the temporal dynamics more detailed than the spatial variability. This kind of monitoring programmes, including the well described NABO and KABO sites, can help to identify the changes in SOC stocks under conditions of natural dynamics (e.g. forest or nature reserves) or under conditions where the management has been monitored (e.g. pilot farms, LTE). The information may then be used to interpret changes on farms at similar geoclimatic locations taking part in compensation programmes.

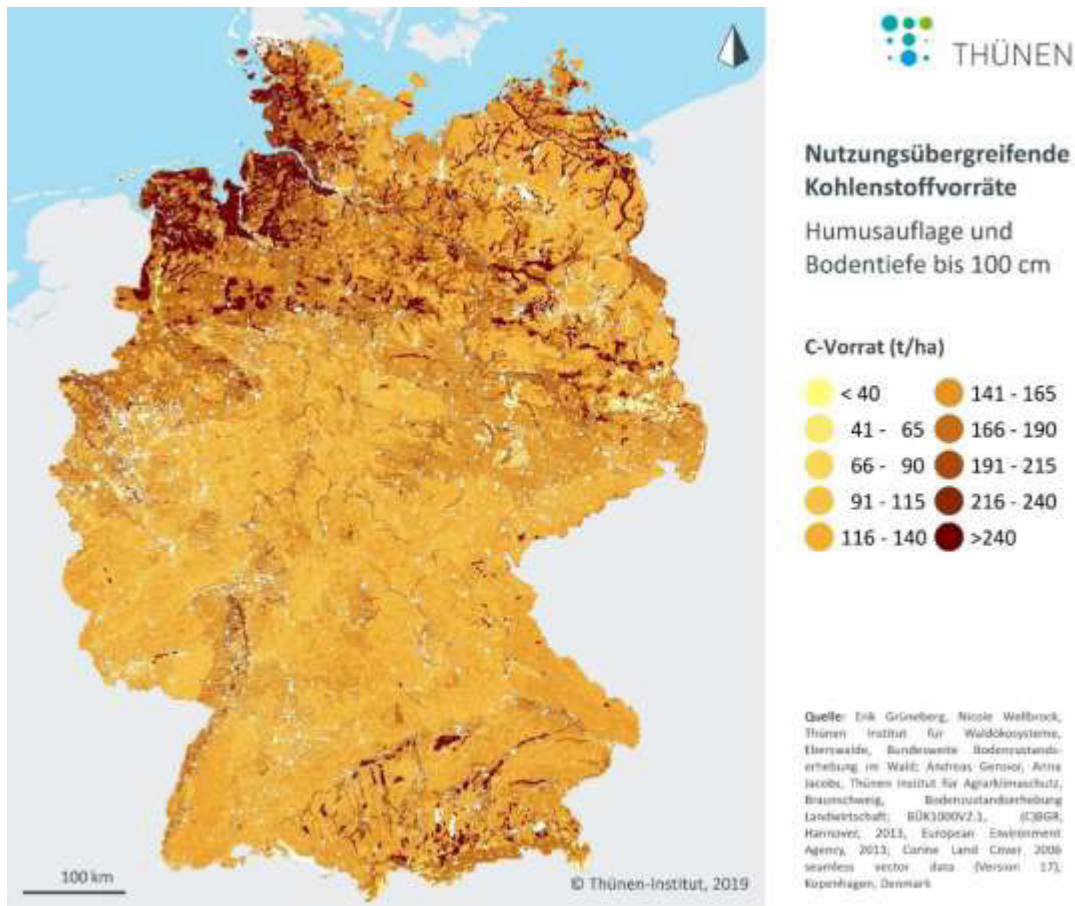


Fig. 6: Soil carbon stocks down to 100 cm depth across land use systems in Germany (Flessa *et al.*, 2019).

Schrumpf *et al.* (2011) investigated the minimum detectable differences when taking 100 single cores from a field. On cropland the authors state a minimum detectable difference of 1.05 Mg SOC ha⁻¹ in the 0–10 cm layer, whereas this value in grassland soils was 2.1 and in forest soils 2.5 Mg SOC ha⁻¹. The authors estimate a time period of 2-15 years to detect changes in the upper 10 cm of stone-poor soils (Tab. 4). In comparison, it took 6-14 years after a management change offered a detectable change of 3.7 Mg SOC ha⁻¹ in the Swiss DOK trial (Fliessbach *et al.*, in preparation). Schrumpf *et al.* (2011) used 100 single soil samples on cropland for the detection of change and in the DOK study 12 replicate field plots were analysed separately. At carbon poor forest sites with little or no soil profile disturbance (Conen *et al.*, 2005) suggest a change of 5 Mg ha⁻¹ to be detectable, when 50 samples are collected (Tab. 4). On disturbed forest sites, as in the case of heavy storm damages, the required sample size increases drastically. The involved costs for sampling and analyses in compensation projects would exceed the potential gain from carbon credits by far. Due to high variability, Schrumpf *et al.* (2011) demand direct measurements of bulk density, stone content for unbiased SOC estimations. Based on the NABO dataset Gubler *et al.* (2019) determined a minimum detectable change of 0.35% depending on the number of observation sites and period. This would allow to account for a change of 7% after a 20-year period. Taking together

the sampling effort due to soil variability, the estimated time to detect changes and the cost of a standard soil analysis, a successful SOC sequestration monitoring programme does not appear to be realistic (Smith *et al.*, 2020).

Tab. 4. Summary of the published minimum detectable differences (MDD) and the time needed to reach this level.

	MDD	Nr of samples	Time needed [years]
Conen <i>et al.</i> (2005)	Forest 5 Mg ha ⁻¹	50	
Schrumpf <i>et al.</i> (2011)	arable land 1.1 Mg ha ⁻¹	100	2 – 15
	grassland 2.1 Mg ha ⁻¹	100	
	forest 2.5 Mg ha ⁻¹	100	
Gubler <i>et al.</i> (2019)	7% Corg	30	20
Fließbach <i>et al.</i> (in preparation)	DOK 3.7 Mg ha ⁻¹	3 subplots × 4 replicates	6 – 14

3.1 Verification, irreversibility and additionality

A major barrier to the wide scale implementation of the 4per1000 initiative and the FAO's global assessment of SOC sequestration potential programme is the difficulty to actually measure carbon stock changes. Smith *et al.* (2020) call for credible and reliable monitoring, reporting and verification (MRV) platforms, both for national reporting and for emissions trading. Evidence about potentials of management changes to build SOM exist and scientific as well as practical tools are available to measure SOM in the field. Evidence is based on long-term trials dating back to the 19th century and monitoring programmes in place since the 1970ies. The long-term trials were originally addressing agricultural research objectives but often they also analysed the soils and have a valuable archive of samples and data. Data from field trials can be considered precise and accurate, and even small changes could be verified by statistical testing. Since trials were also documented in any detail, the changes could be related to the management or geological and climatic factors and were thus extremely useful for developing and improving models of SOM turnover. If a compensation programme will be put in action, the ground-based analyses need to be public and added to the available data from field trials and monitoring sites to build models and further develop their predictive power. Soils are not only private properties – they are basis of our existence and provide so many services that a public eye has to survey their condition and function.

Monitoring

Certainly, we cannot afford and carry out the effort to analyse SOC stock changes on each farm or field by 50-100 replicate measurements. In our example given below we propose a double sampling of 25 soil cores each that are combined, homogenised and the two samples are then taken to the lab for analysis (Tab. 5, 6, 7). This could also serve as an improvement to the on-farm monitoring system that is in place as an obligation to participate in the ÖLN. Compared to the current procedures, a professional sampling

and soil analysis strategy including IR spectroscopy at a frequency of less than 10 years on a field would be a step forward. Making the analyses of all Swiss soils public at least to the administration would be the next step and combining the soil analyses on the ground with remote sensing spectroscopy data would provide the information needed for a complete national soil carbon accounting. Our proposal for building a Swiss soil database is that all accredited soil laboratories should provide an IR spectrum of each soil sample they receive in addition to any standard analysis.

Tab. 5. Calculation of SOC sequestration for a farm with 10 fields if the 4p1000 goal is reached.

Field	Area ha	SOC [kg Mg ⁻¹]	Bulk density [Mg m ⁻³]	C-stock 0-20cm [Mg SOC ha ⁻¹]	C-stock 0-20cm [Mg SOC]	4pM [kg SOC yr ⁻¹]
Field 1	2	17	1.2	40.8	81.6	326
Field 2	4	18	1.3	46.8	187.2	749
Field 3	3	23	1.4	64.4	193.2	773
Field 4	1	27	1.2	64.8	64.8	259
Field 5	2	16	1.1	35.2	70.4	282
Field 6	5	19	1.3	49.4	247.0	988
Field 7	3	14	1.4	39.2	117.6	470
Field 8	3	27	1.3	70.2	210.6	842
Field 9	2	26	1.1	57.2	114.4	458
Field 10	5	31	1.4	86.8	434.0	1736
...						

Satellites are crossing Switzerland frequently enough, and flyovers by airplanes can be targeted to generate information at higher resolution and at times when soil is open to the sky. In particular cases, drone flights can be organised to analyse the specific variability of a field with hyperspectral cameras.

Tab. 6. Sum of the carbon gain and CO₂-sequestration from the last column above. Calculation of returns at various prices for a ton of CO₂ if a compensation project is in place

SOC build-up [Mg SOC yr ⁻¹ farm ⁻¹]	6.88
CO ₂ -seq. [Mg CO ₂ yr ⁻¹ farm ⁻¹]	25.24
Price for 1 Mg CO₂ [CHF]	total return per farm and year [CHF]
10.00	252.38
20.00	504.77
40.00	1009.54
80.00	2019.07
160.00	4038.14
141.05	3560.00

Bodenproben.ch is offering the price given in table 7 for one automated and GIS monitored sampling per field. In order to approach the needed 50-100 soil cores and as a control, we calculate with a double sampling per field. A price of 141 CHF per ton of CO₂ would just cover the costs, however, at higher uncertainty as in the above cited papers. If all 50 soil cores would be analysed separately the costs can hardly be covered

by reasonable prices of CO₂. This holds true even if the measurements had to be performed only every third year as the draft of the new CO₂ ordinance proposes.

The costs for bulk density estimates are high because they need manual labour. If volumetric soil samples are taken the costs related to bulk density may be omitted.

Tab. 7. Cost for measuring the SOC content twice under present conditions. Considering own logistics and automated routine measures the costs can be lowered.

Laboratory	description		Price [CHF]
Bodenproben.ch	Travel flat rate (only once)	50-100	100
	2 composite samples of 25 cores for each of the ten fields	2*71	142
Sol.conseil	Analysis, sieving, dry matter	2*22	44
Travel costs + 10 fields			1960
Estimate of 2 working days for a technician at 800 CHF per day for bulk density measurement		2*800	1600
Total			3560

Irreversibility

It is possible that the sequestered CO₂ is emitted again from soils, when management practices are no longer maintained. It may also happen as a climate change effect because of temperature rise or weather extremes. In order to report changes, a permanent monitoring has to be in place, which needs to be adjusted to detect the risk of a decrease in SOC stocks (Rumpel *et al.*, 2020). The principle of constant care for SOM has to be established in all types of soil management. While our current farming systems are traditionally depleting SOM rather than building it up, this can be called a paradigm shift.

Irreversibility is closely linked to the needs of farmers and their daily choices. If the selected farming systems are useful and suitable for making a living, they will be adopted. Subsidy programmes that usually come from agricultural policies that care for the livelihood of farmers need to be better adjusted to the climate goals that are coming from the policies that care for the environment and the society.

Changes in land use types such as **afforestation** are currently seen as a permanent measure. So, the time horizon for permanence may be the time needed for a planted tree to reach maturity for harvesting.

Verification

If we were to implement a compensation project immediately or within the next months the simple idea to copy the principles of the ÖLN and combine them with the ideas of the 4per1000 approach is tempting. However, concluding from a management change

to a change in SOC stocks remains a daring hypothesis that needs a proof. A robust evaluation of the ÖLN programme would help to answer this question.

The simulation of SOC stock dynamics and the calibration with IR remote sensing data needs a major effort. Our proposal to equip each soil laboratory with an IR spectrometer to take an IR spectrum of each sample they get and store it together with the data they analyse by standard methodology is feasible as a first step to build a database. In a few years only, all agricultural fields in Switzerland would have an IR signature.

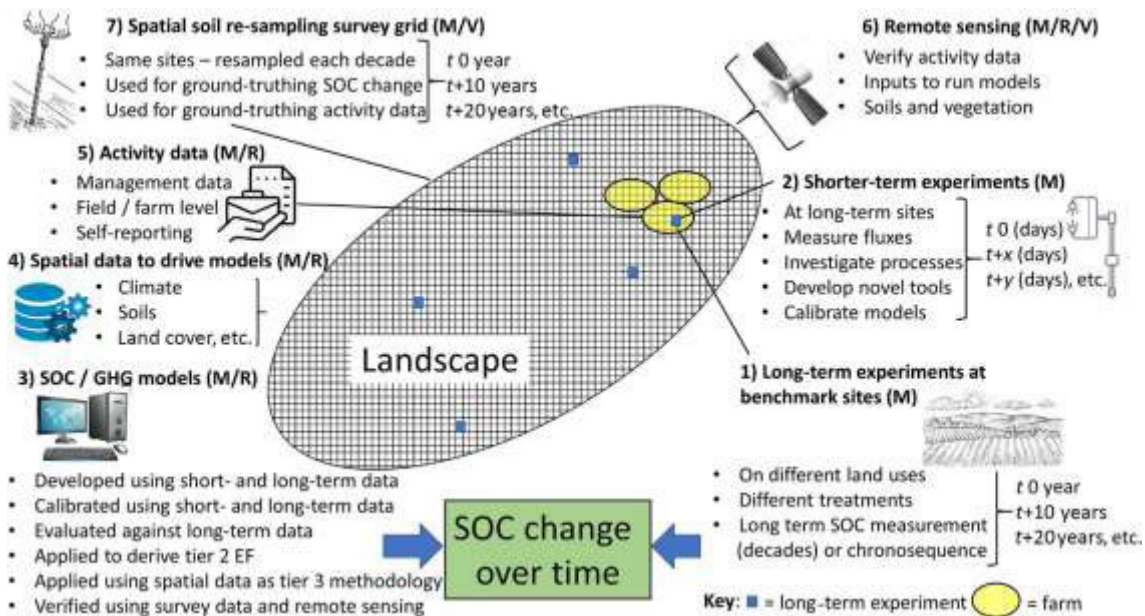


Figure 7: Components of a framework indicating the contribution to monitoring (M), reporting (R) and verification (V) (Smith *et al.*, 2020).

The measured dynamics can be simulated by models. If models are correctly simulating the measured values they can be used for predictions and for filling gaps on the map, where no measures were taken. Smith *et al.* (2020) propose a global platform that includes the insight and knowledge gained from LTEs and on-farm experiments. It also includes reporting mechanisms for the repeated measurements following a baseline assessment and verification of the achieved results by remote sensing and ground truthing control values (Fig. 7). Today the global platform is still restricted by the availability of soil and management information from LTEs and farm networks in countries, where they are less abundant. Possibly, within 5 to 10 years a monitoring program as proposed here could be in place.

Towards a new soil policy in Switzerland, the final synthesis of the NRP 68 (Steiger *et al.*, 2018) calls for a concerted action. Switzerland has a wealth of soil monitoring sites, farm networks and LTEs, but Steiger *et al.* (2018) claim the lack of soil information and a soil map as the basis of information to reduce the loss of soil and to increase soil quality. As a response the Swiss Federal Council has published a soil strategy to tackle the identified challenges (Der Schweizerische Bundesrat, 2020). A detailed soil map is necessary for the implementation of a carbon offset mechanism to compensate for emissions. Some

accompanying information (land use, bare soil etc) can be efficiently taken from remote sensing. The combination of ground data and remote sensing information would be a step forward to a complete nation-wide picture of the quality of soils. Repeatedly, satellites are flying over single fields at various stages of the vegetation and also when the soil is exposed to the sky (B. Nowak, 13.11.2020). This can be used as a tool to define homogenous sampling areas in the field, but it also helps to add information to areas where sampling has not been done. Once the technique has been optimised for a given objective, it can also be used to evaluate and interpret historic pictures of earlier overflights.

3.2 Effects on soil quality

A compensation project addressing CO₂-sequestration in the first place offers opportunities for soil quality improvements. SOC is one of the most frequently measured soil properties related to soil quality that plays an important role how soils carry out their functions in production, regulation and habitat provision. Ideally, the agricultural production will adapt to management methods that grow crops and SOC, simultaneously. In view of global climate change, adaptation, mitigation and food security must be addressed at the same time by enhancing SOC on farmers land (Rumpel *et al.*, 2020). Therefore, adapted risk prevention strategies must be implemented, as farmers in Central Europe, for example, have hardly ever faced droughts and floods, which are now expected to become more frequent. These strategies must include among others the **diversification** of the crops and crop rotations as well as using **nature-based solutions**, by improving the buffering capacity and resilience of the environment. This capacity can be improved by a soil that can take and store water, that mineralises nutrients quickly and timely, that is stabilised by organic matter. Structures in the field can help to avoid erosion and keep the fertilisers in the place they were applied to. The best remedy against erosion is a dense plant cover.

3.3 System boundaries

In the context of carbon sequestration, climate change mitigation and trading of emission rights it is of vital interest to properly define the boundaries of a system. In order to accurately assess the mitigation of greenhouse gas emissions through carbon sequestration it is central to consider the source of organic matter inputs, since they can come from other areas or systems. This report aims at the measurement of SOC stock changes and therefore the limits are given by a unit that is defined by the management and property rights. We define the system boundaries for this report as the managed plot. The plot can be scaled to the farm level.

Setting the field as the system boundary means that the biomass transfer from one field to another would mean a loss at the source and a gain at the target. This transfer has to be recorded in the field books "Schlagkartei". All analyses done at plot level would necessarily be open to public evaluation. Regulations need to be in place on how the data

are used and respect a certain level of confidentiality. This also affects the legal interpretation of property right and duties on soils.

The plot has the inhomogeneities described before. Remote sensing providing data of open soil, but also under vegetation, together with information from historic maps, geology and climate may provide the necessary input to divide a plot into homogenous subareas, that can be represented by one sample on the ground. With time, the data from remotes sensing will probably be more precise and ground based data need to be taken less often. So, it may be possible that a few reference points are measured precisely on a given field to calibrate the remote sensing information. The same observation points can be analysed again after a certain period of time.

Nailing down the plot as the system boundary also means that a farmer harvesting grass-clover on one field or cutting grass on permanent grass plots and feeding it to the livestock is transferring the manure to other fields. So, the fodder areas provide the feed to the cows, who produce the manure for fertilising the arable crops on other fields. For the estimate of leakage, there must be mechanisms in place for the repartition of the annually produced crop and biomass. In addition to the purchase of fodder and other inputs a tool to calculate inputs and fluxes on each plot of the farm has to be developed or adapted.

Modelling tools at scales of space and time are needed in the future to get hold of the system boundaries as well as of the carbon sequestration potentials on the various field areas considered homogenous that may be taken by remote sensing devices, but need to be compared to data taken on the ground by traditional soil analysis.

3.4 Realistic SOC sequestration rates and economic impacts

Sequestration rates from field trials in Switzerland may provide the attainable goals if a soil management can be maintained. In the DOK trial the largest SOC stock change occurred in the top 20 cm of the biodynamic farming system with a rate of $110 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ (Fliessbach *et al.*, in preparation). In the Frick trial running over 13 yrs, Krauss *et al.* (2017) measured differences in SOC stocks $362 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ (0-50 cm) between business as usual (plough 15 cm) and reduced tillage. On the plots of the field trials that had a size of 100 m^2 , 10-15 soil cores were used to form a composite sample. This sampling density will not be possible in compensation projects. Carbon sequestration is usually given in units equivalent to CO_2 so the values have to be multiplied with 3.67. The soils of biodynamic farming system then sequester $405 \text{ kg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ and the reduced tillage system has sequestered $1326 \text{ kg ha}^{-1} \text{ yr}^{-1}$ more CO_2 than the compared plough system. In a meta-analysis, Gattinger *et al.* (2012) showed that average sequestration rates of organically managed soils were $450 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ ($1.65 \text{ Mg CO}_2\text{eq.}$) higher than the ones under conventional management.

In conclusion, also well documented and measured field trials (e.g. DOK and Frick) have considerable variations in SOC sequestration rates, due to for instance differences in the clay content or the soil water content. For realistic SOC sequestration rates, also the

SOM/clay ratios needs to be taken into account (Johannes *et al.*, 2017), including limits for C-sequestration such as saturation levels for SOC (Six *et al.*, 2002). The sampling density has to be adapted to the variability of the field. It is vital to communicate that a specific soil material cannot sequester unlimited amounts of organic carbon in a stabilised form. All soil materials are characterised by a sequestration capacity that is reached at a given time. In addition, the sequestration capacity will be reached asymptotically, meaning the sequestration rate will decrease while approaching the sequestration capacity.

3.5 Conclusions

Measurement: In a homogenized sample the soil organic carbon (SOC) content can be measured at high precision and accuracy. SOC is composed of stable fractions that are protected from decomposition and labile or active fractions that are highly dynamic and take part in the element cycle. For the calculation of SOC stocks, the bulk density and the stone content of the soil have to be determined down to the required soil depth. However, the variability of SOC in samples taken at various locations in a field can be very high, both horizontally and vertically. In addition, SOC varies over time. Therefore, considering this uncertainty is a must in the development of new strategies for SOC stock monitoring in carbon trade or subsidy programmes (e.g. ÖLN). Spatial variability can be accounted for by combining standard analyses of soil samples with a mapping of field variability using spectroscopy. From the planned soil mapping programme, the infield spatial variability can be obtained to design sampling schemes. Defined monitoring sites can give the necessary information for the temporal variation.

The effect of a management change can be measured only several years later in comparison to the baseline or to a reference site where business as usual is continued. Empirical measures by Gubler *et al.* (2019) suggest a minimum detectable difference at an annual change of the soil organic carbon content of 0.35%, which corresponds to a change of 20 to 21.4 g SOC kg⁻¹ soil dry matter 20 years later (at a putative SOC content of 15 g kg⁻¹ and a bulk density of 1.25 Mg m⁻³, a change of 0.35% corresponds to 131 kg ha⁻¹ yr⁻¹). SOC stock changes in the DOK trial, simulating current farming practices, were found significant 6 to 16 years after the change of management and the data were based on highly precise and frequent sampling that are hardly possible for a nation-wide monitoring.

Reporting: With respect to the accounting of C-sequestration on a farmer's field, the effort for taking a mixed sample per field every five or ten years is feasible and the costs are acceptable. However, the precision will not be sufficient to prove a change. If compensation projects need measurements at short intervals (e.g. annual or triennial), the costs may approximate or even exceed the returns from carbon trades. This sampling system is principally in place already for the ÖLN subsidy requirement – it just needs to be standardized by a professional soil sampling, accurate soil analysis including bulk density and a consequent reporting of the SOC stock data including the geographical position to the government authorities. An improved ÖLN protocol will be able to collect

and evaluate data for SOC stocks to support the national carbon accounting and potentially detected changes can be reported back to the farmer. In this way, the evidence helps to adapt the management to enhance the C-sequestration further and simultaneously improve soil quality to fulfil the other requirements for carrying out soil functions and providing ecosystems services.

Verification: In addition to the repeated soil analyses remote sensing data need to be acquired to consider the spatial and temporal variation. High quality data from long-term trials, monitoring networks etc. and the increasing number of soil analyses on farmer fields are then serving as reference to improve the simulation of the spatio-temporal data and the modelling of SOC with easily available yield and organic fertilizer in- and output data from farmer field books, pedoclimatic observations and maps.

4. References

- Ackerson, J.P., Morgan, C.L.S., Ge, Y., 2017. Penetrometer-mounted VisNIR spectroscopy: Application of EPO-PLS to in situ VisNIR spectra. *Geoderma* 286, 131-138.
- Agroscope, 1996-2018. Referenzmethoden der Eidgenössischen landwirtschaftlichen Forschungsanstalten - 1. Bodenuntersuchung zur Düngeberatung. Zürich-Reckenholz.
- Agroscope, 2020a. Liste der anerkannten Laboratorien für die Kontrolle organischer Dünger. In: Agroscope (Ed.), Zürich.
- Agroscope, 2020b. Liste der für den ökologischen Leistungsnachweis zugelassenen und für Bodenuntersuchungen zur Düngeberatung empfohlenen Labors für die Anbauperiode 2020 / 2021. Zürich.
- Askari, M.S., O'Rourke, S.M., Holden, N.M., 2018. A comparison of point and imaging visible-near infrared spectroscopy for determining soil organic carbon. *Journal of near Infrared Spectroscopy* 26, 133-146.
- Baldock, J.A., Beare, M.H., Curtin, D., Hawke, B., 2018. Stocks, composition and vulnerability to loss of soil organic carbon predicted using mid-infrared spectroscopy. *Soil Research* 56, 468-480.
- Barthes, B.G., Chotte, J.L., 2020. Infrared spectroscopy approaches support soil organic carbon estimations to evaluate land degradation. *Land Degradation & Development*.
- Barthes, B.G., Kouakoua, E., Clairotte, M., Lallemand, J., Chapuis-Lardy, L., Rabenarivo, M., Roussel, S., 2019. Performance comparison between a miniaturized and a conventional near infrared reflectance (NIR) spectrometer for characterizing soil carbon and nitrogen. *Geoderma* 338, 422-429.
- Baumann, P., Helfenstein, A., Gubler, A., Keller, A., Meuli, R.G., Wächter, D., Lee, J., Viscarra Rossel, R., Six, J., 2021. Developing the Swiss soil spectral library for local estimation and monitoring. *SOIL Discuss.* 2021, 1-32.
- Braun, S., Hopf, S.-E., de Witte, L.C., 2018. Wie geht es unserem Wald? 34 Jahre Jahre Walddauerbeobachtung. IAP, Schönenbuch.
- Brown, D.J., Shepherd, K.D., Walsh, M.G., Mays, M.D., Reinsch, T.G., 2006. Global soil characterization with VNIR diffuse reflectance spectroscopy. *Geoderma* 132, 273-290.
- Buddenbaum, H., Steffens, M., 2011. Laboratory imaging spectroscopy of soil profiles. *Journal of Spectral Imaging* 2.
- Buddenbaum, H., Steffens, M., 2012. Mapping the distribution of chemical properties in soil profiles using laboratory imaging spectroscopy, SVM and PLS regression. *EARSeL eProceedings* 11, 25-32.

- Cambou, A., Cardinael, R., Kouakoua, E., Villeneuve, M., Durand, C., Barthès, B.G., 2016. Prediction of soil organic carbon stock using visible and near infrared reflectance spectroscopy (VNIRS) in the field. *Geoderma* 261, 151-159.
- Cañasveras, J.C., Barrón, V., del Campillo, M.C., Torrent, J., Gómez, J.A., 2010. Estimation of aggregate stability indices in Mediterranean soils by diffuse reflectance spectroscopy. *Geoderma* 158, 78-84.
- Capriel, P., 2010. Standorttypische Humusgehalte von Ackerböden in Bayern. In: Bayerische Landesanstalt für Landwirtschaft (LfL) (Ed.), LfL- Schriftenreihe 16, Freising-Weihenstephan, p. 46.
- Castaldi, F., Chabrillat, S., Jones, A., Vreys, K., Bomans, B., van Wesemael, B., 2018. Soil Organic Carbon Estimation in Croplands by Hyperspectral Remote APEX Data Using the LUCAS Topsoil Database. *Remote Sensing* 10.
- Castaldi, F., Hueni, A., Chabrillat, S., Ward, K., Buttafuoco, G., Bomans, B., Vreys, K., Brell, M., van Wesemael, B., 2019. Evaluating the capability of the Sentinel 2 data for soil organic carbon prediction in croplands. *Isprs Journal of Photogrammetry and Remote Sensing* 147, 267-282.
- Claïrotte, M., Grinand, C., Kouakoua, E., Thebault, A., Saby, N.P.A., Bernoux, M., Barthes, B.G., 2016. National calibration of soil organic carbon concentration using diffuse infrared reflectance spectroscopy. *Geoderma* 276, 41-52.
- Conen, F., Zerva, A., Arrouays, D., Jolivet, C., Jarvis, P.G., Grace, J., Mencuccini, M., 2005. The carbon balance of forest soils: detectability of changes in soil carbon stocks in temperate and boreal forests. In: Griffith, H., Jarvis, P. (Eds.), *The carbon balance of forest biomes*. Taylor & Francis, London, pp. 235-249.
- Deluz, C., 2019. Film: L'échantillonnage à la parcelle.
- Der Schweizerische Bundesrat, 2020. Bodenstrategie Schweiz für einen nachhaltigen Umgang mit dem Boden. In: Bundesamt für Umwelt (Ed.), Bern, p. 69.
- Dexter, A.R., Richard, G., Arrouays, D., Czyż, E.A., Jolivet, C., Duval, O., 2008. Complexed organic matter controls soil physical properties. *Geoderma* 144, 620-627.
- Diek, S., Fornallaz, F., Schaepman, M.E., De Jong, R., 2017. Barest Pixel Composite for Agricultural Areas Using Landsat Time Series. *Remote Sensing* 9, 1245.
- Dvorakova, K., Shi, P., Limbourg, Q., van Wesemael, B., 2020. Soil Organic Carbon Mapping from Remote Sensing: The Effect of Crop Residues. *Remote Sensing* 12.
- Ellert, B., Janzen, H., VandenBygaart, A., Bremer, E., 2008. Measuring change in soil organic carbon storage. In: Carter, M.R., Gregorich, E.G. (Eds.), *Soil sampling and methods of analysis*. Taylor & Francis, Boca Raton, FL, pp. 25-38.
- England, J.R., Viscarra Rossel, R.A., 2018. Proximal sensing for soil carbon accounting. *SOIL* 4, 101-122.
- Fang, Q., Hong, H.L., Zhao, L.L., Kukulich, S., Yin, K., Wang, C.W., 2018. Visible and Near-Infrared Reflectance Spectroscopy for Investigating Soil Mineralogy: A Review. *Journal of Spectroscopy*.
- FAO, 2020. A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes. In: FAO (Ed.), *GSOC-MRV Protocol*, Rome, p. 140.
- Flessa, H., Don, A., Jacobs, A., Dechow, R., Tiemeyer, B., Poeplau, C., 2019. Humus in landwirtschaftlich genutzten Böden Deutschlands - Ausgewählte Ergebnisse der Bodenzustandserhebung. In: Bundesministerium für Ernährung und Landwirtschaft (BMEL) (Ed.), *Thünen-Institut für Agrarklimaschutz*, Bonn, p. 48.
- Fliessbach, A., Bünemann, E., Mäder, P., 2020. Humus-Referenzwert für Ackerböden. p. 10.
- Fliessbach, A., Krause, H.-M., Stehle, B., Munyangabe, A., Steffens, M., Kuhn, A., Sauter, M., Mäder, P., in preparation. Change of soil carbon stocks and biological soil quality in the forty-

two-years-old DOK trial comparing organic and conventional farming. *Agriculture Ecosystems and Environment*.

- Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.L.V., Wilcox, J., del Mar Zamora Dominguez, M., Minx, J.C., 2018. Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters* 13, 063002.
- Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fließbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., Scialabba, N.E.-H., Niggli, U., 2012. Enhanced top soil carbon stocks under organic farming. *Proc. Nat. Acad. Sci. USA* 109, 18226-18231.
- Gholizadeh, A., Boruvka, L., Saberioon, M., Vasat, R., 2013. Visible, Near-Infrared, and Mid-Infrared Spectroscopy Applications for Soil Assessment with Emphasis on Soil Organic Matter Content and Quality: State-of-the-Art and Key Issues. *Applied Spectroscopy* 67, 1349-1362.
- Gholizadeh, A., Žižala, D., Saberioon, M., Borůvka, L., 2018. Soil organic carbon and texture retrieving and mapping using proximal, airborne and Sentinel-2 spectral imaging. *Remote Sensing of Environment* 218, 89-103.
- Grüneberg, E., Schöning, I., Riek, W., Ziche, D., Evers, J., 2019. Carbon Stocks and Carbon Stock Changes in German Forest Soils. *Status and Dynamics of Forests in Germany*. Springer, Cham, pp. 167-198.
- Gubler, A., Schwab, P., Wächter, D., Meuli, R.G., Keller, A., 2015. Ergebnisse der Nationalen Bodenbeobachtung (NABO) 1985-2009. Zustand und Veränderungen der anorganischen Schadstoffe und Bodenbegleitparameter. In: Bundesamt für Umwelt (Ed.), *Umwelt-Zustand. NABO*, Bern, p. 81.
- Gubler, A., Wächter, D., Schwab, P., 2018. Homogenisierung von Bodenkohlenstoff-Daten: Harmonisierung der Resultate aus Nassoxydation (FAL-Methode) und Trockenveraschung. In: Agroscope (Ed.), *Agroscope Science*. Agroscope, Zürich-Reckenholz.
- Gubler, A., Wächter, D., Schwab, P., Müller, M., Keller, A., 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.
- Hämmann, M., Desaulles, A., 2003. Probenahme und Probenvorbereitung für Schadstoffuntersuchungen in Böden - Handbuch Bodenprobenahme VBBo. In: Bundesamt für Umwelt, W.u.L.B. (Ed.), Bern, p. 90.
- Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil* 191, 77-87.
- Heanes, D.L., 1984. Determination of total organic - C in soils by an improved chromic acid digestion and spectrophotometric procedure. *Commun Soil Sci Plant Anal* 15, 1191-1213.
- Hermansen, C., Knadel, M., Moldrup, P., Greve, M.H., Gislum, R., de Jonge, L.W., 2016. Visible-Near-Infrared Spectroscopy Can Predict the Clay/Organic Carbon and Mineral Fines/Organic Carbon Ratios. *Soil Science Society of America Journal* 80, 1486-1495.
- Hermansen, C., Knadel, M., Moldrup, P., Greve, M.H., Karup, D., de Jonge, L.W., 2017. Complete Soil Texture is Accurately Predicted by Visible Near-Infrared Spectroscopy. *Soil Science Society of America Journal* 81, 758-769.
- Hobley, E., Steffens, M., Bauke, S.L., Kögel-Knabner, I., 2018a. Hotspots of soil organic carbon storage revealed by laboratory hyperspectral imaging. *Scientific Reports* 8, 13900.
- Hobley, E.U., Murphy, B., Simmons, A., 2018b. Comment on "Soil organic stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content" by Poeplau et al. (2017). *SOIL* 4, 169-171.

Hutengs, C., Seidel, M., Oertel, F., Ludwig, B., Vohland, M., 2019. In situ and laboratory soil spectroscopy with portable visible-to-near-infrared and mid-infrared instruments for the assessment of organic carbon in soils. *Geoderma* 355.

Jacobs, A., Flessa, H., Don, A., Heidkamp, A., Prietz, R., Dechow, R., Gensior, A., Poeplau, C., Riggers, C., Schneider, F., Tiemeyer, B., Vos, C., Wittnebel, M., Müller, T., Säurich, A., Fahrion-Nitschke, A., Gebbert, S., Hopfstock, R., Jaconi, A., Kolata, H., Lorbeer, M., Schröder, J., Laggner, A., Weiser, C., Freibauer, A., 2018. Landwirtschaftlich genutzte Böden in Deutschland - Ergebnisse der Bodenzustandserhebung. Thünen Rep. Johann Heinrich von Thünen-Institut, Braunschweig, p. 316.

Jaconi, A., Don, A., Freibauer, A., 2017. Prediction of soil organic carbon at the country scale: stratification strategies for near-infrared data. *Eur. J. Soil Sci.* 68, 919-929.

Jaconi, A., Vos, C., Don, A., 2019. Near infrared spectroscopy as an easy and precise method to estimate soil texture. *Geoderma* 337, 906-913.

Jenkinson, D.S., 1976. The effect of biocidal treatments on metabolism in soil-IV. The decomposition of fumigated organisms in soil. *Soil Biol. Biochem.* 8, 203-208.

Jenkinson, D.S., Powlson, D.S., 1976. The effects of biocidal treatments on metabolism in soil-V. A method for measuring soil biomass. *Soil Biol. Biochem.* 8, 209-213.

Jenkinson, D.S., Rayner, J.H., 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Sci.* 123, 298-305.

Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P.C., Boivin, P., 2017. Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? *Geoderma* 302, 14-21.

Jurgensen, M.F., Page-Dumroese, D.S., Brown, R.E., Tirocke, J.M., Miller, C.A., Pickens, J.B., Wang, M., 2017. Estimating Carbon and Nitrogen Pools in a Forest Soil: Influence of Soil Bulk Density Methods and Rock Content. *Soil Sci. Soc. Am. J.* 81, 1689-1696.

Kerven, G.L., Menzies, N.W., Geyer, M.D., 2000. Analytical methods and quality assurance. *Commun Soil Sci Plant Anal* 31, 1935-1939.

KIP c/o AGRIDEA, 2019. KIP-Richtlinien für den ökologischen Leistungsnachweis (ÖLN). Eschikon, Lindau.

Krauss, M., Ruser, R., Müller, T., Hansen, S., Mäder, P., Gattinger, A., 2017. Impact of reduced tillage on greenhouse gas emissions and soil carbon stocks in an organic grass-clover ley - winter wheat cropping sequence. *Agric. Ecosys. Environ.* 239, 324-333.

Lal, R., 2007. Soil Science and the Carbon Civilization. pp. 1425-1437.

Lehmann, J., Hansel, C.M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S., Nunan, N., Reichstein, M., Schimel, J.P., Torn, M.S., Wieder, W.R., Kögel-Knabner, I., 2020. Persistence of soil organic carbon caused by functional complexity. *Nature Geoscience* 13, 529-534.

Leifeld, J., Müller, A., Steffens, M., 2019. Kriterien für die Zertifizierung von Kohlenstoffsenken in Landwirtschaftsböden. *Agrarforschung* 10, 346-349.

Levasseur, C., Favrelière, E., Niederhäusern, A.v., 2019. Réseau fribourgeois d'observation des sols 1987 – 2016 Etat de Fribourg, Fribourg, p. 132.

Lobsey, C.R., Viscarra Rossel, R.A., 2016. Sensing of soil bulk density for more accurate carbon accounting. *Eur. J. Soil Sci.* 67, 504-513.

Lucas, M., Pihlap, E., Steffens, M., Vetterlein, D., Kögel-Knabner, I., 2020. Combination of Imaging Infrared Spectroscopy and X-ray Computed Microtomography for the Investigation of Bio- and Physicochemical Processes in Structured Soils. *Frontiers in Environmental Science* 8.

Ludwig, B., Murugan, R., Parama, V.R.R., Vohland, M., 2019. Accuracy of Estimating Soil Properties with Mid-Infrared Spectroscopy: Implications of Different Chemometric Approaches

and Software Packages Related to Calibration Sample Size. *Soil Science Society of America Journal* 83, 1542-1552.

Madhavan, D.B., Baldock, J.A., Read, Z.J., Murphy, S.C., Cunningham, S.C., Perring, M.P., Herrmann, T., Lewis, T., Cavagnaro, T.R., England, J.R., Paul, K.I., Weston, C.J., Baker, T.G., 2017. Rapid prediction of particulate, humus and resistant fractions of soil organic carbon in reforested lands using infrared spectroscopy. *J. Environ. Manage.* 193, 290-299.

Magid, J., Gorissen, A., Giller, K.E., 1996. In search of the elusive "active" fraction of soil organic matter: three size-density fractionation methods for tracing the fate of homogeneously ¹⁴C-labelled plant materials. *Soil Biol. Biochem.* 28, 89-99.

Magid, J., Müller, T., Jensen, J.S., Nielsen, N.E., 1997. Modelling the measurable: interpretation of field-scale CO₂ and N-mineralization, soil microbial biomass and light fractions as indicators of oilseed rape, maize and barley straw decomposition. In: Cadisch, G., Giller, K.E. (Eds.), *Driven by Nature - Plant Litter Quality and Decomposition*. CAB International, Wye College, University of London, UK, pp. 349-362.

Margenot, A., O' Neill, T., Sommer, R., Akella, V., 2020. Predicting soil permanganate oxidizable carbon (POXC) by coupling DRIFT spectroscopy and artificial neural networks (ANN). *Computers and Electronics in Agriculture* 168, 105098.

Maurer-Troxler, C., Chervet, A., Ramseier, L., Sturny, W.G., Oberholzer, H.-R., 2005. *Bodenbiologie nach zehn Jahren Direktsaat und Pflug. Agrarforschung* 12, 460-465.

Maurer, C., Sturny, W., Fliessbach, A., Mäder, P., Dierauer, H., 2016. Bodenleben aktivieren. *UFA Revue* 7-8, 34-35.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. *Geoderma* 292, 59-86.

Minu, S., Shetty, A., Minasny, B., Gomez, C., 2017. The role of atmospheric correction algorithms in the prediction of soil organic carbon from Hyperion data. *International Journal of Remote Sensing* 38, 6435-6456.

Montgomery, D.R., 2012. *Dirt: The Erosion of Civilizations*. University of California Press.

Mouazen, A.M., De Baerdemaeker, J., Ramon, H., 2005. Towards development of on-line soil moisture content sensor using a fibre-type NIR spectrophotometer. *Soil and Tillage Research* 80, 171-183.

Mouazen, A.M., Steffens, M., Borisover, M., 2016. Reflectance and fluorescence spectroscopy in soil science—current and future research and developments. *Soil Till. Res.*, 448-449.

Mueller, C.W., Steffens, M., Buddenbaum, H., 2019. Permafrost soil complexity evaluated by laboratory imaging Vis-NIR spectroscopy. *European Journal of Soil Science*.

Nawar, S., Mouazen, A.M., 2019. On-line vis-NIR spectroscopy prediction of soil organic carbon using machine learning. *Soil & Tillage Research* 190, 120-127.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 3 Chemical methods* 5, 961-1010.

Nocita, M., Stevens, A., van Wesemael, B., Aitkenhead, M., Bachmann, M., Barthès, B., Ben Dor, E., Brown, D.J., Clairotte, M., Csorba, A., Dardenne, P., Demattè, J.A.M., Genot, V., Guerrero, C., Knadel, M., Montanarella, L., Noon, C., Ramirez-Lopez, L., Robertson, J., Sakai, H., Soriano-Disla, J.M., Shepherd, K.D., Stenberg, B., Towett, E.K., Vargas, R., Wetterlind, J., 2015. Chapter Four - Soil Spectroscopy: An Alternative to Wet Chemistry for Soil Monitoring. In: Sparks, D.L. (Ed.), *Adv Agron. Academic Press*, pp. 139-159.

- O'Rourke, S.M., Holden, N.M., 2011. Optical sensing and chemometric analysis of soil organic carbon - a cost effective alternative to conventional laboratory methods? *Soil Use and Management* 27, 143-155.
- O'Rourke, S.M., Holden, N.M., 2012. Determination of Soil Organic Matter and Carbon Fractions in Forest Top Soils using Spectral Data Acquired from Visible-Near Infrared Hyperspectral Images. *Soil Sci. Soc. Am. J.* 76, 586-596.
- Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., Fernandez-Ugalde, O., 2018. LUCAS Soil, the largest expandable soil dataset for Europe: a review. *European Journal of Soil Science* 69, 140-153.
- Parton, W.J., Ojima, D.S., Schimel, D.S., 1996. Models to evaluate soil organic matter storage and dynamics. In: Carter, M.R., Stewart, B.A. (Eds.), *Structure and organic matter storage in agricultural soils*. Lewis Publ. CRC Press, Boca Raton, FL, pp. 421-448.
- Paul, S.S., Coops, N.C., Johnson, M.S., Krzic, M., Chandna, A., Smukler, S.M., 2020. Mapping soil organic carbon and clay using remote sensing to predict soil workability for enhanced climate change adaptation. *Geoderma* 363.
- Poeplau, C., Vos, C., Axel, D., 2017. Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. *Soil* 3, 61.
- Poggio, L., Vrščaj, B., 2009. A GIS-based human health risk assessment for urban green space planning—An example from Grugliasco (Italy). *Sci. Total Environ.* 407, 5961-5970.
- Poggio, L., Vrščaj, B., Hepperle, E., Schulin, R., Marsan, F.A., 2008. Introducing a method of human health risk evaluation for planning and soil quality management of heavy metal-polluted soils—An example from Grugliasco (Italy). *Landscape Urban Plan* 88, 64-72.
- Reeves, J.B., 2010. Near- versus mid-infrared diffuse reflectance spectroscopy for soil analysis emphasizing carbon and laboratory versus on-site analysis: Where are we and what needs to be done? *Geoderma* 158, 3-14.
- Reijneveld, A., van Wensem, J., Oenema, O., 2009. Soil organic carbon contents of agricultural land in the Netherlands between 1984 and 2004. *Geoderma* 152, 231-238.
- Riedel, F., Denk, M., Muller, I., Barth, N., Glasser, C., 2018. Prediction of soil parameters using the spectral range between 350 and 15,000 nm: A case study based on the Permanent Soil Monitoring Program in Saxony, Germany. *Geoderma* 315, 188-198.
- Riggers, C., Poeplau, C., Don, A., Frühauf, C., Dechow, R., 2021. How much carbon input is required to preserve or increase projected soil organic carbon stocks in German croplands under climate change? *Plant Soil*.
- Rose, B., 2020. The Soil Carbon Research Program (SCaRP). *CSIROPedia*.
- Rumpel, C., Amiraslani, F., Chenu, C., Garcia Cardenas, M., Kaonga, M., Koutika, L.-S., Ladha, J., Madari, B., Shirato, Y., Smith, P., Soudi, B., Soussana, J.-F., Whitehead, D., Wollenberg, E., 2020. The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio* 49, 350-360.
- Sanderman, J., Savage, K., Dangal, S.R.S., 2020. Mid-infrared spectroscopy for prediction of soil health indicators in the United States. *Soil Science Society of America Journal* 84, 251-261.
- Schreiner, S., Buddenbaum, H., Emmerling, C., Steffens, M., 2015. VNIR/SWIR Laboratory Imaging Spectroscopy for Wall-to-Wall Mapping of Elemental Concentrations in Soil Cores. *Photogrammetrie Fernerkundung Geoinformation*, 423-435.
- Schrumpf, M., Schulze, E.D., Kaiser, K., Schumacher, J., 2011. How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? *Biogeosciences* 8, 1193-1212.
- Schumacher, B.A., 2002. Methods for the determination of total organic carbon (TOC) in soils and sediments.

Sebag, D., Verrecchia, E.P., Cécillon, L., Adatte, T., Albrecht, R., Aubert, M., Bureau, F., Cailleau, G., Copard, Y., Decaens, T., Disnar, J.R., Hetényi, M., Nyilas, T., Trombino, L., 2016. Dynamics of soil organic matter based on new Rock-Eval indices. *Geoderma* 284, 185-203.

Segarra, J., Buchailot, M.L., Araus, J.L., Kefauver, S.C., 2020. Remote Sensing for Precision Agriculture: Sentinel-2 Improved Features and Applications. *Agronomy-Basel* 10.

Shi, P., Castaldi, F., van Wesemael, B., Van Oost, K., 2020a. Large-Scale, High-Resolution Mapping of Soil Aggregate Stability in Croplands Using APEX Hyperspectral Imagery. *Remote Sensing* 12.

Shi, P., Castaldi, F., van Wesemael, B., Van Oost, K., 2020b. Vis-NIR spectroscopic assessment of soil aggregate stability and aggregate size distribution in the Belgian Loam Belt. *Geoderma* 357.

Siewert, C., 2004. Rapid Screening of Soil Properties using Thermogravimetry. *Soil Sci. Soc. Am. J.* 68, 1656-1661.

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* 241, 155-176.

Smith, P., 2004. How long before a change in soil organic carbon can be detected? *Glob Change Biol* 10.

Smith, P., Smith, J.U., Powlson, D.S., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frohling, S., Gunnewick, H.K., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M., , A.P.W., 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long term experiments. *Geoderma* 81, 153-225.

Smith, P., Soussana, J.-F., Angers, D., Schipper, L., Chenu, C., Rasse, D.P., Batjes, N.H., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J.E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., Klumpp, K., 2020. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biol.* 26, 219-241.

Soriano-Disla, J.M., Janik, L.J., Allen, D.J., McLaughlin, M.J., 2017. Evaluation of the performance of portable visible-infrared instruments for the prediction of soil properties. *Biosystems Engineering* 161, 24-36.

St. Luce, M., Ziadi, N., Zebarth, B.J., Grant, C.A., Tremblay, G.F., Gregorich, E.G., 2014. Rapid determination of soil organic matter quality indicators using visible near infrared reflectance spectroscopy. *Geoderma* 232-234, 449-458.

Steffens, M., Buddenbaum, H., 2013. Laboratory imaging spectroscopy of a stagnic Luvisol profile - High resolution soil characterisation, classification and mapping of elemental concentrations. *Geoderma* 195-196, 122-132.

Steffens, M., Kohlpaintner, M., Buddenbaum, H., 2014. Fine spatial resolution mapping of soil organic matter quality in a Histosol profile. *Eur. J. Soil Sci.* 65, 827-839.

Steiger, U., Knüsel, P., Rey, L., 2018. Die Ressource Boden nachhaltig nutzen. *Gesamtsynthese des Nationalen Forschungsprogramms «Nachhaltige Nutzung der Ressource Boden»* (nfp 68). Bern.

Stenberg, B., Viscarra Rossel, R.A., Mouazen, A.M., Wetterlind, J., 2010. Chapter Five - Visible and Near Infrared Spectroscopy in Soil Science. In: Sparks, D.L. (Ed.), *Adv Agron.* Academic Press, pp. 163-215.

Stevens, A., Nocita, M., Tóth, G., Montanarella, L., van Wesemael, B., 2013. Prediction of Soil Organic Carbon at the European Scale by Visible and Near InfraRed Reflectance Spectroscopy. *PLOS ONE* 8, e66409.

- Stevens, A., Van Wesemael, B., Vandenschrick, G., Toure, S., Tychon, B., 2006. Detection of carbon stock change in agricultural soils using spectroscopic techniques. *Soil Science Society of America Journal* 70, 844-850.
- Taghizadeh-Toosi, A., Olesen, J.E., Kristensen, K., Elsgaard, L., Østergaard, H.S., Lægdsmand, M., Greve, M.H., Christensen, B.T., 2014. Changes in carbon stocks of Danish agricultural mineral soils between 1986 and 2009. *Eur. J. Soil Sci.* 65, 730-740.
- Tang, Y., Jones, E., Minasny, B., 2020. Evaluating low-cost portable near infrared sensors for rapid analysis of soils from South Eastern Australia. *Geoderma Regional* 20, e00240.
- Terhoeven-Urselmans, T., Michel, K., Helfrich, M., Flessa, H., Ludwig, B., 2006. Near-infrared spectroscopy can predict the composition of organic matter in soil and litter. *J. Plant Nutr. Soil Sci.* 169, 168-174.
- Terhoeven-Urselmans, T., Vagen, T.G., Spaargaren, O., Shepherd, K.D., 2010. Prediction of Soil Fertility Properties from a Globally Distributed Soil Mid-Infrared Spectral Library. *Soil Science Society of America Journal* 74, 1792-1799.
- Tiessen, H., Moir, J., 1993. Total and organic carbon. *Soil sampling and methods of analysis*, 187-199.
- Vanguelova, E.I., Bonifacio, E., De Vos, B., Hoosbeek, M.R., Berger, T.W., Vesterdal, L., Armolaitis, K., Celi, L., Dinca, L., Kjønaas, O.J., Pavlenda, P., Pumpanen, J., Püttsepp, Ü., Reidy, B., Simončič, P., Tobin, B., Zhiyanski, M., 2016. Sources of errors and uncertainties in the assessment of forest soil carbon stocks at different scales—review and recommendations. *Environmental Monitoring and Assessment* 188, 630.
- VBBio - BioSA (Ed), 2015. VBBio Bulletin BioSA.
<https://www.bafu.admin.ch/bafu/de/home/themen/boden/fachinformationen/massnahmen-fuer-den-bodenschutz/arbeitsgruppe-vollzug-bodenbiologie--vbb-.html>.
- Viscarra Rossel, R.A., Behrens, T., Ben-Dor, E., Brown, D.J., Dematte, J.A.M., Shepherd, K.D., Shi, Z., Stenberg, B., Stevens, A., Adamchuk, V., Aichi, H., Barthes, B.G., Bartholomeus, H.M., Bayer, A.D., Bernoux, M., Bottcher, K., Brodsky, L., Du, C.W., Chappell, A., Fouad, Y., Genot, V., Gomez, C., Grunwald, S., Gubler, A., Guerrero, C., Hedley, C.B., Knadel, M., Morras, H.J.M., Nocita, M., Ramirez-Lopez, L., Roudier, P., Campos, E.M.R., Sanborn, P., Sellitto, V.M., Sudduth, K.A., Rawlins, B.G., Walter, C., Winowiecki, L.A., Hong, S.Y., Ji, W., 2016. A global spectral library to characterize the world's soil. *Earth-Science Reviews* 155, 198-230.
- Viscarra Rossel, R.A., Bouma, J., 2016. Soil sensing: A new paradigm for agriculture. *Agric. Syst.* 148, 71-74.
- Viscarra Rossel, R.A., Hicks, W.S., 2015. Soil organic carbon and its fractions estimated by visible–near infrared transfer functions. *Eur. J. Soil Sci.* 66, 438-450.
- Viscarra Rossel, R.A., Lee, J., Behrens, T., Luo, Z., Baldock, J., Richards, A., 2019. Continental-scale soil carbon composition and vulnerability modulated by regional environmental controls. *Nature Geoscience* 12, 547-+.
- Viscarra Rossel, R.A., Lobsey, C.R., Sharman, C., Flick, P., McLachlan, G., 2017. Novel Proximal Sensing for Monitoring Soil Organic C Stocks and Condition. *Environmental Science & Technology* 51, 5630-5641.
- Viscarra Rossel, R.A., Webster, R., 2012. Predicting soil properties from the Australian soil visible-near infrared spectroscopic database. *European Journal of Soil Science* 63, 848-860.
- Viscarra Rossel, R.A., Webster, R., Bui, E.N., Baldock, J.A., 2014. Baseline map of organic carbon in Australian soil to support national carbon accounting and monitoring under climate change. *Global Change Biol.* 20, 2953-2970.
- Viscarra Rossel, R.A., Brus, D.J., 2018. The cost-efficiency and reliability of two methods for soil organic C accounting. *Land Degradation & Development* 29, 506-520.

- Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29-38.
- Wellbrock, N., Bolte, A., Flessa, H., 2016. Dynamik und räumliche Muster forstlicher Standorte in Deutschland: Ergebnisse der Bodenzustandserhebung im Wald 2006 bis 2008. Johann Heinrich von Thünen Institute, Federal Research Institute for Rural
- Wiesmeier, M., Mayer, S., Paul, C., Helming, K., Don, A., Franko, U., Steffens, M., Kögel-Knabner, I., 2020. CO₂-Zertifikate für die Festlegung atmosphärischen Kohlenstoffs in Böden: Methoden, Maßnahmen und Grenzen. *BonaRes Series 1*, 1-24.
- Wijewardane, N.K., Ge, Y.F., Wills, S., Loecke, T., 2016. Prediction of Soil Carbon in the Conterminous United States: Visible and Near Infrared Reflectance Spectroscopy Analysis of the Rapid Carbon Assessment Project. *Soil Science Society of America Journal* 80, 973-982.
- Wijewardane, N.K., Hetrick, S., Ackerson, J., Morgan, C.L.S., Ge, Y.F., 2020. VisNIR integrated multi-sensing penetrometer for in situ high-resolution vertical soil sensing. *Soil & Tillage Research* 199.
- Yuzugullu, O., Lorenz, F., Frohlich, P., Liebisch, F., 2020. Understanding Fields by Remote Sensing: Soil Zoning and Property Mapping. *Remote Sensing* 12.
- Zhou, T., Geng, Y.J., Chen, J., Pan, J.J., Haase, D., Lausch, A., 2020. High-resolution digital mapping of soil organic carbon and soil total nitrogen using DEM derivatives, Sentinel-1 and Sentinel-2 data based on machine learning algorithms. *Science of the Total Environment* 729.
- Zimmermann, M., Leifeld, J., Fuhrer, J., 2007. Quantifying soil organic carbon fractions by infrared-spectroscopy. *Soil Biology & Biochemistry* 39, 224-231.
- Zimmermann, M., Leifeld, J., Schmidt, M.W.I., Smith, P., Fuhrer, J., 2006. Measured soil organic matter fractions can be related to pools in the RothC model. *Eur. J. Soil Sci.* 58, 658-667.