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Abstract

Agricultural soils have a great potential for carbon (C) sequestration due to the build-up of soil organic matter (SOM), which consists of about 58% C. Positive efforts in SOM management could therefore make a significant contribution to climate protection. For farmers, CO_2 certificates for the build-up of soil organic carbon (SOC) represent an additional incentive to implement SOM-enhancing management measures. These CO_2 certificates are issued by private initiatives and companies in the voluntary CO_2 market. Especially in the field of agriculture, certificate trading for sequestered C in agricultural soils is currently growing in the German-speaking countries. In order to contribute to climate protection, certain criteria must be met when issuing certificates. In practice, however, minimum scientific standards have so far been given little consideration. In this study, recommendations are given regarding the quantifcation of SOC (sampling, analytics, SOC stock calculation), an evaluation of agricultural practices for C sequestration, as well as information on general limitations regarding climate protection via CO_2 certificates. Generally, CO_2-certificates can give a positive impulse for farmers to deal with sustainable cultivation and SOM supply of their soils. Since SOM is a key property for many soil functions and not least soil fertility, every effort to increase SOM is important. Farmers who are interested in building up SOC should therefore receive comprehensive support and advice on site-specific and farm-specific options for the sequestration of C in their soils.

Keywords Soil organic matter, climate change, carbon sequestration, organic fertilization, catch crops, biochar, reduced tillage, land-use change, agroforestry

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CO_2 certificates for carbon sequestration in soils: methods, management practices and limitations

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1. Introduction

The European Union has set itself the goal of achieving climate neutrality by 2050. In addition to a reduction of avoidable emissions of greenhouse gases (GHG), CO_2 sinks are necessary to compensate for unavoidable GHG emissions. Besides technical CO_2 sinks, the biological CO_2 sink potentials of oceans, plants and soils play a central role. Soils have a considerable potential for carbon (C) sequestration through their organic carbon (SOC) stocks. Globally, soils store at least twice as much C as is contained in the atmosphere in the form of CO_2 (Scharlemann et al., 2014). By building up soil organic matter (SOM), which consists of about 58% C, soils could play an important role in climate protection.

To strengthen the importance of soils as global carbon sinks, the "4 per 1000" initiative was launched at the World Climate Conference in Paris in 2015 (www.4p1000.org). This is a voluntary network to promote C sequestration based on the assumption that an annual increase of 0.4% in global SOC stocks could compensate the anthropogenic increase in atmospheric CO_2 concentrations.

In order to put C sequestration into practice, public or private incentive systems must be created that make C sequestration attractive for farmers. Private incentives include CO_2 certificates for the build-up of SOC ("humus certificates"). These CO_2 certificates are not part of the European Emissions Trading Scheme (EU-ETS), but are issued by private initiatives and companies in the voluntary CO_2 market. Especially in the field of agriculture, there are numerous companies that already issue CO_2 certificates for sequestered C in agricultural soils. However, little attention has been paid to scientific standards and effectiveness.

In the following chapters, we present an overview of the basics of C sequestration in soils, recommendations regarding the quantifcation of SOC (sampling, analysis, SOC stock calculation), an evaluation of agricultural practices fostering the build-up of SOC, as well as information on general limitations regarding climate protection via CO_2 certificates.

2. Basic principles of soil organic matter formation and C sequestration

SOC is the total organic C bound in the SOM. Organic matter can be present in many different forms and degrees of degradation in the soil at the same time, e.g. either as fresh harvest residues or microbially transformed components. SOM serves as a source of nutrients and energy for soil organisms and is successively broken down and metabolized by them. The SOC is either incorporated into new biomass or consumed by the organisms with the release of CO_2.

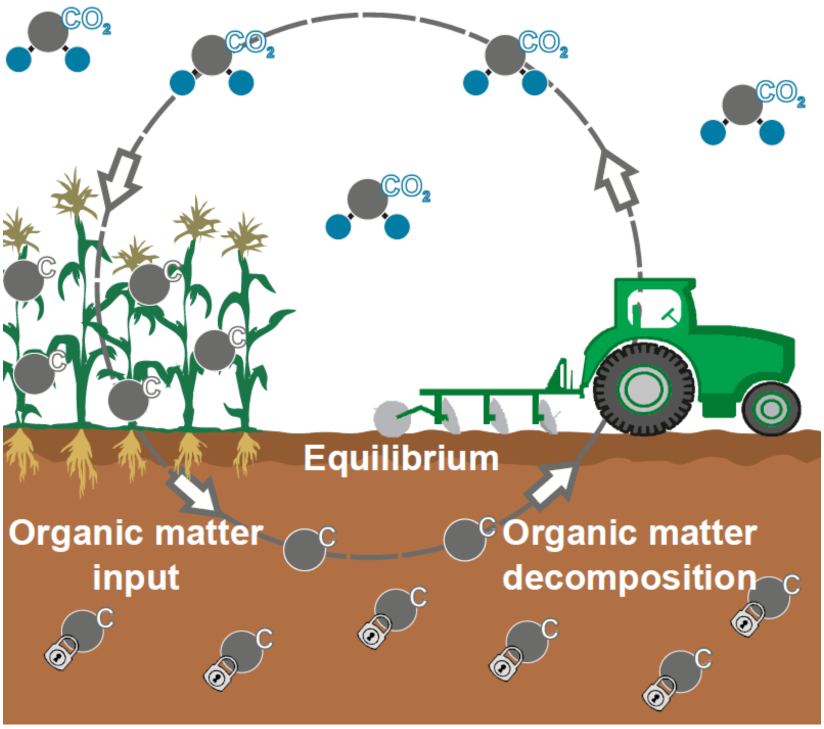

Figure 1: Under constant climatic and management conditions, the SOC stock approaches a long-term equilibrium of input (e.g. crop residues, organic fertilizers) and the decomposition of organic matter.

Various mechanisms result in SOC being protected from degradation in the short or long term. These mechanisms include

1) the inclusion in soil aggregates and thus a spatial separation of decomposers and organic matter
2) stabilization by binding to clay minerals or iron oxides, and

3) the preferential metabolism of easily degradable C compounds as opposed to more difficult to degrade aromatic compounds such as charcoal (recalcitrance) (von Lützow et al., 2006)

Under constant environmental conditions, the SOC stock approaches a long-term equilibrium of input (e.g. biomass from harvest residues, roots, organic fertilization) and the degradation of organic matter in the soil (Figure 1). This dynamic equilibrium can be changed by different measures and processes, for example by changes in cultivation or climate.

In order to store more organic carbon (OC) in the soil, not only the existing SOC must be preserved, but also more C from the atmosphere must be bound in the soil (C sequestration) (Chenu et al., 2019; Olson, 2013). Only an additional long-term sequestration of C from the atmosphere in the soil can compensate CO_2 emissions and thus have a positive effect on the climate. This process is explicitly area-bound, i.e. if SOC is redistributed e.g. by transfer of organic fertilizers or SOC-rich sediments from external areas, this does not constitute additional sequestration of C (Olson, 2013).

The build-up and decomposition of SOM occurs as nonlinear processes (Chenu et al., 2019; Poeplau et al., 2011) and the turnover rates are proportional to the amount of SOM. The quantitative relationship between turnover rate and SOM quantity is site-specific and e.g. higher in coarse-textured soils under warmer climates than in fine-textured soils and lower temperatures. In order to increase the SOC stock of a site to a higher level, the annual C input into the soil must be increased permanently (Figure 2). The intensity of SOC accumulation decreases over time, since an increase of SOC stocks also leads to increased degradation. The curve of SOC accumulation finally approaches a new equilibrium. This means that at the beginning the C supply is utilized much better, i.e. SOC accumulation is faster than shortly before reaching the new equilibrium (high effectiveness of C input). In order to keep the SOC stock constant at the new level, a higher C input than before the start of the measure must therefore be permanently maintained. The period until a new equilibrium is reached depends on the location and the management measure and can vary considerably.

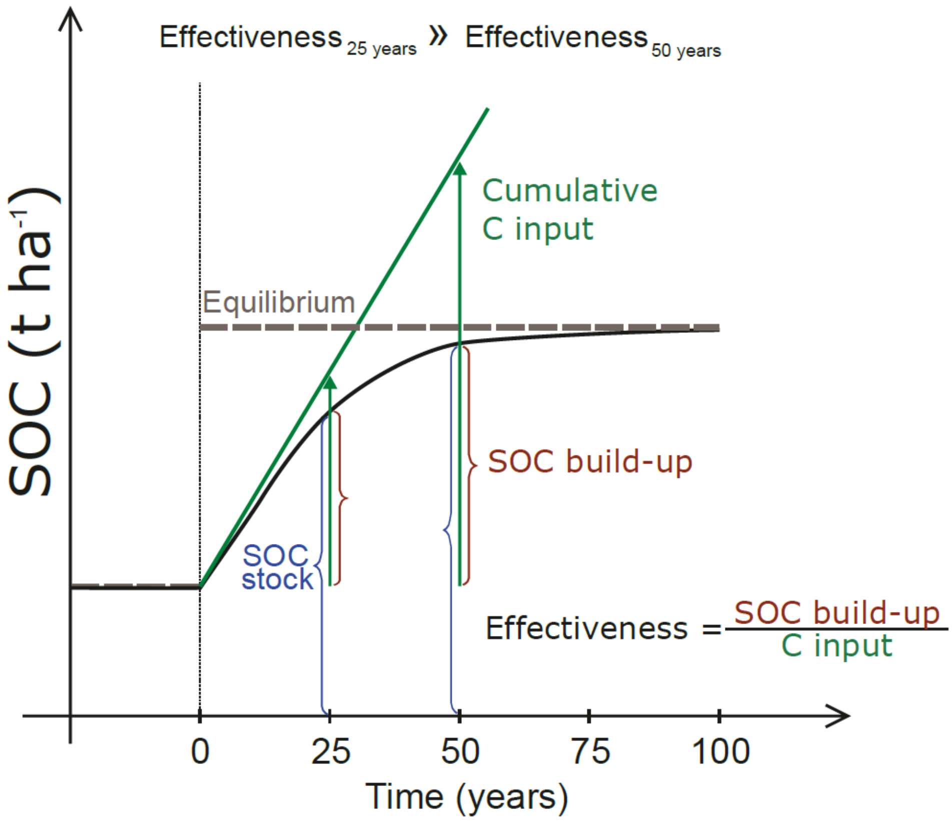

Figure 2: The non-linear relationship between C input and SOC build-up leads to a steadily decreasing effectiveness of SOC accumulation. The effectiveness of SOC accumulation results from the ratio of the SOC build-up to the C input.

Due to the different characteristics of different soils (parent material, texture, mineralogy etc.), soils have clearly different SOC storage potentials, which cannot be compensated even with optimized management. In general, fine-textured soils with high silt and clay contents can store higher SOC stocks than coarse-textured soils.

3. Quantification of SOC stock changes

The methodological approach for determination of SOC stocks presented here is essentially based on the standards of the VDLUFA for the investigation of soils (VDLUFA, 1991), a guide to soil sampling, published by the Bavarian State Research Center for Agriculture (Bayerische Landesanstalt für Landwirtschaft, 2009), and the respective DIN standards.

Soil sampling

For a quantitative determination of SOC stocks (unit kg m^{-2} or t ha^{-1}), a representative sampling of the area is carried out, followed by the measurement of the SOC content and the determination of the bulk density (dry bulk density) in the laboratory.

As in the context of CO_2 certificates the SOC changes are determined for individual, uniformly managed plots, the sampling must be carried out for each plot. A representative mixed sample should be taken from at least 15 locations per hectare distributed over the field (VDLUFA, 1991). The advantage of the mixed sample is that the analysis is less expensive than several individual samples and it still takes into account the heterogeneity of the SOC contents on the field. However, the heterogeneity of the SOC contents within a field cannot be quantified with this method (e.g. by means of the statistical standard deviation).

Sampling should be carried out either in spring (in arable soils preferably in winter crops) before tillage and fertilisation, or in autumn. If soil cultivation or fertilization has already been carried out, it is absolutely necessary to observe a large time interval (at least 6 weeks), otherwise the results of the determination of the bulk density and the SOC contents will be biased.

In arable soils, the sampling depth should be based on the tillage depth (usually 20-30 cm); a standardized sampling depth of 25 cm is recommended. This depth must also be adhered to when switching to reduced tillage systems with reduced tillage depths, otherwise the results may be misinterpreted. The sample must either be sent immediately to the laboratory for analysis or immediately air-dried (≤60 °C).

Repeated sampling is necessary to detect changes of SOC stocks. Since there can be a high spatial variability of SOC at the field scale, the locations of initial sampling have to be re-sampled as exactly as possible under identical field conditions (especially with regard to soil moisture). An exact documentation of the sampling in a protocol is therefore recommended. However, since changes of SOC stocks occur slowly, re-sampling is considered to be useful after 3 to 5 years at the earliest.

Determination of SOC, bulk density and rock fragments

The SOC content (mass % or mg g^{-1}) of the sample is determined on the fine soil (<2 mm). It is the difference between the total C (C_{tot}) and the inorganic C content (C_{inorg}) of the fine soil (equation 1):

$$\mathrm{SOC} = \mathrm{C_{tot}} - \mathrm{C_{inorg}} \text{ (equation 1)}$$

For this purpose, C_{tot} is determined by combustion at up to 1,500 °C in CN analyzers (DIN EN 15936:2012-11). The inorganic C content is determined by gas volumetry (DIN EN ISO 10693:2014-06; ISO 10693:1995).

The determination of the bulk density (see equation 2) is usually carried out on undisturbed samples using steel cylinders (DIN EN ISO 11272:2017-07). However, other sampling devices with a known volume are also suitable, provided that intact, undisturbed soil samples can be taken with them.

The rock fragment content of the sample (stones and fragments >2 mm particle size), is an important factor for the calculation of SOC stocks (equation 2). At the same time its determination is connected with considerable effort and uncertainties (taking and sieving of larger sample quantities or estimation at the profile wall of a soil profile). With rock fragment contents <5 vol%, which is to be expected in the topsoil of most of the German agricultural soils (Poeplau et al., 2017), rock fragments can be neglected in the calculation of SOC stocks.

SOC stock calculation

In order to determine the amount of SOC stored in the soil, it is necessary to normalize the SOC content of the fine soil to a certain volume or area unit of soil. For this purpose, the SOC stock is calculated taking into account the bulk density as well as the rock fragment content (Hobley et al., 2018; Poeplau et al., 2017) (equation 2):

$$\mathrm{SOC}_{stock} = \mathrm{SOC}_{\mathrm{content}} \times \mathrm{BD} \times \mathrm{depth} \times (1 - \mathrm{RF}) \times 100 \text{ (equation 2)}$$

The SOC_{stock} (kg m^{-2}) depends on the $SOC_{content}$ of the fine soil (mg g^{-1}), the bulk density of the sample (BD, g cm^{-3}), the sampling depth (depth, cm) and the rock fragment content (RF, g kg^{-1}). An initial determination of the bulk density as well as at least an estimation of the rock fragment content is essential for a correct SOC inventory. An estimation of the bulk density from pedotransfer functions is error-prone and should therefore be avoided (Wiesmeier et al., 2012). In the case of repeated sampling, it is not necessary to determine the bulk density and rock fragment contents again; only the SOC content needs to be determined. The SOC stock calculation is performed using the initial values for bulk density and rock fragment content and thus follows the principle of equivalent soil masses (Ellert & Bettany, 1995; Wendt & Hauser, 2013).

The conversion of SOC stocks into CO_2 equivalents is derived from the mass ratio of the element C in the CO_2 molecule (equation 3):

$$\text{conversion factor} = \frac{\text{molar mass}_{\mathrm{CO_2}}}{\text{molar mass}_{\mathrm{C}}} = \frac{44 \text{ g mol}^{-1}}{12 \text{ g mol}^{-1}} \approx 3.67 \text{ (equation 3)}$$

Uncertainties

Measurement uncertainties in the form of random errors cannot be completely ruled out even when working carefully and include e.g. the smallest fluctuations in the measurement process or errors due to the heterogeneity of soils. These can be minimized by repeating measurements or mixed samples. It is therefore all the more important to distinguish an actual increase in SOC stocks from natural fluctuations or random measurement errors.

Trends in SOC stocks can be identified at the earliest by means of two data points and can be statistically tested using three data points.

The question of whether SOC stocks show an actual increase over time can formally be expressed in statistical terms by the hypothesis: "The slope of the regression line from SOC stock (y) and time (x) differs significantly from 0". This hypothesis can be statistically tested by means of a t-test procedure (if more than two samples were taken), which is only permissible, though, under the conditions of normal distribution, linearity, independence and variance homogeneity of the data. However, the result of a statistical evaluation based on three data points is very likely to lead to a misinterpretation due to the low statistical power at n = 3. The principle applies that the greater the number of observations, the greater the statistical power. Therefore, more data points would be necessary for a statistically verifiable statement as to whether there is a significant increase in SOC stocks over time (Leifeld et al., 2019). This in turn requires both repeated measurements and time.

4. Suitability of managament practices for C sequestration

In the following section, management practices are assessed that could lead to an increase of SOC stocks in agricultural soils and are therefore relevant in the context of CO_2 certificates. The mentioned mean C sequestration rates are linearly determined values from controlled field experiments and managed agricultural fields, which were taken from the literature. They can serve as average values for the temperate zone.

Improved crop rotations/permanent crops

The design of crop rotations is a central measure to increase SOC stocks in arable soils. The cultivation of legumes, crops with a dense and deep root system and perennial crops lead to an increase of SOC stocks. The observed C sequestration rates are highly variable depending on the crop and range from 0.15 to 0.36 t ha^{-1} yr^{-1} (Bolinder et al., 2012; West & Post, 2002).

The integration of catch crops such as intercrops or undersown crops into the rotation for use as green manure or animal feed results in an additional input of organic matter into arable soils and a corresponding increase of SOC stocks. In an annual catch crop cultivation with green manure an average of 0.32 t SOC ha^{-1} a^{-1} is built up (Poeplau & Don, 2015). In addition, catch crops and undersown crops offer a number of other advantages such as reduced erosion, weed control, promotion of biodiversity, nutrient binding after the main crop and thus reduced nitrate leaching.

Harvest residue management

The retention or increased recycling of crop residues increases the input of organic matter into soils and thus leads to an increase of SOC stocks. In particular, the increased retention of aboveground crop residues such as straw, stubble or beet leaves or a return in the form of manure, slurry or digestate plays a central role. The accumulation of crop residues can be optimized by the choice of varieties and a high yield potential. However, the energetic use of crop residues can be more advantageous in terms of climate protection than their retention on agricultural land with the aim of increasing SOC (Powlson et al., 2008). The energetic use of harvest residues in biogas plants and a return of the digestate can contribute to the SOM balance to a similar extent as leaving the harvest residues on the land, since fermentation residues have a relatively high SOM reproduction potential (Burmeister et al., 2019). However, a choice among possible pathways for the use of harvest residues should not only be made with regard to the climate protection effects, but should also include other aspects such as effects on soil structure, flora and fauna.

Land use changes

Since grassland soils have significantly higher SOC stocks than arable soils, mainly due to higher root-derived C-inputs, a conversion from cropland to grassland is a very effective measure to increase SOC stocks. In the long run, a mean SOC build-up of 0.73 t ha^{-1} yr^{-1} can be expected from a conversion of arable land to grassland (Conant et al., 2001; Poeplau et al., 2011). There are further advantages in terms of water protection and erosion control as well as the promotion of biodiversity. However, in cases when the expansion of permanent grassland induces an increase in livestock numbers, GHG emissions would significantly increase, which would reduce or cancel out the climate impact of the additional C sequestration in the soil.

Reforestation of arable land also leads to a significant enrichment of SOC by an average of 0.79 t ha^{-1} yr^{-1} (Poeplau et al., 2011). However, about one third of SOC is bound in the litter layer of afforested forests and thus susceptible to disturbance. Moreover, the loss of agricultural land can lead to leakage effects when comsumption remains constant (see Chapter 5). On average, afforestation of grassland does not lead to significant changes in SOC stocks.

Agroforestry systems

Agroforestry systems are land use systems that occur globally in various forms and combine woody species with agricultural land. In Germany, agroforestry has so far only been widespread in the form of traditional systems such as hedges and orchard meadows; modern energy or high grade wood systems are not yet in use. In addition to various positive environmental effects in terms of erosion control, increased habitat diversity and biodiversity, and an improved microclimate, agroforestry systems can make an important contribution to climate protection by fixing atmospheric C in the woody biomass and soil. Studies on temperate agroforestry systems show an average SOC build-up of 0.68 t ha^{-1} yr^{-1} (Cardinael et al., 2017; Cardinael et al., 2019; De Stefano & Jacobson, 2018; Shi et al., 2018). However, on average, no additional SOC storage was found when establishing short rotation coppices in Germany (Walter et al., 2015). In general, the establishment of agroforestry systems on arable land is much more effective than on grassland, since only a small additional C fixation in the soil is expected due to the high SOC stocks in grassland soils.

Organic fertilization/Compost

By applying organic fertilizers such as manure, slurry, digestate and compost, C and nutrients removed during harvesting are returned to the agricultural land. Organic fertilization is thus a central component of a SOM balance and sustainable land use in terms of nutrient recycling. In doing so, the requirements of the fertilization legislation in Germany must be complied with and a high nutrient use efficiency should always be aimed at for economic and ecological reasons. The use of organic fertilizers can reduce the use of mineral fertilizers, whose production is very energy-intensive.

However, the use of external C sources for the build-up of SOC does not represent a contribution to climate protection, as SOC is merely relocated and locally concentrated, provided that the total amount of organic fertilizers (manure, compost etc.) remains the same. This relocation reduces the SOM reproduction potential of the areas from which the external organic matter originates. Such a spatial shift can contribute to climate protection if the export of organic fertilizers from regions with nutrient surpluses leads to a more efficient use of nutrients (Don et al., 2018). However, a spatial shift of C sources for SOM formation cannot be recognized as a contribution to climate protection in the context of CO_2 certificates. Only in the case of an increase in yield due to the promotion of soil fertility through organic fertilization can an increased fixation of atmospheric C occur indirectly (Sykes et al., 2019). However, this is difficult to distinguish from the direct increase of SOC stocks due to the applied organic fertilizers.

Biochar

Biochar is an organic substance that is thermally converted by pyrolysis and is mainly used as a soil additive to improve soil fertility and as an additive to slurry. In addition, substrates with high residual water contents can be turned into lignite-like products called HTC coals by hydrothermal carbonization (HTC) under high pressure and significantly lower temperatures. With regard to an additional C fixation in the soil by biochar, its stability towards degradation is decisive, which depends largely on the production conditions, especially the pyrolysis temperature. Biochars produced at temperatures >450 °C generally have a high stability and therefore contribute to C fixation in the soil (Crombie and Masek, 2015). However, spatial redistribution effects of organic matter analogous to organic fertilizers have to be taken into account, so that the suitability of biochar in the context of CO_2 certificates is extremely limited. HTC coals are also characterized by a much lower stability against degradation and are therefore not suitable for long-term C fixation (Bach, 2017).

In Germany, only biochar from untreated wood with a C content of at least 80% is permitted under fertilizer legislation. In principle, only biochar certified with the European Biochar Certificate (EBC) should be used to ensure that the soil is not contaminated with organic and/or inorganic pollutants. Reliable C sequestration rates cannot be derived for Germany due to a lack of long-term tests under practical conditions. They would also dependend on the amount of biochar applied.

It should be noted that the availability of suitable residues for biochar production is very limited (Teichmann, 2014). Substrates with high nutrient contents such as slurry or digestate are not suitable and not permitted for biochar production. In addition, relevant soil-improving effects or an increase in yield have so far only been demonstrated on tropical soils, but not in temperate regions (Jeffery et al., 2017). There are therefore doubts about the benefits of applying relatively expensive biochar in agriculture (Teichmann, 2014).

Reduced tillage

Reduced tillage systems are essential components of effective erosion control and can have advantages in terms of soil structure, water holding capacity and soil macrofauna. However, an increase of SOC stocks cannot generally be achieved by reduced tillage, only a vertical redistribution of SOC in the topsoil. A reduction of the tillage depth leads to an increase of SOC in the upper topsoil (usually in 0-10 cm), because the input of organic matter is concentrated in this depth. However, in the lower topsoil the SOC stock decreases because the input of organic matter is reduced (except for root-derived inputs).

In sum, even after decades of observation there are in most cases no significant changes of SOC stocks compared to conventional tillage systems (Powlson et al., 2014). In addition, depending on the soil type, a permanent lack of tillage can lead to increased nitrous oxide (N_2O) emissions due to higher bulk density. Only if reduced tillage is accompanied by an increase in yields and thus an increase in the amount of crop residues, reduced tillage can indirectly lead to increased SOC stocks.

5. Limitations

The sequestration of C in soils differs in some important aspects from climate compensation measures that aim at reducing emissions. For example, the positive climate impact of C sequestration in soils is based on the one-time replenishment of a C reservoir and is therefore limited. The larger the remaining free storage capacity, the greater the achievable climate impact, which has implications for questions of fairness. Emission reductions can have cumulative effects. Therefore, reductions at an early point of time are more advantageous from a climate perspective than later ones. However, this is not the case with SOM accumulation. This makes it difficult to assess the additionality of measures. In contrast to avoided emissions, SOM accumulation is also reversible, which makes it necessary to ensure the permanence of the positive climate impact. The consequences of these differences are discussed below.

Fairness

The potential for C sequestration is greatest in soils where the SOC content is low as a result of the previous management practices (Galati et al., 2016). Therefore, farmers whose long-time management reduced SOC stocks could benefit most from a certification of increasing SOC stocks, while farmers who have successfully built up SOC in their soils could benefit little or not at all. Climate protection measures already implemented by the latter group would therefore not be rewarded. Farmers should be advised in advance on the expected effectiveness of agricultural measures for C sequestration on their land (see Figure 2).

Permanence

Contrary to a direct avoidance of GHG emissions, the increase of SOC as a climate protection measure is only effective if the C storage is permanent and the corresponding amount of CO_2 is thus removed from the atmosphere for the foreseeable future. However, the positive effect of a SOC build-up is completely reversible. Losses of sequestered C by the described measures (see chapter 4) can occur both through external influences, such as climate change, or through another change of management. If certificates are used to offset unavoidable emissions in other sectors, farmers would therefore have to make a permanent commitment to maintain SOC-increasing farming measures or otherwise offset later re-emissions by purchasing other certificates (Thamo & Pannell, 2016). Theoretically, such a commitment would even have to include a perpetuity clause, as the effect of the certificate can be completely cancelled out even if a change of cultivation takes place much later. So far, there are no reliable forecasts of how SOC contents will change solely as a result of recent and expected climate changes. Additionally stored SOC could be lost due to these changes even without the intervention of land managers.

Nitrogen emissions

In addition to C, SOM also contains nutrients such as nitrogen (N) and therefore makes an important contribution to plant nutrition through its turnover. However, this only applies as long as the growing plant stock absorbs the nutrients released. In the long term, readily available SOM can lead to increasing N_2O emissions (Lugato et al., 2018). In the case of very high SOM stocks and associated high turnover rates, an excess of mineral N can occur, depending on temperature, pH, soil moisture and/or texture, so that negative consequences for the environment cannot be ruled out. However, a SOC build-up can have a positive climate protection effect over several decades until rising N_2O emissions may reverse the effect and soils become GHG sources (Lugato et al., 2018).

Additionality

According to current definitions, emission compensations must meet the criterion of additionality (Leifeld et al., 2019). Accordingly, actions that are taken or omitted anyway cannot be considered as compensation. SOM building measures that are usually carried out anyway within the framework of the respective cultivation system (conventional or organic) therefore do not constitute compensations. For additionality, SOC should be built up through measures motivated and financed by the CO_2 certificates. Double funding should be avoided, as it would reduce the efficiency of the funds for climate protection. Additionality may only be assumed if the corresponding measures would be uneconomic without financial support. However, even in this case, additionality is not always given, as farmers are guided in their management decisions not only by economic but also by social considerations (Bartkowski & Bartke, 2018; Thamo & Pannell, 2016).

Measures that fulfill the criterion of additionality at one point in time may also not fulfill it anymore at a later stage. To assess the climate impact of a measure, additionality must be considered retrospectively (Thamo & Pannell, 2016). If, for example, certificates issued in 2020 enabled the introduction of SOC-increasing management that would otherwise not have been economical, they would build up a SOC stock that is initially considered additional. However, if in the following years technical progress makes these or equivalent practices profitable and widely applied even without subsidies, the benefit of the CO_2 certificates for climate protection would be cancelled out. With or without certificates, the same SOC stock would be built up in the long term.

Leakage effects

Measures that greatly reduce agricultural productivity (such as the large-scale conversion of arable land into short rotation coppices) can contribute to indirect land use change (Leifeld et al., 2019). If forests and savannahs in other world regions are converted to arable land as a result of an emerging imbalance between supply and demand for agricultural products, it results in very high GHG emissions with negative impacts for the overall climate effect of climate protection measures (Searchinger et al., 2008).

If only part of the farms in a region or part of the land on a farm participate in SOM management rewarded by CO_2 certificates, there is a risk that SOC-building measures will be concentrated on these areas (e.g. the cultivation of catch crops, the application of organic fertilizers), but appropriate management on the remaining areas will be reduced (Leifeld et al., 2019). If the total amount of positive measures remains the same on the farm or in the region, no positive climate impact is to be expected.

If, on the other hand, the quantity or intensity of SOC-building measures increases (e.g. more catch cropping), the associated emissions must also be deducted from the positive climate effect of SOC build-up. Depending on the ratio of positive and negative climate impacts, this sooner or later leads to an overall negative climate impact (Thamo & Pannell, 2016).

Trade-offs with other targets

For an overall assessment of the suitability of SOC-building measures to compensate for GHG emissions, not only the intended climate impact but also additional positive (synergies) and negative (trade-offs) effects on societal targets must be taken into account.

Possible synergies include an increase in yield stability and biological activity in the soil, as well as an increase in above-ground biodiversity through extended crop rotations and agroforestry systems, a reduction in the mineral N fertilizer requirement through legumes, as well as a reduction in soil erosion through increased use of catch crops and reduced tillage. In addition, there is an improved water infiltration and water storage capacity of SOM-rich soils, so that SOC build-up is also considered an important adaptation measure to periods of drought and more frequent heavy rainfall (Hamidov et al., 2018).

The biggest trade-off under current market conditions is reduced economic return. Almost all of the measures discussed to increase SOC stocks reduce the economic return for farmers under the current price system of agricultural products. This is exactly where certificates can come into play.

Currently, there are also discussions about implementing financial incentives for improved ecosystem services of modified cultivation systems, which are associated with the build-up of SOM, as part of the reform of the Common Agricultural Policy (CAP). The Swiss agricultural policy is taking a similar approach by attempting to put ecosystem services of agriculture into market values as part of the recently presented Agricultural Policy 2022 (AP22+). This could shift the pricing system in such a way that SOC-promoting cultivation methods with positive ecological side effects become economically viable under certain conditions.

Other possible trade-offs are an increase in N_2O emissions with increasing SOC content in the soil (Gu et al., 2017) and a reduction in biomass production for food and energy when converting to organic farming.

6. Summary

CO_2 certificates can provide a positive impetus for farmers to focus on sustainable cultivation and SOM supply of their soils. Since SOM is the key property for many soil functions, not least soil fertility, every effort to increase SOC is worthwhile. In order to contribute to climate protection, however, certain criteria must be met when awarding certificates.

In particular, shifting effects in the form of GHG emissions between locations must be avoided and emissions generated by the climate protection measures themselves must be taken into account. Furthermore, the permanence of the sequestered C in soils must be ensured. The latter can be achieved e.g. by building up SOC in specially protected ecosystems (e.g. hedges or permanent grassland), which can reduce potential losses of increased SOC stocks. In addition, CO_2 certificates should be designed in such a way that they do not reward measures that usually only lead to a redistribution of SOC, but not to an additional sequestration of atmospheric C (e.g. application of compost).

The proof of a SOC build-up is costly and requires in addition to a representative sampling an exact determination of the SOC content as well as an at least one-time determination of the bulk density and the rock fragment content. A change in the tillage depth, however, can lead to misinterpretations, even with proper sampling. Farmers who are interested in SOC build-up should be supported and advised comprehensively regarding site- and farm specific options for the sequestration of C in their soils.

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