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RESEARCH ARTICLE

SOIL CARBON CHECK: A TOOL FOR MONITORING AND GUIDING SOIL CARBON SEQUESTRATION IN FARMER FIELDS

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KEYWORDS

4 per 1000 initiative, carbon sequestration, climate action, farmer fields, SDG13, soil organic carbon, soil testing

HIGHLIGHTS

- Establishment of a rapid tool for monitoring soil carbon sequestration in farmer fields.
- Novel linkage of multiconstituent soil analyses with a carbon mineralization model.
- Extensive calibration and validation of the results of the near-infrared spectroscopy NIRS analyses.
- Soil bulk density derived from NIRS analyses and pedotransfer functions.

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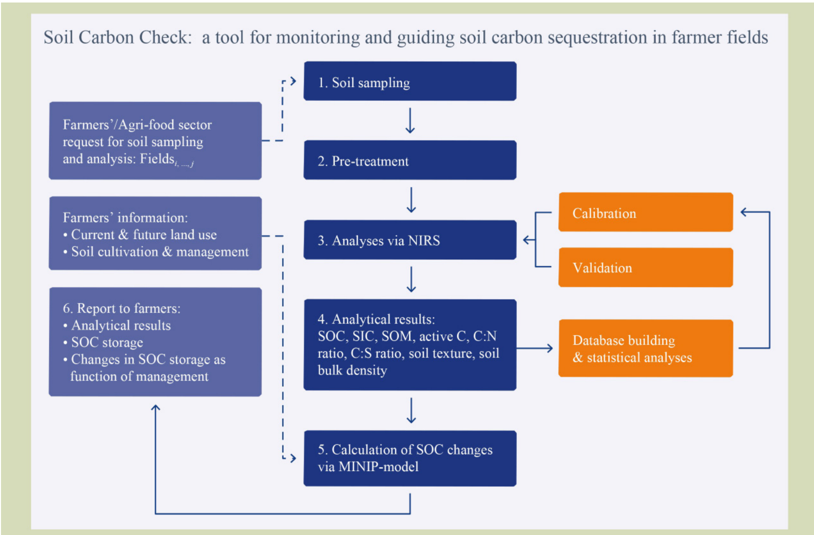
GRAPHICAL ABSTRACT



ABSTRACT

In 2015, 17 Sustainable Development Goals (SDGs) were approved, including SDG13, which addresses actions to increase carbon capture (CO_2-C storage) for climate change mitigation. However, no analytical procedures have been defined for quantifying soil organic carbon (SOC) sequestration. This paper presents a rapid tool for guiding farmers and for monitoring SOC sequestration in farmer fields. The tool consists of multiconstituent soil analyses through near-infrared spectroscopy (NIRS) and an SOC mineralization model. The tool provides forecasts of SOC sequestration over time. Soil analyses by NIRS have been calibrated and validated for farmer fields in European countries, China, New Zealand, and Vietnam. Results indicate a high accuracy of determination for SOC ($R^2 \geqslant 0.93$), and for inorganic C, soil texture, and soil bulk density. Permanganate oxidizable soil C is used as proxy for active SOC, to detect early management-induced changes in SOC contents, and is also quantified by NIRS ($R^2 = 0.92$). A pedotransfer function is used to convert the results of the soil analyses to SOC sequestration in kg·ha^{-1} C as well as CO_2. In conclusion, the tool allows fast, quantitative, and action-driven monitoring of SOC sequestration in farmer fields, and thereby is an essential tool for monitoring progress of SDG13.

1 INTRODUCTION

Soil organic matter (SOM) is generally considered a pivotal constituent of soil fertility and soil health[1–4]. Thus increasing SOM content is often seen as a desirable objective in agriculture[5,6] since increasing SOM has many benefits including: (1) improving the capacity of a soil to bind, exchange and deliver essential nutrients[7,8], (2) increasing the capacity of a soil to bind water[9], (3) increasing soil biodiversity and thereby the disease suppressiveness against soilborne plant pathogens[10], and (4) improving soil structure, thus giving plant roots and soil life improved living conditions, and farmers improved soil cultivation conditions. Organic matter consists of variable fractions of carbon, oxygen, hydrogen, nitrogen, phosphorus and sulfur[11], and part of its benefits for soil health arises from its decomposition[12,13], during which N, P and S are released and become available for plant nutrition.

In 2015, the General Assembly of the United Nations approved 17 Sustainable Development Goals (SDGs), to address the main global challenges for sustainable development. SDG13 addresses climate action, i.e., decreasing greenhouse gas emissions and increasing carbon capture for climate change mitigation, and improved adaptation to climate change. Thus, sequestration of C in soils is also promoted as strategy to address SDG 13. Also, the dynamics of organic matter have significant functions for food production and quality (SDGs 2 and 3), water quality (SDG 6), biodiversity and soil health (SDG 15)[12,14,15].

On a global scale, about 1500 Pg C (1 Pg = 10^{15} g) is stored in the upper meter of the soil. This amount is about three times the amount of C in the aboveground biomass and twice the amount of C as CO_2 in the atmosphere[12,16]. More carbon in the soil means less CO_2 in the atmosphere. This principle is the background of the 4 per 1000 initiative[17], which saw the light at COP21 (INRA, IRD and CIRAD in 2016). The initiative aims to increase the soil organic carbon (SOC) content of all agricultural land relatively by 0.4% (i.e., 4 per 1000) annually. Sequestration of C in soils can be increased through a wide range of possible management measures, including reduced tillage (to decrease mineralization), improved crop rotations, green manuring, catch crops, incorporating crop residues in the soil, and manure and compost application[18–20]. However, the success of these measures is not guaranteed; instead many studies show that SOC of agricultural land has been decreasing during the last decades[21–25]. These decreases have been ascribed to changes in land use, intensification of soil cultivation practices, erosion and possibly an increased global temperature[26,27].

Though SOC contents can be measured relatively easily and farmers appreciate SOC as a soil quality indicator[28,29], the SOC content of farmer fields are not always analyzed routinely by laboratories that conduct soil analyses for farmers. For example, a routine soil test in Germany commonly includes only P, K, Mg and pH, and in New Zealand commonly pH, P, S and 4 cations (Ca, Mg, K and Na). The neglect of SOC is partly related to the fact that farmers are primarily interested in the availability of critical nutrients for crop growth. Also, the appraisal of the SOC content depends in part on soil texture and soil bulk density, which are not easily determined, and thus are not routinely analyzed by laboratories that conduct soil analyses for farmers. The lack of rapid and relatively cheap methods for accurate monitoring of SOC contents is a main bottleneck for large-scale monitoring of SOC contents in farmer fields around the world. Thus, there is a need for rapid methods and for guiding farmers about the best options for specific fields to increase SOC sequestration.

In this paper, we report on the development and results of a new tool, Soil Carbon Check, which provides a rapid way to monitor SOC contents in farmer fields and to guide farmers to increase SOC sequestration. Basically, the tool consists of a novel combination of soil analyses by NIRS[30] and the SOC mineralization model MINIP[31]. Result of the NIRS analyses are input to MINIP, together with general and farm-specific information. Overall results are presented in a report to farmers, which includes also an organic carbon balance to provide insight to farmers in how much carbon is needed to annually increase SOC content by 0.4% annually. The tool can be seen as example of translational research, linking research with relevant societal applications[32]; its use can also be expanded relatively easy.

2 MATERIALS AND METHODS

2.1 Conceptual framework of Soil Carbon Check

A new tool, Soil Carbon Check, was developed to guide farmers and their advisors to monitor SOC sequestration in farmer fields in a uniform manner and at low cost (Fig. 1). Commonly, soil samples are taken from targeted fields at the request of farmers (or land managers), using a scientifically sound soil sampling scheme, at a prescribed soil depth and after the growing season (before fertilizer application). According to the default sampling scheme, 40 subsamples from the top 30 cm of soil are taken along a zigzag transect within a field (up to 5 ha) with the sampling points are georeferenced (other soil sampling designs and sampling depth are possible, including stratified and random sampling designs, depending on the nature of the field and the purpose of the study). In the default scheme, subsamples are bulked and mixed to a homogenous sample for each field, dried at 40 °C, gently milled and sieved (2 mm) to remove gravel, stubble and roots. Then 125 g of soil is transferred to glass jars to be scanned with a Q-interline FT-NIRS analyzer in a climate-controlled room. The NIRS spectra of all individual samples are calibrated to results of standard soil analysis methods, using a large database and a so-called nearest neighbor statistical procedure, which selects for each individual sample 300 results from the database for calibration[30]. The following soil characteristics are estimated: SOC, soil inorganic carbon (SIC), SOM, active SOC (a proxy for microbial biomass carbon), clay (particles with a size < 2 μm), total soil sulfur and total soil nitrogen (Table 1, Tables S1–S3). The results of the NIRS analyses have been validated to results of analyses of independent soil samples, taken from various countries in Europe, but also from China, New Zealand and Vietnam.

The SOC mineralization model MINIP[31] of Soil Carbon Check allows making estimations of the changes in SOC over time as function of soil type (primarily defined by a combination of soil texture, soil organic matter content and drainage) and characteristics, climate and soil organic matter management. The required inputs are soil texture, soil pH, N-total, SOC and SOM contents, which are provided through the NIRS analyses, and information about soil cultivation, crop types and crop yields, crop residue management, and manure and compost applications. Information about manure and compost are commonly provided by the farmer. The impacts of

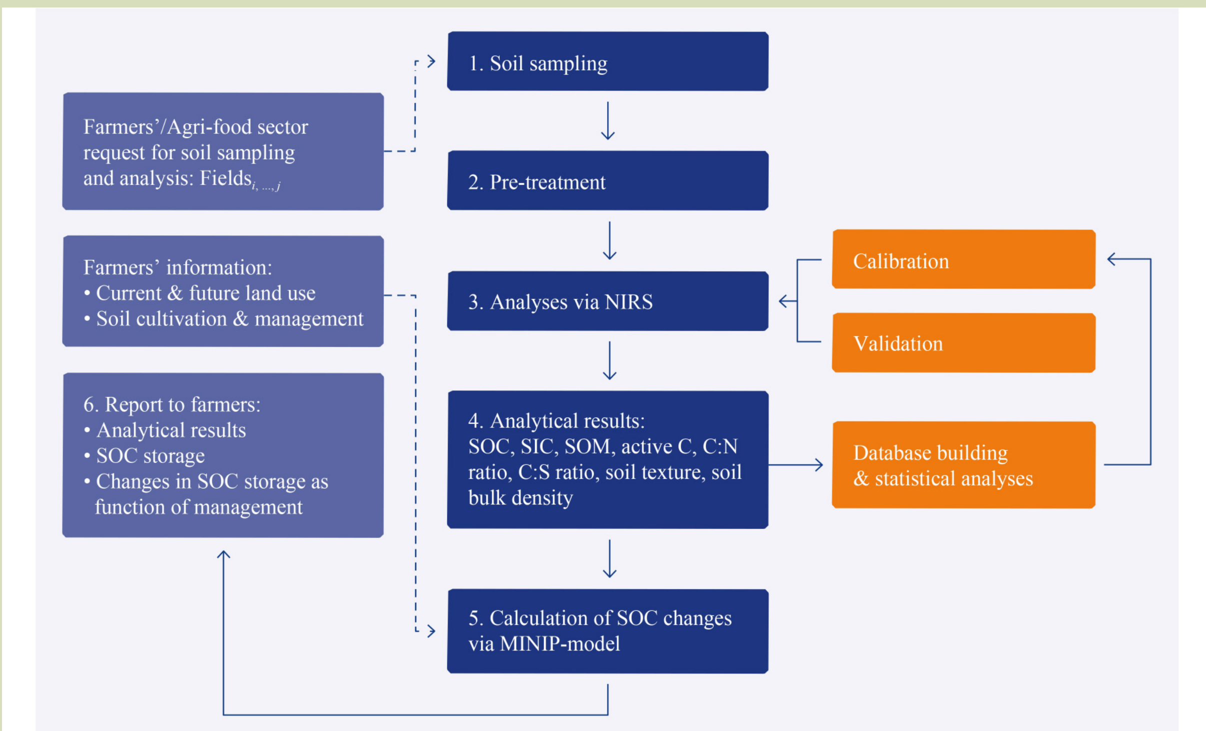


Fig. 1 Conceptual framework of Soil Carbon Check, which is a rapid tool for guiding and monitoring soil organic carbon (SOC) sequestration in farmer fields. The processes on the left indicate farmer involvement (dashed lines), those in the center the sequential analytical steps, and those on the right interactive calibration and validation (solid lines).

Table 1 Results of the calibration and validation of the determination of SOC contents by NIRS

Type	Country	n	P5	Mean	SD	P95	R^2	RPD	RMSEP
Calibration	/	21,976	0.7	1.99	1.7	4.88	0.99	12.9	0.49
Validation	China	138	0.5	1.1	1.0	2.7	0.96	4.7	0.23
	Vietnam	77	0.4	1.3	0.6	2.3	0.96	4.8	0.13
	New Zealand	153	2.0	5.9	5.4	13.0	0.99	14.3	0.31
	Belarus	87	1.2	7.5	6.7	18.9	1.00	13.7	0.49
	Finland	109	0.9	3.3	2.9	9.9	1.00	15.5	0.19
	Germany	100	0.8	1.5	1.6	2.1	0.93	3.5	0.16
	France	48	0.6	1.4	0.6	2.5	0.96	–	0.13
	Lithuania	100	0.7	2.3	2.8	5.2	0.99	6.4	0.44
	Norway	50	1.8	2.9	1.1	5.1	0.97	–	0.23
	Sweden	49	0.9	5.4	4.9	16.0	0.99	–	0.40
	UK	54	1.6	3.0	1.6	6.7	0.97	–	0.24
	The Netherlands	1840	0.8	2.5	1.9	6.2	0.98	6.4	0.30

Note: Samples have been taken in different countries, but were analyzed following the same standard procedures. Results are presented for number of samples, the 5th (P5), and 95th (P95) percentiles, mean, standard deviation (SD), determination coefficient (R^2), relative percentage difference (RPD; for $n \geqslant 75$), and root mean squared error of prediction (RMSEP). SOC, soil organic carbon; NIRS, near-infrared spectroscopy.

soil cultivation, crop species and crop yields, crop residue management on soil carbon were based in part on a recent literature review and meta-analysis[33]. The model MINIP has been extensively tested, using results of long-term field experiments in China[34,35] and the Netherlands[36,37].

The results of the NIRS analyses and of the calculations with MINIP are presented to farmers in a readily understood report (Fig. S1). Seminars have been and are organized annually in various regions for farmers and farm advisors during the off-seasons, to explain the background, mechanisms, meaning and results of the tool.

2.2 Analytical procedures

Evidently, the tool is simple as it consists only of NIRS determinations and model calculations with the model MINIP, but the underlying calibration and validation of the NIRS determinations and model calculations are critical; it has taken over 10 years to build the database and to conduct satisfactorily calibrations and validations. For the determination of the SOC and SIC contents, NIRS spectra are related to the results of elementary C analysis following dry combustion according ISO 10694 and NEN-EN 15936[38,39]. The reference method for active SOC is potassium permanganate oxidizable soil C and discrete analysis[40,41]. Active SOC has been identified as a useful indicator of the labile fraction of SOC that is sensitive to management-induced changes in soil C content. The reference method of total soil N is elementary N analysis by mass spectrometry following dry combustion according ISO 13878 and NEN 6966[42,43]. Determination of S-total involves a microwave digestion of dried and ground soil with nitric acid followed by ICP analyses[43,44]. The reference method for soil texture (relative proportions of clay, silt and sand particles) is sieving and pipetting following the removal of organic material, carbonates and ferric iron according to NEN 5753[45]. Soil bulk density is estimated on the basis of the pedotransfer functions developed by Hollis et al.[46]: soil bulk density ($g \cdot cm^{-3}$) = 0.39859 + (1.18462 × exp(− 0.08794 × % SOC)) + (0.000599 × % total sand) – (0.001538 × % clay). Further details of the analytical procedures have been described by Reijneveld et al.[30].

2.3 Analytical calibration and validation procedures

Eurofins Agro started with NIRS for soil fertility assessments in 2003, in parallel with conventional soil test methods so as to build a solid calibration and validation database. NIRS spectral data are measured as absorbance. The spectra are trimmed to include only the wavelength between 1.0 and 2.7 μm with a resolution of 16 cm^{-1}. Spectra are then related to results of reference methods using statistical models based on a set of four filters (AMX-S2000, 2018). First, spectra are transformed into a new latent space by applying the Savitzky-Golay method[47,48] and the partial least squares method[49]. The nearest neighbor method[50] is then submitted to Gaussian processes[51] to generate the final result.

Calibration models are currently based on a minimum of 1000 reference samples (i.e., results of standard analyses, but for some test over 100,000 reference samples are available), depending on the year of introduction of the specific soil characteristics. For expressing the goodness-of-fit, we use the relative percentage difference (RPD), correlation coefficients (R^2) and root mean squared error of prediction (RMSEP; average difference between predicted and measured values). Commonly, an RPD value of > 2 is used as threshold for adequacy, following the guidelines of Chang et al.[52].

2.4 SOC mineralization model MINIP

The soil organic matter decomposition and accumulation model MINIP was developed by Yang[34] in 1996 and Yang & Janssen[31] in 2000. MINIP is a monocomponent model, as it distinguishes just one soil organic matter pool, which decays at variable rate over time. The mineralization of the organic C is given by the basic equation $\mathrm{d}C/\mathrm{d}t = k_{\mathrm{m}} \times C$, where C denotes the amount of carbon in the single pool. The time-dependent mineralization coefficient k_{m} is determined as $R \times (1 - S) \times t^{-S}$, where R and S (dimensionless) denote parameters dependent on type of the organic material, soil type, temperature and moisture. There is a good relation between the two parameters; R increases with increasing S, while $0 \leqslant S \leqslant 1$. MINIP has been calibrated for soils and plant materials with data derived from experiments lasting between 3 months and 20 years. It has successfully been used to analyze the impacts of farming practices in China over decades[34,35] and in the Netherlands[36,37]. MINIP was also successfully calibrated to results from experiments conducted in France, India, New Zealand and Sweden[31,53].

2.5 Agronomic validation of Soil Carbon Check in farmer fields

The robustness of Soil Carbon Check was tested on several farms. In one case study, we checked the robustness of the sampling and soil analyses. Two fields on light textured soils in the Netherlands were sampled every month for 2 years (with 40 subsamples per sample), and the samples analyzed for SOC, SOM, $CaCO_3$, N-total, clay, sand, pH-$CaCl_2$ and effective CEC. The fields were not fertilized and/or manured during these years. In another case study, we verified the forecasts of the MINIP model with the results of the soil analyses from 70 fields (on eight farms) over a 12-year period. Crop rotation, soil organic matter management and organic matter inputs were based on interviews with farmers in 2017[54].

3 RESULTS

3.1 Analytical validation of soil measurements

Results of the calibration of NIRS spectra in relative to the results of the analyses with the reference method for SOC are presented in Table 1. This calibration was based on over 20,000 samples from different countries. Validation of the SOC determinations by NIRS was done for different countries with on average about 100 samples. Results show that the calibration and validation of the SOC determinations are relatively very good for the mineral soils analyzed.

Results of the validations of SIC and clay contents determinations by NIRS are presented in Fig. 2. Despite some scatter, there is on average a good fit between the results of the NIRS determinations and those of the reference methods. Results of the validations of SOM, N-total (C:N), S-total (C:S), and clay (clay:SOC) for China, European countries, New Zealand, and Vietnam are presented in Table S1.

3.2 Validation of active SOC and soil bulk density measurements

Active SOC is a relatively new indicator for farmers and is suggested to provide insight into early changes in SOC contents of fields following changes in soil organic management. Soil bulk density is also not a routinely-measured soil indicator, but it is essential for translating SOC contents to SOC stocks expressed in $\mathrm{kg \cdot ha^{-1}}$. Results of the validations of active SOC and soil bulk density are presented in Table 2. Soil samples originated from different countries and from different soil types. Results indicate again good fits between the results of the NIRS determinations and those of the reference methods, though slightly better for soil bulk density than for active SOC (Fig. 3). Notably, active SOC was on average only 2.6% of the SOC content, but with a relative large variation. However, not many samples had a relatively high active SOC content (Fig. 3).

The relationships between active SOC and SOC contents, and between active SOC and clay contents are further illustrated in Fig. 4. The scatter in active SOC contents increases with SOC contents, which is likely related to variations in soil organic

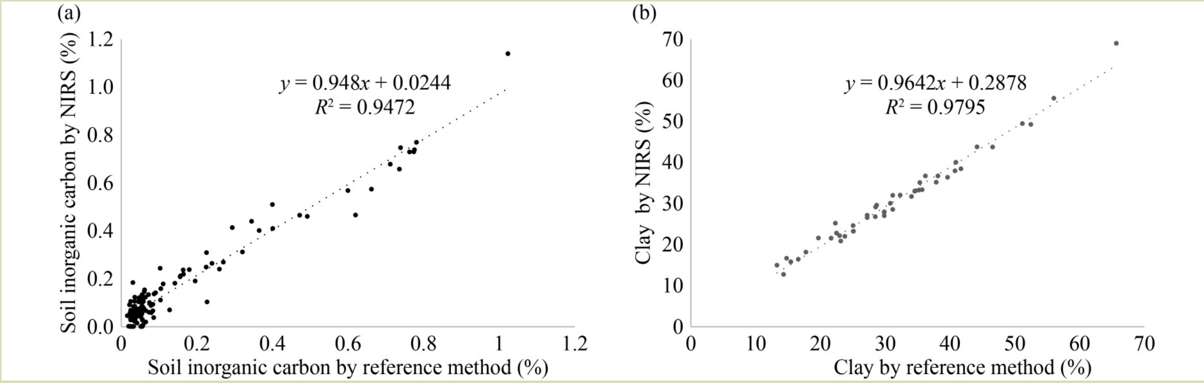


Fig. 2 Scatter plots showing the results of the validation of soil inorganic carbon (SIC) content (a) and clay (particles < 2 μm) content (b) determinations using NIRS for samples taken in the eastern provinces in China versus reference methods.

Table 2 Results of the validation of active SOC and soil bulk density determinations by NIRS

Soil characteristic	n	P5	Mean	SD	P95	R^2	RPD	RMSEP
Active carbon	893	306	804	601	1955	0.93	3.5	175
Soil bulk density	47,625	1.1	1.38	0.15	1.53	0.99	29.8	0.005
Active C of SOC (%)	893	1.1	2.6	1.0	4.3	n.a.	n.a.	n.a.

Note: Results indicate the number of samples, 5th (P5) and 95th (P95) percentiles, mean, standard deviation (SD), determination coefficient (R^2), relative percentage difference (RPD), and root mean squared error of prediction (RMSEP). n.a., not applicable. SOC, soil organic carbon; NIRS, near-infrared spectroscopy.

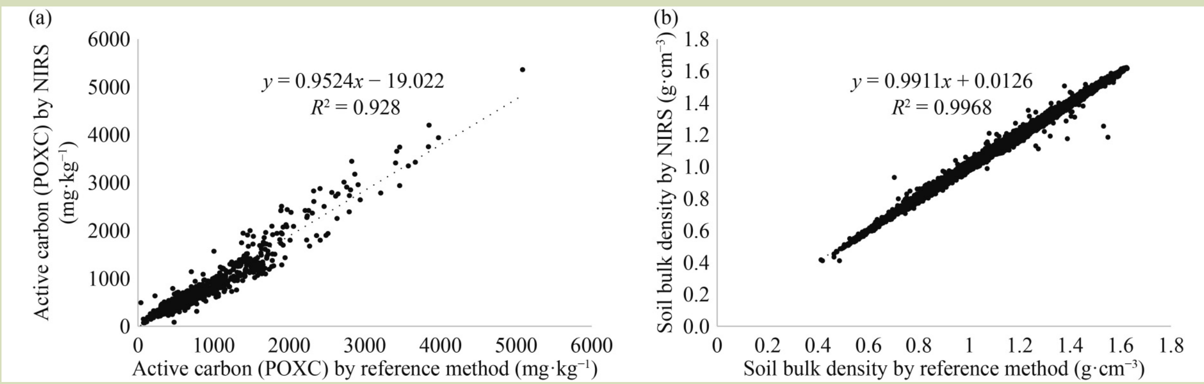


Fig. 3 Scatter plots showing the results of the validation of active carbon (POXC) (a) and soil bulk density (b) determinations by NIRS versus reference methods.

carbon management. Active SOC contents were not clearly related to clay content (Fig. 4(b)).

3.3 Running the MINIP model

The MINIP model was extensively tested with input data from nearly 30,500 soil tests of samples taken in the Netherlands. The mean SOC breakdown was estimated at 2.8% ± 0.4% per year, but ranging from 2.2% to 3.4% (i.e., the 5th and 95th percentiles), depending on soil characteristics and climate conditions (Table 3). Without organic matter inputs, the average SOC content would decrease from 3.2% to 1.1% in 25 years, clearly indicating that a steady input of organic matter is needed to maintain SOC contents constant.

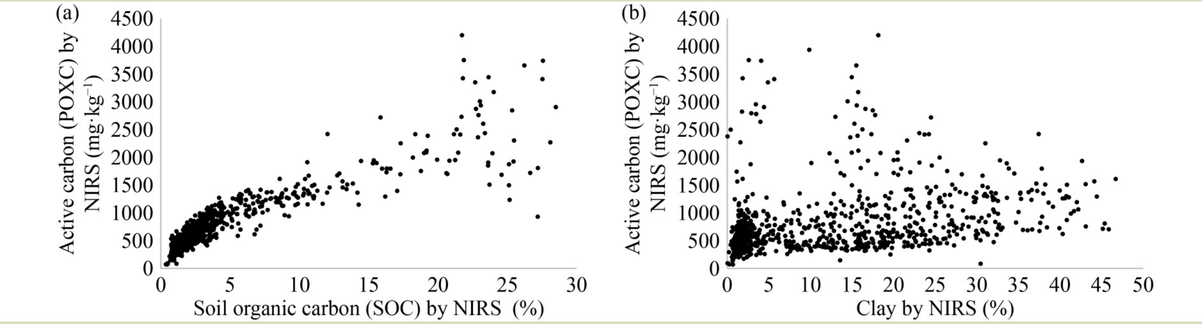


Fig. 4 Scatter plots showing the relationships between SOC content and active SOC carbon (a), clay content and active SOC (b).

Table 3 Calculated mean SOC breakdown (% per year) with the MINIP model, using results of 30,451 soil tests of samples taken in the Netherlands

Initial values	P5	Mean	SD	P95
SOC (%)	0.83	3.19	3.17	9.12
SOM (%)	1.70	5.96	5.92	16.9
N-total (mg·kg^{-1} N)	750	2552	2377	7395
C:N	9.0	12.5	3.7	19
pH	4.8	6.1	0.95	7.4
Amount of C (kg·ha^{-1})	24,900	95,556	95,106	273,600
C breakdown (%)	2.20	2.84	0.36	3.40
SOC after 25 years (%)	0.13	1.07	1.25	3.56

Note: The MINIP model inputs included soil organic carbon (SOC), soil organic matter (SOM), N-total, and pH. The expected SOC content after 25 years (without carbon input) is also presented.

3.4 Validation of Soil Carbon Check on a farm scale

The reproducibility of the SOC determinations by NIRS for two fields over a 2-year period was good (Table 4). Relative standard deviations for SOC were less than 10%, while SOC contents were relatively low (for conditions in the Netherlands). Low relative standard deviations were also found for other soil characteristics, apart from clay content and the $CaCO_3$ content (however, the absolute contents of clay and $CaCO_3$ were low in these marine sandy soils).

The validation of Soil Carbon Check on 70 fields on eight farms showed that SOC content declined in 60% of the fields, and increased in 40% of the fields during the 12-year monitoring period. The net changes over time in SOC content of the 70 fields were aggregated to farm level, and were related to the SOC input through crop residues, manure and composts according to the records and recollections of the farmers, which were used as input to the MINIP model. Results indicate that farms with a positive C balance (according to the MINIP model) had on average an increasing SOC content, while farms with a negative C balance had decreasing SOC contents (R^2 = 0.44, P < 0.075). Evidently, the relationship is not particularly strong (Fig. 5), but we hope that the relationship improves when more data become available.

4 DISCUSSION

4.1 Main findings

Soil Carbon Check was developed for monitoring SOC sequestration and guiding farmers to increase SOC sequestration at relatively low cost. Increasing SOC contents in soils is a mutually beneficial strategy, as it contributes to climate change mitigation and adaptation[55–57], and to increasing soil quality and health[58]. There are various global and regional initiatives now that promote SOC sequestration, including the 4 per 1000 initiative[17], Platform of Latin America and the Caribbean for Climate Action on Agriculture[59], Adapting African Agriculture[60], Living Soils

Table 4 Soil characteristics (soil layer 0–25 cm) of arable land that received no fertilization, measured monthly from September 2016 to October 2018 (Field A) and from November 2018 to April 2019 (Field B)

	SOC (%)	N-total ($mg \cdot kg^{-1}$ N)	C:N	S-total ($mg \cdot kg^{-1}$ S)	SOM (%)	$CaCO_3$ (%)	Clay (%)	Sand (%)	pH-$CaCl_2$	Effective CEC ($mmol^+ \cdot kg^{-1}$)
Field A (n = 33)										
Mean	0.98	913	10.9	283	2.05	0.7	1.0	91.3	6.9	59.2
SD	0.08	89	1.2	30	0.16	0.3	0.2	1.9	0.1	4.0
SD%	8.2	7.4	11.0	10.6	7.8	43	20	2.1	1.4	6.8
Field B (n = 8)										
Mean	1.05	946	11.1	314	2.28	0.8	1.1	90.4	6.9	60.9
SD	0.05	86	1.0	46	0.12	0.3	0.4	3.6	0.1	3.9
SD%	4.8	9.1	9.0	14.6	5.2	38	36	3.9	1.4	6.4

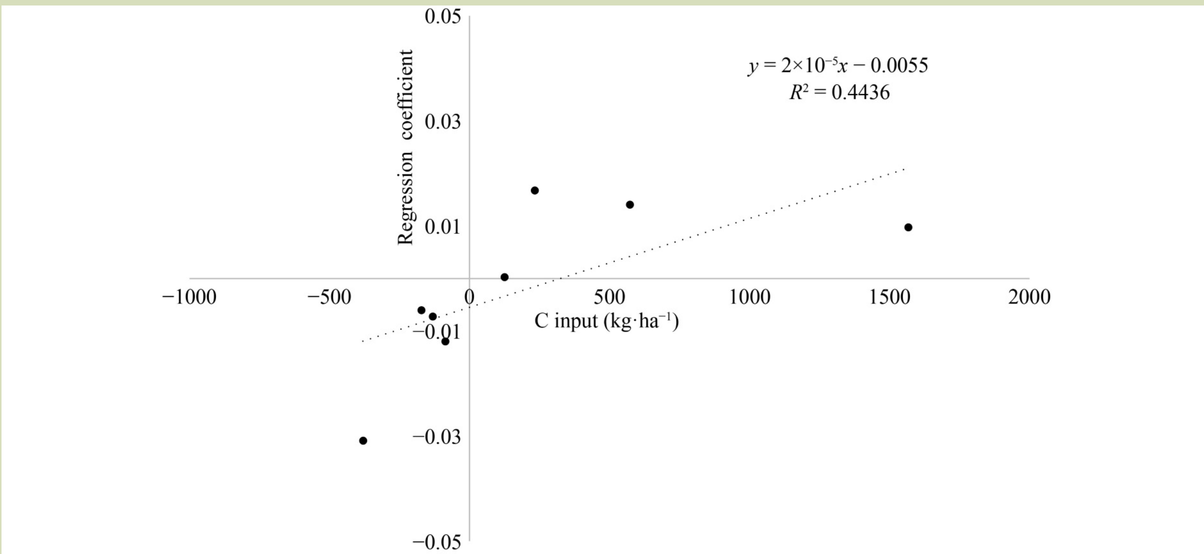


Fig. 5 Changes in soil organic carbon (SOC) content (as regression coefficients from the linear regression of SOC content determinations over time) versus effective carbon input (from MINIP model calculations) for 70 fields on eight farms in the Netherlands.

of the Americas[61], and the Green Deal in the European Union[62]. However, increasing SOC contents in soils of farmer fields is not simple; several reports indicate that SOC contents in soils of farmer fields tend to decrease, probably as a result of increased soil cultivation and climate change[21,63–65]. Thus more efforts are needed, including tools for systematic monitoring of SOC sequestration and guidance of farmers to increase SOC sequestration. Clearly, Soil Carbon Check can be used to clarify this issue when applied to a series of farms on a given soil type in a given region. In the European context this could be done as a Living Laboratory, where C dynamics can be coupled with certain forms of management or natural phenomena (such as erosion). Soil Carbon Check offers a unique operational possibility to do this and therefore represents a breakthrough.

Soil Carbon Check consists of a linkage of multi soil constituent analyses by NIRS with the organic matter mineralization model MINIP. Using NIRS has the advantage that the contents of many soil constituents can be determined accurately in one sample within a minute, provided that all conditions during pretreatment and analysis of the samples are standardized and results are well-validated[30,66]. Results presented in Table 1 and Table 2, and in Fig. 2 and Fig. 3 indicate indeed that the results of the NIRS-analyses are accurate, especially for SOC, SOM, SIC, N-total and soil bulk density. Linking the results of the NIRS-analyses to the MINIP model has the advantage that the results of NIRS analyses and farmer actions are put in the perspective of SOC sequestration and the 4 per 1000 initiative. Results presented in Table 3 and Table 4, and in Fig. 5 provide evidence that the results of Soil Carbon Check are robust and consistent, although it is also clear that information from farmers on soil organic matter management and model calculations of SOM breakdown do not directly translate to changes in SOC contents in soil (Fig. 5). The scatter in the relationship presented in Fig. 5 is likely related to inaccuracies introduced through repeated soil sampling, the soil analyses, farmers assessments of soil organic matter management, as well as in the model calculations of SOM breakdown (in part due to fluctuations in climate during the 12-year period). Likely, the relationships between organic matter inputs and changes in SOC contents of farmer fields will improve when more data become available over time. Determination of active SOC (Fig. 3 and Fig. 4) was included in the tool, as it may provide insights in the early effects of management-induced changes in SOC contents[40,41,67]. However, its value to farmers aiming to increase SOC sequestration still has to be proven.

Soil Carbon Check is now being implemented, tested and validated further in Belarus/Poland, China, Finland, France, Germany, Lithuania, New Zealand, Norway, Sweden, the Netherlands, UK, and Vietnam. The results are promising, but there are still analytical, modeling and implementation challenges, as discussed below.

4.2 Analytical challenges

Standard wet-chemical methods for soil analyses have a long history[68], but have the disadvantage of being laborious and thereby expensive. Indirect sensing techniques like NIRS also have a long history[69], but have yet to be widely applied to soil analyses[70]. These indirect techniques have the advantage that they require no hazardous chemicals, may provide information on many soil constituents, and are fast, but they require results of conventional methods for calibration and validation[30,66,71]. However, soils are notoriously heterogeneous across the world and thus the indirect sensing techniques like NIRS require specific soil-type and regional calibrations and validations. Therefore, large databases and advanced statistical tools are needed, along with large capital investments and quality control and assurance certifications. Further, indirect sensing techniques like NIRS have the potential to distinguished different SOC fractions in soil, such as active SOC (Fig. 3 and Fig. 4). Attempts can be made to determine also the microbially labile portions of SOC[72], short-term mineralizable C[73], particulate organic matter[74], soil proteins[75], hot water carbon[76] and clay-protected SOC[77] by NIRS. However, the added value of measuring these fractions for farmers and society still have to be proven.

The successful estimation of soil bulk density by NIRS (Fig. 3, Table 2) is a major breakthrough, as the conventional methods are very laborious[78,79]. However, we note that compaction induced changes in soil bulk density (as a result of heavy wheel loads, a plow pan or naturally induced compaction) are not determined through by approach. Hollis concluded that the pedotransfer functions can be used to estimate the bulk density of a wide range of European soils. We are now testing and validating the pedotransfer model developed by Périé & Ouimet[80] for China[81]. It has been suggested that developing pedotransfer functions for a global-scale model to estimate soil bulk density is an achievable goal[79,82]. This may be attractive for international agrifood companies that operate worldwide and aim at presenting and lowering the environmental footprints of their products.

In arid and semiarid regions, SIC can be a dominant form of total carbon. Dissolution of carbonates and formation of secondary carbonates (through acidification and alkalinization) affect the SIC content of soils, and thereby the net emission of CO_2 to the atmosphere. Commonly, changes of SIC contents are not considered in emission mitigation measures, although monitoring of SIC has been recommended[83]. Therefore, we integrated SIC determinations in Soil Carbon Check to allow its monitoring with Soil Carbon Check, but we note that this is most useful for carbonate-containing soils and arid regions.

It is well known that SOM is heterogeneously dispersed and that its composition differs between soil types and as a result of organic matter management. In addition to active carbon content (Fig. 4), the C:SOM, the C:N, the C:P and the C:S provide information about the quality of SOM[14,84,85]. These ratios form part of Soil Carbon Check, apart from the C:P ratio, which is not easily determined by NIRS[30]. Though progress has been made in the analytical determination of different SOM fractions and in the composition of SOM, further progress is needed. Also, further progress is needed in the agronomic evaluation of various SOM fractions and in the composition of SOM, so as to provide value to farmers and society.

4.3 Modeling challenges

Since the 1930s, numerous models have been developed to quantitatively describe the accumulation and decay of SOM, at different levels of detail. The number and variety of these models mirror a relentless effort to describe and quantify the complex nature of SOM in soils, but the fundamental kinetic and stoichiometric equations are common to most models[86]. We chose a rather simple monocomponent model (MINIP), but with a dynamic rate constant, because such models require few parameters for calibration and validation[34,53], and the results of MINIP were considered most suitable compared to six other advanced models[36]. The main purpose of the MINIP in Soil Carbon Check is to serve as a decision support system so as to assist farmers. Thus, the report of Soil Carbon Check to farmers does provide estimations of the amounts of crop residues, manure, green manure and/or compost needed to maintain SOC contents and/or to increase the relative SOC content by 0.4% annually (Fig. S1). Evidently, the accuracy of these model estimations strongly depend on the parametrization of the model and on the degree the parameters reflect the quality of the SOM and the organic matter sources added to the soil. Efforts are being made to further characterize the decay of SOM and the organic matter inputs into the soil in the countries where Soil Carbon Check has recently been introduced, in cooperation with local institutes and universities, to improve the parametrization of MINIP.

4.4 Implementation challenges

There is great potential for SOC sequestration in various regions of the world[55,87,88]. There is also a great need for SOC sequestration, to mitigate climate change and to contribute to achieving SDG13 (and indirectly SDGs 2, 3, 6 and 15). With reference to the statement, “The time for only talking is long past”[89], there is now need for action, by a range of stakeholders, including farmers, land managers and agrifood companies. There is also need for financial incentives[90] and for tools. Soil Carbon Check is such a tool. Soil Carbon Check provides answers to the questions: (1) How much SOC has been sequestered? (2) Can changes in SOC content be detected? (3) How to increase SOC contents by 0.4% annually? (4) What is the effect of management on SOC over time? It is relatively fast (results are available within a few weeks following sampling), and relatively cheap (about 70 EUR per analysis report in Europe, including soil sampling by accredited samplers and analyses). The results are presented into an easy-to read reports for farmers and their advisors. Soil Carbon Check is increasingly used by the international agrifood companies, which increasingly become involved in attempts to lower the carbon footprint of their food products, in part through guiding and incentivizing farmers.

However, there are a number of remaining implementation challenges of SOC sequestration initiatives. Although the International Organization for Standardization (ISO) gives detailed guidance on the development of sampling strategies and soil testing[91,92], in practice, many other/additional procedures have also been adopted. There is still limited standardization of soil sampling and SOC analyses methods, for various reasons (history, capacity, cost and knowledge). Soil sampling strategies and depth are critical issues here. Are accredited soil sample collectors needed, or can famers take the soil samples? What is the sampling design, soil depth, the number of subsamples, maximum size of the field? These are all critical questions, which are often answered differently by different laboratories. We use and recommend to follow the ISO standards, including georeferencing of the soil sampling positions. Standardization of soil sampling depth is critical here; the 4 per 1000 initiative aspires a relative sequestration rate of 0.4% annually in the upper 30–40 cm of soil, which goes beyond the usual depth of a plow layer (about 15–25 cm deep) and the common soil sampling depth for soil testing. Evidently, pragmatic decisions have to be made here, to make progress.

For assessing significant changes in SOC contents before the target year 2030, the common practice of one soil sample per crop rotation (once each 4–5 years) may have to be adjusted, since a minimum of five results is recommended to be able to report on significant changes over time[93]. Evidently, increasing the frequency of sampling will increase the statistical power of changes in SOC content over time[94]. Consequently, for successful SOC sequestration initiatives in farmer fields, the frequency of soil sampling may need to be increased.

There are also concerns that SOC sequestration in soils through soil conservation practices may increase N_2O emissions from soils, and thus may partly nullify the climate change mitigation effect of SOC sequestration[95,96]. Others have reported that SOC sequestration leads to soil organic N sequestration[97], and thereby to decreases in N_2O emissions and nitrate leaching[98]. Evidently, the interactions between SOC sequestration, N_2O emissions and nitrate leaching need further study.

5 CONCLUSIONS

Soil Carbon Check is a rapid tool for monitoring SOC sequestration in farmer fields and for guiding farmers to increase SOC sequestration. The tool consists of multiconstituent soil analyses by NIRS and the organic matter mineralization model MINIP. The tool has been extensively and successfully tested in farmer fields in a range of representative countries. The report to farmers provide quantitative data and information on SOC, SOM, SIC, active SOC, N-total, clay, soil bulk density, and ratios of C:N, C:S and SOC:clay in soil, as well as answers to the questions: (1) How much SOC has been sequestered? (2) What is the effect of management on SOC content over time? (3) What to do to achieve the goals of the 4 per 1000 initiative?

We discussed various remaining analytical, modeling and implementation challenges. Substantial progress has been made and is being made, but there is still a need for further standardization of especially soil sampling procedures, and for testing and validation of model input parameters for various regions of the world. In addition, there is need for long-term commitment to initiatives and targets for SOC sequestrations. These commitments will allow essential stakeholders (farmers, agrifood sector and laboratories) for implementation of action plans to make the necessary investments and to build the required capacity and institutions. It is also essential to financially reward farmers for their contributions, either through agrifood companies (i.e., increased prices for their products) or through governmental incentives. Soil Carbon Check is an essential tool for ascertaining progress in SOC sequestration and guiding farmers. It can be easily applied/adopted to all agroecosystems and regions of the world, provided that adequate testing, calibrations and validations have been conducted.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2023499 contains supplementary materials (Fig. S1; Tables S1–S3).

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Compliance with ethics guidelines

Jan Adriaan Reijneveld, Martijn Jasper van Oostrum, Karst Michiel Brolsma, and Oene Oenema declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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