Monitoring Soil Carbon: a Practical Field, Farm and Lab Guide

Thanks to our partners and funders

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1. Introduction and aims

This guide was produced as part of the Soil Carbon project and was written as a collaboration between Duchy College, Plymouth University, Rothamsted Research and the Farm Carbon Toolkit. The work was supported through the Agri-tech Cornwall & the Isles of Scilly Project, an £11.8m project to increase Research Development and Innovation in the Agri-tech sector across Cornwall and the Isles of Scilly. Running to December 2021, it is part-funded by the European Regional Development Fund, Cornwall Council and the Council for the Isles of Scilly (award number: 05R16P00366). For more information, please see **www.agritechcornwall.co.uk**.

This guide lists and answers key questions for robust on-farm field monitoring of soil carbon and associated indicators of soil health. This guide will be relevant to farmers seeking to measure and understand their soil carbon stocks - as well as landowners, advisors and researchers supporting them. Supply chains and organisations seeking to reward farmers for improving soil carbon stocks will also find this guide helpful, however it does not act as a standard or protocol. The guide will be accompanied with detailed supplementary materials stemming from the ERDF Agri-Tech Cornwall funded "Soil Carbon Project"(2018 to 2021).

The Soil Carbon Project worked with farmers and growers across the UK to refine soil sampling methodologies, and develop farm-level information on the best practices that will create a system where soil carbon sequestration plays a key part in climate change mitigation efforts.

The research team is immensely grateful to the 85 farmers who engaged in the project.

The guide consists of answers to the following core questions:

1. When to conduct your soil carbon sampling?
2. What fields to select on your farm?
3. How to sample within those fields?
4. At what depths should samples be taken?
5. How often should you repeat your sampling?
6. How to collect and prepare your samples?
7. What are the options for the lab analyses?
8. What are the main soil health indicators that should be monitored?
9. What are the outputs and benefits?

2. Timing

When is the best time of the year to take soil samples?

It is usually best to sample in spring or autumn. This is when the soil is easiest to dig into. It is also a time when soil health indicators, such as worms are most active, so it is easier to count them. However, what is more important than the "best season" is that sampling is consistent for your farm, so if you sample after harvest and before sowing in your first year of monitoring, then keep doing so. There is no best time of day to sample.

Are there any field conditions which preclude soil sampling?

It is important to avoid taking soil samples after a field has been recently disturbed through cultivation. Leave at least three months after ploughing to allow the soil to settle. Fields that have recently had manure or slurry applied to them should also be left because the manure skews the organic matter content of the sample.

> **"There is no best time of day to sample."**

Are there any weather or soil conditions (dry / wet / frozen) to consider?

As long as the soil auger can be put into the ground then technically a soil sample can be taken. However, there are conditions that make the sampling process harder and also factors that will influence the results of other soil health assessments. Drought makes it harder to take a soil sample, it also reduces worm activity with most worms going into dormancy at greater depths to conserve moisture. Very wet fields should also be avoided because it can be difficult to complete infiltration assessments if required. It is not recommended to sample fields that are flooded or underwater. Frozen soil can still be sampled, but infiltration measurements will be more difficult to conduct.

It is recommended to record the field conditions (e.g. dry/wet) when you take a soil sample as any changes in soil results may be explained by changes in the field conditions.

3. Field Selection

How many fields do I have to sample?

In an ideal situation, it is good to test all fields on your farm but given resources it is usually best to be selective. Firstly, try to choose fields that best represent the current and historical land use and the management on your farm (e.g. fields at different stages of a crop rotation; fields reflecting different plough/reseeding intervals; fields which are cropped and those grazed by livestock).

Secondly, at the same time try to base your field selection on any knowledge of underlying soil textures or soil type, capturing all textures across your farm. Project analysis indicates that texture is a much more sensitive indicator of organic carbon than soil type based upon detailed or related Cranfield soil descriptors.

Soil carbon monitoring that captures these two core field characteristics should give an efficient and sufficient understanding of the whole farm soil carbon status without having to test every field. Thus, farms with diverse management and soil textures will require proportionally more fields to be sampled than more uniform farms.

Why is there a difference in soil carbon under different land use and management?

There are various factors that influence soil carbon stocks, such as soil type and climate. However, one of most significant influences relates to how long a soil has had perennial cover; the less it is tilled (disturbed), the more organic carbon it will store. In general, grassland fields are higher in soil carbon than arable fields. However, field management is also a key factor that needs to be taken into consideration. It is important to ensure that you are testing soils / fields that represent the different cropping and management regimes that are present on-farm.

Why does soil carbon depend on soil texture?

Soil texture plays a very important role in determining the amount of carbon that can be sequestered in soil: the more clay the better. Sandy soils are particularly poor at accumulating carbon. Thus, it is important to base sampling decisions on good knowledge of the soil textures on your farm so that you can assess representative samples.

Further details for all of this section are given in the Supplementary Materials, including other potential drivers of soil carbon variation not yet fully understood, so at present do not form part of these recommendations.

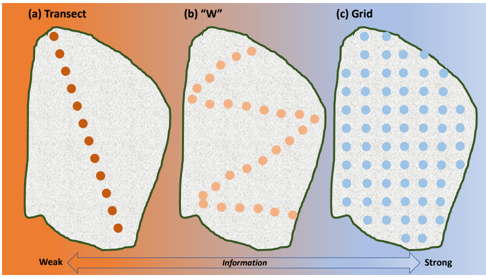
4. Within-field sampling

Where in the field should I take the soil sample?

The results that you get back from soil sampling will only be as good as the sample that is submitted. As such, it is important to try and take a sample which is based on the best decisions and as representative as possible. It is important to avoid sampling in high traffic areas around gateways, troughs, and ring feeders where the soil is disturbed. These areas are likely to provide unusually high or unusually low soil carbon values making final soil carbon field averages grossly over- or under-estimated.

Once these areas have been identified, a sampling pattern should be chosen that traverses as much of the remainder of the field as possible covering all likely sources of soil carbon variation.

This sampling pattern can be done as a linear transect, a "W" configuration or a gridded /snake formulation, where a more robust estimate of soil carbon is likely moving from a transect to a grid.



It is not necessary to traverse a field, say with a transect, across its longest dimension – the key is traversing all likely sources of soil carbon variability and for transects, it may be the field's shortest dimension. Sampling difficulties arise when the field has clear management zones and / or different soil types / textures. In these instances, the field should be sampled in a zonal (stratified) manner with representative samples of each management zone and / or soil type / texture.

If accuracy and precision are important and the sampling is to be repeated in future years, then it's important to GPS log the sample points across the field. This allows the same sample points to be revisited in subsequent years. Revisiting these points avoids any variation in soil carbon across the field affecting the results and allows you to be confident that you are monitoring change over time.

"It is important to take the best quality sample that you can, that represents the field and soil conditions."

How many soil samples should I take?

One sample point is not sufficient for a field estimate of soil carbon. At a bare minimum, 5 sample points are recommended, but preferably 15 points should suffice. Much depends on the perceived complexity of your field (e.g. with respect to management, soil type etc.), where more than 15 points may be required. As indicated above, when a field has clearly different management and / or soil zones, a zonal approach should be followed. For example, to have representative samples in a field of say, 4 clear zones, requires taking 5 to 15 samples in each zone - so 20 to 60 samples in total.

Clearly, 60 samples may be too costly, so in this instance, 20 samples (5 samples in each zone) would be considered the bare minimum for this field. Observe that although larger fields may require more samples than smaller fields, this does depend on the field's complexity (in terms of the number of zones). For example, a 50 ha field with a single management / soil type will commonly require less sampling than a 25 ha field of multiple management / soil types.

Taking more than 15 samples (in a field or zone) will improve the accuracy and precision of your estimate of soil carbon but only up to a point at which diminishing returns sets in. Accuracy, precision and sample size will need to be considered in the context of associated time and laboratory analysis costs. In some circumstances, it is prohibitively costly to take as much as 5 samples, especially when a field contains 5 or more zones. In these instances, 4 samples per zone is recommended, but no fewer.

Is it better to keep soil samples separate or to aggregate across the field or field zone?

Aggregation (bulking) is fine provided the above procedures are adhered to, where the clear upside to aggregation is reducing laboratory analysis costs. In general, a soil carbon value obtained from an aggregated sample is the same as that found by taking the average from unaggregated samples (5 to 15 of them). Aggregation should be performed on a field or zonal basis and never across zones.

The downside to aggregation is that the inherent variability in soil carbon is lost and only estimates of field averages can be determined. Two fields (or field zones) with the same soil carbon estimate (average) may well have very different levels of soil carbon variability and thus would need different (not the same) management, which would not be picked up if only aggregation were used. Thus aggregation tends to be of little worth, if precision farming is the aim.

Further details for all this section are given in the Supplementary Materials.

5. Sampling at different depths

At what depth should I take the soil sample?

For measuring nutrient levels and pH, the typical within-field sampling only occurs at a 0-10/20cm depth. However when analysing soils for organic matter and carbon, it is best to sample to 30cm deep. This allows you to assess the carbon that is held at depth (and is therefore less likely to be released, as it is more stable), and the amount of carbon at the surface (which may fluctuate more due to carbon cycling). In general, samples taken at 0-10cm, 10-30cm and 30-50cm are appropriate. For carbon credit schemes, it is important to research what sample depth is required, as deeper samples (potentially up to 1 metre) may be required. The amount of carbon held within the soil will be highest in the top soil and decrease as you go deeper into the soil profile.

Given within-field sampling will itself involve a trade-off between soil carbon estimation accuracy and sampling cost, further sampling at different depths needs to be considered in this context.

Often within research projects only a subset of the within-field samples are taken at different depths. For example, for a 15 point "W" sampling strategy that is bulked, 15 samples are collected for the top-soil and bulked, while only 5 samples are collected at middle depths and bulked and 5 samples are collected at the lower depths and bulked. However during the Soil Carbon Project, an equal number of samples have been taken at all three depths to assess the carbon stocks at different depths within the soil profiles.

Is it better to keep soil depth samples separate or to aggregate?

It is recommended that soil carbon field estimates are given at different depths, so aggregation down the soil core is not advised.

"When analysing soils for organic matter and carbon, it is best to sample up to 30cm deep."

6. Sampling frequency

How often should I test?

To compare soil carbon results year on year, it is important to sample at the same time of year to minimise any seasonal variations. However, it can be useful to conduct soil health tests (e.g. worm counts) more frequently to get a more detailed understanding of the field's health. Although the soils have been analysed every year as part of this project, results on this time scale can be misleading as short term fluctuations can be misread as long term trends. Annual testing can therefore raise more questions than it answers, and may not provide much value for money when considering the cost of analysis. Recommendations from the Soil Carbon Project would be to assess soil carbon through analysis every 3-5 years depending on crop type and management.

How should the sampling frequency differ depending on changes in land use?

Disturbed soils (e.g. ploughed) will be associated with more rapid changes in soil carbon and soil sampling should be more frequent to reflect this. In contrast, soil under long-term pasture will be accumulating carbon only gradually and can be sampled less frequently. Since there is no mixing of the soil within the field, there is likely to be greater spatial variability in organic carbon and as a result, these fields may require sampling in zones.

"Recommendations from the Soil Carbon Project would be to assess soil carbon through analysis every 3-5 years depending on crop type and management."

7. Sample collection and preparation

What equipment do I need to take a good sample?

The gold standard tool for completing soil sampling is a soil auger. This is useful for two reasons - firstly the narrow tip makes it easier to penetrate soils that are dry, or stony; secondly if you are planning on sampling at different depths, augers are usually marked with a depth meter which allows easier separation of the soil carbon samples. However not everyone has access to one of these and so digging a hole and removing soil by hand is acceptable as a starting point. It is recommended that for frequent analysis an auger is used. The benefit of digging holes using a spade, is that you get the chance to assess other aspects of soil health at the same time. Clean buckets for bulking soil and sandwich style plastic bags are also necessary to collect the samples. To take a more in-depth look at soil health you will need the equipment shown in the photo below.

This includes a mallet and a cylinder with a known volume to take bulk density samples for use in the calculation of soil carbon budgets (see below). The equipment also includes water and a stopwatch for infiltration measurements. A full explanation of these in-depth soil health measures is given below (section 9). Once a sample is collected, make sure any vegetation, roots and worms are removed by hand as these add organic matter that is not part of the soil.

If bulking, mix the sample thoroughly before bagging up to ensure any small part is representative of the field and/or the depth taken.

Why is bulk density so important and how is it measured?

Bulk density is a measure of the mass of soil in the field (calculated based on the weight of soil in a known volume). This is crucial for effectively measuring the quantity of carbon stored in the soil in tonnes per hectare.

To take a bulk density sample, dig a soil pit and within each depth that a soil sample is taken for analysis (i.e. 0-10cm, 10-30cm , 30-50cm) insert an open-ended cylinder (such as an offcut of steel pipe). Using a mallet, fully knock the cylinder into the side of the soil pit at each depth and carefully remove this core and transfer all soil inside into a bag. The volume of the cylinder must be provided to the lab with the sample. This can be calculated from the internal diameter and length, either by you or by the lab.

How quickly should the samples be sent off to the lab?

The sooner the better. Within a few days is ideal and up to two weeks is acceptable as long as the soil samples are kept refrigerated. It is possible for the organic matter to break down over longer time periods in warmer temperatures so it is best to avoid the risk of this affecting the results.

How much soil should I send?

For the Loss on Ignition (LOI) method of estimating soil organic matter, about 100 g (a mug's worth) is best so that the analysis can be repeated with some left over as a back-up. Only about 20 g (an egg cup's worth) of wet soil is used for each measurement, but this is the absolute minimum. Much more than this will be a waste and could be a nuisance to keep cool.

Should I keep the samples in the fridge?

In the same way that organic matter is broken down in a field by microbes, organic matter will break down over time when bagged up. Using a fridge will slow this down significantly. It is therefore recommended to refrigerate especially if there might be a long time before analysis. If samples cannot be refrigerated for a few days, however, it should not significantly affect the measured organic matter because even partially broken-down organic matter will still be included in the measurement.

Should I take a separate sample to my nutrient sample?

It is generally best practice to have all soil tests from the same bagged up sample so that the different results can be directly linked to one another. Bear in mind however, that the depth of soil sampled and keeping consistency with this depth is far more important and might not match your past nutrient sampling, so separate bags may be needed.

"Once a sample is collected, make sure any vegetation, roots and worms are removed by hand as these add organic matter that is not part of the soil."

8. Lab analysis

What should I ask the lab to test for?

If you are mostly interested in organic matter to make management decisions on-farm, ask for "organic matter by loss on ignition (LOI)". By having these organic matter results, you get some additional rough insight into the soil carbon content of your soil. As long as these are only used to monitor changes over time for a specific soil type on the farm, these results are sufficiently good for estimating carbon balances. If a more accurate calculation of absolute carbon stocks on-farm is required or you want to compare across different soils types, we recommend asking for "Soil carbon by DUMAS" which is a more direct and much more accurate measure.

Is there a difference between LOI and DUMAS – if so, what is it?

Yes, LOI will give you a rough idea of the soil organic carbon content of your soil and is generally slightly cheaper. The disadvantages of the LOI method are that it is not standardised between labs, so it is highly important that you stick with the same one, and it is also less accurate than DUMAS because LOI technically measures the soil's organic matter content. A conversion factor is needed to determine how much of this is carbon relative to the rest; oxygen, hydrogen and nitrogen etc.. There are significant issues of over estimating the organic matter content in soils with higher clay content. If the same lab is used each time, LOI can still be a great tool for seeing changes over time as the errors due to clay and the conversion are similar each time it is measured. DUMAS will give you a direct and far more accurate measure of the actual carbon stocks independent of the clay content. It is important for alkaline soils (pH 7 or greater) that the inorganic carbon (carbonates; limestone, chalk etc.) is accounted for by the lab and that you know whether your results are for total carbon or just the organic carbon portion. Inorganic and organic carbon are both important parts of the farm carbon cycle, but they react in different ways to management practices. Most farms (any with soil pH 7 or lower) do not need to worry about inorganic carbon as there will be none present. Ultimately, for many farms the best choice between LOI and DUMAS will come down to the most important factor; sticking with the same measure from the same lab. Further details are given in the Supplementary Materials.

Is there a difference between different standard lab methods?

DUMAS is generally a well standardised technique, with good comparability between labs. For the LOI method however, the ignition temperature used by the laboratory has a significant influence upon the estimates of organic carbon which can affect the result by a few percent depending where the soil is analysed. In light of this, we recommend first that you keep using the same laboratory, and second, request and keep a record of the temperature used by the laboratory when generating organic carbon estimates using the LOI technique.

What is the standard way to test for carbon?

There is not one standard way to measure soil carbon. The three most common ways are; LOI, DUMAS, and potassium permanganate oxidation. LOI is the most common due to its traditional usage in evaluating the organic matter content. DUMAS is the most accurate and direct measure. Potassium permanganate oxidation (sometimes; permanganate oxidisable carbon (POXC)) is another way of characterising organic matter. It is less common and indicates “active carbon”. Although this is an informative quantity, if only one method is to be used, we want to measure all organic carbon that is built up and stable for the long-term. Each method has its own advantages and disadvantages for different soil types, budgets and uses.

How is the analysis usually carried out in the lab?

For LOI, firstly a portion of the bagged soil is dried out. Clumps are then broken up so that it can be passed through a sieve to remove larger stones. The soil is then fully dried again to get rid of any water that has been absorbed from the atmosphere whilst processing the sample and about 10 g is weighed at a precision of 0.001 g or greater. A batch of these soil samples are then placed in a furnace which will be set to a temperature that burns off only the organic matter in the soil. Once the samples have cooled down, but again minimising the moisture absorbed from the atmosphere, the samples can be accurately weighed once more. The difference between weights is the organic matter “lost on ignition” and we divide this by the pre-burn dry weight to give you the organic matter as a proportion of soil which we represent as a percentage. About half of soil organic matter is carbon, therefore we can estimate the percentage of soil organic carbon.

How do you get soil carbon content from the organic matter?

Soil organic matter is traditionally said to be 58% carbon. This figure is only a very rough estimate used to cover a range of soil types. Soils often have organic matter with a carbon content of anywhere from 30 to 60% and usually significantly lower than 58% for agricultural soils.

Multiplying by a conversion factor of 0.58 (or dividing by 1.724) is common and reasonable to use in many situations. It can give a misleading sense of precision and accuracy when using LOI to calculate soil carbon stocks. Our recommendation is to halve the soil organic matter result for an estimate of soil carbon and use DUMAS if an accurate assessment of carbon stocks is needed. Most important is that the same conversion factor is used each time organic matter is measured and converted to soil carbon. In doing this, the error from the difference between the conversion factor used and the actual soil carbon content of your organic matter is kept constant which allows for valid assessments of changes in soil carbon over time, even if the absolute carbon stock on a given occasion is inaccurate. Further details are given in the of Supplementary Materials.

9. Soil Health Indicators

What are the other soil health indicators important to soil carbon?

The key soil health indicators conducted in the Soil Carbon Project are outlined below. These can be used alongside the results from lab analysis to gain a full understanding of the state of your soils.

Aggregate Stability – this is a measure of how well the soil holds together when saturated with water. Take a lump of soil from the field and leave to dry on a sunny windowsill for a few days. Once dry, submerge the soil in water and give a score after 5 minutes and again after 2 hours. The scoring system is as follows:

0 – soil remains intact

1 – soil crumbles around the edges

2 – soil breaks up into angular pieces

3 – soil slumps into a pyramid

4 – soil has completely disintegrated

Correlating the aggregate score with the field SOM% (at 0-10cm) shows a good relationship between the two, with soil with higher organic matter content remaining more intact in water. This suggests that aggregate stability can be an easy on-farm indicator of soil organic matter content and therefore carbon content. Lower aggregate scores suggest the soil is more resilient to saturation and erosion. The theory is that soils with high organic matter content contain more glomalin, a protein which acts as a glue, binding soil particles together.

Visual Evaluation of Soil Structure – VESS is a guide to soil compaction, based on how difficult a block of soil is to break apart and how well plants can root in the soil. Dig a soil pit one spade deep by one spade wide (leaving one side of the square undisturbed) and remove the block of soil. With some soil in hand, a score from 1 to 5 can be given by visual inspection, with one being least compacted and 5 most compacted:

1. Friable – soil crumbles easily, highly porous, roots throughout the soil profile
2. Intact – soil is easy to break with one hand, most aggregates are porous, roots throughout the soil profile
3. Firm – most aggregates break with one hand, pores and cracks present in aggregates roots growing through aggregates
4. Compact – considerable effort required to break the soil with one hand, few pores and cracks, roots are clustered in around aggregates
5. Very compact – difficult to break the soil block up, very low porosity, few roots

Be sure to keep good records of locations and results that can be referred back to in the future.

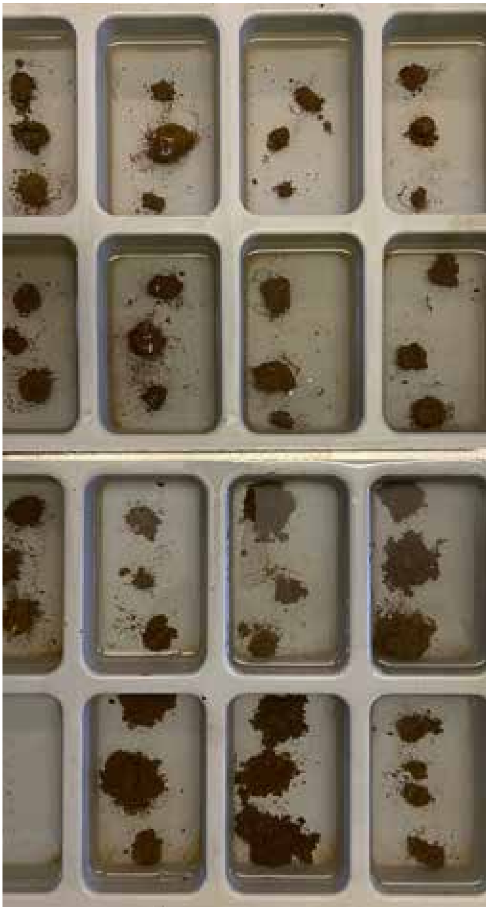
Infiltration – this is also an indicator of compaction. Insert an open-ended cylinder into the soil surface to form a seal and pour 100ml of water into the cylinder. Record the time taken for the water to soak away. Short infiltration times are better because they mean water can soak away into the soil rather than running off the surface.

A major way carbon is lost from soils is in dramatic events through surface erosion, making compaction an incredibly important factor in assessing soil carbon on-farm. Long infiltration times suggest that the soil is compacted.

However, infiltration is influenced by the weather conditions on the sample date. Very wet weather will saturate the soil, increasing the infiltration time.
Very dry weather will mean that water rapidly drains away. Therefore, the general weather conditions should be considered and recorded alongside the infiltration result.

Worm Counts – this is quite simple in that the more worms present in the soil pit, the better. Worms aerate the soil with their burrows, and are important for nutrient cycling and soil creation by breaking down organic material.

"Be sure to keep good records of locations and results that can be referred back to in the future."



10. What Next?

What is a good amount of soil carbon?

This very much depends upon soil texture with sandy soil having a lower capacity to store carbon than clay soil. 3% is often used as an arbitrary target but there is limited scientific consensus regarding the usefulness of this. The soil type can indicate very roughly the general upper limit to how much carbon can be stored (depending on depth), but generally agricultural soils are significantly below this and a "good amount" is more than when measured previously. It takes a significant amount of time to build carbon and any gains will help mitigate climate change and often benefit the farm productivity. Measuring soil carbon allows this hidden quantity to be seen which is the first step in noticing changes and making improvements.

What can I do with the results?

The results can be used to assess several important aspects relating to the "health" of your soil. For soils with a reasonable amount of clay, a high organic carbon concentration is indicative of an increased water holding capacity and of soils associated with greater nutrient use efficiency. Crops, livestock and milk etc. produced on soil which is accumulating greater amounts of soil carbon will typically have a lower carbon footprint, so tracking carbon will inform you of your progress in creating and maintaining an efficient and "carbon neutral" farming system. Having assessed carbon stocks across your fields, you can then identify fields that require "carbon investment" and prioritize where carbon inputs should go to maximize sequestration and farm efficiency, particularly if you have limited carbon inputs (e.g. farmyard manure). Also, understanding which soils on your farm are already saturated with carbon can help you understand which soils may require fewer inputs.

Is there a market for soil carbon sequestration?

In the UK, there's rising interest in the opportunities for farmers to get paid for soil carbon sequestration, whether through supply chain incentives or carbon offset markets. New schemes are emerging however an absence of formal, UK-specific protocols around quantification, qualification and verification, can mean that organisations lack reassurance about the robustness and credibility of schemes.

There are efforts from a consortium of organisations to establish a Farm Soil Carbon Code. However, with carbon credits specifically, there is still a great deal to be worked out regarding methodologies to manage exclusive claims, additionality, permanence and transparency.

"It takes a significant amount of time to build carbon and any gains will help mitigate climate change and often benefit the farm productivity."

11. Further Reading

FAO. 2020. A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes – GSOC-MRV Protocol. Rome. **https://doi.org/10.4060/cb0509en**

VESS Score: **https://soils.vidacycle.com/wp-content/uploads/2019/08/VESS_score_chart.pdf**

Worm classification: **https://www.earthwormwatch.org/sites/default/files/EarthwormandSoilChart.pdf**

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