STUDY

POTENTIAL FOR SOIL CARBON SEQUESTRATION FROM REHABILITATED DEGRADED PASTURES IN THE CERRADO

3

GTPastagens

Summary

PART 1: Soil carbon sequestration evaluation guide: sampling, preparation, analysis, and calculation

PART 2: Estimating soil carbon sequestration through rehabilitation of degraded pastures in the Cerrado

PART 1

Soil carbon sequestration evaluation guide: sampling, preparation, analysis, and calculation

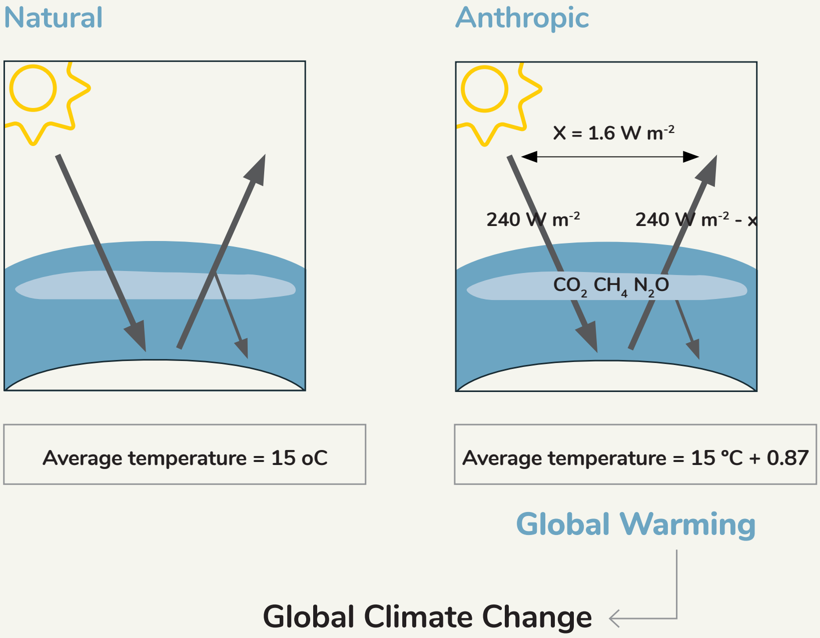
Introduction

There has been an increasing global concern about climate change, mainly due to excessive emissions of carbon dioxide (CO_2) and other gases, such as methane (CH_4) and nitrous oxide (N_2O). In theory, these gases are responsible for keeping the Earth’s average temperature between 16-18 °C, causing the so-called “greenhouse effect,” without which life on Earth would not be possible.

Studies show that over the past 200 years the concentration of these gases in the atmosphere, especially CO_2, has slowly increased, and more steeply over the past few decades (IPCC, 2019).

One of the main consequences is the so-called “increased greenhouse effect” or “anthropogenic greenhouse effect,” due to increased levels of reflected infrared rays, leading to the Earth’s energy imbalance ***(Figure 1)***.

Figure 1.
Natural and anthropic greenhouse effect, and their impact on the Earth’s average temperature.



According to the Intergovernmental Panel on Climate Change’s (IPCC) most recent report, Climate Change and Land (IPCC, 2019), from 1850-1900 to 2006-2015, the average air temperature on the surface of the Earth has already risen 1.53 degrees, whereas the global average temperature (land and ocean) has increased 0.87 degrees. Global warming has led to the increased frequency, intensity and duration of heat-related events in most parts of the planet.

The frequency and intensity of droughts have gone up in some regions (including the Mediterranean, Western Asia, many parts of South America, and most of Africa and Northeast Asia), and there has been a surge in the intensity of heavy rainstorms worldwide (IPCC, 2019).

The Agriculture, Forestry, and Other Land Use (AFOLU) sector accounts for less than 25% of global anthropogenic greenhouse gas (GHG) emissions (approximately 10 to 12 $GtCO_2eq$/year) – mostly as a result of deforestation and livestock farming, in addition to the use of nitrogen fertilizers. Between 2000 and 2010, the farming industry's estimated annual GHG emissions were between 5.0 and 5.8 $GtCO_2eq$/year, whereas the annual GHG flow caused by land use activities and change of use was approximately 4.3 to 5.5 GtCO2eq/year (IPCC, 2014).

However, it is estimated that the global roll-out of improved farming and livestock production practices may allow a 20 to 40% mitigation of GHG emissions to meet the target of the Paris Agreement, which aims to limit global warming between 1.5 °C and 2 °C by the end of the next century (IPCC, 2019).

In its Nationally Determined Contributions (NDC) – a set of commitments and contributions countries have pledged to fulfill the Paris Agreement (UNFCCC, 2015) –, Brazil pledged to reduce its GHG emissions by 43% by 2030, compared to 2005 levels. The domestic farming industry's contribution would come by strengthening the low carbon agriculture plan, called ABC Plan, whereby sustainable farming practices are introduced (Brazil, 2015).

These practices mostly focus on recovering degraded pastures, no-till farming, and integrated crop-livestock-forestry in nearly 20 million hectares. Implementing said practices can boost the efficiency of farming production and cut down GHG emissions, primarily by removing part of the carbon currently found in the atmosphere, as CO_2, and fixing it in the soil, a process called "soil carbon sequestration."

However, although Brazil has already invested more than 16 billion reals into the ABC Plan between 2010 and 2019, and has several producers who have implemented and conducted good production practices in their rural properties, the country still cannot demonstrate carbon sequestration in soil as a result of these actions. One of the main obstacles is the lack of knowledge about the assessment of soil carbon stocks.

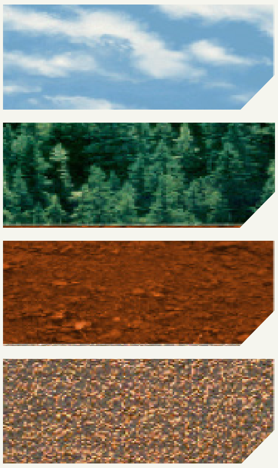
Consequently, the country cannot ensure a transparent implementation of its NDCs in the sector, which prevents it from boosting green funding, makes it difficult for new producers to adhere to more efficient practices, and for current producers to get recognition in the domestic and global markets.

In this context, this study aims to help understand the main aspects associated with the proper evaluation of soil carbon stocks and sequestration in farming systems, gathering relevant information for decision-making in relation to monitoring public policies and soil carbon sequestration programs and initiatives.

Organic matter and soil carbon stocks

Carbon (C) is a vital element as, together with oxygen (O_2), it forms CO_2, participating in the photosynthesis process, which is at the base of the trophic chain. Thus, carbon circulates in all spheres: atmosphere, biosphere, pedosphere (humusphere), lithosphere, and hydrosphere.

It participates as both very simple organic compounds (CO_2) and complex vegetable tissues (cellulose, lignin) and animals, and as more condensed compounds, such as the case of humus, charcoal, oil, and others. Considering only the atmosphere and land ecosystems, estimates from the IPCC show there are approximately 730-750 PgC in the atmosphere (1 Pg = 1015 g or 1 billion tons of C), 470-655 PgC in the vegetation, and 1,500-2,000 PgC in the soil, at a one-meter depth (about 800 PgC are stored in the first 30 cm of depth). These figures show that there are two to three times more carbon in the soil (as organic matter) than is stored in vegetation, and two times more in comparison to the atmosphere ***(Figure 2)***.



	Pg
Atmosphere	730
Vegetation	470 - 655
Soil (0-30 cm)	≈ 800
Soil (1 m)	1500 - 2000

Figure 2. Global carbon stocks in land ecosystems.

In GT of C (1GT = 10^9t = 1 Pg)

In the pedosphere, carbon is found in both organic and inorganic forms. The organic form is related to the components of the soil organic matter (SOM), and humic substances are the most abundant components, but it is also present in living organisms and their metabolites, plant remains and animals in several stages of decomposition. Carbon in the mineral form can present itself as carbonated minerals in various changing stages, as well as supplies and residues commonly used in agriculture, such as limestone.

Knowingly, there are four main components of soil: air, water, mineral matter, and SOM. The main sources of SOM are plant and animal remains that are deposited on the soil surface, as well as plant root exudates or the radicular system itself, when decomposing.

The input of these plant and animal remains is a source of energy for soil organisms (both macro and mesofauna, as well as microbial mass).

This interaction between organisms and SOM sources, usually defined as decomposition, forms humic and non-humic substances, in addition to other mineral and gas products. Although it accounts for only about 1-5%, SOM is one of the main components of soil, as it strongly influences the productivity of plants and environmental aspects, providing nutrients to plants, in addition to influencing the soil's physical, chemical, and biological properties, promoting favorable conditions for plant growth.

SOM is a very important soil component in terms of sustainability of vegetal production. Despite existing in small amounts, when mineralized it is important to supply nutrients to plants, in addition to influencing the soil's physical (reducing soil bulk density and consequently increasing porosity and water retention levels), chemical (creating negative charges and increasing the soil's cation exchange capacity), and biological (mainly those related to nutrient cycling for plants) properties. Therefore, SOM (expressed by soil carbon) is vital to maintain and even improve soil quality ("health").

It also assists directly in promoting favorable conditions for plant growth. However, SOM products do not remain in the soil indefinitely. The average time it resides in the soil is called mean residence time. According to this concept, SOM can be categorized by active fraction (MRT of days-months), slow fraction (years-decades), and passive (centuries-millenniums). Therefore, carbon travels in and out of the soil. In this context, there are at least two metrics to express this element in the soil: carbon level (example units: %C or milligrams of carbon per gram of soil) and carbon stock (an amount of carbon in a certain layer of soil per unit of area).

Clearly, the latter form of expression, soil carbon stock, is technically more accurate,
and the most commonly used units for each soil layer (e.g.: 0-10 cm, 0-30 cm, or 0-100 deep), have been kilogram per square meter
(kg m^{-2}) or even tons per hectare (t ha^{-1}).

Methods to assess soil carbon stock changes

In a certain native system, soil carbon stocks are dynamically balanced (steady), that is, carbon inputs and outputs balance each other out. When the native system is changed by anthropogenic action, the dynamic balance is disrupted and usually outputs exceed inputs, leading to a reduced amount of carbon and modifying the quality of organic mineral compounds.

The soil carbon stock is also influenced by a series of factors, such as type of soil (mainly in terms of mineral fraction), type of vegetation (contribution of air part and radicular system), climate (dry/cold vs humid/warm), terrain (for instance, topography may favor, for instance, carbon accumulation in certain lower areas), living organisms (quantity and functional diversity), farming practices (for instance, conservation practices, such as a well-managed pastures, no-till planting, and integrated crop-livestock-forestry tend to increase soil carbon, whereas degraded pastures and excessive tillage/harrowing tend to reduce soil carbon). Therefore, considering the various factors that influence directly soil carbon stocks, their proper evaluation is a complex task whose results present various uncertainties.

Thus, several methods have been proposed in an attempt to assess soil carbon stocks, especially due to land use change and/ or the adoption of management practices.

Among the main existing methods to estimate carbon stock changes, using calculation tools or spreadsheets, it is worth mentioning the system proposed by the “Carbon Benefits Project” (CBP) and the “EX-ACT” tool, proposed by FAO. Additionally, there are the calculation methods based on the IPCC’s Tier 1, Tier 2, and Tier 3. These approaches are useful to obtain general data, but do not replace a more specific or thorough evaluation based on field samples and measuring soil carbon levels using an elemental analyzer (dry method).

The Carbon Benefits Project (CBP) provides tools for projects intended in the farming and forestry industries to estimate the impact of their activities in mitigating climate changes, comprehending both changes to carbon stocks and GHG emissions. The tools may be employed in all stages of a project, and they are free and relatively user-friendly. The tools are split into “simple” and “detailed” modules, and have been developed by the Colorado State University and their partners under a project co-funded by the Global Environment Facility (GEF), led by the United Nations Environment Program (UNEP).

The simplified module uses standardized values ("default") taken from the literature to estimate carbon stocks and gas emissions, whereas in the detailed module, the user must insert more specific information regarding land use change and/or farming practices, such as the amount of fertilizer used, types of crops, soil preparation methods, etc. Both CBP modules produce general information about the evaluated situation and provide uncertainties associated with the estimates. Such tools are useful for a general evaluation of projects that, directly or indirectly wish to roughly assess the impact of their activities to carbon stocks and gas emissions. Even the CBP suggests that more precise evaluations for monitoring purposes be carried out using data obtained directly from the field and measured specifically for each situation (https://banr.nrel.colostate.edu/CBP/). The EX-ACT (Ex-Ante Carbon-balance Tool) was developed by FAO with the purpose of providing ex-ante estimates of the impact of farming and forestry development projects in GHG emissions and carbon sequestration, showing their effects in the carbon balance. To that end, the tools employ standard values obtained from the IPCC's reports (Tier 1) and/or more specific coefficients obtained from the literature for some situations associated with farming and forestry systems (Tier 2).

The user has access to a set of interconnected Excel spreadsheets to estimate the potential carbon accumulation or loss in the soil and GHG emissions. There is information that reveals the uncertainties associated with these estimates. Like the CBP tools, the EX-ACT was not conceived to provide detailed or situation-specific information. These are useful tools to acquire general knowledge regarding the magnitude of carbon stock and GHG emission values as a result of farming and forestry activities (http://www.fao.org/tc/exact/ex-act-inicio/pt/).

The IPCC has classified the methodologies for estimating domestic GHG emissions and carbon stocks in three different “Tiers” (levels) according to the amount of required information and analytical complexity (IPCC, 2003, 2006). Tier 1 uses the standard (“default”) emission factors provided by the IPCC, which are more generic. Thus, according to the IPCC’s document (IPCC 2003, 2006), the method to assess changes to stock levels does not apply in the context of Tier 1 because more specific data regarding the situation under evaluation is required. Tier 2 is based on the same methodology as Tier 1, but uses emission factors and other country-specific parameters.

Country-specific emission factors and parameters are the most suitable for that country’s forests, climate

Country-specific emission factors and parameters are the most suitable for that country's forests, climate regions, and land use systems. More highly-stratified data may be required for the Tier 2 approach in order to match that country's specific emission factors and parameters for certain regions and specialized land use categories. Tier 3 uses simulation models that must be adapted to suit country-specific circumstances. If properly implemented, the simulation models can be combined with geographic information systems to cover larger portions of the country.

Moving from Tier 1 to Tier 3 may potentially reduce uncertainties associated with GHG emissions and changes to carbon stocks, but it is not on par with the reduced uncertainties associated with the procedure that recommends field sampling, specialized lab testing, and carbon stock calculation, as shown below.

The methods presented here are useful to acquire general knowledge about carbon stock values, usually accompanied by high uncertainty levels, since the goal of said tools is to provide generic/rough information, usually more applicable to broader contexts of inventories and estimates, before a certain project or action has been effectively implemented (i.e. "ex-ante").

Therefore, to quantify specific situations involving land use change and/or management practices, and to monitor soil carbon stocks, it is highly recommended that the evaluation be based on sampling data collected in real field conditions, as proposed by the IPCC (2006).

To that end, it is necessary to collect soil samples in the field, prepare the samples properly, measure the soil carbon level in a specialized laboratory, and correctly express the results in the form of “carbon stocks”, as shown in the following items.

Soil carbon stock calculation

More precise and accurate assessments of soil carbon stocks must be based on soil sampling, preparing these samples, finding their carbon levels through specialized lab testing, and properly expressing the analytical results (by calculating carbon stock levels for each soil layer). Carbon stock calculation is based on the following equation:

Carbon stock = Carbon level x soil bulk density x evaluated layer thickness

Therefore, it is necessary to find out not only the soil carbon level, but also its bulk density and how thick the evaluated layer is. In the following section, we'll present some important information for proper soil carbon stock level evaluation.

Soil sampling to find out carbon stock levels

When measuring the soil carbon level in a certain area, it is usually not possible to examine it as a whole; therefore, samples must be collected. The collected soil samples must be the most representative of the whole area under evaluation. Pre-selecting the area may be achieved by using soil maps, land use maps, aerial shots, satellite images, and interviews about land use history. Concomitantly to office tasks, field visits may be used to determine the exact locations samples will be taken from. Ideally, this site should be as homogeneous as possible and representative of local land use or management practice. If possible, select the terrain's flattest part and pay special attention to the type of soil the samples will be collected from, primarily with regards to texture.

Comparisons between land uses and management practices must be performed in same-texture soils (preferably with a lower than 5-10% difference in clay levels).

Grid sampling provides good area coverage, allowing for future identification of the site for a new sample collection. Each area must be georeferenced using a GPS device and sampling spots must be plotted into a map of the area. A 3x3 grid, for a total of 9 trenches 50 meters apart from each other ***(Figure 3)***, spanning a 1-hecatre area, is adequate for evaluating areas covered by native vegetation and changed by anthropogenic activities (crop, livestock, forestry, etc.).

The IPCC suggests considering at least a 0.3 m deep surface profile. However, several authors stress the need to investigate soil carbon stock levels in deeper layers to assess the impact of land use and management practice changes, preferably 1.0 m deep.

To do that, it is necessary to collect samples from the soil's stratified layers, since soil carbon does not present a linear behavior along the profile. Sampling should be performed in 0.1-1 m deep layers in three of the nine trenches. Samples from the three deepest trenches must be taken from the following layers: 0-0.1; 0.1-0.2; 0.2-0.3; 0.3-0.4; 0.4-0.5; 0.5-0.6; 0.6-0.7; 0.7-0.8; 0.8-0.9; and 0.9-1.0 m.

Samples from the six other trenches may be taken only from the superficial layers (0.0-0.1; 0.1-0.2; and 0.2-0.3 m), as suggested by Cerri et al. 2013 and illustrated in ***Figure 3***.

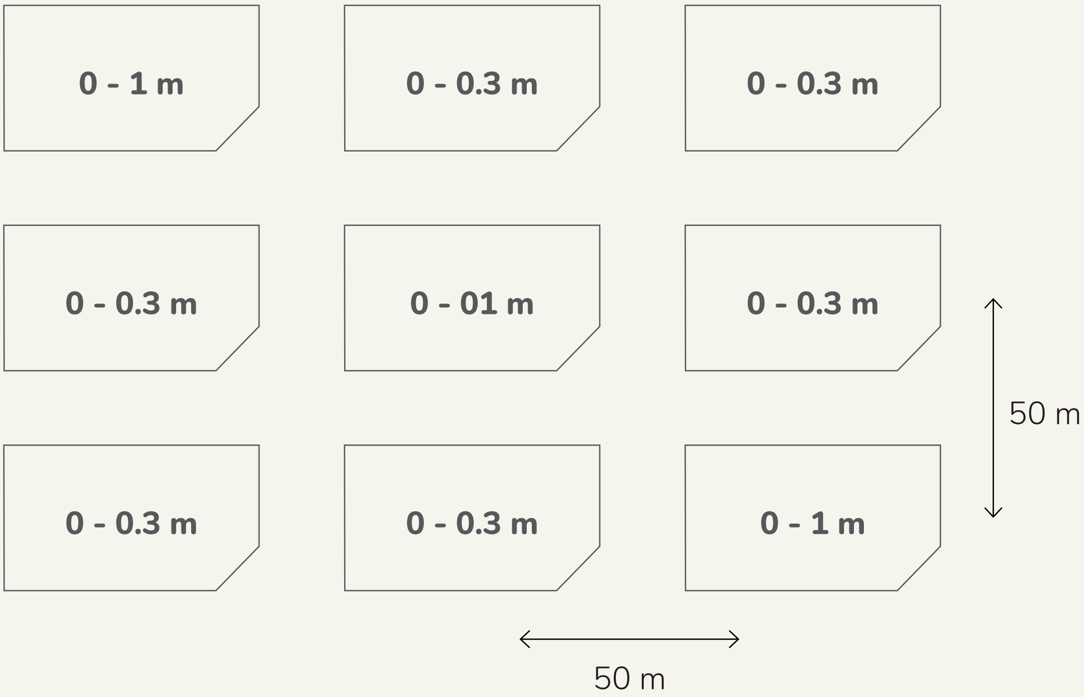


Figure 3. Sampling scheme for measuring soil carbon and soil bulk density. The nine trenches span a 1-hectare area. Samples from six trenches are taken at 0.0-0.1; 0.1-0.2; and 0.2-0.3 m depths. Soil samples from the other three trenches are taken in 0.1 m steps up to a 1-meter depth.

Once the field sampling grid has been established and marked, sampling will be performed in two steps:

- *Getting access to the sampling spot (remove any vegetal material from the soil surface and dig the trenches up to the desired depth);*

- *Collect soil samples.*

Most plant remains that may be on the surface must be carefully removed manually. The deeper trenches must be 1.5-meter deep x 1.5-meter long x 1.0-meter wide, whereas the smaller ones must be 0.4 m x 0.4 m x 0.4 m. Once the trenches have been dug, soil samples are taken in 0.1-meter steps, using a knife, spade, or another tool that allows an amount of soil from the sampled layer to be removed ***(Figure 4)***.

Figure 4.
Soil sampling in 1.5-meter-deep trenches for sampling up to the 90-100 cm layer.

In farming areas, samples must be collected from both the lines and in between the lines in order to detect possible spatial variability caused by machine traffic, soil preparation, and other effects of management practices.

Preparing the collected samples

Once collected, soil samples must prepared for lab testing. To that end, they must be air-dried, homogenized, and sieved using a 2 mm sieve, whereby two fractions are obtained: smaller than 2 mm air-dried fine soil particles and a larger than 2 mm fraction, consisting of roots and small rocks.

To measure carbon level by dry combustion (the most recommended method due to its high accuracy), a 6-gram air-dried fine soil sub-sample must be ground finely enough to get through a 60-mesh sieve, with mesh opening size smaller than 0.250 mm. Then, roughly 20 to 30 mg of ground soil has to be weighed using a 5-decimal analytical balance, placed in 8x5 mm tin capsules to determine the carbon level in the elemental analyzer (dry combustion) ***(Figure 5)***.

Figure 5. Collected samples preparation steps (sieving and grinding), weighing, and elemental analysis device for measuring the sample's C level.

Measuring soil carbon level through “dry combustion” or “elemental analysis”

The general principle of the dry method (also called dry combustion or elemental analysis) is the oxidation of carbon and thermal decomposition of carbonated minerals through heating a soil-catalyzer mixture in a resistance oven or air-circulation oven (temperatures around 1,000 to 1,500 °C).

To do that, a device called elemental analyzer is used. The principle of most testing devices is that soil carbon is measured based on the quantification of CO_2 through mid-infrared, and CO_2 is formed by oxidizing the sample’s organic and inorganic components.

It is worth noting that, when performing soil sampling, it is necessary to check for the presence of carbonated minerals, such as rock fragments or secondary minerals (carbonate nodules), which in farming areas may result from recent use of limestone as soil corrective or nitrogen fertilizers. As the procedure does not discriminate the elements’ sources, knowing the sample’s history is important for evaluating and interpreting the results.

The main advantage of this method is how highly accurate and precise the analytical results are. On the other hand, it is an expensive method that requires advanced equipment (elemental analyzer) and trained operators. Here are some considerations regarding carbon level measurement via dry combustion:

- If you wish to determine the carbon level (when there is limestone), it is necessary to:

1) Acidify the sample to eliminate the limestone's carbon (CO_2);

2) Analyze the sample containing organic carbon.

- If you wish to determine the carbon level (when there is charcoal):

1) Eliminate charcoal through flotation using a high-density inorganic liquid;

2) Analyze the sample without charcoal.

- If you wish to measure organic and mineral carbon levels, when the sample is known to contain organic carbon + limestone (inorganic carbon), the following steps apply:

1) Proceed with determining the total carbon level;

2) Acidify the sample (usually with HCl) to remove carbonates (inorganic fraction);

3) Quantify carbon in the sample without carbonate (containing organic carbon only);

4) Calculate the difference between total carbon and organic carbon (when there is charcoal).

There are other methods to measure soil carbon levels, the best-known of which is the “Walkley & Black,” also known as “wet oxidation” or “potassium dichromate” method. This method is usually recommended for routine testing to evaluate soil fertility and provides lower accuracy than carbon level measurements via elemental analyzer. More information about the soil carbon measurement method for evaluating soil fertility can be found in the BOX below.

SOIL CARBON MEASUREMENT METHOD FOR THE PURPOSES OF SOIL FERTILITY EVALUATION (EXPRESSED IN SOIL ORGANIC MATTER)

The general principle of the wet oxidation carbon method (also called dichromate oxidation or Walkley & Black) is based on oxidizing organic carbon with dichromate ions in an acid medium and measuring easy-to-oxidize material. This method is better suited for evaluating soil fertility in routine testing laboratories. The potassium dichromate, heated in the presence of H_2SO_4 turns all easy-to-oxidize forms of soil carbon into CO_2. The reaction associated with measuring the soil sample’s carbon level is presented below:

$$2\ Cr_2O_7^{-2} + 3C + 16H^+ \longrightarrow 4\ Cr^{+3} + 3CO_2 + 8H_2O$$

The excess dichromate is titrated with a Mohr salt solution $[(NH_4)_2\ Fe(SO_4)_2 \ldots 6\ H_2O$. Additionally, there is a 77% recovery factor (60-86%) for converting easy-to-oxidize organic carbon into total organic carbon. Standardizing is accomplished using 25 and 50 mg of EDTA. More details about this method can be found in Walkley (1947). Some comments and observations about this method are:

- It is the most-widely used method in Brazil's routine laboratories, as it does not require specific equipment;

- It only measures organic carbon (only easy-to-oxidize organic carbon, hence the need to use the recovery factor). Therefore, it is not suited for soils with a substantial amount of inorganic carbon;

- It is not considered a clean method, as it produces residues containing, for instance, chromium and sulfuric acid.

Some laboratories that conduct routine soil fertility evaluation tests present the soil's total OM in their routine analyses. This total OM value is obtained by multiplying the %C by a constant-value factor of approximately 1.73. This factor derives from studies mainly by Russian researcher Kononova, who in the 1950s and 1960s established that the average carbon content of humic acids extracted from different soils was approximately 58.

Since back then researchers used to consider humus as synonymous with SOM, this 1.73 factor (100/58) was introduced to estimate SOM. Although the humic substances account for a larger portion of the SOM, this index is currently no longer used in research, as other components, in addition to humic acids, with varying carbon levels, are also considered SOM.

Soil bulk density measurement

Soil bulk density is defined as the mass of the volume unit. There are two main types of density: real or particle density and apparent or global density. Real or particle density is not affected by how solid particles are arranged in the soil, nor by its texture and porosity. It only depends on its mineralogical nature and organic matter content. Apparent or global density takes into account the total soil volume, including its porosity. To calculate soil carbon stocks, the global or apparent density is used.

Global density has been measured via soil sample ring and by the paraffin or clod method: the former is more commonly used in measurements connected with soil carbon stocks. The procedure involves introducing the ring into the layer you wish to measure (the same soil layer sample used to measure carbon level) carefully not to compact the soil around the cutting edge ***(Figure 6)***. It is necessary to remove the ring and trim excess soil from both sides with a knife. Then put it in an aluminum box, seal it with tape, and dry it in the lab using in a heating chamber at 105-110 °C for 24 hours. Then weigh it (evaluate humidity, if you want to). Calculating the ring volume takes into account the equation $V= \pi r2 h$ and, usually, global density is expressed in g cm^{-3} (or t m^{-3}).

Figure 6. Undisturbed soil sampler (using a soil sample ring to measure soil bulk density).

SOIL BULK DENSITY ESTIMATION BY PEDOTRANSFER EQUATION

Pedotransfer equations are an increasingly utilized strategy to estimate soil attributes with the purpose of making up for the lack of information regarding certain properties. This approach has been used to estimate soil attributes that require long execution times and/or are expensive. In this context, regression models or pedotransfer functions can be used to estimate, for instance, soil bulk density for layers that have not been sampled.

Soil bulk density estimation is one of the main sources of uncertainty for calculating carbon stocks. Although global soil bulk density is measured by the relation between mass of soil and volume taken up – variables that are, in theory, easily obtained – the truth of the matter is that it is hard to obtain safe, accurate information regarding this density (Barros & Fearnside, 2015). That has prompted the emergence of several soil bulk density predictions that exploit the relations between this parameter and other variables more commonly available in pedology inventories in order to ensure reliable information about carbon stocks and reduce measurement costs (Bernoux et al., 1998).

Pedotransfer equations built based on parameters commonly found in pedology inventories, such as carbon level and amount of clay, have great potential to represent direct soil bulk density measurements when these are hard to access or unavailable (Benites et al., 2007).

Soil bulk density (0-30 cm) (g cm^{-3}) = 1.56 – (0.0005 x CLAY) – (0.01 x CO) – (0.0075 x SB)

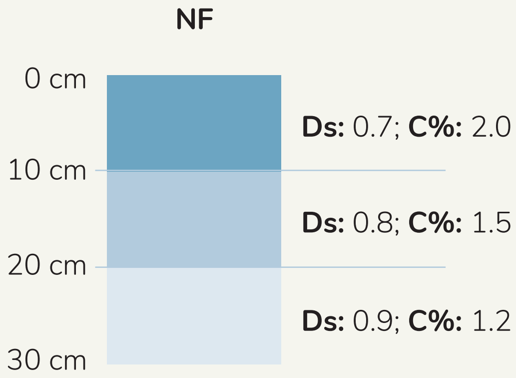
(r^2 = 66%, Benites et al., 2007)

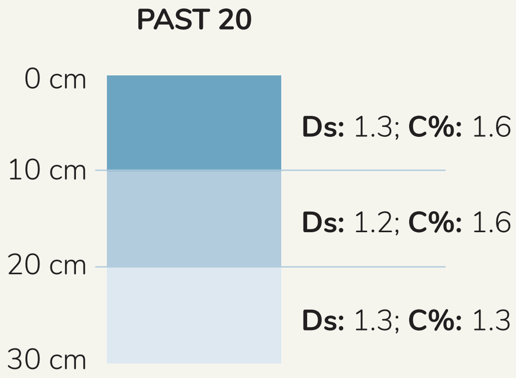
Where: CLAY = clay content (g kg-1); OC = organic carbon (g kg-1); SB = Sum of bases (cmol$_c$ kg-1).

However, it should be noted that measuring global soil bulk density values in field conditions is always more reliable and ensures less uncertainty than using values estimated from pedotransfer equations created from attributes that are as or more complex and that may present high spatial variability.

Expressing soil carbon stock results: comparing the same mass of soil

As soil samples are always collected in the field in fixed layers, there could be mistakes in the calculation of carbon stocks due to soil bulk density variations resulting from vegetation or management practice changes. Therefore, considering the carbon stock is also a function of soil bulk density, factors such as machine traffic and soil preparation, which affect density, may influence the results. Correcting the density of all sites to a reference area, the stock comparison will be made considering the same mass of soil (Ellert and Bettany, 1996). Carbon stocks in the evaluated sites must be calculated using an equivalent depth, considering a depth that contains the same mass of soil as the corresponding layer in the reference area. Reference areas are usually a site covered by native vegetation or previous land use (e.g. a pasture), depending on the evaluated area's land use history. Considering all data provided below, it is worth noting the difference in carbon stock calculation by the equivalent layer (fixed layer) method and considering the equivalent mass (i.e. comparing carbon stock considering the same mass of soil for two land uses) for distinct environments of native forest (NF) and 20-year pastures (PAST20).





Resolution Carbon Stock (CS)

Equivalent Layer				Equivalent Mass			
System	**Layer**	**Mass of soil**	**CS**	**System**	**Layer**	**Mass of soil**	**CS**
	m	**kg/m^2**	**kg/m^2**		**m**	**kg/m^2**	**kg/m^2**
	0-0.1	70	1.40	NF	00-0.1	70	1.40
	0.1-0.2	80	1.20		0.1-0.2	80	1.20
NF	0.2-0.3	90	1.08		0.2-0.3	90	1.08
Total for 0.30 m			**3.68**				**3.68**
	0-0.1	130	2.08	PAST 20	00-0.054	70	1.12
PAST 20	0.1-0.2	120	1.80		0.053-0.067	80	1.20
	0.2-0.3	130	1.69		0.067-0.069	90	1.17
Total for 0.30 m			**5.57**				**3.49**

CALCULATION BASIS

Mass of soil for native forest

Layer 0-0.1: ((100*100*0.7*0.1)*1000)/10000= 70 kg/m^2

Layer 0-0.2: ((100*100*0.8*0.1)*1000)/10000= 80 kg/m^2

Layer 0-0.3: ((100*100*0.9*0.1)*1000)/10000= 90 kg/m^2

Mass of soil for pasture

Layer 0-0.1: ((100*100*1.3*0.1)*1000)/10000= 130 kg/m^2

Layer 0-0.2: ((100*100*1.2*0.1)*1000)/10000= 120 kg/m^2

Layer 0-0.3: ((100*100*1.3*0.1)*1000)/10000= 130 kg/m^2

Layer correction for pasture soil based on the forest's mass of soil

First layer
0.1..............130
X..................70
= 0.054 m

Second layer
0.1..............120
X..................80
= 0.067 m

Third layer
0.1..............130
X..................90
= 0.069 m

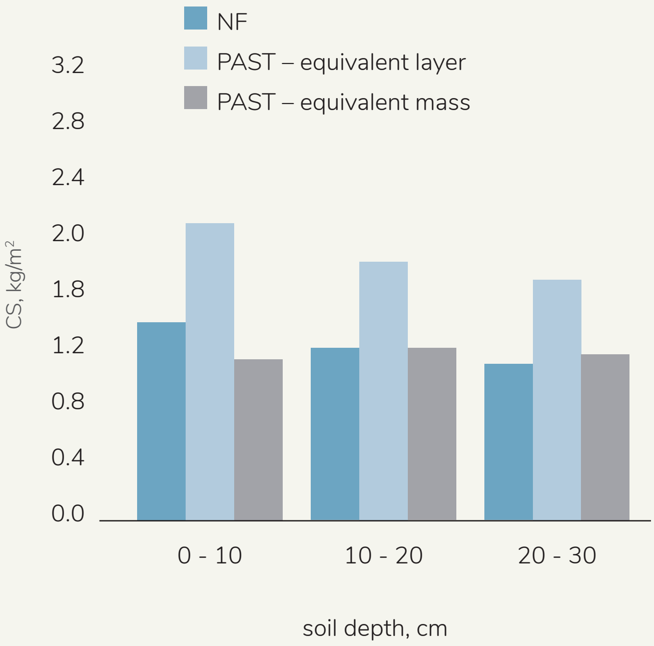
Corrected carbon stock for pasture

Layer 0-0.1: ((0.054 * 2.08 *10) = 1.12 kg/m^2

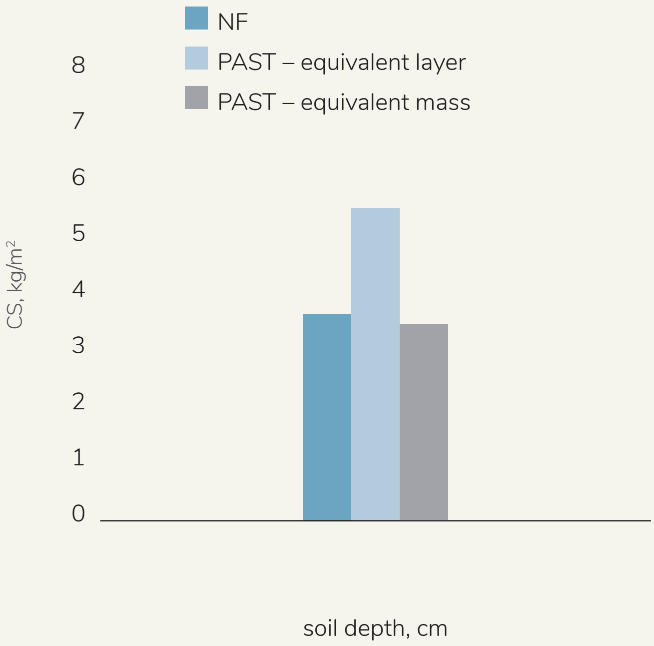
Layer 0-0.2: ((0.067*1.8*10) = 1.20 kg/m^2

Layer 0-0.3: ((0.069*1.69*10) = 1.17 kg/m^2

SOIL CARBON STOCK PER LAYER



SOIL CARBON STOCK PER DEPTH FROM 0 TO 30 CM

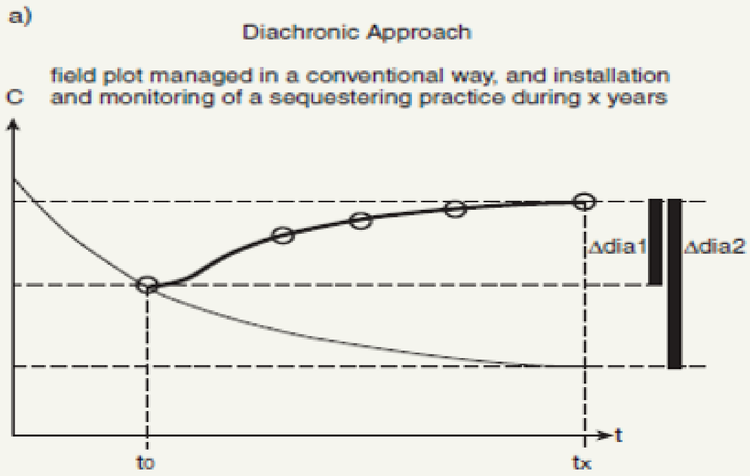


DIACHRONIC AND SYNCHRONIC APPROACHES

There are two different approaches to soil sampling for soil carbon stock assessment: diachronic and synchronic (***Figure 7***, Source: Bernoux et al., 2006).

- Diachoric, soil carbon stocks are measured over time at the same site (field plots) with different land treatments, use, or management (example: field experiment). That is costly and generally there are time limitations, since it may take long for soil carbon to show substantial differences.
- Synchronic (or chrono sequence) samples are taken at the same time from field plots under different land use or management systems. In this approach, soil carbon stocks in the area being evaluated are compared to soil stocks as original reference (usually under native vegetation). The main premise of the synchronic approach or chrono sequence, where space replaces time, is that soil conditions, topography, climate, etc. are similar and the only variable would be how long a land use or management practice has been in place (Costa Junior et al., 2013).

In theory, the diachronic and synchronic approaches should provide pretty much the same results with regards to soil carbon stocks. However, in practice, with the synchronic approach it is virtually impossible to eliminate all environmental factors that influence soil carbon stocks due to its high spatial variability, especially with regards to soil properties.



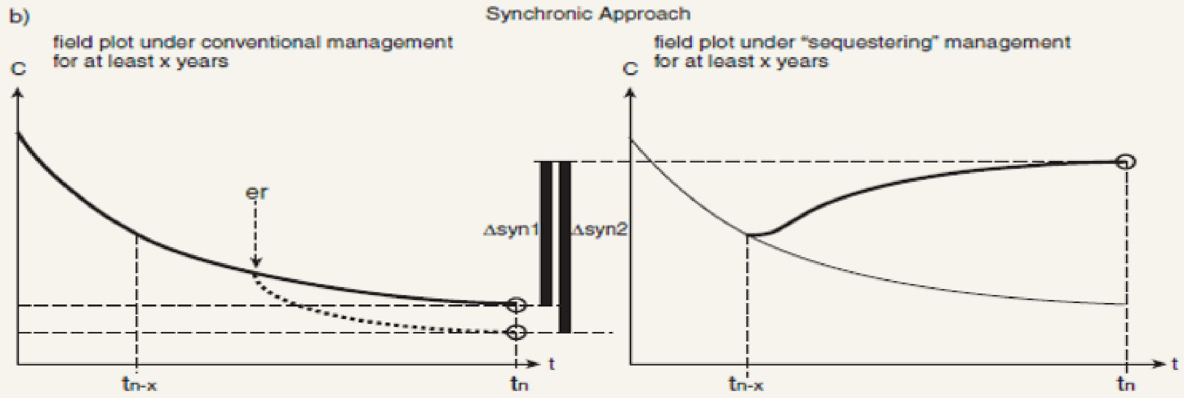


Figure 7.
Comparison between diachronic (a) and synchronic (b) approaches.
The black circles indicate carbon stock measurements. "Er" means erosion.

Source: Bernoux et al. (2006).

UNCERTAINTY ASSOCIATED WITH CARBON STOCK MEASUREMENT

As it has been previously mentioned in this document, there are several methods to measure soil carbon levels (such as the wet oxidation, also called Walkley & Black, and the dry combustion or elemental analyzer) and ways to estimate soil bulk density levels (such as pedotransfer equations). Both are essential for calculating soil carbon stocks.

Although it is possible to use carbon measurements obtained through wet oxidation and soil bulk density estimates by pedotransfer equations, these options usually provide high uncertainty levels associated with soil carbon stock calculations. ***Figure 8*** shows a three-level gradient for carbon level and soil bulk density measurements and their respective associated uncertainties.

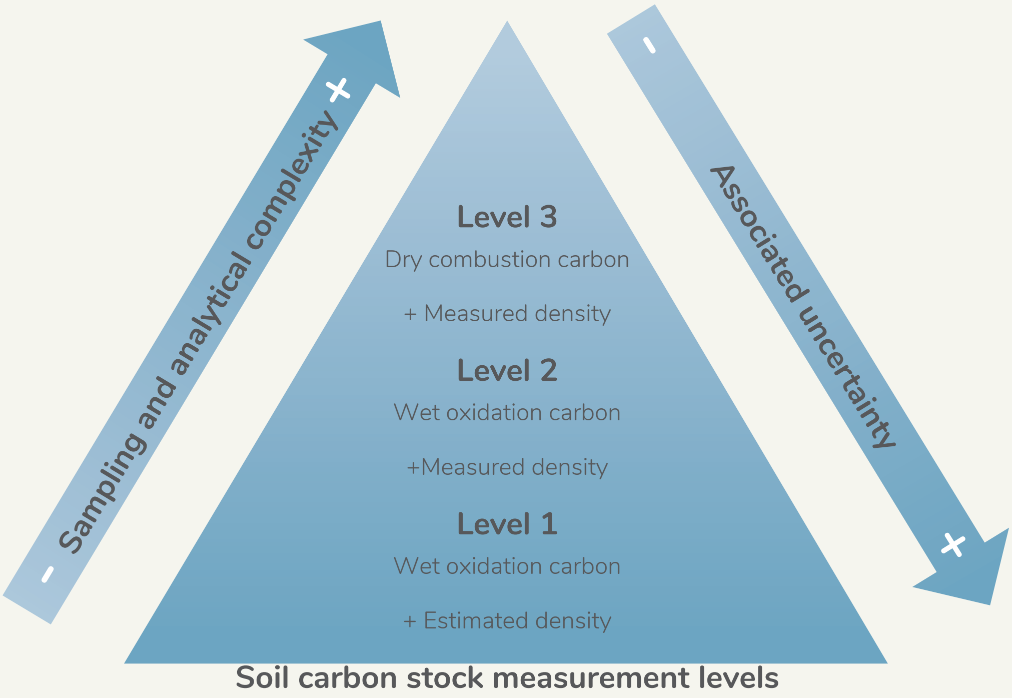


Figure 8.
Schematic illustration of soil carbon stock measurement levels.

In this context, level 3 ***(Figure 8)*** is recommended to ensure lower uncertainty associated with soil carbon stock calculation. That means sampling in field conditions to measure carbon levels via dry combustion method (elemental analyzer), measuring soil bulk density in field conditions (using pedotransfer equations in very specific cases for which it is not possible to make direct measurements using field samples), and maybe adjusting the calculations so equivalent masses of soil are compared in situations which aim to compare carbon stocks (see more details in the previous BOX). Levels 1 and 2 of ***Figure 8*** are useful to provide a general idea about trends and estimated magnitude of stock values, but they bring more uncertainty, which usually does not suit the requirements of institutions directly connected with soil carbon measurement matters.

Final thoughts

The agricultural use of soil using conventional crop-growing techniques, including tilling and harrowing, in addition to pasture degradation, have been considered the main culprits of GHG emissions in the atmosphere, worsening global warming, whose adverse consequences may influence farming productivity itself. More recently, conservation management systems, no-till farming, pasture management techniques, and integrated crop-livestock-forestry (CLF) have changed this paradigm. Research shows that these practices can both reduce gas emissions in the atmosphere, and incorporate and store in the soil carbon previously found in the atmosphere as CO_2.

Thus, conservation management systems, in addition to cutting down production costs without compromising productivity, are meant to mitigate global climate changes. However, in spite of their clear environmental benefit, these systems are not necessarily recognized for the purposes of requesting carbon credits under the United Nations Framework Convention on Climate Change.

Therefore, immediate political actions need to be taken to make sure the adoption of eco-friendly land uses and systems, which reduce gas emissions and promote soil carbon sequestration, are more widely recognized as eligible activities. However, one of the obstacles to do that, though, is the lack of knowledge about soil carbon stock measurements for carbon sequestration evaluations. This study helps elucidate some important aspects associated with the proper evaluation of soil carbon stocks and consequent approach to potential carbon sequestration in systems under native vegetation, in addition to those changed by anthropogenic activities.

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PART 2

Estimating soil carbon sequestration through rehabilitation of degraded pastures in the Cerrado

Introduction

In Brazil, land use change (LUC) and agriculture account for 72% of greenhouse gas (GHG) emissions, and feeder cattle farming is the activity that contributes the most to these emissions (Seeg, 2020). Pastures are the main form of soil use in Brazil, covering roughly 181 million hectares (Lapig, 2020[1]). Historically, pastures are the first form of land use, and they are implemented by cutting and burning native vegetation (Mazzetto et al., 2015). Pastures benefit from the soil's natural fertility and nutrients released by ashes from the burning process (Araújo et al., 2011). However, due to the extensive nature of livestock activities, little or no management is adopted in pastures after their implementation, leading to their degradation (Mazzetto et al., 2015).

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[1] https://pastagem.org/atlas/map

It is estimated that 35% (64 million hectares) of pastures in Brazil present some degree of degradation, of which 37% (23.7 million hectares) are in the Cerrado(Lapig, 2020). The main causes are the lack of nutrient replacement and overgrazing, which cause plants to lose strength and die (Oliveira, et al., 2016; Xu et al., 2016).

Several studies show that, when pastures are degraded, the soil loses carbon, as the death of grasses leads a reduced carbon input in the soil (Braz et al., 2013; Oliveira, et al., 2016). On the other hand, several studies also show the potential of recovering pastures by carbon accumulation, allowing soil carbon stock levels to be the same or higher than those of native vegetation (Braz et al., 2013; Oliveira et al., 2016). Cycling the robust radicular system associated with little or no soil stirring are considered the main factors that play a role in carbon accumulation in the soil when degraded areas are rehabilitated.

Taking into account the potential for soil carbon accumulation in degraded pastures, their recovery is considered a way to mitigate GHG emissions. Thus, in order for the farming industry to reduce their emissions, the Brazilian government launched in 2010 the ABC Plan (Brasil, 2012).

One of the main actions under this plan is to recover 15 million ha of pastures by 2020. In 2015, through the iNDC (Brasil, 2015), the Brazilian government set out to cut down GHG emissions by 43% considering 2005 and 2030 levels. The farming sector is vital to reach that target, as it is the main source of emissions and, at the same time, has a high capacity to hold carbon in the soil and biomass. This way, combining the targets set by the ABC plan and NDC, Brazil proposes to recover 30 million hectares of pastures by 2030.

In this context, the goal of this document is to (1) recommend ways to quantify carbon sequestration through soil samples, using different precision levels, and (2), based on data from the literature, evaluate potential soil carbon sequestration by recovering degraded pastures in the Cerrado.

Recommended soil sampling for carbon sequestration estimation from the rehabilitation of degraded pastures

Considering the soil compartment in carbon pools primarily connected with sustainable pasture management is extremely relevant.

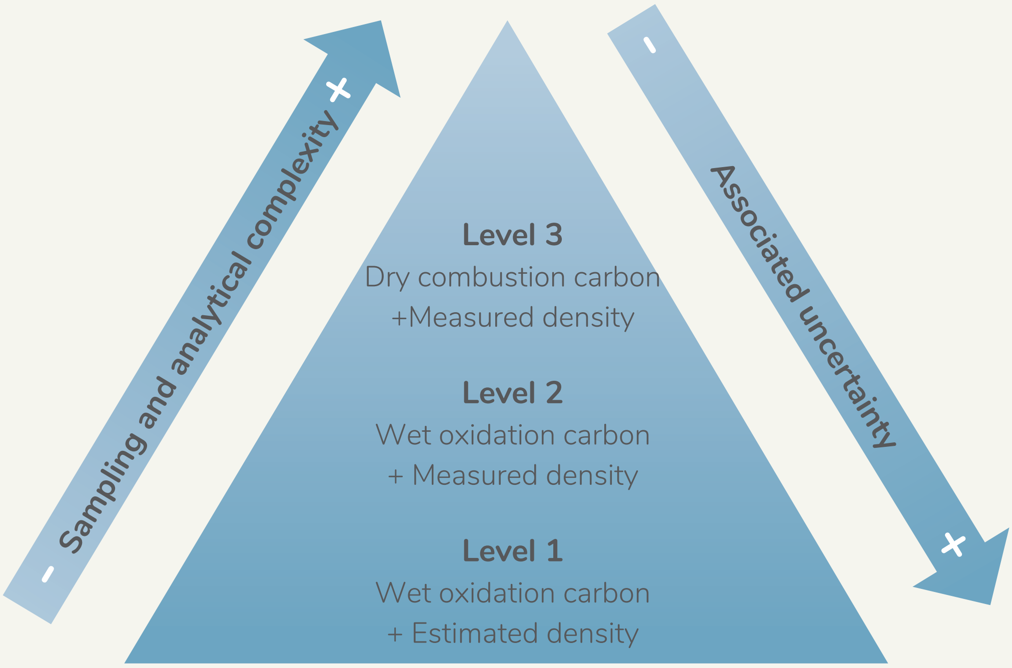
Crop-growing soils may serve as a GHG drain or source, depending on the management system they are subjected to (IPCC, 2001). Management systems that increase the addition of plant residues and carbon retention in the soil are important alternatives to boost the capacity to drain atmospheric CO2, helping to mitigate global warming (Bayer et al., 2006). Uncovered soils or soils subjected to intense movement practices, in different stages of degradation, constitute a source of GHG.

However, estimating carbons stocks (CS) in the soil is the main bottleneck faced by farming industry in terms of emission inventories and GHG removal. Monitoring carbon stocks in soils has been a challenge to help projects that promote the adoption of low-carbon-footprint farming practices.

CS estimates in the soil depend on carbon (C) level and soil density (SD), used to convert carbon into a percentage of dry weight per unit of area (Howard et al., 1995). Furthermore, soils are highly complex systems, spatially heterogeneous at different scales, and include biogeochemical processes with specific temporal dynamics. Estimating soil carbon in crop and livestock systems involves added complexity in comparison to other land uses. Additionally, whereas the methodologies used to quantify GHG emission cuts recommended by programs that verify carbon projects, academic institutions, and the IPCC are technically solid, they tend to be economically unfeasible for farmers.

The first part of this reports sought to highlight the technical robustness of the methodology considered the "standard" for estimating soil carbon stocks. It also recommended alternative methodological aspects, with the purpose of providing more scale to the estimation of GHG emission reductions for rehabilitating pastures in Brazil. The scheme below elucidates the methodological relations and their respective levels, which will be covered throughout the report ***(Figure 9)***.

Figure 9. Undisturbed soil sampler (using a soil sample ring to measure soil bulk density).



Soil carbon stock measurement levels

Finally, there are different methods available to measure carbon stocks in farming soils. Selecting the most suitable method for each project must take into account several factors, including the nature of the soils, how accurate the method is, and how costly it is to analyze it (LAL, 2004).

Generally, analytical procedures recover all carbon forms by converting these forms into CO_2, using dry or wet combustion. CO_2 is extracted and quantified through volumetric, titrimetric, gravimetric, spectrometric, or chromatographic techniques (Silva et al., 1999).

However, there are differences in the results of carbon analyses according to the chosen method (Ferreira, 2013). Therefore, it is possible to find a correlation between soil analysis protocols by applying a correlation index between each method (Sato, 2013), making it possible to view carbon stock results in the same soil samples obtained via different analytical methods. This way, data collected in the field from different sites can be comparable to those found in the literature, regardless of chosen lab testing method.

Measuring carbon stocks: soil carbon level via “dry combustion” or “elemental analyzer”, and soil density by sampling

This is considered the standard method and serves to estimate soil carbon sequestration where carbon levels are measured by dry combustion, and when soil density is measured using a soil sample ring. Typically, this level applies to soil samples taken, for instance, according to criteria set based on the IPCC 2003 Good Practice Guidance for Land Use, Land-Use Change and Forestry guide (IPCC, 2003) and the standards for certifying carbon emission reduction in carbon credit projects.

Carbon measurements obtained by elemental analysis via dry combustion is the direct method used by the IPCC (Intergovernmental Panel on Climate Change) in its guidelines for preparing greenhouse gas (GHG) emission inventories across the globe. It is considered the standard method. The first study comparing the dry combustion and wet oxidation methods was carried out by Kalembasa and Jenkinson (1973), who showed this method is more efficient in recovering organic carbon that all other tested methods.

This method consists of dry oxidation via elemental analysis, in which, typically, C, H, N, S, and O are quantified. Sample oxidation is performed at high temperatures (nearly 1,000 ºC). Then, they are finely ground and placed into a tin capsule, which does not contain carbon. Once total combustion has been achieved, gases containing each element are separated and their concentrations measured by different types of detectors, which vary according to device/manufacturer. The most common are the thermal conductivity detector (TCD) and infrared detector (IR).

However, it is still a costly method, with high testing and equipment maintenance costs, unaffordable to many farmers in comparison to total soil carbon level measurements obtained by other methods[2]. Additionally, in Brazil, only research institutes and universities are prepared to carry out dry combustion carbon analysis (elemental analysis), but they have reached their operational capacity. Furthermore, through this method, soil density is measured directly by field sampling using a soil sample ring. It consists of obtaining mass by weighing, and volume by collecting undisturbed soil samples; done using a cylinder with known internal volume. Depending on how deep you dig to collect the sample, it is necessary to dig trenches, which may cause physical changes to the sampled area.

In general, this method is suitable for well-structured soils. It is convenient to sample a wet soil (friable). Overly dry soils may be humidified for better sampling if the current humidity level is not suitable. For some soils (expansive), it is recommended to describe the humidity or soil potential at the moment of sampling. The cylinders must have a bezel cut to facilitate penetration into the soil and prevent sample compaction in the cylinder. The cylinder is inserted into the soil by percussion or using hydraulic jacks.

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[2] Technical limitations of the elemental analysis (dry combustion): since this type of analysis measures total soil carbon, the amount of CO in soils that have recently been treated with limestone or more alkaline soils may be overestimated.

In short, sampling for soil density measurement purposes, despite being a direct approach internationally accepted by several GHG inventory protocols, requires expertise and involves high costs with field material and technical consulting. Therefore, in addition to alternative methods, it is necessary to use more easily obtained parameters for measuring soil density and, then, carbon stocks. In the following items, new methodological paths will be proposed for both parameters (soil carbon and density), taking into account the premise of obtaining technically robust results.

Carbon stock measurement: using alternative methods to "dry combustion" and soil density via sampling

This is considered an alternative method. It serves to estimate soil carbon sequestration when the organic carbon level is analyzed by wet combustion and/or soil density tests are not available. Usually, this level applies to soil samples taken and tested for fertility, when the amounts of soil organic matter (SOM) and the soil's physical (i.e. amount of sand, silt, and clay) and chemical (i.e. macro-nutrients) attributes are provided.

SOIL CARBON LEVEL MEASUREMENT FROM SOIL ORGANIC MATTER (SOM) VALUES

Indirect carbon measurement via soil organic matter (SOM), obtained by fertility analysis, which are common in soil laboratories in Brazil and routinely tested by farmers, is the most economically and logistically viable option. Furthermore, this indirect measurement of soil carbon via SOM is also accepted by the new protocol for livestock farming in Brazil, launched by Embrapa in 2018: Carne Baixo Carbono (Low Carbon Beef) and Carne Carbono Neutro (Carbon Neutral Beef).

In general, SOM is said to be comprised of around 58% carbon in relation to its total mass. Thus, total organic carbon (TOC) measurement has been used to estimate the organic fraction of the soil (Nelson; Sommers, 1996). Therefore, TOC is measured indirectly by the SOM[3] level using the following expression:

$$SOM = 1.724 \times COT$$

Source: (NELSON; SOMMERS, 1982)

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[3] On average, SOM is 58% C.

Currently, several methods are used in routine and research laboratories to measure TOC. Each method has advantages and limitations, and a different relation with soil texture (Madari et al., 2005), minerology (Zinn et al., 2007), use, and type of substrate (Conyers et al., 2011; Carmo; Silva, 2012). For this reason, it still has not been deemed the most precise and accurate method. There are several methodologies in use, making it difficult to compare experimental results when distinct methods are employed, and causing problems in soil carbon stock comparisons.

Among several methodologies used to measure carbon, the one developed by Walkley & Black (WB), which uses the principle of wet combustion by oxidizing agents, such as dichromate, stands out. Straightforward, low-cost, and requiring simple instrumentation, Walkley & Black (1934) is still the most commonly employed method in soil laboratories, and it quantifies easy-to-oxidize organic matter, which is of great interest for soil fertility. However, environmental problems, due to the use of chromium, have prompted this method to be replaced by others that generate less potentially toxic residues.

Over the years, there have been variations and improvements to this method, such as adding external heating to favor the reaction (Mebius, 1960) (ME), in addition to several variations to the carbon quantification step, like using the colorimetric method (CO).

With the expansion of governmental programs that incentivize the use of conservation, low carbon emission systems, there has been an increasing need to monitor soil carbon variations and, consequently, the need to standardize carbon values by using linear regression factors across all methods.

Table 1 below shows the correlations between carbon levels obtained through different analytical wet oxidation methods, especially compared to the standard CNH (dry) method. The study reviewed different analytical methods employed to measure organic carbon in a wide range of Cerrado's soils, seeking to identify those that are more precise and accurate, and also sought possible correlations between currently used protocols (Sato, 2013). It can be noted that there was over 85% correlation between the standard (CHN) method and other wet oxidation methods (WB, ME, and COL), showing that oxidation reactions and carbon recovery are similar (Gatto et al., 2009).

Table 1. Linear correlation between carbon obtained through different wet and dry methods[4].

Relation	Equation	R2*
CHN x WB	$C_{WB} = 0.8411C_{CHN} – 3.8053$	0.86
CHN x ME	$C_{ME} = 0.9262C_{CHN} - 3.6793$	0.88
CHN x COL	$C_{COL} = 0.961\ C_{CHN} - 5.7021$	0.85

CHN – Elemental analysis (IPCC standard method)
WB – Walkley & Black/ME – Mebius
COL – Colorimetric
* Corresponding to a 5% probability

Source: Sato (2013)

SOIL DENSITY MEASUREMENT FROM PHYSICAL AND CHEMICAL ATTRIBUTES (PEDOTRANSFER EQUATION)

Soil carbon stock (CS) estimates depend on carbon level (C) and soil density (SD), used to convert C from a percentage of dry weight into C weight per unit of area (Howard et al., 1995). However, these variables show large spatial and temporal variability, and quantifying them is laborious, little precise, and negatively impacts the environment (Machado, 2005). SD information is not always available in the literature, as It is hard to obtain in the field, especially at depths below 30 cm (Frazão et al., 2010; Siqueira Neto, 2009).

SD can be estimated by several easy-to-obtain soil attributes.

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[4] Using fifty-four soil samples from the 0-20 cm depth collected in areas that are representative of different regions of the biome.

Clay, sand, and silt fractions are known to affect SD (Manrique; Jones, 1991; De Vos et al., 2005; Pachepsky, et al., 2015). Kaur et al. (2002) used clay, silt, sand, and carbon levels. In Brazil, Bernoux et al. (1998), Tomasella and Hodnett (1998), and Benites et al. (2007) used clay, silt, carbon, and pH in water.

The pedotransfer function (PTF) was proposed by Bouma (1989) to refer to mathematical models used to predict hard-to-obtain soil attributes, which use as variables for diagnosis attributes that are easily measured at low cost (MacBratney et al., 2002).

Cidin (2016) and Boschi et al. (2015) put together a database of Embrapa soils with 38,456 samples. After a screening process, pedotransfer functions (PTF) were developed to evaluate the effect in CS estimates, evaluate PTF performance, and CS estimation. A sub-set of 974 pieces of data was used to develop the PTF in order to estimate soil density (SD). The best PTF that was developed explained a 60% SD[5] variation. ***Table 2*** shows CS values calculated from SD and estimated by PTF. Furthermore, results obtained by Cidin (2016) and Boschi et al. (2015) have shown that errors observed in SD estimates did not propagate to CS calculation. Confirmation through testing is an important contribution to defining CS monitoring strategies in Brazilian soils.

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[5] SD = 1.112 + (0.0002913 Sand) - (0.007817C) - (0.0002217 Clay) + (0.06125 pH_{H2O}) R2 = 0.6; SD: soil density g cm^{-3}, Clay and Sand g kg^{-1}, C: Soil organic carbon g kg^{-1} and pH_{H2O} (dimensionless).

Soil density	Average	Standard deviation	Min value	10 quartile	Median	30 quartile	Max value
	Mg ha^{-1}						
OBS	62.04	39.49	11.18	37.08	57.58	75.94	290.40
PTF	61.63	33.11	12.80	39.19	56.45	74.52	214.98

Table 2. carbon stock values C (Mg ha-1) calculated from observed SD (Obs) and SD estimated from developed PTF (Boschi et al., 2015).

PTFs developed by other authors also show good variation coefficients (R^2) in Brazil and globally. Bernoux et al. (1998) were the first to propose a PTF to estimate SD in tropical soils and used as predictive attributes texture, carbon levels, and type of soil. Benites et al. (2007)[6], using chemical and physical attributes of 1,542 Brazilian soil horizons, developed a PTF to predict the density of Brazilian soils from most biomes from data regarding clay, carbon, and sum of bases (SB)[7]. They found an adjusted R^2 of 0.71. Huntington et al. (1989) obtained an R^2 of 0.75 to estimate SD from organic matter levels of 60 pieces of soil data. Additionally, 75% of CS values at a 30 cm depth, calculated by PTF to estimate density, ranged from 72.55 to 79.71 Mg ha^{-1}; that is, close to observed CS, which was 75.94 Mg ha^{-1}.

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[6] SD = 1.56 – (0.0005. Clay) – (0.01.C) + (0.0075. SB) R2 = 0.7; SD: soil density g cm^{-3}, Clay g kg^{-1}, C: Soil organic carbon g kg^{-1} and SB: sum of bases (Ca^2+ +Mg^2+ +K+ +Na+)

[7] The Sum of Cations or Sum of Bases is a type of information routinely obtained in soil fertility testing usually carried out by famers on an annual basis before planting begins.

Soil carbon stock comparison from standard and alternative methodological procedures

Here, three methodological groups for measuring soil carbonn stocks were considered:

- **Standard approach:** soil carbon level measured by dry method + soil density obtained by soil ring sample;

- **Alternative approach:** soil carbon level measure by SOM + soil density by PTF;

- **Hybrid approach:** soil carbon level measure by dry method + soil density by PTF.

In order to compare soil carbon stock results obtained through different methods, sampling for posterior soil carbon stock measurement via dry and wet methods and density by direct method (soil ring sample)[8] was carried out at Grupo Roncador's Fazenda Água Viva (Roncador Group's Água Viva Farm). Below are the respective results ***(Tables 3 and 4)***.

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[8] Soil sampling carried out in 2015 as part of Liga do Araguaia's Carbono do Araguaia project. More details: http://www.ligadoaraguaia.com.br/

Description	C level dry method	C level SOM method	Observed carbon stock dry method	Observed carbon stock SOM method	Estimated carbon stock dry method and PTF	Estimated carbon stock SOM and PTF	Observed density	Estimated density[9]
	g/kg^{-1}		(t.ha^{-1})				(g cm^{-3})	
Degraded pasture	5.95	8.27	24.24	34.70	27.61	37.78	1.60	1.52
Recovered pasture	13.72	21.77	57.18	95.20	59.04	88.39	1.30	1.35

Table 3.
Carbon stock along soil profile from sampled sites at Fazenda Água Viva (0-30 cm).

Description	Carbon level dry method	Carbon level SOM method	Observed carbon stock dry method	Observed carbon stock SOM method	Estimated carbon stock dry method and PTF	Estimated carbon stock SOM and PTF	Observed density	Estimated density
	%							
Degraded pasture	-	38.88	-	43.15	13.90	55.86	-	-5.00
Recovered pasture	-	58.62	-	66.49	3.25	54.58	-	3.85

Table 4.
Difference between carbon stocks and soil density measured via standard and alternative methods at Fazenda Água Viva (0-30 cm) in percentage.

It is possible to see that the PTF proposed by Benites et al (2007) worked very well for the soils of the farm located in the city of Água Boa, state of Mato Grosso, in the Cerrado, as the difference between observed soil density (measured directly via soil ring sample) and estimated density (by PTF) was only 5% for the degraded pasture, and 3.85% for the recovered pasture. Accordingly, we can conclude that soil carbon stock calculated using the standard and alternative analytical methods were achieved mainly by the analytical difference of soil carbon level (dry method via SOM).

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[9] According to the PTF developed in Benites et al. (2007).

However, by using the hybrid approach (carbon stock estimated via dry method and PTF), there was a small difference in soil C stocks between this approach and the standard approach, with 13.90 for degraded pasture and only 3.25% for recovered pasture.

Despite some bigger differences with some estimates, it is true that good pasture management can increase soil carbon stocks in the surface (up to 30 cm deep) in comparison to stocks in well-managed pastures.

Pros and cons, uncertainty, complexity, and cost

Soil carbon stock monitoring has been a challenge for the farming industry. Soil carbon measured by dry combustion is the direct method used by the IPCC (Intergovernmental Panel on Climate Change) – considered the standard method. However, as previously mentioned, it is still a costly method that requires many specific samples, with high testing and equipment maintenance costs that are inaccessible to farmers. Additionally, in Brazil, only research institutes and universities are prepared to carry out dry combustion carbon analysis. Currently, several wet combustion methods are used in routine and research laboratories to measure SOC.

Wet combustion methods in general have the following characteristics:

- Routine testing carried out by Brazilian laboratories (SOM estimated in soil fertility testing);
- The correlation factor can be used to compare different analytical methods;
- Included in farmer’s overhead costs (low cost).

In addition to soil carbon estimation, the report proposes to estimate apparent density (AD) by pedotransfer function (PTF) (indirect estimate of apparent density), eliminating the disturbed soil sample (taken with a soil ring sample). Direct measurement of apparent density requires field sampling by a specialized technical crew, taking undisturbed samples collected using a known-volume ring (cylinders) and subsequent lab testing, making this evaluation extremely expensive and time-consuming.

Therefore, the table below ***(Table 5)*** sums up the most used alternative methodologies in Brazil to measure soil carbon (carbon wet method and gravimetry), the standard methodology (carbon dry method), and soil density via ring sample and PTF, with their respective pros and cons. Using these alternative methodologies (wet method and PTF) in Brazil may provide some scale to carbon projects for regenerative agriculture in Brazil

Methods	Overview	Advantages	Disadvantages
Soil C wet method			
Walkley & Black (WB)	Soil organic carbon is oxidized by dichromate ions in a strongly acidic solution, and the number of Cr3 ions + reduced ions is determined by dichromate titration (in excess) with Fe2 + ions.	It is the most commonly used method in Brazilian laboratories, offering simple execution, low cost, good accuracy, and does not require specialized equipment, in addition to oxidizing the soil's most reactive organic matter fractions.	Wet methods do not promote full soil organic carbon oxidation, and do not hit the carbon elemental forms. Generates potentially toxic residues (chromium), especially in WB.
Mebius (ME)	The ME method is similar to WB. However, the soil's organic carbon oxidation is maximized by adding heat, making the reaction more efficient.	It is a common method in Brazilian laboratories, offering simple execution, and does not require specialized equipment, providing low cost, high soil organic carbon oxidation, and a larger amount of detected carbon (compared to the WB method).	
Colorimetric (COL)	This method works similarly to the dichromate oxidation, but the final measurement is obtained by spectrophotometry and not titration (WB and ME).	Uses smaller amounts of reagents, simple reproducibility, and easy, error-free titration.	
Soil C dry method – standard method			
Elemental analysis	Based on quantitative combustion procedures, measuring carbon as CO_2. Called dry combustion.	Method used by the IPCC in its guidelines for GHG emission used globally. It allows a larger number of samples to be analyzed in less time.	Expensive method, high testing and equipment maintenance costs, inaccessible to most farmers. Technical limitations: **i)** Requires overly fine sample grinding, making the process more costly; **ii)** Small sample amount used (typically 10 to 1,000 mg), which may result in soil representativeness problems (Chatterjee et al., 2009).

Methods	Overview	Advantages	Disadvantages
Apparent density			
Pedotransfer function (PTF)	PTFs are mathematical models used to estimate hard-to-determine soil attributes using easy-to-determine, low-cost attributes. Indirect apparent density estimation by PTF.	Density estimation using easy-to-determine soil attributes (clay and carbon content, and sum of exchangeable bases, for example). In accordance with the conservation principle.	The function's performance may be lower when applied to a different environment than that it was adjusted to.
Soil ring sampler	Undisturbed sample collection using a soil ring sampler, where apparent density is defined as the ratio between the soil's solid mass and its total volume.	Direct measurement of a key parameter to characterize the soil's physical structure and as a compaction indicator.	Laborious, low-precision quantification that negatively impacts the environment (trench digging). Sampling: a lot of repetitions are necessary. Time-consuming lab testing.

Table 5.
Methodological recommendations to estimate soil carbon and apparent density.

With regards to uncertainties, soil carbon stock estimation requires several decision to be taken, whether they are connected with sampling coverage or methodological paths, all of which result in intra and interspecific uncertainties.

Regarding coverage, it is essential to set transparent boundaries in terms of regional and temporal limits, unit of analysis, and productive system that comprises it. Each decision makes a piece of study data more specific, making it less applicable for general comparisons with other studies (interspecific uncertainties).

Still, coverage can be defined with a certain degree of clarity and low impact to intraspecific uncertainties.

Finally, in addition to decisions related to coverage, carbon stock calculation prompt important methodological decisions. Firstly, with regards to the methodological guidelines that will govern the study – whether direct or indirect methodologies will be used to determine the necessary parameters. More details about the qualitative classification of uncertainties for soil carbon stock measurement approaches are available in ***Table 6*** below.

Table 6.
Uncertainties related to the lab step of soil samples for carbon stock measurement.

Approach	Source of data	Uncertainty analysis
Standard	C dry method + density via soil ring sampler	**Low:** C and SD directly estimated; therefore, uncertainties in estimates of both parameters are related, especially with regards to soil sampling.
Hybrid	C dry method + density via PTF	**Average:** uncertainty is related to the use of PTFs developed in distinct sites in the areas assessed by the project.
Alternative	C via MOS + density via PTF	**High:** C and SD indirectly estimated. In this case, the uncertainties are related to the incorrect choice of PTF in incomplete SOM oxidation.

Another important factor that should be taken into account in soil carbon stock-related projects (allowing estimation of annual soil carbon change rates for different land uses and management practices) is soil sampling design. Understanding the dynamics of carbon removal in the farm over time requires years of observation. In this type of approach, called diachronic, soil carbon stocks are calculated over time for the same site (field parcels) with different land use and management treatments (e.g. field experiment). That is costly and generally limited in terms of evaluation time, since it may take long for soil carbon to show significant differences.

Therefore, the alternative method called synchronic or chrono sequence aims to overcome obstacles related with the matter of time required by the diachronic approach. In the latter approach, samples are taken at the same time from field parcels under different land use or management systems. In the synchronic approach or chrono sequence, where space replaces time, the main premise is that soil conditions, topography, climate, etc. are similar among themselves; the only variable would be how long the land use our management practice has been in place.

This approach provides an integrated evaluation of soil carbon change in an area larger than, for instance, in sampling over time with one or two experimental fields. Ideally, the chrono sequence approach provides the same results as the diachronic approach. However, chrono sequences must be used carefully, as they are susceptible to the confusing effects of spatial heterogeneity and soil management. Braz et al. (2013), through diachronic and synchronic sampling, verified that texture (clay level) was the parameter that mostly influenced soil carbon dynamics in different uses.

To estimate soil carbon stocks, in addition to choosing a sampling approach, it is necessary to consider other field issues:

- **Strategy:** sampling spots must be georeferenced and, preferably, the contour of the sampled field or area should be digitally identified, in order to precise its general position in localization maps. The geographic location should be as precise as possible to allow returning to the sampled site afterwards. Data must be recorded combined with other field information and filed in the project's database.

- **Stratification** the choice of sampling site is linked to a previous evaluation of how locally and regionally representative it is, based on consultations to available soil databases and forestry inventories in the studied areas. Said representativeness must comprehend the site's physical characteristics (soil class, geology, topography, landscape position, micro-climate, etc.) and also production system (genetic material planted, production system adopted, history of the area, use planning, etc.). It is recommended that all evaluated areas have been previously studied for soil classification purposes (Santos et al., 2013), as well as a history of previous crops, fertilization doses and sources, management practices, and crop-growing time.

- **Layers:** 0 to 40 cm layers are recommended, at stratified depths 10 cm apart, like the ones required in the initial phase and follow-up phase regarding soil carbon level evaluations. Using stratified layers, every 10 cm up to 100 cm deep, is a welcome option to improve the follow-up process.

- **Reference area:** It is recommended that an initial study reference area be identified. This reference area will be used as baseline to quantify soil carbon stock changes, and should preferably be an area under native vegetation or an area subjected to soil use control prior to conversion to forest. When the reference area is a native forest, it should be located in a legal reservation and/or permanent preservation area (PPA).

With regards to costs, ***Table 7*** shows the costs involved in all soil analyses required for correctly stratifying the area to be inventoried, in addition to measuring soil carbon stocks in the baseline and throughout the monitoring of LAC activity (low carbon emission agriculture), such as well-managed or rehabilitated pastures. The costs were established based on current values, considering: i) requirements described in standard GHG inventory methodologies; and ii) requirements for alternative soil carbon stock measurement methodologies.

Table 7 does not include costs for technical consulting required for sampling undisturbed soil using a cylinder to determine apparent soil density. This is a sampling procedure that requires prior technical expertise of protocols, as any kind of sampling error may influence the resulting carbon stock measurement.

This is a hard-to-estimate cost, as it depends on how experienced the contracted consulting is, region, sampling time, type of soil, etc. Therefore, the total cost of soil sampling for carbon stock measurement purposes, considering the standard methodology, is higher than what is shown in ***Table 7***.

Table 7.
Costs per soil sample for analyzing the required elements, considering the standard and alternative methodologies for soil carbon stocks.

Parameters	Standard method	US$[10]/sample	Alternative method[11]	US$/sample
Soil C	Direct – total soil C	15.00	Indirect – SOM	4.94
Fertility[12]	-	-	Direct	-
Density	Direct	7.73	-	-
Texture	Direct	3.22	Direct	3.22
Field material	Stainless steel cylinder	6.44	-	-
Total		**32.39**		**8.16**

It can be noted that the methodology proposed by this report cuts sampling costs by 75%, considering only laboratory and equipment costs.

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[10] Exchange rate verified on 3/10/2020: US$1.00 = BRL$4.66 (https://www.bcb.gov.br/).

[11] Prices by ESALQ/USP (http://www.esalq.usp.br/departamentos/lso/Tabela_Preco_Completa.pdf.pdf)

[12] Including: pH, SOM, P, K, Ca, Mg, H+Al

Potential carbon sequestration by recovering degraded pastures in the Cerrado

Agricultural systems or chosen management conditions can increase or mitigate GHG emitted to the atmosphere. In general, pastures combined with foraging vegetables and fully integrated systems can store carbon in the soil, and may neutralize the system's emissions. It is important to stress that achieving net-zero emissions in systems where there is the animal component (livestock farming) is directly dependent on the number of animals in the considered area. Therefore, an optimum productivity-emission balance should be considered.

Additionally, proper management of livestock farming and integrated systems can increase carbon stocks to higher levels than those found in native vegetation (Neill et al.,1996). However, in deeper layers, this stock tends to be smaller (Nepstad et al., 1994).

Carbon removal and storage, as well as its continuation and reversibility, have been a concern for sectors that deal with land use and global warming, not only from a scientific and political perspective, but also economic, with matters like carbon credits becoming part of the debate (FAO, 2019).

Depending on the adopted management practice, the soil may act as CO_{2eq} drain or source. In the case of storage, on average, the soil can balance out part or all of the system's GHG emissions in 20 to 50 years. The opposite is still true for degraded or poorly-managed systems, and sticks to an average time limit to lose carbon. This saturation or loss limit is considered a finite effect (Stewart et al., 2007; Hillel; Rosenweig, 2010). In tropical soils, this average time is 20 years after adopting the system, but there is evidence of stabilization in up to 30 years in southern Brazil (Bayer et al., 2006). Finally, the Good Practice Guidance (IPCC, 2003) says that soil carbon input or output resulting from land use change occur for 20 years at the most.

Furthermore, there are three levels defined by the IPCC (2006), Tier 1, 2, and 3, for emission factors and parameters used to calculate soil carbon flows.

It is important that GHG flow calculations in farms use factors that are coherent with the country's reality, classified as regional factors (Tier 2) by the Intergovernmental Panel on Climate Change (IPCC) and developed by Embrapa's other institutes' researchers. However, there are no specific values for Brazil. So, global default emission factors (Tier 1) published by internationally-renowned organizations in the field of climate change, like the IPCC, are used. Country-specific emission factors and parameters are the most suitable for that country's forests, climate regions, and land use systems. Data from more highly-stratified activities may be necessary for the Tier 2 approach to match Tier 2 country-specific factors and parameters for specialized land use regions and categories. Tier 3 uses simulation models that must adapted to suit domestic circumstances.

If properly implemented, simulation models can be combined with geographic information systems to cover larger territories.

Substituting native vegetation leads to soil carbon stock increases or declines, depending on management system and change stability period. Thus, to better understand the potential for soil carbon sequestration, data from the literature evaluating soil carbon stocks under pastures with different status was compiled.

The criteria to be included in the study were: having used samples from the Cerrado biome and having performed the stocks correction to the same soil mass (Ellert; Bettany, 1995) ***(Table 8)***.

Table 8.
Estimated soil carbon flows in different use and management transitions.

Initial condition	End condition / use	Soil C sequestration (t/ha/year)	Depth	Reference	Notes
Degraded pasture	Nominal pasture	0.36	cm	Oliveira, 2018	Meta-analysis including more than 60 papers between articles and theses
	Well-recovered pasture	0.40	0-30	Oliveira, 2018	Meta-analysis including more than 60 papers between articles and theses
	Well-managed pasture	0.61	0-30	Maia et al., 2009	Meta-analysis including dozens of well-managed pastures in the Cerrado
Degraded pasture	Grain – direct planting	0.19	0-30	Maia et al., 2009	
Degrade pasture	ICL	1.5 – 1.7	0-30	Martins et al., 2018; Assad e Martins, 2015	Filed surveys conducted in different locations in Brazil used as baseline for the ABC Plan
Direct planting	ICL	0.8 to 2.8 mg	0-30	Carvalho et al., 2009	
Direct planting	ICL	0.28	0-30	Maia et al., 2013	
Degraded pasture	Reforestation - Eucalyptus	0.29 – 0.42	0-30	Lima et al., 2008	Areas taken by Eucalyptus for 34 years
Degraded pasture	Restoration (AFS)	0.44	0-20	Forest GHG Protocol	
Cerrado	Degraded pasture	0.33	0-30	Oliveira, 2008	Vila Bela da Santíssima Trindade (MT), Vila Bela da Santíssima Trindade (MT), Carmolândia (TO)
Cerrado	Degraded pasture	-0.35			Nova Xavantina (MT), Dueré (TO), Conquista D'Oeste (MT), Paraíso (TO)
Cerrado	Nominal pasture	1.07		Maia et al., 2009	Cáceres, MT; sandy soil
NV	ICL	-1.53	0-30	Lemos, 2011	4-year Paricá and Braquiarão plantation, and bovine livestock (secondary forest 52.3 tC/ ha and ICL 46,2 tC/ha)

Final thoughts

Based on previously presented data, it can be noted that most carbon that is emitted can be recovered through farming practices that boost the ecosystem's productivity, removing CO_2 from the atmosphere and increasing carbon storage in the system. This way, carbon becomes another indicator of good property management, showing there is a highly-productive regenerative system.

The estimates in this report show there is a great chance of securing certifications that confirm cattle and crop products produced in Brazilian farms are sustainable. To that end, it is necessary to begin monitoring the reduction of GHG emissions as a result of sustainable livestock farming practices. Furthermore, it is an attractive opportunity for companies interested in acquiring credits through direct or indirect emission cuts in their activities. Also, there are business and value generation opportunities, as well as a positive impact to society. For producers, it means a safer production system, better risk management in their activity, and new sustainability indicators. For consumers, it means healthier, more sustainable food.

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