METHODOLOGICAL DOCUMENT
AFOLU SECTOR

BCR0009 SOIL ORGANIC CARBON (SOC) stock increase by adding high organic content from anaerobic digestate

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Terms, definitions and acronyms

AD	Anaerobic digestion
Anaerobic digestate	Is the liquid or solid material processed through anaerobic digestion. Labeling digestate materials shall be designated by prefixing the name of the feedstock from which it is produced, i.e., cow manure digestate, biosolids digestate, etc.
Agroecosystem	Are the ecosystems supporting the food, fiber and other production systems in farms and gardens.
Baseline scenario	Hypothetical development reference that best represents the conditions most likely to arise in the absence of a GHG project.
BCR / SOP	BioCarbon / Standard operating procedures.
C	Carbon
CO_2	Carbon dioxide.
$CO_{2\text{-}e}$	Carbon dioxide equivalent.
CT	Conventional tillage.
Digestate	Is a physical output of the anaerobic digestion (AD). It can be a liquid or solid depending on the digestion technology employed and postprocessing (e.g., dewatering, drying, pelletizing).
DAI	Defined area of intervention.
DBD	Dry bulk density.
DM	Dry matter.
EPrA	Eligible project area.
GHG	Greenhouse gas.
GHG baseline (Greenhouse gas baseline)	Quantified reference point(s) for GHG emissions and/or GHG removals that would occur in the absence of the GHG project, expressing the baseline scenario against which project emissions and GHG removals are compared.
GHG – PDs (Greenhouse gas project developer)	Individual or organization that has overall control and responsibility for a GHG project.

GHG project (Greenhouse gas project)	A set of measures ensuring the reduction (prevention) of greenhouse gas emissions or an increase in the absorption of greenhouse gases.
GWP_{N_2O}	Global Warming Potential for N_2O, kg-$CO_{2\text{-}e}$ (kg-N_2O)$^{-1}$.
HC	Humic carbon
IAs	Intervention areas.
LMSP	Land management sustainable practices.
Monitoring	Continuous or periodic evaluation of GHG emissions, GHG removals, or other GHG-related data.
N_2O	Nitrous oxide.
NT	No tillage
OM	Organic matter.
Org-N	Organic nitrogen.
PTF	Pedotransfer functions.
RMWN_2O	Ratio of molecular weights of $N_2O$and N (44/28), tonne-N_2O (t-N)$^{-1}$.
RMWCO_2	Ratio of molecular weights of CO_2 and C (44/12), tonne-CO_2 (t-C)$^{-1}$.
SALM	Sustainable agriculture land management.
SC	Soil carbon
SOC	Soil organic carbon is the solid carbon stored in soil organic matter.
SOCBS	Soil organic carbon in the eligible project area before the project start.
SOM	Soil organic matter
SSM	Sustainable soil management
ST	Soil texture
t	Metric ton (or tonne)
TOC	Total organic carbon
Tot-N	Total nitrogen

1 Introduction

Organic matter (OM) is a key component of soil that affects its physical, chemical, and biological properties, contributing greatly to its proper functioning on which human societies depend. OM supports soil structure, nutrient retention and turnover, moisture availability and retention, pollutant breakdown, and carbon sequestration. Benefits of soil organic matter (SOM) include improvement of soil quality through increased retention of water and nutrients, resulting in greater productivity of plants in natural environments and agricultural settings. SOM improves soil structure and reduces erosion, leading to improved water quality in groundwater and surface waters, and ultimately to increased food security and decreased negative impacts to ecosystems (Ontl & Schulte, 2012). Soil organic carbon (SOC) plays a significant influence in the physical, chemical, and biological function of agricultural soils although making up only 2 - 10% of the mass of most soils (Bar-On *et al*, 2018).

Soils are the largest pool of carbon (C) in the terrestrial environment (Jobbagy & Jackson, 2000; Schlesinger et al,1995). The amount of C stored in soils is twice the amount of C in the atmosphere and three times the amount of C stored in living plants (Kimble & Stewart,1995). Therefore, a change in the size of the soil C pool could significantly alter current atmospheric CO2 concentrations (Wang et al.,1999). Carbon stored in soils is derived from litter, root inputs, sediment deposits, and exogenous applications of manures/mulches or high organic content material, while losses result from microbial degradation of soil organic matter, eluviation, and erosion (Entry & Emmingham,1998). As an agroecosystem is restored and the soil approaches its productivity potential, C sequestration through the profile increases and this is controlled by pedogenesis, climate, topography, management, and prevailing cover (Harmon et al.,1990; Dewar,1991; Van Cleve et al.,1993). At equilibrium, the rate and amount of C added to the soil from plant residues and roots, organic amendments as well as erosion deposits, are equal to the rate and amount of C lost through organic matter mineralization and soil erosion processes (Henderson,1995; Paustian et al.,1997). Within limits, C in soil increases with increasing soil water and decreases with temperature (Wang et al., 1999; Liski et al., 1999).

According to Robinson et al (1996), SOC and its evolution into humic carbon (HC) is arguably the best single indicator of soil quality. The term soil humic carbon or humus refers to a mixture of organic compounds produced by decomposition of plant tissues or external OM added to soil. Humus is defined by Stevenson (1994) as the total organic fraction in soils exclusive of non-decomposed plant and animal material, their partial decomposition products, and the soil biomass. Humic substances (HS) (e.g., humic acids and fulvic acids) make up the bulk of humus (Tan, 1998). Therefore, organic carbon (OC) is a good indicator of soil fertility and humic carbon (HC) is an indicator of the SOM fraction that achieves the greatest stabilization in the soil.

Land use changes can impact the amount of C stored in the soil by altering C inputs and losses. Agricultural practices that can partially restore, or avoid losses depleted SOC include: (1) adoption of conservation tillage including no-tillage; (2) intensification of cropping by eliminating fallow, increasing cover crops and including more perennial vegetation (Sperow et al.,2003); and (3) improving biomass production through the use of soil amendments (manures), high organic content material, fertilizers and high yielding crop varieties (Lal et al., 1998; Follett, 2001; Collins et al, 2012).

Three soil conceptual C pools are generally defined according to their degradation rate (von Lützow et al. 2008). 1) Labile C in OM turnover occurs within a day to a year. C in OM turnover in the intermediate pool occurs within a few years to decades. Both pools originate predominantly from plant, animal, bacterial, fungal residues and high organic content material. 2) The intermediate C pool is also supplied by OM degradation products from the labile pool. This OM pool is rather active with rather fast turnover, so it is highly influenced by soil management practices. 3) Finally, the turnover of the stable C in OM pool occurs on time scales ranging from decades to centuries. It originates from labile and intermediate pools and involves most of the soil organic C (Torn et al, 2009). It consists of plant, animal, bacterial or fungal residues and microbial metabolic products from different sources. C in OM in the stable pool can be found in aggregates and/or adsorbed on mineral surfaces (Dignac et al, 2017).

Anaerobic digestion (AD) has been recognized as an effective waste management technology and has been used for treating various waste types, including agricultural and agro-industrial waste, the organic fraction of municipal solid waste, livestock effluents, sludge, etc. (Da Ros et al., 2016). AD involves the biological conversion of the organic matter present in waste materials, through the action of a microbial consortium under anaerobic conditions (Ward et al., 2008). The main product of AD is a methane-rich biogas. Methane obtained through AD is considered as a renewable energy source and an excellent alternative to fossil fuels for heat and electricity generation. Apart from biogas, anaerobic digestion also results in the production of digestate, which usually has a nutrient-rich composition and, depending on its characteristics, may be composted or utilized as a fertilizer or soil conditioner (Pellera & Gidarakos, 2017; Barrantes et al., 2014; Fitamo et al., 2016; Kim and Oh, 2011; Ward et al., 2008). The physicochemical characteristics of digestate vary strongly depending on the nature and composition of the digested substrates as well as on the operational parameters of the biogas processes.

Digestates contain less organic C than feedstock (Moller and Müller, 2012; Alburquerque et al, 2012). However, Möller (2015) concluded that the loss of organic C during the anaerobic digestion process is compensated by lower organic C degradation after an application of digestates. Long-term experiments did not prove any negative impact of digestate application on SOC content when compared to treatment with manure and/or slurries (Bachmann et al, 2014; Moller, 2009; Thomsen et al, 2013). Nevertheless, some authors suggest that digestate fractionation or composting may improve the C sequestration in soils (De la Fuente et al, 2013; Tambone et al, 2010). Tiwari et al (2000), suggest that maintaining an adequate level of SOC with years-long application of digestate requires an additional source of organic C, which is mainly provided by incorporating crop residues into soil, especially cereal straw. Straw is responsible for the recycling of C, as well as other elements (Liu et al, 2014; Wang et al, 2017).

This methodology incorporates into projects with a vision of land management sustainable practices - LMSP, the framework and requirements for agricultural fields and areas where pastures are improved, to increase the stock of soil organic carbon (SOC), through the application of digestates or effluents with high organic content, which come from previously treated anaerobic reactors (which may include biodigester sludge), improving the physical, chemical and microbiological conditions of the soil, increasing its productivity and its condition as a carbon sink.

2 Version and validity

The document constitutes the Version 1.0. November 4, 2024.

The use of this methodology will be valid from the date it is officially published by BioCarbon Cert.

3 Scope, applicability and eligibility

This methodology follows the BCR Standard and BCR / SOP principles[1].

3.1 Scope

The methodology is applied to productive agricultural and pasture production activities, from small to large scale, where the sum of activities in large areas of land gradually increases the carbon stock in the soil, contributing to the reduction of atmospheric carbon dioxide and better managing the dynamics of nitrogen in the soil.

This methodology provides a new dataset on global soil change that will uniquely utilize the world's previous investment in soil data infrastructure, including the use of default factors from the IPCC Guidelines for National Greenhouse Gas Inventories requirement for baseline and project activity scenarios identification along with the respective GHG emission sources/reductions or removals.

The general frame of this methodology includes:

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[1] BioCarbon Cert. 2024. BCR SOP. Standard Operating Procedures. Version 1.3. June 14, 2024. 40 p. https://biocarbonstandard.com/wp-content/uploads/BCR_Standard-Operating-Procedures.pdf

(a) Provide methodological requirements for monitoring procedures and management practices of land as part of the project implementation and operation.

(b) Provide the frame for the project certification including length of crediting period, monitoring periods and project activity start date definition.

3.2 Applicability

The typical project eligible and covered by this methodology includes the application of digestates or effluents produced in biodigesters, as well as the extracted sediments, to crop fields that include orchards of perennial species (such as vineyards or fruit trees) or pasture improvement areas, using LMSP with the aim of improving soil conditions and increasing SOC reserves. This implies a holistic approach to achieve productive and healthy agroecosystems by integrating social, economic, physical and biological needs and values, and contributes to rural and sustainable development.

This methodology is applied to a wide range of scales (micro, small and large), or level of technology (traditional agriculture and industrial agriculture).

The application of digestates or effluents as a source of organic compounds are compatible with LMSP aimed at improving soil productivity and its capacity as a carbon sink, which include the management of agricultural campaign residues, the type of tillage practices, fertilizer management (both mineral fertilizers and organic amendments), crop type and intensity of crop management (e.g., continuous cropping versus crop rotation, with bare fallow periods), irrigation management, and mixed cropping systems crops and pastures or hay in rotating sequences.

Methodology for the estimation of SOC stocks is based on direct measurements from field samplings. However, the estimate of the future variation of SOC stocks shall be made using SOC dynamic models.

The implementation and scope of the project must include the evaluation of CO_2 and N_2O emissions (direct and indirect N_2O emissions) and comply with the conditions described in the following sections.

3.2.1 Project start day

The project start date is defined as the date when the digestate or effluent is applied.

3.2.2 Geographic location

Projects to add digestate or effluent to cropland or pasture are eligible in all regions around the world.

Some actions related to the addition of digestates, or effluents may be limited by geographical conditions (see bullets below), which shall be taken into account by the project holder.

Project activities related to increasing SOC through the addition of digestates or effluents include:

i. Although the activity is applicable worldwide, at the local level it may be limited to the specific conditions of the topography, the type of soil, its physical, chemical and biological characteristics, the climatic offer and the availability of data e.g annual mean temperature, annual mean precipitation.

ii. The availability of the digestate or effluent, its quality, including COD, composition and distance to the application site, which condition the applicability of the activity due to cost-effectiveness.

iii. The requirements for prior measurement and specific monitoring of the activity's contribution to the increase in SOC and its C storage capacity.

iv. The capacity of the PD to supply the data and its sources and that of the use of the models applied to the activity, even if it is with regional application data.

3.2.3 Project area

As an area suitable for the implementation of the project, there are crop fields used for annual crops or orchards of perennial crops, cultivation of fodder grasses and extensive pastures and include fallow lands.

The project activity will be carried out on the same area of land that was delimited and used for the definition of the baseline.

The project will be applicable at the scale of agricultural activities in defined areas of intervention - DAI. Each DAI may include one or several fields either within an individual farm or on different farms owned or operated by the same or different companies that are part of the same project. If one part of the area where the project will be implemented is substantially different from another, more than one DAI will be defined due to the higher probability of detecting changes in the increase in SOC and soil C storage capacity; In this way, the topography, relief and type of soil, among other aspects, will have an influence.

i. The project cannot be implemented in wetland areas, including drained peatlands.

ii. The project area can be grassland, with the condition there has not been a land use change from agricultural land to grassland.

iii. The project cannot be implemented in forest areas. The project area shall be demonstrated being agricultural land in the last 10 years.

iv. The flood irrigation, high rainfall, and cultivation on organic soils reduce the SOC stock. Similarly, changes in land use and intensification of management have an influence on the decrease in SOC, due to changes in erosion rates and the subsequent loss of SOC due to mass flow.

v. The area where the project is implemented does not include the infrastructure areas in the fields where the activity is carried out, therefore they will not be taken into account for the calculations.

vi. The project cannot be implemented in abandoned areas that require tillage activities for their use to seasonal, permanent, or pasture production systems.

3.2.4 Site preparation

In the project implementation area, burning stubble or crop residue biomass may not be carried out under any circumstances.

3.2.5 Water regime

Activities in the project area should not include changes in the superficial and shallow (<1 m) soil water regimes through flood irrigation, drainage, or other significant anthropogenic changes in the groundwater table. The amount of digestate or effluent applied should be calculated according to the nutritional needs of the crop or pasture and, in addition, account for the addition of mineral fertilizers in such a way that the seasonal water supply does not lead to an increase in the mobility of C and N both at the surface level or by percolation into subsurface waters in the subsoil, with greater eutrophication of water bodies.

3.2.6 Land use

The project implementation area and the management of both seasonal cropping systems (e.g., single cropping or crop rotation); permanent perennials, as well as pastures, must have existed for at least five (5) years before the start of the project, which must be demonstrable and verifiable.

The activity in the project implementation area must not lead to changes in land use e.g. pasture to agriculture.

The calculations made for the soils in the project areas must show, prior to its implementation and addition of digestate or effluent, the potential to increase the SOC and C reserves, in accordance with the adoption of the LMSP.

3.2.7 Food security

No reduction in crop yield which can be attributed to the project activity shall be allowed.

Activities in the project area shall deliver a yield at least equivalent to the baseline yield (five - year average, prior to the project start). If regional crop productivity changes (e.g., due to climatic factors), yield in the project area shall not decrease significantly (5%) more than yield in the project region.

The direct impacts related to the increase in SOC and the emissions derived from the project must take into account the following:

i. Agrochemical inputs, e.g., mineral fertilizers or other amendments, pesticides and other additives.

ii. Change in hydrology, e.g., due to irrigation, drainage, and seasonal change in crop and pasture cover.

iii. Change in crop-related inputs, including plant residues and N fixation.

iv. Change in the technical management of the crop (e.g., the use of machinery for sowing, cultivation and harvesting).

v. Seasonal change in crop management activities (e.g., harvest, fallow periods, mulch season).

vi. Change in crop yield (outside the normal variation) expressed in mass (t) and in relation to caloric value and end user (crops for animal/human use).

3.2.8 Digestate or effluent characteristics and quality

Anaerobic digestion (AD) is a widely used technology whereby organic material is converted into energy-rich biogas and a plant nutrient-rich residue (digestate). The flexibility of AD means that many different types of organic material are suitable as feedstock for the process, such as organic municipal waste, sludge from wastewater treatment, waste from food processing industries, energy crops and agricultural wastes such as manure and plant residues (Appels et al., 2011; Risberg et al, 2017). The digestate can be used as a fertilizer on arable land, enabling recirculation of plant nutrients and thus reducing the need for fossil fuel-dependent mineral fertilizers (Holm-Nielsen et al., 2009).

Digestates contain less organic C than feedstock (Moller and Müller, 2012; Alburquerque et al, 2012). However, Möller (2015) concluded that the loss of organic C during the anaerobic digestion process is compensated by lower organic C degradation after an application of digestates. Long-term experiments did not prove any negative impact of digestate application on SOC content when compared to treatment with manure and/or slurries (Bachmann et al, 2014; Moller, 2009; Thomsen et al, 2013). Nevertheless, some authors suggest that digestate fractionation or composting may improve the C sequestration in soils (De la Fuente et al, 2013; Tambone et al, 2010). Tiwari et al (2000), suggest that maintaining an adequate level of SOC with years-long application of digestate requires an additional source of organic C, which is mainly provided by incorporating crop residues into soil, especially cereal straw. Straw is responsible for the recycling of C, as well as other elements (Liu et al, 2014; Wang et al, 2017).

To make use of the digestate or effluent used in the activity covered by this methodology, the following must be taken into consideration:

i. The digestate or effluent to be applied should come from an anaerobic reactor (biodigester) with a minimum retention time of 28 - 30 days. Which is supported by the fundamental analysis of the detailed microbiological study known as the leach bed process (Silvey et al., 1999); in which, according to the temperature that develops inside the biodigester, optimal digestion is reached between 18 - 38 days, instead of 60 - 90 days. In this way, the digestates or effluents from anaerobic digestion, which generally do not reach the thermophilic temperature ranges and the average minimum time of twenty-eight (28) days, are not suitable to be discharged directly into the ground, since they have high humidity, contain a notable quantity of somewhat phytotoxic volatile fatty acids and since they do not reach the thermophilic range of temperatures, they are not sanitized. This would lead to these partially produced digestates or effluents requiring further treatment after anaerobic digestion to obtain a high-quality, usable product (Poggi, et al., 1999). In this way, the PD must show that the digestates or effluents that will be used in the project activity comply with the minimum digestion time of 28 days and that they comply with the first order hydrolysis kinetic constants that range between 0.003 - 0.15 day-1 at 20°C, up to 0.24 - 0.47 day-1 at 40°C, values that are consistent with those reported for carbohydrates and mixtures of food waste and other sources of biomass by (Christ et al., 1999; Vavilin et al., 1999).

ii. The content of plant macronutrients, micronutrients and organic components in the digestate or effluent depends on the origin of the ingoing substrate and the management of the digestion process (Risberg et al, 2017; Möller and Müller, 2012; Zirkler et al., 2014). The nutrient composition of different manures also varies greatly, due to factors such as type of animal (omnivore, ruminant, etc.), sex, species, age and the diet fed to the animal, as well as geographical and climate conditions (Lukehurst et al., 2010). The proportion of ammonium (NH4+) is generally higher in digestate than in the organic substrate going into the AD process (Arthurson, 2009). Spreading organic fertilizers on arable land generally has positive effects on soil chemical properties (Doran, 2002; Joshua et al., 1998) and may increase the soil organic matter content, which is very important for maintaining or improving soil quality (Nkoa, 2013). However, digestate and animal manure may also contain heavy metals (Kupper et al., 2014), different organic pollutants (Limam et al., 2013; Govasmark et al., 2011) and antibiotic residues (Spielmeyer et al., 2014). This could explain why different organic fertilizers have been found to induce both positive and negative effects on the soil microbial community (Sänger et al., 2014; Abubaker et al., 2013).

To this end, the methodology recommends that the PD review the European Union health regulation regarding the use of animal by-products and derived products not intended for consumption (EC No. 1069/2009; http://eur-lex.europa.eu/; 25 /11/14), which includes, e.g., raw material controls, treatment process and declaration of content in terms of composition of plant nutrients, levels of heavy metals, human pathogens and visual contaminants (SPCR120, 2010). However, the content of organic pollutants is not currently taken into account.

In case the anaerobic digester where the digestate or effluent come from an already certified (or in process of certification as) carbon project under any standard or scheme, this should be declared transparently and shall be demonstrated that the methodology applied does not cover emissions2 from digestates and stream effluents after the anaerobic treatment.

This methodology is not applicable where the biodigester includes a secondary treatment, for example (but not limited), clarification pond after the biodigester, secondary (or tertiary) evaporation lagoon after the biodigester.

In case the thermophilic temperature ranges are below 50°C, the effluents should be subject of hygienization3. If transportation and storage is required, the maximum storage time should be 2 days.

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[2] It includes emission reductions and project emission from outlet effluents/sludge.

[3] Within the scope of "Environmental Regulations and Technology Control of Pathogens and Vector Attraction in Sewage Sludge" liquid fermented product shall be heat treated for 3 hours at 50°C in a separate pool in order to

3.2.9 Ownership of the carbon rights

PD shall demonstrate to hold and maintain the exclusive legal right to the project and claim carbon credits. Said demonstration can include to have the legal right by land ownership or hold a lease to the project land. In case of multiple landowners or more than one entity involved in the leasing contract, the project proponent needs a written agreement including all owners or lessors to show having the exclusive legal right to run the project and own the carbon credits. In case the land is under mortgage scheme, the entities involved shall be notified about the project development.

4 Baseline methodology

The project developer (PD) must consider all possible reference scenarios that are included in the project that seeks to increase carbon storage in the soil, by making additions of digestates or effluents, that allow maintaining or increasing soil productivity in the project area.

When defining the baseline, the project holder shall submit the values and procedures from which these are derived and justify the assumptions that guarantee that the results of the project will increase soil carbon fixation due to the addition of digestates or effluents, without overestimating the expected values or confusing them with the increases derived from other management actions in the project area, included in the defined baseline.

To start the project, the project holder shall develop the base scenario that will be determined by identifying the following conditions:

(a) The georeferenced polygon of the project area must be explicitly indicated, which includes the topographic, physical and chemical characteristics of the soil and the infrastructure (roads, warehouses, stables, houses, etc.), which are part of the area, but exclude from the intervention and calculations due to the addition of digestate or effluent.

(b) The historical climate offer for the (5) five years (reported monthly) prior to the start of the project, mainly for the variables accumulated precipitation, monthly average maximum, average and minimum air temperatures and accumulated radiation.

(c) The use, management and productive practices in the project area must be listed and supported during the (5) five years prior to the start date of the project intervention.

(d) The conditions of use and management practices for the use of land for agricultural and pasture management must be included in the baseline document, in accordance with local legislation.

The scenario of identified practices must be realistic and credible based on verifiable information sources, such as agricultural company reports, local or regional agricultural

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ensure hygiene of the final product. The hygienization protocol can be changed according to country specific regulations. Other treatment including electro-technology, microwave, pressurization, ultrasound and chemical treatment can be considered as well.

statistics reports, documented public management records of land users, published and reviewed studies by pairs in the project region. results of surveys conducted by or on behalf of the project developer prior to the start of project activities.

The definition of the reference scenario for the project area that is included in the baseline will be the same intervention area and is based on the provision of five-year historical activity data that will be evaluated and includes:

(a) Commercial and cover crops per year (approximate planting and harvest dates), and harvested yields or biomass (kg DM/ha/year).

(b) In the case of fruit plantation orchards and vineyards, information per year (sowing and harvest dates), and yields obtained.

(c) Waste management; evaluation of waste elimination and return (percentage or kg DM/ha/year).

(d) Tillage practices (tillage system, number and type of tillage operations per year) annual mechanized agricultural operations.

(e) Tillage, planting, pest control, organic and inorganic fertilizers/amendments/manure application and distribution, harvesting, mowing, hay baling, internal transportation, other operations.

(f) Use of fertilizers and inorganic amendments (product, application method, timing/of application, doses of fertilizers and nutrients per year in kg/ha).

(g) Uses of organic amendments (type, form of application, placement method, timing and application rate per year).

(h) Irrigation annual consumption of fossil fuels.

4.1 Baseline and Additionality

4.1.1 Baseline

To determine the baseline scenario and demonstrate additionality, the project proponent must apply the latest version of 'BCR Guidelines Baseline and Additionality[4]'.

4.1.2 Additionality

To demonstrate that project activities generate Verified Carbon Credits (VCs) that represent additional GHG emission reductions or removals, the project holder shall follow the guidance contained in the 'BCR Guidelines Baseline and Additionality'. This guide contains the provisions related to additionality and baseline for projects under the BCR Standard.

The BCR Guidelines Baseline and Additionality is a mandatory guidance that includes requirements to ensure a realistic and conservative baseline estimate of emissions; it also

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[4] https://biocarbonstandard.com/wp-content/uploads/BCR_additionality.pdf

provides requirements to ensure that activities are additional in all eligible sectors. In addition, GHG project owners must demonstrate that emissions reductions (or removals) do not correspond to emissions reductions attributable to the implementation of actions required by law.

4.1.3 Compliance with laws, regulations and other regulatory frameworks

The GHG project owner must demonstrate the project is in compliance with all relevant local, regional and national laws, statutes and regulatory frameworks. Additionally, it must demonstrate that it complies with legislation related to activities carried out in the field of GHG mitigation.

Legal compliance includes, among others, laws related to the protection of human rights and indigenous peoples, in accordance with international standards, such as the United Nations Declaration on the Rights of Indigenous Peoples and ILO Convention 169 on Indigenous People.

In this regard, the project owner must have a documented procedure (Document Management System) in which relevant legislation and regulations are identified and continuously accessed, demonstrating that it has a procedure to periodically review compliance with such legislation and regulation.

Consequently, the project owner must maintain an updated list of all legislative requirements relevant for the GHG project.

Additionally, in compliance with the documented procedures explained above, the GHG project owner must[5]:

(a) determine and have access to the legal and other requirements related to its activities;

(b) determine how these legal and other requirements apply to the GHG project;

(c) take these legal and other requirements into account when establishing, implementing, maintaining and continually improving its document management system.

4.2 SOC baseline estimation

For each eligible project area, the project holder shall present a baseline, where SOC stocks are quantified, prior to the start of activities and incorporation of the digestate or effluent, using the following approaches:

1) Soil carbon - SC is linked to soil organic matter - SOM, as 50% of SOM is SOC. Soil organic matter ensures a part of soil fertility as it allows for storage of nutriments for

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[5] Adapted from ISO 14001. ENVIRONMENTAL MANAGEMENT SYSTEMS. REQUIREMENTS WITH GUIDANCE FOR USE.

plant growth, stimulates soil biodiversity and contributes to soil structure stability. Maintaining the soil organic matter pool is essential in sustainable land management and soil productivity.

2) Based on the characteristics and management of the soil in homogeneous units duly mapped in the project area, composite samples of the soil will be taken to measure the variables that allow determining the stocks of organic carbon in the soil. Proper soil sample collection relies on three principles:

   i. Organization: Having a georeferenced and orderly system for collecting and handling soil samples simplifies sample collection and minimizes the possibility of human error, such as incorrect labeling or incorrect placement of soil samples.

   ii. Consistency: Collecting each sample in a uniform manner between years and within the course of a sampling event will greatly improve the quality and reliability of results. This means taking samples in the same manner for each sample.

   iii. Simplicity: following simple procedures will help ensure sample collection is consistent and easily organized.

Soils can be highly variable, even over short distances. Because of this variability, it is often insufficient to collect soil at just one location. Instead, it is preferable to collect so-called composite samples. Composite samples are a mixture of individual samples, or subsamples, generally collected from multiple locations and mixed together to form a single composite sample; subsamples are distributed across large areas to ensure the entire field is represented. To achieve this, collect composite samples in a zig-zag pattern (Fig. 1). Each composite sample should consist of 10 to 20 subsamples spread evenly across a field. Collect at least one composite sample per 20 hectares.

An example of zig zag sampling pattern (Figure 1) for whole field sampling. Subsamples are collected by traveling in a zig-zag pattern collecting subsamples at each location indicated by black dots. Background lines represent the various soil types in the field. Ideally, zigzag sampling samples each soil type equally. Source: Soil sampling guidelines – Purdue extension, 2018.

Figure 1. Zig-zag sampling pattern

Composite samples must be obtained according to the indicated methodology, for the first 0.3m of soil depth for seasonal crops; According to (Smith et al, 2014; West & Post, 2022), the vertical distribution of sequestered C in the soil profile depending on the addition of digestate or effluent and the change from conventional tillage - CT to zero tillage - NT, showed that 93% of the C was captured between 0.07 and 0.15 m depth. Meanwhile, for tree orchards and vineyards the sampling depth will be 0 - 0.3m and 0.3 - 0.6m deep, due to the spatial distribution in depth and diametrically of the roots.

The dry matter (DM) content of the soil is analyzed by gravimetric method and oven drying at 105 C overnight according to the standard method (APHA, 1998). Total carbon (Tot-C) is determined according to ISO 10694:1995; total nitrogen (Tot-N) and organic nitrogen (Org-N) are determined according to ISO 13878:1998 using an elemental analyzer.

Both humic and fulvic acids content is determined in accordance with ISO 19822, 2018.

The dry bulk density (DBD) of the soil is determined in accordance with ISO 11272:2017; and the pH of the soil in accordance with the ISO 10390:2021 standard.

The soil texture (ST), associate with particle size distribution related to a wide range of mineral soil materials, including the mineral fraction of organic soils, is determined in accordance with ISO 11277:2020 standard.

The measurement of greenhouse gases emission (CO_2, N_2O, CH_4) and ammonia (NH_3) fluxes between soils and the atmosphere, is determined in accordance with methods include in ISO 20951:2019 standard.

(1) Regarding the influence of tillage intensity on soil C fixation, several studies show that when comparing the amount of SOC as TOC accumulated over long periods of time, under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT); resulted in different amounts of fixed or sequestered SOC. Soil organic C levels under NT were significantly higher than those under CT and RT; while SOC levels under CT and RT were not significantly different from each other (West & Post, 2022). The depletion of TOC is also related to tillage techniques. The most immediate effect of tillage is to mix and aerate the soil, which stimulates microbial decomposition and accounts for much of the organic matter loss that follows (Vance, 2000). The type of addition of organic matter, such as digestates or effluents, also influences the humification process, the performance of which is described by the HC/TOC ratio as previously reported by McDonnell et al (2001).

(2) Estimation of soil C stocks requires soil dry bulk density – DBD values to convert C content (g C kg-1 soil) to a mass of C per unit area (tC ha-1). Generally, OC content, measured in g per kg, and with inorganic particle-size expressed as a % of the fine earth (fraction < 2mm), has been the most important variables in Pedotransfer

functions - PTFs, and followed by clay percent. The relative importance of OC and particle-size parameters is reversed for soil horizons deep because of the less impact of OC with depth (Bernoux et al, 1998; Brahim et al, 2012). Using soil horizons covering a wide range of soil textural classes, thus, together with the amount of OC, the particle-size distribution could be used for predicting the DBD of soils.

(3) The pH of the soil changes considerably as OM is added, due to the processes of mineralization and production of organic acids and other metabolites that interact with the clays that constitute it. The pH value changes differentially, in accordance with the texture of the soil, the amount of OM present at the time of starting the addition or incorporation of external Mo (digestates or effluents and/or crop residues) and the quality of the OM. Soil acidification is related to the SOM mineralization process, which produces nutrient elements (particularly NH3), whose oxidation can contribute to the production of H+ (Stevenson, 1994; Tan, 1998). The reaction can also be affected by mineral fertilizers, especially NH4+ sources (Havlin et al., 1999).

(4) SOC simulation models can simulate SOC dynamics under different land uses, climatic conditions, exogenous OM additions, and management practices of seasonal or permanent crops such as fruit trees and vineyards. These include models such as ROTHC (Coleman & Jenkinson, 1996; Coleman, 2009), or the IPCC Tier II Steady State Soil Carbon Method (IPCC, 2019 Volume 4 AFOLU, Chapter 5 Cropland) that can be used. If there is reliable evidence that the soil carbon stocks of the project area are in a stable state according to traditional practice, then it is only possible to measure the initial average soil carbon stocks as a baseline.

(5) The soil organic carbon reference level (SOCstock) content, as well as other parameters to initiate the SOC stock, are measured from a representative number of soil samples using the ISO standard methods stated above.

Baseline SOC stocks for seasonal crops or pastures are determined as the sum of C stocks before project start; SOC stocks are determined in the same way for subsequent periods considering the previous period comparing the stocks e.g. Baseline SOC stock VS 1st period Project SOC Stock; 1st Period Project SOC Stock VS 2nd Period Project SOC Stock and so on.

SOC stocks are determined as per the following equations:[6]

$$(D_b) = (M_s) / (V_t) \qquad \text{Equation 1}$$

Where:

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[6] The equation shown in this section are based on the 'World Bank. 2021. Soil Organic Carbon MRV Sourcebook for Agricultural Landscapes © WorldBank, Washington, DC' calculation methods.

(D_b) = Soil bulk density. D_b is reported as g cm^3. Note that the sample unit volume represents the volume of the sample unit at the time of the original collection.

M_s = Dried soil mass.

V_t = Refers to the volume of solids and pore space. The volume is based on the sampling soil core extracted and calculated based on the dimension of the auger or soil prove used, diameter and depth of the sample.

Coarse roots and mineral fragments (i.e. greater than 2 mm size) should be removed. Soils with gravel and stones within the core would need a D_b corrected for the gravel and stone fraction. The D_b corrected is calculated as follows:

$$(Db) = (Ms) / (Vt - [RF/PD]) \qquad \text{Equation 2}$$

Where:

(D_b) = Corrected Soil bulk density. D_b is reported g cm^3. The corrected (D_b) is required when prese coarse roots and mineral fragments >2mm.

M_s = Dried soil mass.

V_t = Refers to the volume of solids and pore space.

RF = is the mass of coarse root and fragments

PD = is the density of rocks fragments (a default of 2.65 g cm-3 can be assumed).

Where differentiation of coarse fragment across depth is identified, extracted vertical soil cores need to be divided into depth increments without disturbing their integrity, while open pit cores are taken directly horizontally from the depth of interest. To divide vertical soil cores into equal depth increments, cut the soil sections perpendicular to the core with a sharp knife e.g. increments of 0-10cm; 10-20cm and 20-30cm depth. D_b, M_S, and V_t (RF and PD when applicable) shall be determined for each depth segment.

Soil carbon stocks are typically calculated at fixed depths. To do so, use the laboratory results on soil carbon content (%), the calculated bulk density, and measured soil depth of the extracted core as:

$$\text{Soil } C_{stock,pj} = 100 * [D_b \text{ * soil depth (cm) * \%C }] \qquad \text{Equation 3}$$

Where:

Soil $C_{stock,pj}$ = Soil carbon stocks (t/ha^{-1}), in period, j

(D_b) = Soil bulk density (g/cm^3)

Soil depth = Soil Depth (cm) of the samples taken considering the depth increments (if any).

%C = Soil Carbon content (%)

In order to determine the carbon gains or losses in the soil, it is required to measure the carbon stock over the time to determine carbon (C) stock changes through a stock change approach. The equation below shows how stocks are determined.

$$\text{Soil C}_{\text{Stock change}} = \text{Soil C}_{\text{stock},p2} - \text{Soil C}_{\text{stock},p1} \qquad \text{Equation 4}$$

Where:

$\text{Soil C}_{\text{stock exchange}}$ = Soil stocks exchange (t/ha^{-1})

$\text{Soil C}_{\text{stock,p2}}$ = Soil stocks exchange (t/ha^{-1}) period 2

$\text{Soil C}_{\text{stock,p1}}$ = Soil stocks exchange (t/ha^{-1}) period 1

For the calculation of the net impact, the SCO stock is calculated based on subsequent period (period 2) minus precedent period (period 1). For example, SOC stock from the first intervention at the project scenario, minus the SOC stock from the baseline scenario. For subsequent period, SOC stock from the second intervention at the project scenario, minus the SOC stock from first intervention at the project scenario, and so on.

When the difference between two consecutive measurement periods reaches zero, it indicates that the Soil Organic Carbon (SOC) has achieved its maximum value. This means that a balance has been established between the input of organic matter and its decomposition. At this stage, soil management practices should focus on maintaining the maximum SOC value throughout the crediting period. From this point forward, the annual credits for SOC will be calculated by dividing the maximum SOC achieved by the remaining years for the project's permanence.

$$\text{Soil C}_{\text{annual stock}} = \text{Soil C}_{\text{max stock}} \,/\, t_{\text{remaining years of the crediting period}}$$

Agricultural practices change soil carbon content by increasing carbon inputs or decreasing carbon outputs, rather than by changing soil accumulation. Estimating soil gain over time is therefore not necessary. However, practices expected to increase sediment accumulation will need to measure sedimentation rates to determine soil gains. Examples of field techniques to measure sedimentation are marker horizons (e.g., feldspar markers).

4.3 Estimation of baseline N_2O emissions

As a result of anaerobic digestion, a byproduct (digestate or effluent) is obtained with a higher concentration of ammonium ions (NH_4^+) in relation to total N than the original organic feedstock (Arthurson,2009; Barłóg *et al*, 2020). Nitrogen, incorporated into the soil with digestate, undergoes various transformations such as mineralization, immobilization, nitrification, etc. (Moller, 2015). In general, the mineral N from digestate is hardly immobilized in soil because of the low carbon C/N ratio and the content of highly stable organic substances. At the same time, once incorporated into the soil, NH_4^+ ions undergo an immediate process of nitrification (Alburquerque *et al*, 2012). Tambone & Adani (2017) reported that digestate derived from sewage sludge demonstrated not only a high rate of nitrification but also mineralization of organic matter.

Consequently, the fertilizer's capacity to supply plants with mineral N was comparable with urea. Some studies also indicate that digestate application leads to stimulation of soil organic matter (SOM) decomposition, named the "priming effect" (Fontaine *et al*, 2003). As a result, the soil gains an additional pool of mineral N readily available for plants. On the other hand, application of digestate carries a risk of excess ammonia (NH_3) volatilization and/or dispersal of oxidized forms of N, through nitrate ions (NO_3^-) leaching or nitrous oxide (N_2O) emission. Moreover, high rates of digestate application may trigger phytotoxic NH_3 (Barłóg *et al*, 2020).

5 Monitoring Plan

The monitoring plan shall provide for the collection of all relevant data necessary to:

(a) Verify that the applicability conditions are met;

(b) Verify changes in carbon stock in selected areas;

(c) Verify project emissions and leakages.

The data collected shall be archived for at least two years after Project's last period. It shall include data and parameters monitored, processed related to models, methods used to generate data, sampling, and quality control thereof, and appropriate collection and archiving. As well, it is required to store the validation and verification opinions provided along the project period.

The monitoring plan shall include:

(a) Monitoring project boundaries;

(b) Monitoring of the implementation of project activities including digestate application and land management.

The table below summarizes the monitoring parameters that shall be monitored.

Table 1. Monitoring parameters

Parameter	Unit	Measure (m), Calculate (c), estimated (e), or Default (d)	Monitoring frequency	Coverage, kind of measurement	Comments
Digestate COD	Mg/L	m	Yearly	Measure the COD according to national or international standards. COD is measured through representative sampling	Samples and measurements shall ensure a 90/30 confidence/precision level
Location	Geographic coordinates	m	Continuously	100%	Using GPS to identify the geographic coordinates of each plot included in the project
Project Area	hectare	c	Continuously	100%	Polygons of the areas include in the project
Defined Area of intervention (DAI)	hectare	c	Continuously	100% of the intervened	Polygons of the areas where the digestate is applied.
Date of digestate application	alphanumeric	m	Dates when digestated is applied to soil	100%	Dates can include ranges of consecutive or no consecutive days
Type(s) of crop(s)	dimensionless	m	Continuously	100%	Description current crops and changes over the time e.g. from single cropping to rotational crop.
Annual average crop yield	Tonnes/ha	m	Continuously	100%	The corp's productivity shall be

Parameter	Unit	Measure (m), Calculate (c), estimated (e), or Default (d)	Monitoring frequency	Coverage, kind of measurement	Comments
					crosschecked with average regional yields for the specific crop(s).
Amount of fertilizers, pesticides, additives used	Kg/ha	m	Continuously	100%	Invoices and application records can be sued to report this parameter.
Change in hydrology	dimensionless	e	Annual	100%	Annual report of changes in irrigation patterns, drainage and crop/pasture cover.
Change in the technical management of the crop	dimensionless	e	Annual	100%	Annual report of changes in machinery used for sowing, cultivation and harvesting.
Change in the technical activities	dimensionless	e	Annual	100%	Annual report of changes in harvest, fallow period, mulch season.
Retention time of digestate at anaerobic reactor	days	m, c	Monthly	100%	Operation information of the reactor can be used as source for this parameter. Alternatively, the retention time can be estimated based on volume

Parameter	Unit	Measure (m), Calculate (c), estimated (e), or Default (d)	Monitoring frequency	Coverage, kind of measurement	Comments
					capacity of the reactor and amount of inflow volume.
Tillage practices	dimensionless	m	Annual	100%	Report of the tillage system, number and type of tillage operations per year, including all annual mechanized agricultural operations
Fossil fuel consumption	liters	m, c	Monthly	100%	Fossil fuel consumed in vehicles and pumps used to transport and application of the digestate.
Parameter	Unit	Measure (m), Calculate (c), estimated (e), or Default (d)	Monitoring frequency	Coverage, kind of measurement	Comments
Soil bulk density (D_b)	g/cm^3	c	Every carbon stock campaign	Representative sampling	Sampling should met 90/10 confidence interval and precision level.
Depth of the sample	cm	m	Every sample taken	100% of the samples	When required, depth increments

Parameter	Unit	Measure (m), Calculate (c), estimated (e), or Default (d)	Monitoring frequency	Coverage, kind of measurement	Comments
					should be recorded as well.
Diameter of the sample	cm	m	Every sample taken	100% of the samples	It is based on the diameter of the auger used for taking the samples.
Volume of the soil samples	cm^3	c	Every sample taken	100% of the samples	The volume is based on the sampling soil core extracted and calculated based on the dimension of the auger or soil prove used, diameter and depth of the sample.
Corrected Soil bulk density. D_b	g/cm^3	c	Every carbon stock campaign	Representative sampling	Sampling should met 90/10 confidence interval and precision level.[7] The corrected (D_b) is required when prese coarse roots and mineral fragments >2mm.

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[7] For guidance on statistical measure and uncertainty assessment, please observe the guidance provided in the box 3.3 from the World Bank. 2021. Soil Organic Carbon MRV Sourcebook for Agricultural Landscapes © WorldBank, Washington, DC' calculation methods.

Parameter	Unit	Measure (m), Calculate (c), estimated (e), or Default (d)	Monitoring frequency	Coverage, kind of measurement	Comments
Mass of coarse root and fragments RF	grams	m	Every sample taken	100% of the samples (if applicable)	Applicable when presence of coarse root and fragments.
Density of rocks fragments PF	g/cm^3	e	Every sample taken	100% of the samples (if applicable)	A default of 2.65 g cm-3 can be Assumed. Applicable when presence of coarse root and fragments.
Soil carbon stocks, in period, j	t/ha	c	Representative samples	Calculated for each area strata.	Calculated for a given period (j), and recalculated in later periods to determine carbon gains or losses.

For field soil samples, please follow the procedure and recommendations stated in the 'Modue A: Field measurement of soil carbon', Part A: Field methods to assess soil carbon, Part B. Laboratory methods to assess soil carbon, and Part C: Hoe to design a soil carbon measurement plan, from the the 'World Bank. 2021. Soil Organic Carbon MRV Sourcebook for Agricultural Landscapes © WorldBank, Washington, DC' calculation methods.

6 References

Alburquerque, J.; de la Fuente, C.; Bernal, M. 2012. Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils. Agric. Ecosyst. Environ. 160: 15–22.

APHA, 1998. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, American Water Works Association, and Water Environment Federation.

Appels, L., Lauwers, J., Degrève, J., Helsen, L., Lievens, B., Willems, J.V.I., Dewil, R., 2011. Anaerobic digestion in global bio-energy production: potential and research challenges. Renew. Sustain. Energy Rev. 15: 4295 – 4301.

Arthurson, V., 2009. Closing the global energy and nutrient cycles through application of biogas residues to agricultural land – potential benefits and drawbacks. Energies 2: 226–242.

Bachmann, S.; Gropp, M.; Eichler-Löberman, B. 2014. Phosphorus availability and soil microbial activity in a 3-year field experiment amended with digested dairy slurry. Biomass Bioenergy. 70: 429 – 439.

Barłóg, P.; Hlisnikovský, L.; Kunzová, E. 2020. Effect of digestate on soil organic carbon and plant available nutrient content compared to cattle slurry and mineral fertilization. Agronomy, 10: 379.

Bar-On, Y., Phillips, R., Milo, R. 2018. The biomass distribution on Earth. Proceedings of the National Academy of Sciences USA, 115(25): 6506 – 6511.

Barrantes Leiva, M., Koupaie, E.H., Eskicioglu, C., 2014. Anaerobic co-digestion of wine/fruit -juice production waste with landfill leachate diluted municipal sludge cake under semi-continuous flow operation. Waste Manage. 34 (10): 1860 – 1870.

Bernoux, M.; Arrouays, D.; Cerri, C.; Bourennane, H. 1998. Modeling vertical distribution of carbon in Oxisols of the western Brazilian Amazon (Rondonia). Soil Science 163 (12): 941 - 951.

BioCarbon Cert. 2024. BCR SOP. Standard Operating Procedures. Version 1.2. May 14, 2024. 37 p. https://biocarbonstandard.com/wp-content/uploads/BCR_Standard-Operating-Procedures.pdf

Brahim, N.; Bernoux, M.; Gallali, T. 2012. Pedotransfer functions to estimate soil bulk density for Northern Africa: Tunisia case. Journal of Arid Environments. 81: 77 – 83.

Coleman, K.; Jenkinson, D. 1996. ROTHC a model for the turnover of carbon in soil. *In*: Powlson, D.; Smith, P.; Smith, J. editors. Evaluation of soil organic matter models using existing long-term datasets. NATO ASI Series I, Vol 38. Springer, Berlin; p. 237–46.

Coleman, K. 2009. Rothamsted carbon model – ROTHC. https://www.rothamsted.ac.uk/rothamsted-carbon-model-rothc

Collins, H., Mikha, M., Brown, T., Smith, J., Huggins, D., Sainju, U. 2012. Agricultural management and soil carbon dynamics: Wester U.S. croplands. Chapter 5. In: Managing agricultural greenhouse gases. Liegig, M., Franzluebbers, A., Follet, R. Eds. Elsevier, p. 59 – 77.

Christ, O., Faulstich, M., Wilderer, P., 1999. Mathematical modelling of the hydrolysis of anaerobic processes. In: Mata-Alvarez, J., Tilche, A., Cecchi, F (Eds.), Proceedings of the Second International Symposium on Anaerobic Digestion of Solid Wastes, Barcelona, vol. 2., pp. 5 - 8.

Da Ros, C., Cavinato, C., Pavan, P., Bolsonella, D. 2016. Mesophilic and termophylic anaerobic co-digestion of winery wastewater sludge and wine lees: an integrated approach for sustainable wine production. Jour. Environ. Management. p. 1 – 8.

De la Fuente, C.; Alburquerque, J.A.; Clemente, R.; Bernal, M.P. 2013. Soil C and N mineralization and agricultural value of the products of an anaerobic digestion system. Biol. Fertil. Soils. 49: 313 - 322.

Dewar, R.C., 1991. Analytical model of carbon storage in the trees, soils, and wood products of managed forests. Tree Physiol. 8: 239 - 258.

Dignac, M., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G., Garnier, P., Guenet, B., Hedde, M., Klumpp, K., Lashermes, G., Alain, P., Nunan, N., Roumet, C., Basile, I. 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agronomy for sustainable development 37: 14.

Doran, J.W., 2002. Soil health and global sustainability: translating science into practice. Agric. Ecosyst. Environ. 88: 119–127.

Entry, J.A., Emmingham, W.H., 1998. Influence of forest age on forms of carbon in Douglas-fir soils in the Oregon Coast Range. Can. J. For. Res. 28: 390 - 395.

Fitamo, T., Boldrin, A., Boe, K., Angelidaki, I., Scheutz, C., 2016. Co-digestion of food and garden waste with mixed sludge from wastewater treatment in continuously stirred tank reactors. Biores. Technol. 206: 245–254.

Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res. 61: 77 – 92.

Fontaine, S.; Mariotti, A.; Abbadie, L. 2003. The priming effect of organic matter: A question of microbial competition? Soil Biol. Biochem. 35: 837 – 843.

Govasmark, E., Stäb, J., Holen, B., Hoornstra, D., Nesbakk, T., Salkinoja-Salonen, M., 2011. Chemical and microbiological hazards associated with recycling of anaerobic digested residue intended for agricultural use. Waste Manage. 31: 2577–2583.

Harmon, M.E., Ferrell, W., Franklin, J.F., 1990. Effects on carbon storage of conversion of old growth forests to young growth forests. Science 247: 699 - 702.

Havlin, J.; Beaton, J.; Tisdale, S.; Nelson, W. 1999. Soil Fertility and Fertilizers. An Introduction to Nutrient Management. Prentice Hall, Upper Saddle, NJ.

Henderson, G.S., 1995. Soil organic matter: a link between forest management and productivity. *In*: McFee, W.F., Kelley, J.M. (Eds.), Carbon Forms and Functions in Forest Soils. SSSA, Madison, WI, pp. 419 - 436.

Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresour. Technol. 100: 5478 – 5484.

IPCC. 2019. 2019 Refinement to the 2006 IPPCC guidelines for national greenhouse gas inventories. Volume 4 AFOLU, Chapter 5, Cropland. 102 p.

ISO 10390, 2021. Soil treated biowaste and sludge – determination of pH. International Organization for Standardization.

ISO 10694, 1995. Soil Quality – Determination of Organic and Total Carbon After Dry Combustion (Elementary Analysis). International Organization for Standardization.

ISO 11272, 2017. Soil Quality – Determination of dry bulk density. International Organization for Standardization.

ISO 11277, 2020. Soil Quality – Determination of particle size distribution in mineral soil material – Method by sieving and sedimentation. International Organization for Standardization.

ISO 13878, 1998. Soil Quality – Determination of Total Nitrogen after Dry Combustion (Elementary Analysis). International Organization for Standardization.

ISO 19822, 2018. Fertilizers and soil conditioners – Determination of humic and hydrophobic fulvic acids concentration in fertilizers materials. International Organization for Standardization.

ISO 20951, 2019. Soil Quality — Guidance on methods for measuring greenhouse gases (CO_2, N_2O, CH_4) and ammonia (NH_3) fluxes between soils and the atmosphere. International Organization for Standardization.

Jobbagy, E.G., Jackson, R.B., 2000. The vertical distribution of organic carbon and its relation to climate and vegetation. Ecol. Appl. 10: 423 - 436.

Joshua, W.D., Michalk, D.L., Curtis, I.H., Salt, M., Osborn, G.J., 1998. The potential for contamination of soil and surface water from sewage sludge (biosolids) in a sheep grazing study, Australia. Geoderma 84: 135–156.

Kim, D., Oh, S. 2011. Continuous high-solids anaerobic co-digestion of organic solid wastes under mesophilic conditions. Waste Manage. 31: 1943 – 1948.

Kimble, L., Stewart, B.A., 1995. World soils as a source or sink for radiatively active gases. In: Lal, R. (Ed.), Soils and Global Change. CRC Press, Boca Raton, FL, pp. 1 - 7.

Kupper, T., Bürge, D., Bachmann, H.J., Güsewell, S., Mayer, J., 2014. Heavy metals in source-separated compost and digestates. Waste Manage. 34: 867–874.

Lal, R., Kimble, J.M., Follett, R.F., Cole, C.V., 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Sleeping Bear Press, Inc., Chelsea.

Limam, I., Mezni, M., Guenne, A., Madigou, C., Driss, M.R., Bouchez, T., Mazéas, L., 2013. Evaluation of biodegradability of phenol and bisphenol A during mesophilic and thermophilic municipal solid waste anaerobic digestion using 13C-labeled contaminants. Chemosphere 90: 512–520.

Liski, J., Iivesniemi, H., Makela, A., Westman, C.J., 1999. CO2 emissions from soil in response to climatic warming are overestimated the decomposition of old soil organic matter is tolerant of temperature. Ambio 28: 171 - 174.

Liu, C.; Lu, M.; Cui, J.; Li, B.; Fang, C. 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. Global Chang. Biol. 20: 1366 – 1381.

Lukehurst, C.T., Frost, P., Al Seadi, T., 2010. Utilization of Digestate from Biogas Plants as Biofertilizer. IEA Bioenergy. Task 37.

McDonnell, R.; Golden, N.; Ward, S.; Collins, J.; Farrell, E.; Hayes, M. 2001. Characteristics of humic substances in heathland and forested peat soils of the wicklow mountains. In: Proceedings of the Royal Irish Academy on the Biology and Environment, vol. 101B, 3, pp. 187–197.

Möller, K.; Müller, T. 2012. Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. Eng. Life Sci. 12: 242–257.

Möller, K. 2009. Effects of biogas digestion on soil organic matter and nitrogen inputs, flows and budgets in organic cropping systems. Nutr. Cycl. Agroecosyst. 84: 179 – 202.

Möller, K. 2015. Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. Agron. Sustain. Dev. 35: 1021–1041.

Nkoa, R., 2013. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. Agron. Sustain. Dev. 34: 473–492.

Ontl, T., Schulte, L. A. 2012. Soil Carbon Storage. Nature Education Knowledge 3(10):35.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A. (Ed.), Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America. Lewis Publishers, CRC Press, Boca Raton, FL, pp. 15e49.

Pellera, M., Gidarakos, E. 2017. Anaerobic digestion of solid agro-industrial waste in semi-continuous mode: Evaluation of mono-digestion and co-digestion systems. Waste management. 68: 103 – 119.

Poggi, H.; Gómez, E.; Fernández, G.; Esparza, F.; Rinderknecht, N. 1999. Aerobic post-composting of digestates from anaerobic digestion of paper mill sludge and the organic fraction of municipal wastes. In: Mata- Alvarez, J., Tilche, A., Cecchi, F. (Eds.), Proceedings of the Second International Symposium on Anaerobic Digestion of Solid Wastes, Barcelona, vol. 1. pp. 258 - 265.

Purdue extension, 2018. Soil sampling guidelines. Agronomy, Ag.purdue.edu/Agry AY-368-W. https://www.extension.purdue.edu/extmedia/AY/AY-368-w.pdf.

Risberg, K., Cederlund, H., PellL, M., Arthurson, A., Schnürer, A. 2017. Comparative characterization of digestate versus pig slurry and cow manure – Chemical composition and effects on soil microbial activity. Waste management. 61: 529 – 538.

Robinson, C.; Cruse, R.; Ghaffarzadeh, M. 1996. Cropping system and nitrogen effects on Mollisol organic carbon. Soil Sci. Soc. Am. J. 60: 264 – 269.

Sänger, A., Geisseler, D., Ludwig, B., 2014. C and N dynamics of a range of biogas slurries as a function of application rate and soil texture: a laboratory experiment. Arch. Agron. Soil Sci. 60 (12): 1779–1794.

Schlesinger, W.M., et al., 1995. An overview of the C cycle. In: Lal, R. (Ed.), Soils and Global Change. CRC Press, Boca Raton, FL, pp. 9 - 26.

Silvey, P., Blackall, L., Pullammanappallil, P., 1999. Microbial ecology of the leach-bed anaerobic digestion of unsorted municipal solid waste. In: Mata-Alvarez, J., Tilche, A., Cecchi, F. (Eds.), Proceedings of the Second International Symposium on Anaerobic Digestion of Solid Wastes, Barcelona, vol. 1. pp. 17 - 24.

Smith.J.; Abegaz, A.; Matthews, R., Subedi, M.; Orskov, B.; Tumwesige, V.; Smith, P. 2014. What is the potential for biogas digesters to improve soil carbon sequestration in Sub-Saharan Africa? Comparison with other uses of organic residues. Biomass and Bioenergy. 70:73-86.

Sperow, M., Eve, M., Paustian, K., 2003. Potential soil C sequestration on US agricultural soils. Climate Change 57: 319 - 339.

Spielmeyer, A., Ahlborn, J., Hamscher, G., 2014. Simultaneous determination of 14 sulfonamides and tetracyclines in biogas plants by liquid-liquid-extraction and liquid chromatography tandem mass spectrometry. Anal. Bioanal. Chem. 406: 2513–2524.

Stevenson, F. 1994. Humus Chemistry: Genesis, Composition, Reaction, 2nd ed. Wiley, New York.

Tan, K. 1998. Principles of Soil Chemistry, 3rd ed. Marcel Dekker, New York, 521 pp.

Tambone, F.; Adani, F. 2017. Nitrogen mineralization from digestate in comparison to sewage sludge, compost and urea in a laboratory incubated soil experiment. J. Plant Nutr. Soil Sci. 180: 355 – 365.

Tambone, F.; Scaglia, B.; D'Imporzano, G.; Schievano, A.; Orzi, V.; Salati, S.; Adani, F. 2010. Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. Chemosphere. 81: 577 – 583.

Thomsen, I.K.; Olesen, J.E.; Møller, H.B.; Sørensen, P.; Christensen, B.T. 2013. Carbon dynamics and retention in soil after anaerobic digestion of dairy cattle feed and faeces. Soil Biol. Biochem. 58: 82 – 87.

Tiwari, V.; Tiwari, K.; Upadhyay, R. 2000. Effect of crop residues and biogas slurry incorporation in wheat on yield and soil fertility. J. Indian Soc. Soil Sci. 48: 515 – 520.

Torn, M.; Swanston, C.; Castanha, C.; Trumbore, S. 2009. Storage and turnover of organic matter in soil. In: Biophysico-chemical processes involving natural nonliving organic matter in environmental systems (Senesi, N., Xing, B., Huang, P., eds), Chap 6, pp 219 – 272, John Wiley & Sons, Inc.

Vance, E.D., 2000. Agricultural site productivity: principles derived from long-term experiments and their implications for intensively managed forests. Forest Ecol. Manage. 138, 369–396.

Van Cleve, K., Dryness, C.T., Marion, G.M., Erickson, R., 1993. Control of soil development on the Tanana River floodplain, interior, Alaska. Can. J. For. Res. 23: 941 - 955.

Vavilin, V., Rytov, S., Lokshina, L., Rintala, J. 1999. Description of hydrolysis and acetoclastic methanogenensis as the rate-limiting steps during anaerobic conversion of solid waste into methane. In: Mata-Alvarez, J., Tilche, A., Cecchi, F. (Eds.), Proceedings of the Second International Symposium on Anaerobic Digestion of Solid Wastes, Barcelona, vol. 2. pp. 1 - 4.

Von Lützow M, Kögel-Knabner I, Ludwig B, Matzner E, Flessa H, Ekschmitt K, Guggenberg G, Marschner B, Kalbitz K (2008) Stabilization mechanisms of organic matter in four temperate soils: Development and application of a conceptual model. J Plant Nutr. Soil Sci 171:111–124.

Wang, Y., Amundson, R., Trumbore, S., 1999. The impact of land use change on C turnover in soils. Global Biogeochemistry. Cycles 13: 47 - 57.

Wang, W.; Sardans, S.; Wang, C.; Pan, T.; Zeng, C.; Lai, D.Y.I.; Bartrons, B.; Peñuelas, J. 2017. Straw application strategy to optimize nutrient release in a southeastern China rice cropland. Agronomy 7: 84 - 92.

Ward, A., Hobbs, P., Holliman, P., Jones, D. 2008. Optimization of the anaerobic digestion of agricultural resources. Bioresour. Technol. 99: 7928–7940.

West, T.; Post, W. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Division S-6 – soil & water management & conservation. Soil science of America journal. 66:1930-1946.

World Bank. 2021. Soil Organic Carbon MRV Sourcebook for Agricultural Landscapes © WorldBank, Washington, DC.

Zirkler, D., Peters, A., Kaupenjohann, M., 2014. Elemental composition of biogas residues: variability and alteration during anaerobic digestion. Biomass Bioenergy 67, 89–98.