Global Biochar C-Sink Standard 3.1

Guidelines for the Certification of Biochar-Based Carbon Sinks

(formerly known as EBC Biochar C-Sink)

Developed by the Ithaka Institute for Carbon Strategies, 2024 - version 3.1 (26th October 2024)

Hans-Peter Schmidt[1], Claudia Kammann[2], and Nikolas Hagemann[1,3]*

[1] Ithaka Institute, Ancienne Eglise 9, 1974 Arbaz, Switzerland

[2] Department of Applied Ecology, Hochschule Geisenheim University, Von-Lade-Str. 1, 65366 Geisenheim, Germany

[3] Agroscope, Environmental Analytics, Reckenholzstrasse 191, 8046 Zurich, Switzerland

[*]corresponding author: schmidt@ithaka-institut.org

Version 3.0 of the present standard was published in August 2024 and is valid as of 1st September 2024. The updated version 3.1 was released on 26th October 2024. For already certified companies, the transition period was extended until 1st June 2025.

Please cite as:

Global Biochar C-Sink Standard (2024), Ithaka Institute, Arbaz, Switzerland. (http://carbon-standards.com). Version 3.1 of 26th October 2024

Summary

The certification of carbon sinks (C-sinks) is a crucial step in scientifically grounded climate protection strategies. While reducing emissions and phasing out fossil carbon are essential to limit global warming, only active carbon removal from the atmosphere can address the climatic impact of past industrial emissions.

The Global Biochar C-Sink Standard represents a significant advancement from the earlier European Biochar Certificate (EBC) C-Sink Standard, which was introduced as the first of its kind in 2020. The EBC C-Sink Standard was the pioneering standard for negative emissions, focusing on biochar-based carbon sinks. The present new standard builds upon and enhances the initial framework, incorporating more comprehensive measures and methodologies for the calculation, tracking, and certification of biochar-based carbon sinks.

Key updates in the Global Biochar C-Sink Standard include rigorous tracking, more holistic GHG accounting, and advanced carbon and energy efficiency requirements. These processes ensure that every carbon unit sequestered through biochar methods is meticulously followed from its extraction from the atmosphere to its final storage or entry point to geology. The mandatory tracking system guarantees the integrity and transparent quantification of the carbon sinks.

Furthermore, the Global Biochar C-Sink Standard places a strong emphasis on accounting for all direct and indirect greenhouse gas emissions associated with the lifecycle of the biomass, transportation, processing, storage, pyrolytic transformation, application, and monitoring of C-sink materials. By requiring these emissions to be fully offset before the C-sink can be registered, the standard ensures a more accurate representation of the climate impact of each Global Biochar C-Sink.

In summary, this updated standard sets a more robust and comprehensive framework for the creation and certification of material and geological carbon sinks.

Table of Contents

Glossary

Biochar Processor	A company that uses biochar to produce biochar-based products (processed biochar). A Biochar Processor must be EBC/WBC certified to register and label its products as C-sinks.
Biochar Trader	A company that trades biochar or biochar-based products. If the products contain > 1 t CO_2e from biochar, the trader must be registered at Carbon Standards as part of tracking process from factory gate to the final C-sink.
C-sink	Non fossil derived carbon that is verifiably stored for more than one year (temporary C-sink), preferentially for more than 1000 years (geological C-sink)
C-sink matrix	Organic and mineral substrates to which biochar is mixed. The biochar to matrix ratio must be lower than 1:1 (v/v) to exclude that the biochar may burn unintendedly or might be recovered to be used in a way that the carbon could be emitted. See matrix positive list on the Carbon Standards' website.
C-sink owner	Owner of a C-sink material or, when applied to soil, owner of the climate effect of the C-sink.
C-sink potential	The pyrogenic carbon of a biochar that was not yet applied to a C-sink matrix but is temporarily stored in packing units, e.g., at the factory gate of a biochar production facility. Its unit is t CO_2e.
C-sink trader	An endorsed company or organization that trades the climate effect of a C-sink.
C-sink unit	A C-sink unit is the registered amount of a geo-localized biochar C-sink of the same EBC/WBC certified quality. The minimum size of a C-sink unit is 1 t CO_2e.
C-Sink_X	Annual average amount of biochar carbon sequestered over X years. For each year, the stored biochar carbon is evaluated. These annual carbon values from year 1 through year X are summed and then divided by X years to obtain the metric C-Sink_X, expressed in tons of annual CO_2e (t aCO_2e). Examples are C-Sink_100, C-Sink_20, or C-Sink_10.
Certifier	The Certifier is a Carbon Standards' endorsed third party inspection and certification body (= Validation & Verification Body). The certifier is accredited in accordance with ISO 17065:2012 or is in the process of accreditation. In the present

	standard, the Certifier is synonym with the Validation & Certification Body.
Diffuse C-sink	Biochar C-sinks containing not more than 1 t CO_2e of biochar that was mixed to a C-sink matrix preventing the oxidation of biochar.
dMRV provider	A company that is endorsed to monitor and digitally track biochar from the production site to the C-sink site, assessing all occurring emissions, potential carbon leakages, and verifying the compensation and offsetting of those emissions.
Emission portfolio	Registered list of all GHG emissions caused by a production facility or a company or the entire production and establishment of a C-sink.
Endorsing agent	The Carbon Standards International AG is in the role of endorsing agent. Carbon Standards (1) endorses dMRV provider, (2) endorses tracking and monitoring tools and IT systems used by dMRV provider, (4) conducts trainings for the certifier, (5) endorses the certifier, (6) verifies the reporting by the dMRV provider and the certifier, (7) endorses laboratories.
Geological C-sink	Non-fossil carbon that was applied to soil, sediments, the oceans, or the lithosphere and presents a persistence of more than 1000 years such as the PAC fraction of biochar.
Global Cooling	The climate impact of a carbon removal and its storage, measured in tons of annual CO_2e, over a specified period. An amount of global cooling can compensate an equivalent amount of global warming for the duration that the persistence of the cooling effect is demonstrable.
Global C-Sink Registry	The Global C-Sink Registry contains all relevant information about a C-sink to ensure the corresponding climate service and prevent double counting.
Temporary C-sink	Non-fossil carbon that is stored and/or used for a verifiable time of at least one year and preferably for more than 35 years as suggested by the EU for the carbon removal policy. Temporary C-sinks are a function of time given in years. The carbon contained in the temporary C-sink is calculated for each registered year as annual carbon (aCO_2e). The global cooling effect of the temporary C-sink depends on the year of the initial carbon removal and its expected decomposition.
Methane compensation	A temporary carbon sink that has the same or higher global cooling effect during 20 years as the absolute global warming effect of the methane emission over 100 years.

Negative Emission Technology (NET)	Negative Emission Technologies (NETs) are techniques that remove more carbon dioxide from the atmosphere than they emit, thereby reducing the atmospheric concentration of CO_2 to mitigate the effects of climate change.
Non-fossil carbon	Non-fossil carbon refers to carbon originating from the atmosphere, which includes CO_2 obtained from biomass, direct air-capture, and any biomass-derived material or substance. It excludes fossil carbon such as coal, lignite, peat and similar materials. It also excludes carbon in rocks, e.g. CO_2 from calcination.
PAC fraction	The persistent aromatic carbon (PAC) fraction of biochar is defined as the biochar carbon that persists longer than 1000 years in soil. The portion of biochar carbon bound in clusters of more than seven aromatic rings as analyzed by the hydro pyrolysis method is considered as PAC though other analytical methods and descriptions of PAC may equally be eligible.
Persistence	Persistence refers to the duration that a defined fraction of biochar is stable in the environment or in a matrix to which the biochar was applied and does not degrade or decay and emit GHG emissions. Sometimes also referred to as "durability".
SPC fraction	The semi persistent carbon (SPC) fraction of biochar is defined as the biochar-carbon fraction that is expected to decay within the first 1000 years after soil application.
Standard developer & holder	The Global Biochar C-Sink Standard was developed and is continuously updated by the Ithaka Institute. The Global Biochar C-Sink Standard is owned by Carbon Standards and can only be used under a licensing agreement. Carbon Standards is the standard owner managing the entire licensing and endorsement process of biochar producers, biochar processors and traders, dMRV providers, laboratories, the registry and C-sink traders.
Validation & Verification Body	Independent, internationally accredited organization that does the on-site production inspection, controls the IT systems of dMRV providers and registries, and verifies the transaction in the Global C-Sink Registry. In the present standard the Validation & Verification Body is synonym to the certifier.

1. Introduction to Biochar C-Sink Certification

When the EBC certification of carbon sinks (C-sinks) was introduced in 2020, it represented a decisive step towards implementing climate change mitigation. While traditional carbon dioxide (CO_2) credits mostly certified the reduction of emissions compared to a reference scenario, the newly introduced certification of C-sinks guaranteed storage of carbon in the terrestrial system that can be verified at any time and be traced back to the year of the initial carbon removal from the atmosphere.

Carbon sinks are the result of (1) an active removal of CO_2 from the atmosphere, (2) the transformation of the removed carbon into a storable form, and (3) its verifiable storage outside the atmosphere. In the case of biochar, the removal occurs through biomass growth (photosynthesis), transformation through pyrolysis, and storage via application, e.g., to soils or materials (C-sink matrix). Complete and batch-accurate tracking of each sequestered unit of biochar-carbon ensures the occurred removal of CO_2 from the atmosphere, quantifies the C-sink, and accounts for its persistence. All C-sinks must be registered in the Global C-Sink Registry to allow monitoring, reporting, and verification (MRV) and thus create the transparency and trust needed in the new carbon economy.

Likewise, all greenhouse gas (GHG) emissions that occurred due to the biomass production (carbon removal) and all other activities necessary to establish and maintain the C-sink have to be assessed. For biochar, this includes all emissions of biomass provision, storage, transport, transformation, and biochar application. These emissions must be registered in an emission portfolio in the Global C-Sink Registry. All those emissions caused by the C-sink production must be compensated before the C-sink can be validated in the Global C-Sink Registry and, therefore, used to compensate GHG emissions.

The Global Biochar C-Sink certifies the amount of carbon that is effectively and measurably stored in the form of biochar and thus prevented from returning to the atmosphere but does not issue CO_2 certificates for the avoidance of emissions.

As of 2023, biochar from pyrogenic carbon capture and storage (PyCCS, cf. Schmidt 2019) was the most mature and in terms of delivered C-sinks the most important negative emission technology (NET). However, the portfolio of NETs is steadily growing. Reforestation with single tree tracking, biomass materials, enhanced rock weathering, and marine biomass deposition are equally scaling. Certification standards for the different types of C-sinks allow interlinkages between the standards and follow overarching principles of carbon accounting and registration.

1.1 Global Biochar Carbon Sinks

Plant biomass consists of approximately 50% carbon in its dry matter, which was removed during the plant's lifecycle from the atmosphere in the form of CO_2. Using the energy from sunlight, the plant uses CO_2 and builds it into organic molecules such as glucose, cellulose, or lignin.

When plant biomass is burnt or decomposed, the assimilated carbon is released again in the form of CO_2. However, if the plant biomass is pyrolyzed, about half of the plant carbon is transformed into a mixture of predominantly very persistent carbon compounds that form a solid material known as biochar. While in the environment, carbon compounds are subject to degradation; for most components of biochar, this process is extremely slow and hard to measure for a span of thousands of years. Provided that the biochar is not burned, the biochar carbon remains as a C-sink in the terrestrial system.

If biochar with an H to C_{org} ratio < 0.40 is applied to soil, a major part of its carbon is considered Persistent Aromatic Carbon (PAC) and will constitute a carbon sink for several millennia (Camps-Arbestain et al., 2015; Howell et al., 2022; Schmidt et al., 2022). A minor though relevant part of the biochar-carbon is less persistent and likely to be microbially degraded within decades to centuries, presenting a mean residence time (NRT) of 69 years. The biochar carbon that may be decomposed within the first 1000 years after the application to soil is called Semi-Persistent Carbon (SPC) and constitutes a temporary C- sink. For biochars presenting an H to C_{org} ratio ≤ 0.40, the PAC fraction is conservatively fixed by the standard at 75% and the SPC fraction at 25%. Biochars with a H/Corg ratio > 0.40 is considered entirely semi-persistent (SPC). More precise analytical methods to define the portions of PAC and SPC of biochar are expected to be published in 2024. The present standard will be updated accordingly as soon as it becomes possible to draw scientifically reliable conclusions.

If biochar is used as a functional additive in materials such as asphalt, composites, and plastics (c.f., matrix positive list), it is assumed that the entire carbon content of the biochar persists and remains a C-sink for as long as the material itself persists. Only when the biochar-containing material is disposed of, destroyed, or decomposed can the sequestered carbon be released back into the atmosphere, causing the C-sink to lose its value. It must be removed then from the Global C-Sink Registry.

Construction materials using cement, lime, clay, gypsum, or geopolymers as binders are considered a permanent matrix for biochar C-sinks, given that they are either recycled to new construction aggregates or disposed of in soil matrixes. For the latter case, the same persistence curves apply as for soil application, starting with the year of soil application.

1.2 Global C-Sink Registry

The Global C-Sink Registry (www.global-c-registry.org/) is a blockchain-secured digital database for temporary and permanent carbon sinks. All biochar C-sinks certified under the present standard are registered in the Global C-Sink Registry, which is owned and run by the not-for-profit Global Carbon Register Foundation established under Swiss laws. The registry contains all relevant information to evaluate certified carbon sinks and to trade their climate cooling effects. The amount and location of biochar application, the biochar quality, the persistence of the C-sink, the year of the original carbon removal, and the owner of the C-sink are the most important information contained in the registry. Moreover, all GHG emissions caused by establishing a C-sink are registered in the emission portfolio. CO_2 and N_2O emissions must be offset with permanent C-sinks (i.e., C-Sink_1000+), and CH_4 emissions must be compensated with C-Sink_20 certificates before a registered C-sink can be used for further emission compensation or offsets. The register allows the conversion of every C-sink and every GHG emission into annual global cooling and annual global warming effects, respectively, to correctly match C-sinks and CO_2 emissions for annual compensation of climate effects.

1.3 Executive Summary: Global Biochar C-Sink Certification and Registration

To certify the carbon sink and its sustainable establishment, to calculate the global cooling effect of the carbon sink, and to assess all emissions that occurred during the carbon sink establishment, the following parameters must be assessed, controlled, and registered:

- The year of the initial biomass CO_2 removal is assessed so that the Annual Global Cooling effect of the C-sink can eventually be calculated.
- All greenhouse gases, with the exception of non-fossil CO_2 emissions, released during the cultivation of the biomass, the pyrolysis process, packaging, further product transformation, transport, mixing to a C-sink matrix, and application to the C-sink are tracked and registered in an emission portfolio (c.f., Chapter 4).
- All emissions in the emission portfolio of the biochar production must be offset by retiring a corresponding part of a C-sink in the Global C-Sink Registry.
- The C-sink efficiency of the transformation of biomass into pyrolytic carbon is assessed and must be declared. It is controlled that the biochar C-sink does not replace a more carbon-efficient baseline scenario. The pyrolytic use of biomass must be additional (c.f., Chapter 8.1).

- The energy efficiency of the entire process of transforming biomass carbon into pyrolytic carbon sinks, materials, and energy must be higher than 60% (c.f., Chapter 8.2)
- The emission of fossil carbon, i.e. the use of fossil fuels and fossil-fuel-derived electricity within the entire process from biomass production to biochar packaging at the pyrolysis facility must be reduced to less than 100 kg CO_2e per ton of biochar until 2030 and to less 20 kg CO_2e per ton of biochar until 2035 (c.f., Chapter 8.2).
- Only biochar certified under the European Biochar Certificate (EBC) or the World Biochar Certificate (WBC) is entitled to Global Biochar C-Sink certification. The EBC/WBC certification guarantees the sustainability of the biochar production and use.
- The EBC/WBC certificates provide the analytical values needed to calculate the size and persistence of the biochar C-sink.
- The C-sink matrix and, when indicated in the matrix positive list, the GPS location of the final biochar application site is recorded.
- The establishment of C-sinks can only be certified when the biochar is used according to its EBC or WBC certification class. To give two examples, only biochar that is at least certified as EBC-Agro or WBC-Agro can be used to establish a C-sink in agricultural soil. WBC-Material and EBC-BasicMaterial must not be used to establish a C-sink in a soil matrix.
- If the biochar is applied to soil, the registered landowner or tenant must agree that his land acts as an entry point for the biochar carbon to become a geological C-sink (chapter 10.1).
- If the persistence of the biochar C-sink does not follow an acknowledged decay function (c.f., Chapter 2.4, Chapter 11), the monitoring method and controlling period of the C-sink are fixed by the standard depending on the C-sink matrix.
- The verified C-sinks are registered in the Global C-Sink Registry run by the Global Carbon Register Foundation in Switzerland.

The necessary inspections at the production site must be carried out by a verification and validation body (VVB) endorsed by Carbon Standards. The relevant inspection requirements and calculation templates for certifying biochar carbon sinks are detailed in the following pages of the Global Biochar C-Sink Standard.

2. Biochar Use and C-Sinks

2.1 Calculation of Biochar C-Sinks

To account for the carbon stored in a biochar C-sink, the organic carbon (C_{org}) content of the biochar must be determined according to the EBC or WBC standard. It is indicated as a mass proportion (in %) based on the biochar's dry weight. The mass of a biochar C-sink at the time of application (C-Sink_(0)) is thus:

$$\text{C-Sink\_(0)} = \text{Corg}_{\text{biochar}} * \text{dry mass}_{\text{applied biochar}}$$

Equation 1: Amount of carbon stored in a biochar C-sink just after applying. The unit of C-Sink_(0) is tons of carbon.

However, every biochar C-sink underlies a time-dependent evolution, and the C-sink is a measure of the mass of carbon that is physically present in the C-sink matrix at any given moment in time since the establishment of the C-sink. The size of a biochar C-sink is, thus, a function of the type of biochar determining its specific persistence in a specific C-sink matrix and the time since the application to the C-sink matrix.

$$C_{\text{remain}}\ (\text{years}) = \text{C-Sink\_(0)} * \text{specific persistence (years)}$$

Equation 2: Size of C-sink at a defined time in years after the application. The specific persistence is nondimensional and depends on the biochar and the type of C-Sink matrix. The unit of C_{remain} (years) is tons of carbon.

To assess the short- to medium-term climate effect of a biochar C-sink over a given number of years, the carbon that is stored on average during this period is calculated using the following equation:

$$\text{C-Sink\_X} = \frac{\sum_{n=1}^{\text{years}} C_{\text{remain}}(n)}{n}$$

Equation 3: Average annual biochar C-sink over a period of X years. The range of X is least one to a max. of 100 years ($1 \leq years \leq 100$) using the sum of the amounts of biochar carbon remaining in a C-sink (C_{remain}) each year after application. C-Sink_X is provided in t aCO_2 (annual CO_2) as detailed in the text.

While some labile fractions of the biochar decompose more quickly during the first 50 to 100 years, the persistent fractions are stable over geological time spans of more than a thousand years. Biochar C-sinks present the highest sequestered carbon in the first years, which decreases more quickly in the beginning and ever more slowly after the first decade. To specify the climate effect (i.e., negative warming) of biochar-based C-sinks, one may calculate the average mass of a biochar C-sink over 35 (C-Sink_35), 50 (C-Sink_50), or 100 years (C-Sink_100). This average is also referred to as the average annual biochar C-sink expressed in t aCO_2 (tons of annual CO_2). For soil-applied biochar, the average slightly underestimates the amount of sequestered carbon and thus the climate effect in the first few years and slightly overestimates it in later years. Potential uses of average annual biochar C-sink are discussed in Chapter 3 below. Calculation examples are presented in Table 1.

As strong climate action is urgently needed in the near future to limit global climate change, the average annual biochar C-sink becomes an important marketable asset to enable funding of biochar projects. However, to guarantee a reliable climate service over time, the average annual biochar C-sink may only be marketed for at least one year and, at maximum, 100 years. The fraction of biochar C-sinks presenting persistence over 1000 years is expressed as C-Sink_1000+.

As long as biochar materials are not applied to soil or another long-lasting matrix, total or partial losses of biochar-carbon are possible. Fire could destroy biochar, or a customer could buy it for co-firing in a biomass power plant or use it as a reducing agent for steel production. Therefore, biochar must not only be tracked from the production site to the final C-sink site, but the final C-sink site must be monitored for as long as the biochar or biochar-material is not applied to soil (i.e., for all C-sinks > 1 t CO_2e).

As long as there is a risk that the stored carbon may be released into the atmosphere, the biochar carbon must be considered a temporal C-sink. Contrary to geological C-sinks, temporal C-sinks have to be monitored and controlled regularly to guarantee their persistence. Certificates for temporary C-Sinks should not be used for CO_2 offsets.

When biochar is stored for more than one year under controlled conditions (i.e., not exposed to rain and wind) before being applied to a C-sink matrix, it can be certified as a temporary C-sink for the controlled storage time.

2.2 Geological C-Sink (biochar applied to soil)

Even the PAC fraction of biochar can only become a geological (long-term) C-sink when its rapid oxidation, e.g., by burning or smoldering, can be excluded. This status is reached when biochar is mixed irrevocably into an inflammable and irrecoverable C-sink matrix that eventually is applied to soil (c.f., Chapter 11). When mixed with animal feed, manure, compost, liquid fertilizer, or anaerobic digestate, it could theoretically be dried and combusted, but when produced and marketed as a soil amendment or feed, the risk that a significant portion of it may burn is essentially eliminated. Possible partial losses are covered by safety margins, which ensure that in no case more carbon is certified as a C-sink than is present in the C-sink. When biochar eventually reaches the soil after it was used, e.g., as livestock bedding or as part of similar organic substrates for agriculture, or when it becomes an intrinsic component of similar mineral materials, the terrestrial C-sink can be characterized with mathematically defined degradation rates, reflecting the content of PAC/SPC, reaching far into the future (i.e., > 1000 years) which makes it a geological C-sink.

Biochar with an H to C_{org} ratio < 0.40 that is applied to soil enters the slow carbon cycle, passing the pedosphere to the lithosphere (Schmidt and Hagemann, 2024). Soil application can thus be described as the beginning of a transition into geology. As most of such biochar consists of inertinite comparable to fossil coal (Sanei et al., 2023), soil-applied biochar will eventually (in the 10’000+ years perspective) become the future fossil carbon and replenish, thus, the geological carbon pool.

Biochar-containing building materials such as cement-, lime-, or geopolymer-based concrete, clay, or gypsum are usually recycled into aggregates or deposited in land or road fills at the end of the product life. If reused as aggregate, the biochar is protected from decomposing by the new matrix. When deposed in land- or other soil-located fills, the biochar becomes a geological C-sink. Eventually, biochar-containing building materials will enter the soil and, thus, become a geological C-sink.

The geological C-sink is registered with its persistence curve reaching over more than 1000 years (c.f., Chapter 2.4).

2.3 Temporary C-Sink (biochar used in materials)

If biochar is used as an additive in materials such as asphalt, plastics, textiles, and composite materials, it can be assumed that the entire carbon content of the biochar persists and remains a C-sink for as long as the material itself persists. Only when the biochar-containing material is dismantled, recycled, or (waste) incinerated could the sequestered carbon be released back into the atmosphere, causing the C-sink to lose its value. It must by then be removed from the C-sink registry.

Matrixes such as plastics, textiles, paper, or composites cannot fundamentally prevent the oxidation of biochar. The likely end-of-life scenario of such materials is waste incineration, although the deposition in landfills is still common practice in many countries.

Using biochar in materials is often recommended to optimize material properties or replace other materials made from or under the use of fossil fuels. For as long as these biochar materials are in use, the carbon in the biochar remains stored outside the atmosphere and is eligible for global cooling services.

For most consumer products such as water pipes, skis, or car parts, tracking all possible use cases is not feasible. However, as they are produced and marketed in large quantities, statistics for specific products can determine an average lifetime. With a statistically validated lifetime before it may end up in waste incineration, the biochar carbon can be certified as a temporary C-sink for the defined product lifetime. While the C-sink would continue in the case of landfill waste disposal, we do not consider it a sustainable practice. Once CCS of waste incineration is generally in place, the continuation of the C-sink could be registered.

If large amounts of biochar are used in infrastructure (e.g., in asphalt), the location must be registered, and a controlling period is set by the standard verifying if the C-sink is still in place or not.

Thus, temporary material C-sinks are registered once embedded into the C-sink matrix with their statistically validated lifetime or their control period. If the control at the end of the defined controlling period confirms the continued presence of the C-sink, the registry entry of the temporary C-sink is prolonged until the end of the next controlling period. The duration of the new controlling period is updated at the end of each controlling period.

The value of temporary C-sinks is given as the annual average mass of carbon in carbon dioxide equivalents (t aCO_2) over the certified period in years, e.g., C-Sink_35, C-Sink_50, or C-Sink_100.

2.4 Temporary Storage of Biochar

Biochar can be stored to preserve it for later years when, e.g., demand and prices increase. For as long as the biochar is stored under controlled conditions and with regular verification, such as in containers, below ground protected from water and biologically active matrices, and in ancient salt or coal mines, it can be considered a temporary C-sink during the controlled storage time. The control is usually assured remotely with continuous temperature and/or CO_2 concentration measurements (for more details see Chapter 12.5).

A temporary storage of biochar is defined by the fact that the biochar can be recovered as such and used later in various industrial ways of the circular carbon economy. When biochar is mixed into a C-sink matrix such as soil or ash, the largest part of the biochar cannot be recovered to be used as unmixed material, and thus the C-sink is not considered a storage.

The registered amount of carbon in temporary carbon storage must be updated annually. As the biochar in temporary storage can be used at any time, it is not permissible to calculate an average value for the carbon stored beyond the horizon of 1 year.

2.5 Geological Storage of Biochar

If biochar is applied

- deep below the soil in geological horizons,
- where no soil organic matter can be detected,
- where no biological activity is sustained, e.g., in abandoned mining sites,
- where the biochar is protected from air and water and
- where it cannot be recovered because of a sealed cover or because of its embedding in a C-sink matrix (e.g., mixing to ash or sediments),

the storage can be considered a geological carbon storage with no decomposition for > 1000 years. A security leakage margin of 5% must be applied.

For geological storages above 10,000 m3, continuous monitoring of temperature and gas evolution must be set up.

3. Persistence of Soil Applied Biochar

Once applied to soil, a biochar-based C-sink cannot be destroyed anymore. However, despite its persistent nature, a fraction of biochar will eventually degrade in the soil matrix. From a chemical perspective, biochar is a mixture of an extensive variety of carbon compounds ranging from aliphatic, simple aromatic to condensed aromatic hydrocarbons, also called aromatic clusters. Thus, observable biochar degradation is the sum of the degradation of these individual compounds, which can be approximated with an empiric degradation formula. For this purpose, we differentiate biochar carbon into a Semi Persistent Carbon (SPC) pool that degrades within the first thousand years after soil application and a Persistent Aromatic Carbon (PAC) pool that will persist for more than 1000 years in soil, will slowly be transferred into the lithosphere, and can be considered a geological carbon sink (Schmidt et al., 2022). The degradation of SPC can partly be assessed, e.g., by incubation of biochar in soil or controlled lab environments exposed to microbial communities. Reasonable incubation times of 1-10 years have been achieved to provide useful information to this end (Azzi et al., 2024). However, within such reasonable time frames, only the most labile carbon compounds can be degraded. The persistence of PAC must, therefore, be derived from observations of the global pyrogenic carbon cycle (see Appendix 1 in (Schmidt et al., 2022)) or from thermodynamic and kinetic conclusions for the chemical and microbial degradation of the polycyclic molecules (Sanei et al., 2023).

The distinction of these two defined pools changes the key question from “how stable is biochar” to “what is the size of the PAC fraction of a given biochar?” and thus, what portion of a biochar can be considered as geological C-sink once applied to soil. The size of the PAC and SPC fractions depends on the severity of the pyrolysis conditions (i.e., temperature, residence time, pressure) but also on the ash content of the feedstock and its particle size (Bowring et al., 2020, 2022; Zimmerman and Gao, 2013). The proportion of PAC and SPC is related but not determined by the H/C_{org} ratio and the electric conductivity of the solid biochar. Today, the most reliable method to determine the size of the PAC fraction of biochar are hydrogen pyrolysis (HyPy) and random reflectance (McBeath et al., 2015; Petersen et al., 2023).

Hydrogen pyrolysis is an analytical method where the biochar sample is heated to 550 °C in a 150-bar hydrogen atmosphere. All labile organic matter and semi-persistent carbon structures, such as aliphatic compounds and polycyclic aromatic clusters presenting up to seven condensed aromatic rings, react with the hot, high-pressurized hydrogen and are completely removed from the sample. Only the highly stable portion of the carbon compounds, i.e. the PAC, remains. This residue consists of condensed aromatic clusters with more than seven aromatic rings which demonstrate extreme stability in the environment, being highly resistant to biological and chemical degradation. Historical biochar samples dating back centuries appear to validate the geological persistence of the PAC fraction, as indicated by Ascough et al. (2012, 2009) and Meredith et al. (2012). However, the number of studies focusing on biochar persistence in relation to HyPy remains limited (Howell et al., 2022; McBeath et al., 2015). Thus, it remains subject to ongoing research if the HyPy residue exactly equals PAC as defined in these guidelines or if other factors need to be included.

Concurrently, the use of microscopic analysis measuring the total reflectance is suggested to quantify a permanent carbon fraction in biochar, which is referred to as inertinite. The extent to which HyPy measured PAC and inertinite are the same or different has not yet been investigated. Even more than for the above-mentioned case of HyPy, literature on the random reflectance method in relation to biochar persistence is still very limited (Petersen et al., 2023, Sanei et al. 2023) and not yet broadly enough discussed in biochar science. Especially, the significance of the measured inertinite content regarding the stability of biochar in biologically active systems (as opposed to geological storage) is yet missing.

Consequently, there is insufficient confidence to revise the biochar persistence evaluation used in the earlier versions of the present C-Sink Standard. Several scientific papers on biochar persistence using the above-mentioned methods are announced for the academic year 2024, which will likely lead to an update of the biochar persistence chapter in the Global Biochar C-Sink Standard and its recommended analytical methods soon.

The semi-persistent carbon (SPC) fraction of biochar is defined as the part of soil-applied biochar that may decay within the first 1000 years after soil application. The SPC fraction has a mean residence time of 50 years and constitutes a temporary carbon sink. The mean residence time of 50 years for the SPC fraction is based on the most conservative metanalytical estimate for biochar carbon degradation published to date (Schmidt et al., 2022). Other sources determined significantly lower degradation rates depending on the degree of pyrolysis and the experimental design (IPCC, 2019; Kuzyakov et al., 2014; J Lehmann et al., 2015; Zimmerman and Gao, 2013). Also, 50 years correspond to the MRT of bulk soil organic carbon (SOC) (Schmidt et al., 2011). As it is common understanding that SOC is less persistent than biochar (Lehmann et al., 2015; Lehmann et al., 2020; Schmidt et al., 2011), the assumption of a MRT of 69 years (half-life of 50 years) for the SPC fraction is very conservative. However, without more reliable methods and long-term experiments, the present Global Biochar C-Sink Standard uses conservative projections and calculates the climate-relevant effect of C-sinks with a sufficient safety margin.

EBC- and WBC-certified biochar with an H/C_{org} ratio < 0.40 that was applied to soil is therefore registered with a PAC fraction of 75% and SPC fraction of 25% in the Global C-

Sink Registry. Biochars with an H/C_{org} ratio ≥ 0.40 that was applied to soil are registered with an SPC fraction of 100%, and no PAC fraction can be registered.

If the calculation method in the expected update of the standard allows higher PAC proportions for the respective biochar batch, the register entries can be adjusted posteriorly under conditions to be specified.

The remaining carbon of soil-applied biochar with an H/Corg ratio < 0.40 is calculated as a function of time with the following conservative approximation:

$$C_{remain}\,(year) = M_{BC} * C_{cont} * (0.75 + 0.25 *(0.1787 * e^{-0.5337 * years} + 0.8237 * e^{-0.00997 * years}))$$

Equation 4. Decay function of biochar presenting an H to C_{org} ratio < 0.40. M_{BC} = mass of biochar; C_{cont} = carbon content of biochar; C_{remain} = Mass of biochar-carbon remaining in a C-sink after the years since soil application. The equation is valid for 0 to 1000 years since soil application.

The formula is based on the assumption that 75% of the carbon is persistent for more than 1000 years (PAC fraction) and that the semi-persistent fraction (SPC) has an MRT of 69 years as discussed above.

If, e.g., 1000 tons of biochar with a C-content of 80% and an H to C_{org} ratio of 0.2 is applied to soil, the carbon that remains after 20 years, 100 years, and 1000 years in the soil C-sink, respectively, is calculated as follows:

$$C_{remain}(20y) = 1000\,t * 80\% * (0.75 + 0.25 * (0.1787 * e^{-0.5337*20y} + 0.8237 * e^{-0.00997*20y}) = 735.0\,t$$

$$C_{remain}(100y) = 1000\,t * 80\% * (0.75 + 0.25 * (0.1787 * e^{-0.5337*100y} + 0.8237 * e^{-0.00997*100y}) = 660.8\,t$$

$$C_{remain}(1000y) = 1000\,t * 80\% * (0.75 + 0.25 * (0.1787 * e^{-0.5337*1000y} + 0.8237 * e^{-0.00997*1000y}) = 600.0\,t$$

When C-sinks are sold to offset CO_2 emissions, only the PAC fraction must be used. The SPC-fraction of biochar can be used for methane emission offsets (c.f., Chapter 4.3) and global cooling services.

$$C_{remain}\,(year) = M_{BC} * C_{cont} * (0.1787 * e^{-0.5337 * years} + 0.8237 * e^{-0.00997 * years})$$

Equation 5. Decay function of biochar presenting an H to C_{org} ratio ≥ 0.40. M_{BC} = mass of biochar; C_{cont} = carbon content of biochar; C_{remain} = Mass of biochar-carbon remaining in a C-sink after the years since soil application. The equation is valid for 0 to 99 years.

For C-sink trading purposes, the average annual mass of carbon stored for a given number of years (cf. Equation 3) can be displayed in the C-Sink Registry and is provided on the C-sink certificate. It can be used for methane compensation and Global Cooling Services. Currently, most C-Sink traders use the mean annual C-sink over 100 years (C-Sink_100) to compensate for CO_2 emissions. However, also shorter periods such as C-Sink_35 or C-Sink_50 can compensate for the global warming potential of a GHG emission over the indicated time. The calculation of the average annual mass of stored carbon depends on the C-sink matrix. For soil-applied biochar, this depends on the H/C_{org} ratio (c.f., Table 1); for biochar used in concrete, it depends on the expected lifetime of the construction (c.f., Chapter 12.3).

Table 1: Average annual mass of carbon stored in a C-sink for time periods of one to 100 years after the application of 100 t CO_2e biochar to soil calculated according to equation 3. For biochar with H to C_{org} ratios < 0.4, the SPC fraction presents 25%, which degrades in soil following equation 4. For biochar with an H to C_{org} ratio ≥ 0.4, the SPC fraction presents 100%, which degrades in soil following equation 5. If the average annual mass of carbon is calculated not only for the SPC fraction but for the entire biochar, including its PAC fraction, the line "SPC 25% & PAC75%" provides the annual values. Please consult the SPC calculator at the website of Carbon Standards.

100 t CO2e Biochar C-Sink	H/Corg	C-Sink_01	C-Sink_05	C-Sink_10	C-Sink_25	C-Sink_35	C-Sink_50	C-Sink_100
PAC 75%	≤ 0.4	75	75	75	75	75	75	75
SPC 25%	≤ 0.4	25	21.2	20.1	18.4	17.5	16.3	13.0
SPC 25% & PAC 75%	≤ 0.4	100	96.2	95.1	93.4	92.5	91.3	88.0
SPC 100%	> 0.4	100	84.7	80.5	73.6	69.9	65.0	52.1

4. Emission Portfolio and Compensation

The carbon expenditure of a biochar C-sink englobes all GHG emissions caused by biomass production, transport, preparation, pyrolysis, milling, packaging, transportation, mixing, and application to a C-sink matrix. It presents the complete carbon footprint of the biochar from the initial capture of atmospheric carbon till the application to the final C-sink site.

The emissions from biomass production to the packaging of the biochar and its storage at the factory gate are assessed with Carbon Standards' Biochar Tool, and the biochar producer must offset these emissions for every batch and every year of production.

The emissions occurring from the biochar factory gate to the final C-sink site have to be tracked by dMRV providers. Those post-factory-gate emissions are relatively small compared to the C-sink value of the biochar. Post factory-gate emissions must be offset by, e.g., the C-sink owner, processor, or trader which is commonly done by retiring part of the biochar C-sink.

If biochar or biochar products are transported from the producer or processor to a next processor, a trader, or to the C-sink location, the receiving organization (e.g., the trader, the farmer, the construction company, etc.) is responsible for reporting and offsetting the transport emissions.

All production emissions are registered in the ***emission portfolio*** of the production companies for each biochar production batch. Moreover, each packaging unit has its own emission portfolio to ensure that all emissions occurring between the factory gate and the final C-sink are recorded and offset.

All fossil CO_2 emissions from biomass production to C-sink application must be offset by long-term carbon sinks before the registration of a biochar C-sink can be validated in the Global C-Sink Registry. The same must be done for N_2O emissions from biomass cultivation. The global warming effect of CH_4 emissions can be compensated by an equally sized global cooling over a 20-year period, which must be validated in the Global C-Sink Registry (c.f., Chapter 4.3)

4.1 Production Emissions Included in the Emission Portfolio

The emissions of fossil-carbon-derived CH_4, N_2O, and CO_2 caused by biochar production are recorded as follows:

a) Emissions from the provision of biomass (c.f. Chapter 5.3), which covers biomass production, processing, and transportation.

b) Emissions from the storage of the biomass (cf. Chapter 6)

c) Emissions from the pyrolysis process and other equipment at the production site (c.f., Chapter 7.1).

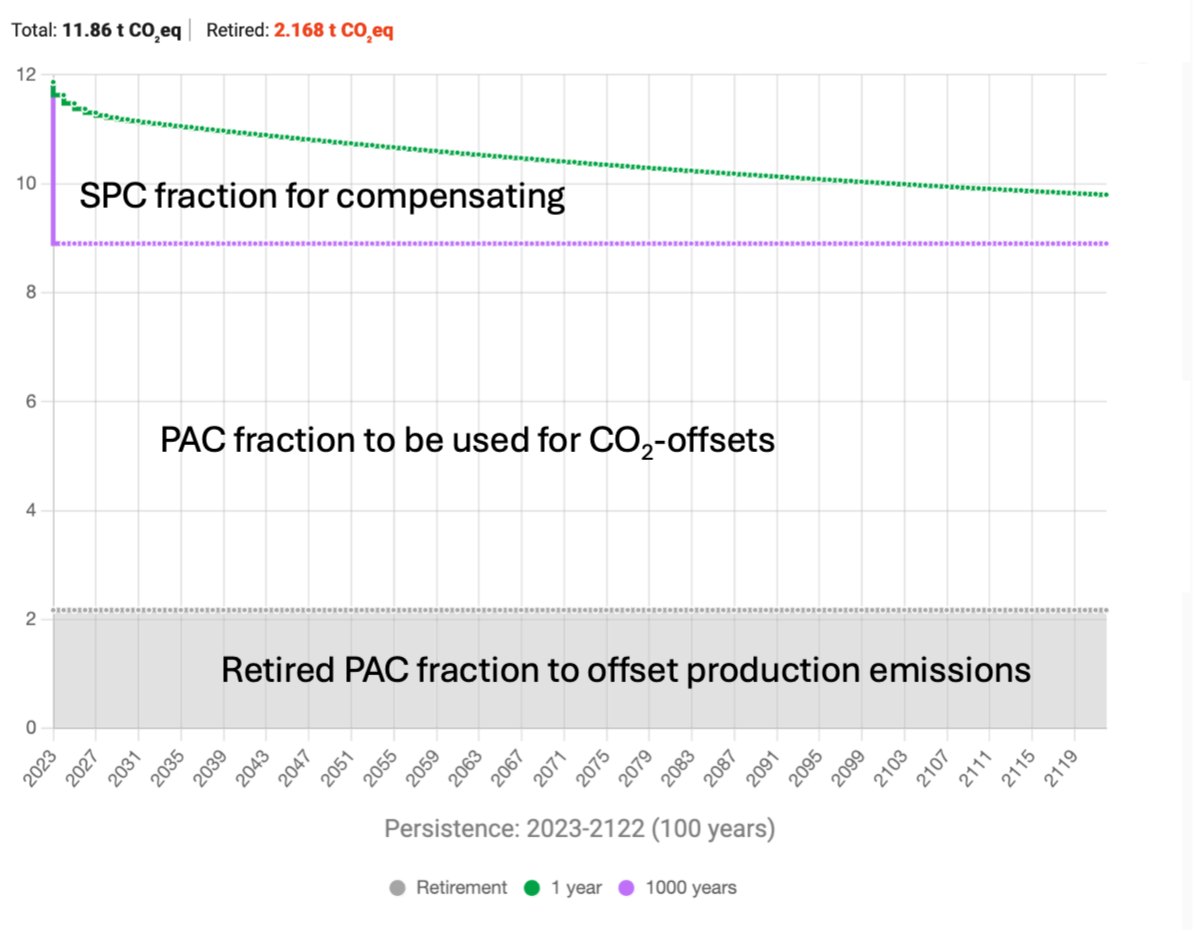
d) Emissions from postproduction and transportation to the C-sink site (c.f. Chap. 10).

e) A safety margin in the amount of 20 kg CO_2e per ton of biochar is added to account for all additional emissions not covered under the regular assessment (cf. Chap. e)).

The emissions are calculated by adding all the above-listed emissions as CO_2e. For N_2O the GWP100 of 298 t CO_2e t^{-1} and for methane the GWP20 of 86 are used as conversion factors, respectively (IPCC, 2022). The emission factor is given as mass proportion based on the dry weight of the biochar (t CO_2e t^{-1}). It is calculated by dividing the total amount of carbon expenditures per batch by the dry weight of the total amount of biochar produced per batch.

4.2 Offsetting of Production Emissions

CO_2 must only be offset with geological C-sinks, such as the PAC fraction of soil-applied biochar, that are registered in the Global C-Sink Registry (c.f., Figure 1).



The global warming potential (GWP100) of methane (CH_4) emissions can be compensated by an equally sized global cooling effect (i.e., negative global warming). However, given that most of the warming caused by CH_4 emissions occurs in the first two decades, the compensation of the GWP100 must be delivered during the first 20 years following the CH_4 emission. Further details are provided in Chapter 4.3

Nitrous oxide (N_2O) has a long residence time in the atmosphere and thus must be offset with geological C-sinks registered in the Global C-Sink Registry. For this purpose, emissions are converted into CO_2e using the GWP100 of 298 tons CO_2 per ton N_2O (Aamaas et al., 2016; Allen et al., 2016; IPCC, 2022; Myhre et al., 2013).

The emission offsets can be realized with the registered biochar C-sink whose production had caused the emission.

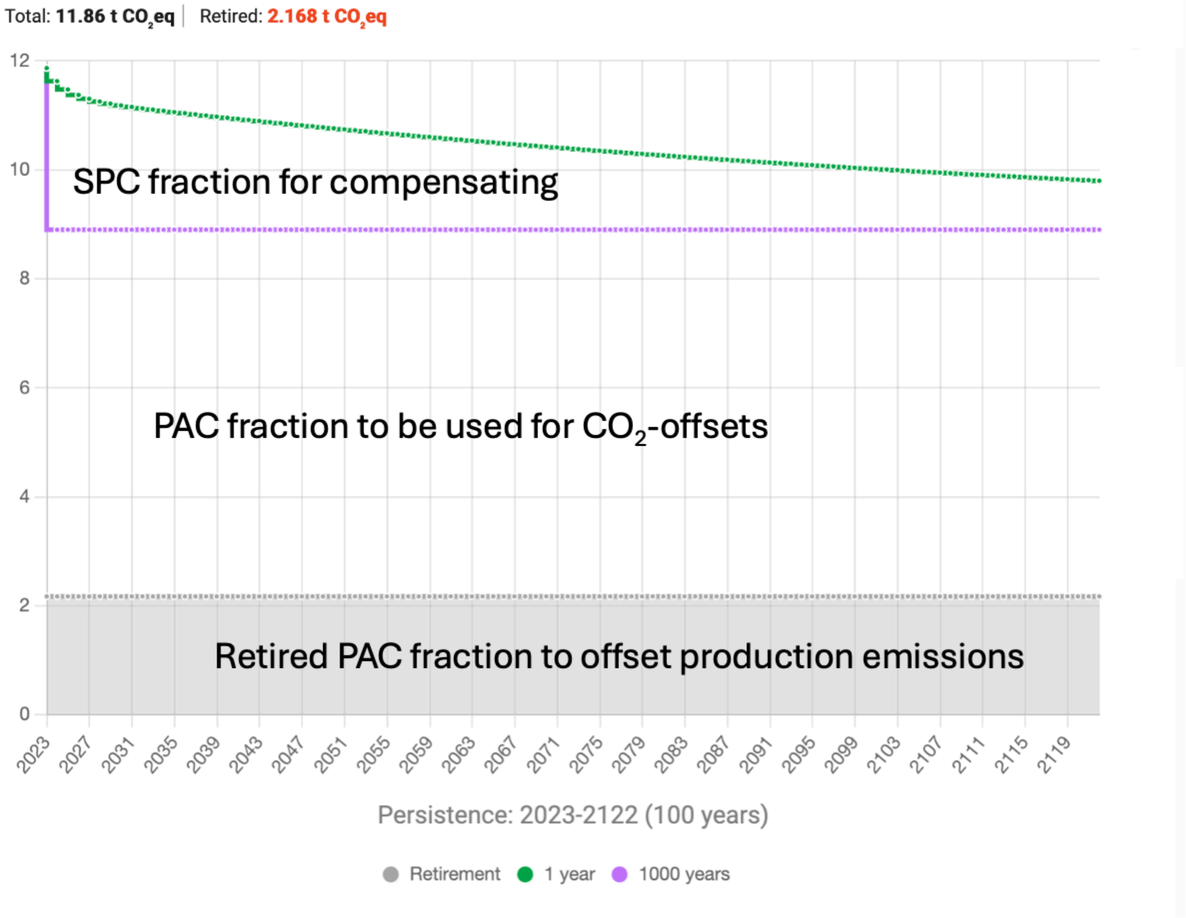


Figure 1: The green line shows the persistence of a biochar C-sink over the next 100 years (slow degradation of the SPC fraction). The lilac line shows the persistence of the PAC fraction on the biochar. The entire area below the lilac line can be traded as a geological carbon sink. The grey area at the bottom of the diagram shows the emissions caused by the biochar production and the establishment of the C-sink, which is then retired from the PAC fraction. The C-sink represented by the area below the green curve and above the grey area is the temporary C-sink that can only be traded for its global cooling effects (e.g., for methane compensation).

4.3 Methane Emissions and their Offsetting

Although the methane concentration in the atmosphere is around 200 times lower than that of CO_2, methane currently contributes between 16 and 30% to global warming, with no consensus between the scientific references. However, unlike CO_2, methane is degraded by various processes in the atmosphere and in the interaction between the atmosphere and the soil, which ultimately result in the formation of CO_2 and H_2O, with various intermediate reaction products. When the emitted methane is of non-fossil origin, the resulting CO_2 can be considered carbon neutral. The mean residence time of methane in the atmosphere is about twelve years, which equals a half-life of 8-9 years (Myhre 2013). The short residence time of methane has two major consequences for offsetting:

(1) There is no need to compensate for global warming caused by methane with geological C-sinks; temporary C-sinks can be used instead. Since the PAC fraction of C-sinks has a negative global warming effect of more than 1000 years, offsetting the short-term global warming of methane with long-term C-sinks is hardly justifiable, it is neither economically nor is it necessary or adequate from a physical point of view.

(2) Compensation must be carried out promptly after the emission. The decades up to 2050 are the decisive period for limiting anthropogenic global warming. Since methane emissions occurring today and in the upcoming decade have a particularly severe climate impact until 2050, the Global Biochar C-Sink Standard requires that methane emissions be compensated during the first 20 years following the emission. This reflects the comparatively short but intense impact of methane and is in line with recommendations from various organizations and scientists (Balcombe et al., 2018).

The global warming potential (GWP) was created as a metric to allow comparison of the effect of different greenhouse gases for a specified period of time. The period of 100 years is most used for this purpose (GWP100) (Fuglestvedt et al., 2003). Various other metrics have been suggested for this purpose; however, despite various limitations, the GWP100 is still the most widely accepted method and was identified as the most useful one for guiding political decision-making (Moosmann and Herold, 2023).

The GWP100 for methane is 25. Thus, the emission of 1 t methane has the same effect as the 25 t CO_2 emitted at the same time – when looking at a time span of 100 years. After 100 years, more than 99.9% of emitted methane is oxidized. The GWP includes both the reduced global warming of CO_2 over time due to the distribution of CO_2 into other spheres (e.g., the ocean (Jeltsch-Thömmes and Joos, 2019)) as well as the decay of methane. Thus, one could suggest using a C-Sink_100 of 25 t aCO_2e to compensate for the emission of 1 t methane, i.e., an average of 25 t CO_2e would be sequestered for 100 years = 2500 tons * years. However, this would result in a considerable under-compensation in the decisive first decades. Instead, the same amount of cooling (2500 tons * years) must be provided within a maximum of 20 years, e.g. by C-Sink_20 of 125 t aCO_2, which equally results in (20y * 125 t aCO2 =) 2500 tons * years.

In the case of industrial biochar production, methane emissions should be offset with temporary biochar C-sinks using the SPC fraction or biochar materials with shorter life cycles as described below. To assess the amount of an SPC fraction or other temporary C-sinks necessary to compensate for specific methane emissions, a calculator for SPC methane compensation is provided on the website of the Carbon Standards.

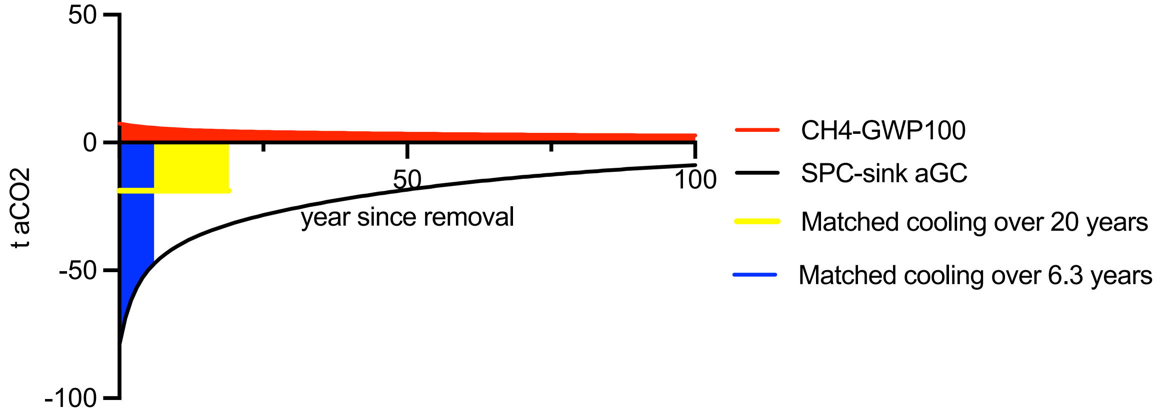


Figure 2: Compensation of the global warming effect of a 300 kg CH_4 emission (area below the red curve) caused by the production of 180 t of biochar with a C content of 48%. As 25% of the biochar carbon is semi-persistent carbon (SPC) with an MRT of 69 years (black curve), the global cooling effect of the biochar's SPC fraction can be used entirely for 6.3 years (blue area) or partially for 20 years (yellow area).

Within Global Biochar C-Sink, the global warming potential of methane emissions that occur during biochar production can be compensated by retiring a carbon sink for a maximum of 20 years, presenting a climate cooling effect equal to the climate warming effect of the methane emission over 100 years. Thus, the total climate forcing of a methane emission must be compensated within 20 years after the initial emission.

4.4 Reduction of Fossil Carbon Emission

Given that global GHG emissions are successfully reduced by 2050 to less than 10% of the emissions recorded for the year 1990, negative emissions of at least 800 Gt CO_2e are still needed until the end of the century to limit global temperature rise to about 2 °C. The remaining 10% of GHG emissions will mainly comprise emissions from agriculture and waste decomposition but must not originate from fossil carbon sources. Consequently, C-sink producers must reduce their fossil carbon emissions, too. It is neither convincing nor acceptable in the long term if C-sink producers consume fossil carbon for the provision of machine fuel and electricity. Therefore, **certified biochar producers must present a plan outlining how to reduce fossil GHG emissions of biochar production as specified below to less than 100 kg CO_2e per ton of biochar-carbon in 2030 and to less than 20 kg CO_2e per ton of biochar-carbon in 2035** (for an example of such a plan, see Carbon Standards' website).

The following fossil carbon emissions must be included: biomass production, harvest, transport, preparation such as chipping or pelletizing, drying, pyrolysis, and packaging. Methane emissions from storing and pyrolysis should equally be avoided but are not included in the fossil carbon emission reduction plan because of their biogenic origin. Fossil carbon emissions from biochar transportation and external processing do not fall under the responsibility of the biochar producer and will be part of the control of biochar traders, biochar product manufacturers, and users.

$$\text{Biochar\_GHG\_balance (t CO2e / t BC)} = \frac{\text{Total emission until factory gate (t CO2e)} - \text{non fossil CH4 emissions (t CO2e)}}{\text{mass of biochar per batch (t DM)} * C_{\text{content}} \text{ of biochar}}$$

Equation 6: Calculation of the GHG balance of biochar production from feedstock production until biochar packaging at the biochar production facility in tons of emitted CO2e per ton of produced biochar. The unit of all emissions is CO_2e. Non-fossil emissions such as methane emissions from storage and pyrolysis are excluded.

The fossil emission reduction plan must be updated annually and include a short progress report. The plan can be managed online in the Global Biochar Tool or uploaded annually in a new version of the tool.

4.5 Pro Rata Calculation of GHG Footprint

It should be expected that not only the biochar production as such but the entire biomass processing facility (i.e., the project) with all resulting products (i.e., biochar, electricity, heat, hydrogen, pyrolysis oil, etc.) will be climate neutral.

However, in most industrial setups, biochar is only a secondary product of the pyrolysis or gasification process. It may, therefore, not be appropriate to attribute the entire carbon footprint of the production facility to biochar alone. Instead, the greenhouse gas (GHG) emissions may be distributed proportionally among the other pyrolysis products (c.f., ISO 14040) such as charcoal, hydrogen, pyrolysis oil, electricity or thermal energy. The GHG allocation between the various products is calculated on the energy base of the products (see Box 6).

To be eligible to use the pro-rata GHG calculation, the producer has to prove that the non-biochar products are regularly traded and generate substantial income or measurable add value. The income or added value for all non-biochar products must not be inferior to 30% of the income generated with biochar.

The input energy (E_{input}) is calculated by multiplying the analyzed lower heating value (LHV) of the biomass feedstock ($LHV_{feedstock}$) with the mass of the feedstock on a dry matter base ($m_{feedstock,\ dm}$). The output energy of the non-biochar products ($E_{nonBCoutput}$) is calculated by multiplying the LHV of the **marketable non-biochar solid** (e.g., charcoal)**, liquid, and gaseous products** with the respective mass of the products on a dry matter base and adding the produced, **measured electric energy** ($E_{electric}$) and **thermic energy** ($E_{thermic}$). A pyrolysis product is considered as marketed when it is sold to or used in processes not directly linked to the pyrolysis/gasification facility. For example, hydrogen is considered a marketable product when hydrogen is produced, stored in a tank, and sold to another company or used, e.g., in a methanol synthesis at the production site. If the hydrogen is combusted in the combustion chamber of the pyrolysis unit or in a directly linked generator for electricity production, the hydrogen is not considered a marketable product. The use of thermic energy to dry the pyrolysis feedstock is considered part of the biochar production and cannot be accounted for the pro-rata GHG allocation.

(1) $E_{input} = LHV_{feedstock} * m_{feedstock,\ dm}$
(2) $E_{nonBCoutput} = LHV_{nonBCsolid} * m_{nonBCsolid}, dm + LHV_{liquid} * m_{liquid} + LHV_{gas} * m_{gas} + E_{electric} + E_{thermic}$
(3) $E_{biochar} = LHV_{biochar} * m_{biochar\ (DM)}$

Equation 7: Calculations of energy content based on the lower heating value (LHV) of the biochar, the pyrolysis oil, the pyrolysis gas, and the electric and thermic energy. Units of E are usually given in MJ and LHV in MJ per kg.

To calculate the GHG attribution of the biochar product, the total emissions assessed for the entire process from biomass production to biochar output are multiplied by the ratio of $E_{biochar}$ to the total E_{output} ($=E_{nonBCoutput} + E_{biochar}$).

$$\boxed{BC_{emission} = \text{Production emissions } \frac{E_{biochar}}{E_{nonBCoutput} + E_{biochar}}}$$

Equation 8: Calculation of the part of total emissions to be accounted for the biochar production on a pro rata base.

All emissions that occur between the biochar output from the pyrolysis unit to the eventual carbon sink must be attributed to the emission portfolio of the biochar.

Box 6: Pro-rata attribution of GHG emissions caused by the biochar facility.

Example for the pro-rata calculation for GHG attribution:

- **Input (feedstock):** Annual feedstock 4000 t of wood with a dry matter content of 65%, carbon content of 48%, and a lower heating value (LHV) of 4 kWh/kg (@ 80% DM) representing (3250 t (@80% DM) * 4 MWh/t =) 13,000 MWh.
- **Output:** The unit produces 260 t biochar (DM) per year with an LHV of 7.9 kWh/kg and a C-content of 85%, representing 2054 MWh; 3140 MWh electricity and 4800 MWh thermic energy for district heating, representing 7940 MWh nonBCoutput.
- **GHG attribution:** The biochar to total products ratio is (2054 MWh / (2054 MWh + 7940 MWh) =) 20.6%. Thus, 20.6% of carbon expenditure (excluding the margin of safety, chap. 4.6) are attributed to the biochar production. To set the biochar production climate neutral, 20.6% of all CO_2 (incl. the margin of safety) and N_2O production emissions must be offset with long-term C-sinks, and 20.6% of CH_4 emissions compensated with temporary C-Sinks (C-Sink_20). GHG emissions occurring from the packaging station to the factory gate and then to the final C-sink are entirely attributed to the biochar.

We hope that latest by 2035, regulations will require all bioenergy and biomaterial productions to become climate-neutral.

4.6 Margin of Safety

In the calculation of carbon footprints of an organization, the emissions accounted for are usually divided into Scope 1 (direct emissions at the production site, in this case, combustion of pyrolysis gas, methane emissions during biomass storage, combustion of natural gas for preheating the reactors), Scope 2 (indirect emissions from externally purchased energy, in this case mainly electricity) and Scope 3 (further indirect emissions, in this case, e.g., production emission of the pyrolysis plant, electricity for external server maintenance, emissions of purchased biomasses, fertilizers, transport of biomass).

For the Global Biochar C-Sink, the emissions from Scope 1 and 2 of each involved and registered organization (producers and processors) are fully recorded. If the conditions for the pro-rata approach (chapter 4.5) are met, the emissions are allocated to the biochar and other products.

For Scope 3 emissions of involved organizations, only the emissions from biomass production and its transport are directly quantified.

Other indirect emissions from Scope 3 are not recorded individually due to their comparatively low volume but are instead included in the calculation with a flat margin of safety to account for the whole value chain. This includes, for example, the emissions caused by:

- Production and disposal of polypropylene bags,
- Electricity for the operation and cooling of the company's external computer servers,
- Potential methane emissions during the first month of storage of the biomass,
- Fuel consumption by employees for commuting to work and for business trips,
- Marketing and management activities including trade shows and conference attendance,
- Operation of chainsaws or harvesters for felling and peeling trees and for digging up roots,
- Emissions from machine fuels during cultivation of agricultural land and plant protection measures,
- Production, maintenance, repair, and disposal of pyrolysis equipment, transport vehicles, warehouses, and other machinery.
- The loss of small amounts of diffuse C-sinks to waste incineration (e.g., potting soil that is discharged to a waste bin).

- The margin further accounts for unavoidable imprecisions in sampling, packaging, volume and dry mater analysis, etc.

There are many small, indirect scope 3 emissions that need to be included when creating a perfect carbon footprint. Compared to the total amount of CO_2e from Scope 1 & 2 as well as from biomass provision within Scope 3, and to the vast amount of carbon accumulated in biomasses, the remaining indirect emissions in Scope 3 play only a minor role. To account for all these GHG emissions that are not directly quantified, a flat margin of safety is defined. The margin of safety generally amounts to 20 kg CO_2e per ton of biochar (dry matter) which corresponds to roughly 0.7 % of the biochar carbon. The margin of safety is applied per ton of biochar at the factory gate of the producer and is, thus, not affected by pro-rata accounting. This is an industry-standard margin for the inherent uncertainty of the overall process that allows Carbon Standards to keep the certification process lean and efficient without misappropriating emissions.

If a company produces like in the example above 260 tons of biochar with a C-content of 85%, the GHG margin would be (260 t biochar * 0.02 t CO2e t biochar^{-1}=) 5.2 t CO_2e. Thus, if the biomass provision causes, e.g., 92 kg CO_2e / t biochar and the pyrolysis process 110 kg CO_2e / t biochar), the total GHG emissions would be (92 kg CO_2e for biomass + 110 kg CO_2e for pyrolysis + 20 kg CO_2e for the margin =) 222 kg CO_2e per ton of biochar. The margin would thus be (20 kg / (92 kg +110 kg) =) 10%. This margin of safety covers the indirect emissions not quantified in the system and unavoidable imprecisions in measuring and analyzing the produced biochar.

The size of the margin will be verified and, if necessary, adapted at least every second year according to the evolution of global GHG emissions and the average footprint of scope 3 emissions.

5. Biomass Feedstock for Biochar C-Sink Production

The overarching goal of the C-sink certification is to increase the total amount of carbon stored in the terrestrial system and thus reduce the concentration of greenhouse gases in the atmosphere. When certifying C-sinks, it must be ensured that the establishment of the certified C-sink does not reduce the total terrestrial carbon sink. The C-sink must be additional to the total terrestrial carbon sink compared to the moment of CO_2 removal.

The evaluation of a biochar C-sink does not start with the production of the biochar or the transport of the feedstock but precisely at the moment when the growing biomass removes CO_2 from the atmosphere. The climate effect of the carbon sinks is caused by the reduced atmospheric CO_2 concentration while preserving the removed carbon in the carbon sink avoids its re-emission.

The Global Biochar C-Sink certification verifies that the use of biomass does not deplete a long-term natural or otherwise registered carbon sink. It evaluates the climate neutrality of the feedstock production and provision along the criteria for the different feedstock types outlined in chapter 4.3 (*Approved biomass and carbon expenditures for their production*).

5.1 Carbon Neutrality of Biomass Feedstock

Feedstock to be used for biochar production must be carbon neutral under the following definition of feedstock carbon neutrality:

A feedstock material (biomass) for the generation of a C-sink is considered C-neutral if it is either the residue of a biomass processing operation or if the biomass removal did not, over the reference period, lead to the reduction of the total carbon stock of the system in which the biomass had been grown.

Only C-neutral biomass input materials are permitted for the production of biochar C-sinks. Biochar produced from biomass whose harvesting resulted in the destruction or depletion of a natural C-sink (e.g., clear-cutting of a forest) or has contributed to the disappearance of an existing sink (e.g., inappropriate agricultural practices on bog soil) does not render any positive climate service and must not be certified as C-sink.

Emissions resulting from biomass cultivation (i.e., fuel consumption for land preparation and harvest, fertilizer, irrigation, etc.) do not in themselves challenge feedstock carbon neutrality but are included as carbon expenditures. They are part of the emission portfolio and must be offset with registered long-term C-sinks.

Biomass cultivation for C-sink production may lead to activity shifts (e.g., from rice production to biomass feedstock) or market transformations (e.g., when biomass used as biochar feedstock can no longer be used in biomass power plants and is replaced by fossil fuels). It is the duty of the biochar producer to assess the risk of activity shifts and market transformation. The risk assessment must be submitted as part of the registration process, evaluated by Carbon Standards during the technical audit, and verified by the Certifier. A re-evaluation can be requested as a consequence of the annual inspection. The emissions resulting from activity shifts and market transformations in the C-sink activity must be incorporated into the emission portfolio and offset with registered long-term C-sinks.

5.2 Biomass Feedstock Additionality

Carbon from biomass shall be preserved as much and for as long as possible. Given the limited surface area of the planet on which plants can grow, natural carbon dioxide removal is limited, and the available biomass must be used responsibly. Biochar C-sinks must be additional to natural C-sinks that could or would have been realized with the same biomass feedstock in the absence of the biochar C-sink solution.

For example, a tree trunk that would normally have been transformed into construction wood or could, economically, be made into construction wood should not be pyrolyzed. Construction wood preserves the entire wood-carbon for as long as the wood is retained in the construction, thus creating a temporary C-sink. Pyrolyzing the same wood would only preserve 30-60% of the wood carbon in the biochar and result in the partial oxidation of the biomass to emitted carbon dioxide. However, if the trunk wood is used to create a C-sink material, the woody residues from processing the tree trunk into construction wood (bark, sawdust, offcuts) could be used as carbon-neutral feedstock for pyrolysis. Also, at the end of the lifecycle of the woody material, pyrolysis could preserve most of its carbon in long-term carbon sinks.

However, the decision about what is the most carbon-efficient use is often not clear. All biomasses can be used in multiple ways, and it is rarely evident which use scenario is more or less sustainable, economical, and carbon-preserving. Straw could be used for animal bedding (good economics, recycling to organic fertilizer replacing synthetic fertilizer, no carbon preservation, additional methane emissions), for biochar production (good economics, renewable energy, 50% of C-preservation), for straw bale housing (small market, 100% C-preservation). It would not make sense to give preference to or exclude one of these three scenarios due to additionality considerations.

If wood from a tree trunk is used to make wood chips for energy production by incineration, replacing fossil fuels, those wood chips could also be utilized in gasification, generating a similar amount of energy and producing some biochar as a byproduct. Carbon-preserving materials would be an even more C-efficient option compared to both scenarios. However, despite their clear climate benefits, when used for carbon-preserving purposes, wood materials are not favored by policymakers (c.f., LULUCF regulations) or the IPCC over bioenergy in today's context.

In light of the preceding factors, it is reasonable to consider that wood sourced from sustainable forest management and biomass residues collected in accordance with the guidelines outlined in chapter 5.1, should not be dismissed as potential biomass feedstock for biochar C-sink production on the ground of additionality considerations.

5.3 Approved Biomasses and Carbon Expenditures for their Production

Only biochar produced from carbon-neutral biomass is eligible for C-sink certification. Nevertheless, the provision of biomass for pyrolysis results in energy consumption and emissions that must be included in the carbon expenditure of biochar production. Depending on the type of biomass and the way it is produced, specific criteria for carbon expenditures apply.

Global Biochar C-Sink defines ten **general feedstock classes:**

(1) Biomass from annual cropping
(2) Biomass from pluriannual and perennial cropping including short rotation plantations
(3) Forest biomass
(4) Wood from landscape conservation, agro-forestry, forest gardens, field margins, and urban areas
(5) Wood processing waste and waste wood materials
(6) Organic residues from biomass processing
(7) Municipal waste and municipal waste digestate
(8) Manure and agricultural digestate
(9) Biosolids and biosolid digestate
(10) Other biogenic residues

The production of biomass usually causes emissions that need to be accounted for as carbon expenditures of the C-sink:

- If mineral nitrogen fertilization was used to produce the biomass, its carbon footprint, including soil borne N_2O emissions, must be accounted for according to the formula 100 kg N = 1 t CO_2e (Zhang et al., 2013).
- If pesticides were used, a flat value of 94 kg CO_2e per hectare (Audsley et al., 2009) is applied for their production-related emissions.
- The input of fuels for cultivation and harvest must also be added to the emission portfolio with a conversion factor of 3.2 ton CO_2e per ton or 2.7 t CO2e per m^3 diesel (Juhrich, 2016).

However, to keep the C-sink certification process lean and appropriate to the developmental stage of the nascent industry, the comparably low emissions for cultivation and harvest are included in the margin of safety (c.f., Chapter 4.6). Still, fertilization, pesticides, and transportation of the biomass from its origin to the pyrolysis plant need to be quantified and accounted for as carbon expenditures.

An overview about the accounting of carbon expenditures for the ten general feedstock classes is given in the following sub-chapters 5.3.1 to 5.3.10.

5.3.1 Biomass from annual cropping

If annual crops are grown on agricultural land, it can be assumed that after one year at the latest, the same amount of biomass will have grown again on the same area, which means that approximately the same amount of CO_2 will again be removed from the atmosphere. The harvested biomass can thus be considered C-neutral based on a one-year period (reference period for annuals) so that a C-sink can be created by producing biochar from cropping residues or the entire annual biomass production. Crop rotations may result in differences of annual CO_2 removals, though over the years those differences even out.

Today, material like straw, the stalks of tomatoes, potatoes, cabbages, and other plants, leaves, and pruning wood are considered agricultural residues. The inclusion of carbon (i.e., biomass) as a full-fledged product of agriculture would change this perception and the definition of agricultural residues. They would be considered an essential part of the agricultural (carbon) crop. The dry weight of any of these biomass types also contains 50 % carbon. Using pyrolysis, more than half of this carbon can be converted into long-term C-sinks instead of being lost as CO_2 in a relatively short period through decomposition or combustion, as is still common practice in most parts of the world. The use of biomass from companion plants and crop residues would become a key component of climate farming and critical to mitigating climate change. However, it is not recommended to completely remove all crop residues from the field and thus reduce the important ecological function of soil cover and organic matter recycling. Rather, the aim is to integrate biomass as an agricultural product into the field management plan while preserving its central ecological functions and replenishment of soil organic matter.

All biomass from annual cropping (i.e., the main crop, residues, companion plants) are considered to be C-neutral input material. The time of the CO_2-removal to be submitted to the Global C-Sink Registry is the year of harvest.

However, it must be ensured that the removal of harvest residues does not decrease soil organic carbon stocks (Whitman and Lehmann, 2015).

If biomass was deliberately grown to produce biochar, i.e., when it was the single or main product of this field, carbon expenditures for fertilization need to be accounted for. It must be included in the emission portfolio according to the formula 100 kg N = 1 t CO_2e (Zhang et al., 2013). If pesticides were used, a flat value of 94 kg CO_2e per hectare must be applied. All other cultivation-related related GHG emissions are included in the margin of safety (cf. chapter 6). If the main crop is used for food, animal feed, or biomaterials, no carbon expenditures for the cultivation must be accounted for the C-sink made from its residues.

Box 2: Calculations of the carbon footprint for biomass production

Example for the calculation of the carbon expenditure for the provision of annual biomass

- On one hectare, 10 t biomass were produced using 50 kg N and 25 kg (30.1 l) diesel, which are processed into 3 t biochar (dry matter = DM) with a carbon content of 75%.
- The emissions amount to (0.05 t N * 10 t CO_2eq * t^{-1} N / 3 t biochar =) 0.167 t CO_2e per ton of biochar for fertilization and (3.2 kg CO_2eq * 25 kg diesel / 3 t biochar =) 0.03 t CO_2e per t of biochar for the diesel used.
- The carbon expenditures for N-fertilization must be included into the emission portfolio. The emissions for the tractor diesel consumption are included in the security margin (c.f., Chapter 4.6) that is part of the emission portfolio.

5.3.2 Biomass from pluriannual and permanent cropping, including short rotation plantations

If pluriannual or permanent crops are harvested annually to provide feedstock for biochar production, there is no difference compared to the accounting for biomass from annual crops (i.e., N-fertilizers are accounted annually, the time of CO_2 removal is the year of harvest).

If the biomass harvest is only every second, fifth, or twentieth year, the carbon expenditures for fertilizers and fuels must be accounted for the entire growing period. The time of CO_2 removal must be tracked for every single year of growth and entered accordingly into the Global C-Sink Registry to correctly calculate the global cooling effect of the resulting biochar carbon sink.

The cultivation of mixed and perennial crops, agroforestry and meadows, which, in addition to biomass production, may promote the build-up of soil organic matter, is preferable to the cultivation of monocultures for biomass production. In principle, biomass from crop residues and companion plants should be recognized as a full-fledged tradable agricultural product ("carbon harvest"). The Global Tree C-Sink certification (cf. chap. 5.3.4) may support and facilitate this process. Food and feed production should be synergistic with the production of additional biomass. This would increase farm productivity, enhance biodiversity, soil organic matter, and enable the removal of CO_2 from the atmosphere.

5.3.3 Forest biomass

Unlike agricultural land, a forest is characterized by a high stock of carbon in the above-ground and below-ground biomass. Thus, the living biomass of a forest is a C-sink itself that must be maintained and must not be compromised when biomass is sourced for biochar production.

If the climate neutrality of a forest is not ensured by the official LULUCF reports of the respective country or by regional legislation, proof can also be provided by *Program for the Endorsement of Forest Certification* (PEFC) or *Forest Stewardship Council* (FSC) certifications and the Global Tree C-sink certification (cf. chap. 5.4). Alternatively, the carbon balance of the forest could be verified by ISO16064-accredited assessment of CO_2 fluxes for the last 20 years. Otherwise, the forest wood is not accepted as biomass input for producing EBC- or WBC-certified biochar. Accordingly, no C-sink of biochar produced from that biomass can be certified.

If, during forest establishment, denser stands are planted and gradually thinned out as they grow, the wood removed in this way is considered a C-neutral input because this measure accelerates the growth of the remaining trees and increases the total accumulation of carbon.

Forest wood damaged by wind, fire, drought, or pests is considered a C-neutral input provided that a climate-change-adapted reforestation plan is submitted to Carbon Standard for approval.

The CO_2e expenditure for forest maintenance and timber harvesting is included in the overall balance via the safety margin for scope 3 emissions (c.f., Chapter 4.6).

It is assumed that no fertilization occurs in the forest; otherwise, the CO_2e expenditure for N-fertilization would have to be deducted from the C-sink potential.

Background reflections about forest biomass

Under the present standard, an area is considered a forest when presenting a canopy density of at least 50%. The forest area units should not exceed 100 ha for efficient control of sustainable forest growth. The total biomass of an existing commercial forest of max. 100 ha must not decrease when the harvested biomass is used for the development of C-sinks. Therefore, the loss of wood must be balanced by the growth of forest wood in the referenced area unit. Furthermore, only a maximum of 80% of the harvested biomass must be removed from the forest to maintain the nutrient cycle and forest biodiversity. The degree of canopy density within the 100 ha must not fall below 50% because of the timber harvest.

If, for example, the annual regrowth of a 100 ha spruce forest amounts to 650 t (dry matter = DM), only a maximum of 650 t DM per year should be felled, of which a maximum of 520 t DM (80%) should be removed from the forest for wood processing and wood use.

However, there is currently no comprehensive forest assessment of area units of 100 ha or less in most countries of the world. The reference area units are considerably larger than 10,000 ha, and the forest regrowth is extrapolated using regional average values.

If, for example, in regional forests such as the Black Forest in Germany or the Arlberg in Austria, the total forest's standing biomass is higher than in the preceding years, the withdrawn biomass is regarded as climate neutral according to the European Regulation [2018/841] (EU-Parliament, 2018). Ecologically, it is at least questionable that, e.g., a densifying mountain forest is allowed to compensate for clear-cutting in a more accessible valley. However, until the expected reform of the EU LULUCF regulation (EU-Parliament, 2018), **all wood from forests whose regrowth demonstrably exceeds the removal, independent of its size and structure, is recognized as C-neutral input for the Global Biochar C-Sink certification. The time of the regrowth is set as time of removal.** If the regrowth of last year is harvested and pyrolyzed, the time of removal is set to the year of harvest. If the regrowth of several years is harvested, the time of removal must be distributed proportionally to the growth years and entered accordingly into the Global C-Sink Registry as described in the Global Tree C-Sink Standard.

We want to justify here the decision to adhere to European forest legislation and UNFCCC accounting rules despite their imperfections. While it is our intention to set all Global C-Sink Standards on scientifically reliable feet, starting with too idealistic restrictions may suffocate the development of the nascent pyrolysis and C-sink economy. If the EU nations promote bioenergy as climate-neutral and allow the regrowth of their forests to be counted as C-sinks in the National Declared Contributions (NDC), it is not up to the Global Biochar C-Sink to classify the same biomass as not climate-neutral. Nevertheless, it is our conviction that forests and forest wood should not be used for energy generation and when generating C-sinks, the process should be more efficient than simply pyrolyzing the extracted biomass for biochar only (Schmidt et al., 2018; Song et al., 2018). Instead, forest wood should first be used as a source for long-lived materials, whereas biochar can still be produced from residues, e.g., sawmills or debris.

5.3.4 Biomass from landscape conservation, agro-forestry, forest gardens, field margins, and urban areas

If trees or hedges on agricultural land are pruned or trimmed but not felled and thus grow back from their roots, the biomass is considered C-neutral. Biomass from nature conservation, landscape management, including disaster debris removal and roadside greenery, and urban areas, is also considered C-neutral.

Trees from forest gardens, orchard meadows, tree lines, and hedges for arable farming are often decades old. They have to be managed so that the amount of wood removed per unit area does not exceed the amount of the average annual regrowth. It should be monitored at the farm level (c.f., Chapter. 5.4).

If trees, hedges, reeds, and others have been newly planted on agricultural land for their ecosystem services and biomass production as co-benefit (e.g., landscape conservation, water management, buffer areas around ponds and streams, or agroforestry), the harvested biomass can be considered C-neutral at the time of harvest. However, it must be ensured that biomass production is maintained in the corresponding area either through new planting or rejuvenation.

For pruning and landscaping material, the time of CO_2 removal is assumed to be the year of cutting. Felled trees that are not used at least partly for material purposes but whose wood is entirely pyrolyzed, burnt or decomposed must be registered with their respective growth and thus CO_2 removal curve according to the Global Tree C-Sink Standard (link).

5.3.5 Wood processing residues and waste timber

Traceability of wood processing residues is often challenging, especially in larger sawmills, and it is, of course, better if the wood waste is used to build up C-sinks instead of being wasted. However, primary waste wood amounts to more than 50% of the harvested forest biomass and must, when used for C-sink and energy production, be considered a raw material and not a waste. Therefore, when using saw dust, bark, and lumber residues (primary wood waste) from a sawmill or directly from pre-processors in the forest or on the way to a sawmill, the wood must be certified as required under 5.3.3. The more primary waste wood gains prominence as a reliable economic asset, the more it influences secondary wood processors to encourage forestry managers to adopt climate-positive and sustainable management practices.

Secondary wood waste from recycled wood products (e.g., recycled construction and service wood such as lumber, pallets, furniture, etc.), often also referred to as waste timber, are considered C-neutral. The time of CO_2 removal is set to the year of pyrolysis.

5.3.6 Organic residues from the processing of food and other biomass

Pomace, nutshells, fruit stones, coffee grounds, and other organic residues from food processing are considered C-neutral input materials because the CO_2 footprint of food production is credited to the production of primary products (e.g., wine, olive, or any other kind of oil, fruit juice, coffee, etc.). Also, other industrial biomass processing residues such us paper sludge, bio fiber washing, fresh palm fruit bunches are considered C-neutral. The time of removal is set to the year of pyrolysis.

5.3.7 Municipal waste and municipal waste digestate

As municipal waste is pure waste, no emissions for its production must be accounted. Pyrolysis reduces emissions compared to incineration and also to landfill applications. Landfill-applied organic waste is, to a large extent, transformed into methane that is only partly recovered as landfill gas. Overall, the climate balance of soil or material applied biochar from municipal wastes is better than from landfills. Moreover, the contamination of soils at waste dumping sites is clearly reduced thanks to pyrolysis.

Municipal waste contains not only biogenic but also fossil carbon, such as plastic polymers, composites, textiles, etc. Only the proportion of biochar from the organic carbon fraction can be certified as C-sink and must be distinguished from fossil carbon.

To distinguish between organic and fossil carbon, the most reliable analytical method uses radiocarbon analysis (fossil carbon does not contain ^{14}C). As radiocarbon analysis is relatively expensive, and mixed waste is highly heterogeneous, biochar from mixed waste should be collected over a longer period (e.g., one month) before taking representative samples and determining the part of organically derived carbon in the well-mixed biochar made from mixed waste. The production, monitoring, homogenization, sampling, and analysis procedures are explained in detail in the *Municipal Waste Annex* to be published in June 2024. For organic waste, up to 5% of plastic contamination can be accepted without the need for further measures to subtract the fossil fraction. The fossil carbon content in the biochar is then covered by the safety margin.

5.3.8 Manure and agricultural digestate

Manure and manure digestate are secondary products of animal farming. The storage and application of animal manure and its digestate cause significant quantities of GHG emissions that can be reduced when manure or manure digestate is pyrolyzed (Rathnayake et al., 2023). The feed that animals transform into manure is made from biomass that has removed its carbon from the atmosphere. As animal growth and production is the operation's main objective, the feed production's carbon footprint is not accounted for in the manure. Manure is thus considered as climate-neutral feedstock. Only transport emissions must be accounted for.

Animal feed may contain biochar already registered as a diffuse carbon sink (c.f., chapter 12.2). However, as diffuse carbon sinks are limited to 1 t CO_2e, there is no significant risk of double accounting, given the security margin exceeding this amount by far. All larger amounts of feed-biochar must be tracked to the field and cannot be used as pyrolysis feedstock.

When biochar was mixed with manure before AD and/or pyrolysis, the biochar must not be accounted for as a C-sink a second time.

The time of CO_2 removal is set to the year of pyrolysis.

5.3.9 Biosolids and biosolid digestate

Regarding the C-sink accounting, biosolids and their digestate are similar to manure. As food is the main original input material for biosolid production and food is mostly made from annual crops, the feedstock is considered carbon neutral. Non-organic polymers used in wastewater treatment (flocculation additives) and some industrial waste liquids containing fossil carbon-derived molecules may enter the sludge. For biosolids from municipal wastewater treatment plants, these aspects are largely covered by the margin of safety. Industrial wastewater treatment plants must document the origin of the carbon. The eligibility of industrial wastewater sludge as feedstock for C-sink certification can only be decided individually during the technical audit.

Overall, biosolids are considered as a climate-neutral feedstock for biochar production, and the time of CO_2 removal is set to the year of pyrolysis.

5.3.10 Other biogenic residues

Carbon neutrality can generally be assumed for all other biomass on the EBC and WBC positive list. However, depending on the feedstock used, this must be considered individually during the certification procedure. The time of removal would generally be the year of pyrolysis, though this is verified during the certification procedure.

New feedstock categories will be added for C-sink certification as required or requested.

5.4 Monitoring Perennial Biomass Production Systems

Until general monitoring of growth, storage, and use of biomass carbon is established on a broad scale, this standard relies on self-declaration by biomass producers regarding carbon neutrality, with the exception of forest wood (chap. 5.3.3), unless there is an urgent suspicion of carbon overexploitation. We encourage forestry biomass producers to become certified under the Global Tree C-Sink Standard, which generates remuneration opportunities for C storage in living biomass and guarantees the carbon neutrality of the biomass produced.

6. Storage of biomass feedstock

If moist biomasses are stored for too long in too large piles, uncontrolled self-heating occurs. In this process, the biomass is microbially degraded, similar to composting, which results in the loss of carbon as CO_2. Depending on the biomass and storage conditions, emissions of CH_4 and N_2O may also occur.

Biomass power plants often use the self-heating of wood chips to dry them. A review of 14 scientific studies on the decomposition of woodchips during storage has shown that depending on storage conditions, wood species, and wood moisture, between 0.6 to 4.3% of biomass carbon is degraded per month (Whittaker et al., 2016). For wood chip piles larger than 1 m^3, biodegradation of the wood leads to oxygen consumption inside the pile, eventually leading to anaerobic degradation and methane emissions. How high the actual methane emissions are depends on factors such as temperature, humidity, pile volume, type and age of the wood, and its C to N ratio. Measurements have shown that up to 20% of the gaseous carbon produced during storage inside the pile is transformed into methane (Pier and Kelly, 1997). However, Jaeckel et al. (2005) found that methanotrophic microorganisms in the heap's better-aerated near-surface layers degrade between 46% and 98% of the methane produced in the core before it can escape as an emission to the atmosphere. In summary, scientific studies of actual methane emissions from wood chip storage are sparsely available and often incomplete, so generalizations regarding storage emissions must be made cautiously (Ferrero et al., 2011).

However, storage emissions can be effectively avoided. Although this involves additional effort and possibly also costs, the avoidance of emission losses has the beneficial side effect of losing less of the biomass's energy content. The following measures are generally recommended for biomass storage and, if implemented correctly, would avoid any storage emissions to be added to the emission portfolio of the batch and production unit.

- Wood and other biomass should be chipped only a few days and at a maximum of four weeks before pyrolysis. Log storage is considered unproblematic regarding methane emissions; coarse wood (thinner logs, branches, cuttings, etc.) should be stored as airy as possible and not mixed with green waste.
- If just-in-time chipping is not possible, the wood chips or biomass should be dried as soon as possible, e.g., with the excess heat from pyrolysis and stored dry with a maximum of 20% residual moisture. If the biomass is sufficiently dry, biodegradation does not take place or is slowed down considerably.
- Pelleting of biomasses and dry storage of pellets avoids rapid biomass decomposition.

- Alternatively, the wood chips or the biomasses can be stored in small, well-ventilated containers such as lattice boxes (max. 2 m^3). Due to sufficient ventilation, anaerobic degradation and, thus, methane emissions can be prevented.
- Other practical methods, such as sieving the fine particles, will certainly also prove efficient.

If none of these recommendations can be implemented, it must be assumed that substantial methane emissions occur, that they are not covered by the margin of safety, and therefore must be calculated as follows:

For the storage of moist wood chips and sawdust, we assume that 2.5% of the biomass carbon is degraded per month, of which 20% is transformed into methane. 75% of this methane gets microbially degraded in the storage pile and is not released into the atmosphere. We thus calculate for moist storage of woody biomass that (2.5% * 20% * 25%=) 0.13% of the biomass C is emitted as methane-C per month.

For storing moist, non-woody biomasses such as straw, crop residues, pomace, etc., but also for wood waste with a high content of green plant material, data on methane emissions during uncontrolled composting are applied. According to the IPCC methodology, 10 g of CH_4 emissions are generated per kilogram of biomass (DM) during complete composting (Pipatti et al., 2006). This corresponds to about 1.5% of the carbon contained in the biomass. Assuming that a conventional windrow composting process takes an average of 6 months (Pier and Kelly, 1997), the composting storage results in an emission rate for methane-C of (1.5% / 6 =) 0.25% per month.

For the storage of wood chips and sawdust with more than 20% moisture for more than one month, CH_4 emissions of 0.13% of the original C-content are imputed per month. For all other biomasses with more than 20% moisture and storage time of more than one month, 0.25% of the original biomass C-content are accounted for CH_4 emissions per month. One kilogram of methane-C equals (1 kg / 12.011 kg $kmol^{-1}$ * 16.04 kg $kmol^{-1}$ =) 1.335 kg methane. Methane emissions that may already occur during the first month of biomass storage are sufficiently covered by the general margin of safety (c.f., Chap. 4.6).

$$\boxed{CH_4\_wood\_storage = \text{Mass of feedstock (DM)} * C\_content \text{ of feedstock} * (\#\text{months of storage} - 1 \text{ month}) * 0.13\,\% * 16 \text{ kg mol}^{-1} / 12 \text{ kg mol}^{-1}}$$

Equation 9: Calculation of CH_4 emissions during the storage of moist woody biomass (> 25% water content) if storage exceeds 1 month.

CH_4_non-wood_storage =	Mass of feedstock (DM) * C_content of feedstock * (#months of storage – 1 month) * 0.25 % * 16 kg mol^{-1} / 12 kg mol^{-1}

Equation 10: Calculation of CH_4 emissions during the storage of moist non-woody biomass (> 25% water content) if storage exceeds 1 month.

For example, if wood chips that are used as feedstock for pyrolysis have a water content above 25% and are stored in a large pile for an average of two and a half months prior to pyrolytic processing, a C loss of ((2.5-1) months * 0.13% =) 0.195% of the total C of the pyrolyzed biomass is assumed. For an annual processing of 4000t (DM) of wood chips with a C-content of 48%, the methane emissions to be estimated for 2.5-month storage without preceded drying would correspond to (4000 t * 48% * 0.195% =) 3.74 t CH_4-C, which equals (3.75 t CH_4-C * 16 kg mol^{-1} / 12 kg mol^{-1} =) 5.0 t CH_4. The calculation is carried out using the values given above and rounded to 0.1 t.

If 4000 t (DM) of grape marc with a C-content of 48% were processed, the methane emissions to be estimated for 2.5 months of storage without prior drying would correspond to (4000 t * 48% C * 0.25% CH_4 * 1.5 months =) 7.2 t CH_4-C and (7.2 t CH_4-C * 16 kg mol^{-1} / 12 kg mol^{-1} =) 9.6 t CH_4.

For the storage period, not only the storage on the premises of the pyrolysis plant is considered, but the entire storage period of the biomass, whether at the harvest site or the site of any biomass processor or trader. For example, for the processing of pomace, the storage start time is considered to be the emptying of the wine press. For wood chips, the moment of chipping applies. During control, the logistics of biomass processing and its transport must be fully traceable.

During the on-site control visit, the core temperature of the biomass has to be measured for all sites where biomass is stored for more than one month. In case of temperatures of more than 5°C above ambient temperature, which cannot be plausibly explained, e.g., by diurnal fluctuations, the above formula is applied to calculate the accruing GHG emissions. The EBC and WBC certification monitoring may also specify an in-house temperature monitoring of the stored biomasses (e.g., daily measurement of the core temperature of one or more biomass storage facilities).

7. The Biochar Production Facility

7.1 Energy and Fuel Consumption for Transportation, Preparation of the biomass, the Pyrolysis Process and Post-Treatment of the Biochar

Biochar production usually produces an energy surplus. Still, some external energy is usually required to operate pyrolysis facilities. For example, electrical power is necessary for control systems as well as for conveying biomass and biochar. Depending on the type of pyrolyzer, (fossil) fuel gas or electricity is also required for preheating the reactors and/or burning chambers. Certain plant types produce pyrolysis oil and pyrolysis gas in addition to biochar but use electrical energy to heat the biomass. Consequently, to calculate the pyrolysis plant's carbon footprint, each plant must be equipped with meters for electricity and if applicable for natural gas and fuel.

The energy and fuel-related carbon expenditure for the entire process chain, from the provision of biomass to the packaging of the biochar, is calculated in CO_2e and included in the emission portfolio of the batch and the respective production unit (i.e., the pyrolysis unit that is used to produce the batch). This concerns in particular:

(1) Transportation of the biomass to the pyrolysis plant.

(2) Chipping, homogenization, pelletizing, and drying of the biomass.

(3) GHG emissions of the pyrolysis plant (i.e., electricity, heat, and fuel consumption).

(4) Post-pyrolysis treatment of the biochar (e.g., drying, mixing, liquid loading, grinding, pelletizing, etc.) and other products (e.g., purification of H_2, CO_2, and/or other gases, refining of pyrolysis oil, etc.).

(5) Transport of the biochar to the collection depot (factory gate).

Emissions due to post-pyrolytic treatment of non-biochar products need to be considered to allow accurate pro-rata calculation of carbon expenditures, even though these products are not certified under the present standard. Accounting for electricity and fuel consumption for all these individual steps is necessary for the certification. The conversion of electricity consumption into CO_2e is based on the specific information provided by the contractual energy provider or the average CO_2e value of the regional electricity mix used. If renewable energy is used, the CO_2e footprint can be close to zero. However, some greenhouse gas emissions occur also for solar, wind, biomass, and hydropower and must thus be declared and included in the emission portfolio. In the case that the energy provider cannot provide a reliable footprint assessment, average literature values will be used by the certifier (IPCC, 2022; Kadiyala et al., 2016; Nugent and Sovacool, 2014). If the pyrolysis plant itself generates at least as much electricity on an annual average as is consumed in the production facility and the entire production facility offsets its emission with biochar C-sinks, a CO_2e of zero may be assumed for electricity consumption.

The amount of fuel used to heat the pyrolysis reactors are to be reported per batch (invoices for purchasing fossil fuels) and are converted to CO_2e by fuel type (usually 65 t CO_2e per TJ (Juhrich, 2016))

For the consumption of diesel or benzine fuel for transportation, chipping, drying, etc., the conversion factor of 2.7 kg CO_2eq per liter of diesel fuel is applied (Juhrich, 2016).

7.2 Energy Surpluses

If the energy balance of a biochar production facility is positive, i.e., measurably more electrical and/or thermal energy is produced than consumed, the positive energy balance can be credited as an emissions reduction with the appropriate agencies, but not within the Global C-Sink. The positive energy balance can neither increase the C-sink nor offset emissions from biomass supply.

If all GHG emissions from biochar production are offset and compensated for, including the CO2 footprint of the production of the other pyrolysis products (e.g., electricity, hydrogen, pyrolysis oil, etc.), those secondary pyrolysis products can be certified as carbon neutral under the present standard. However, if the pro rata approach (chapter 4.5) is employed, carbon neutrality of the non-biochar pyrolysis products cannot be certified.

7.3 Methane Emissions during the Pyrolysis Process

During pyrolysis, the pyrolysis gases are usually oxidized in a suitably designed combustion chamber. Usually, the gaseous combustion products pass a filtration step and are then emitted mostly as CO_2. If the pyrolysis process is well-adjusted and the combustion chamber correctly designed, non-CO_2 GHGs and other pollutants can be kept at very low levels in the exhaust. However, CH_4, NOx, CO, and particulate matter (PM) are, as in all combustion processes, never completely absent and must be controlled. Concerning the net climate impact, methane emission is particularly important to measure. CO, NOx, SOx, and PM are also harmful to the environment, but according to the IPCC, they do not have a clear greenhouse gas effect (IPCC, 2013) and are therefore not accounted for the emission portfolio, while CH_4 is included.

As detailed in Chapter 4.3, for the conversion of the global warming effect of methane, the GWP100 is accounted for with a factor of 25, but it must be compensated within the first 20 years after the emission. Due to the high GWP100 of methane and the short compensation period, even very small methane emissions during the pyrolysis process have a major impact on the carbon footprint of biochar production. In pyrolysis plants without controlled combustion of the pyrolysis gases (e.g., Kon-Tiki or traditional charcoal kilns), the global warming effect of methane emissions can even exceed the climate-positive effect of biochar for the first 20 years.

Measuring methane emissions below 5 ppm is technically complex. Continuous measurement over an entire production year is not possible with currently available technology. Therefore, either at least two CH_4-emission tests per pyrolysis unit with the same feedstock representing the typical operation of the unit are required, or the pyrolysis unit must have a type certification according to EBC or WBC.

For CH_4 emission tests, a detailed measurement strategy with precise details of the measurement technology, measurement intervals, and measurement accuracy must be submitted in advance to Carbon Standards for review. Once the procedures are accepted, the methane emissions factor of the pyrolysis unit is calculated as the mean of the two measurements plus one standard deviation as the margin of security.

Box 4: Calculation of pyrolytic carbon expenditures.

Example for the calculation of the carbon expenditure of pyrolysis (continued)

- With an annual production of 500 t of biochar (DM) having a carbon content of 75.0%, **50,000 kWh of electricity** is used to operate the pyrolysis plant (measured with a dedicated electricity meter at the pyrolysis unit). The local electricity mix emits 450 g CO_2eq per kWh. Thus, the carbon expenditure for electricity consumption is 50,000 kWh * 0.45 kg CO_2e $(kWh)^{-1}$ = 22.5 t CO_2e per year.
- Emission measurement of pyrolysis exhaust gases resulted in a **methane content of 10 ppm** (6.6 mg CH_4 m^{-3}) in the exhaust gas for 7000 operating hours per year at a gas volume flow of 1500 m^3 per hour. This results in methane emissions per annual batch of (1500 m^3/h * 7000 h * 6,6 mg CH_4 m^{-3} =) 69,3 kg CH_4.
- To preheat the pyrolysis reactors, **5 t of liquefied petroleum gas (LPG;** 3 t CO_2e t^{-1}) are consumed per year. This results in a carbon expenditure of 15 t CO_2e per year.
- The above results in an emission portfolio entry of 22.5 t CO_2e electricity + 15 t CO_2e LPG + 69.3 kg CH_4 pyrolysis emissions per batch.

For the EBC and WBC pyrolysis type certification, at least three installations of the same type from the same manufacturer must be in commercial operation at different sites. For each of these three plants, at least two independent, state-accredited emission measurements including CH_4 or C_xH_x must be available. From these measurements, a statistical mean value with standard deviation is calculated. The average methane emission of this type of plant is then set to be the mean value plus one standard deviation. If an emission measurement for methane or C_xH_x is below the measuring accuracy of the instruments, the limit of quantification (LOQ) is used. The assessed methane emissions are thus higher than the calculated average and provide a sufficiently high safety margin to cover any potential emission peaks, e.g., during start-up and shutdown of operation. The measured values for methane emissions are given in ppm of the flue gas (i.e., combusted pyrolysis gas) and converted into g CH_4 per ton of biochar via the flue gas flow per mass unit of biomass input or biochar output. This resulting value is then registered as the methane emission factor for all pyrolysis units of the same type, utilizing a consistent standard feedstock.

8. Carbon and Energy Use Efficiency

Biomass is a valuable resource that must be utilized responsibly. In the Global Biochar C-Sink, this is assessed using the carbon and energy use efficiency. While there is minimum limit value for the energy use efficiency that all certified pyrolysis units must comply with, the carbon use efficiency is only indicative value registered in the Global Biochar Tool.

8.1 Carbon Efficiency of Pyrolysis Operations

Carbon efficiency refers to the ratio of carbon transformed into a storable form (i.e., amount of carbon in a batch of biochar) to the input of carbon (i.e., amount of carbon in the biomass used to produce the biochar). To reach at least 15 Gt CO_2e of global long-term carbon sink establishment per year, the carbon efficiency of biomass-based negative emission technologies must be increased. Plants are highly efficient in concentrating atmospheric carbon into dense carbon molecules. The removed carbon is preserved and acts as a C-sink for as long as a plant lives. Every transformation step of biomass leads to carbon losses, i.e., emissions of (biogenic) CO_2. The harvest induces the decomposition of roots and harvest residues, GHG emissions occur during the manufacturing of food, feed, and biomaterials, and, finally, waste management, where composting, anaerobic digestion, waste incineration, or landfills also result in biomass decomposition in one way or the other. Typically, the carbon balance is zero as all carbon that is emitted from biomass use was initially removed by plants from the atmosphere. However, considering that plants provide a natural carbon service (removing carbon from the atmosphere), humanity could use this carbon pump to tweak the biomass-use systems to remove as much carbon as possible from the atmosphere. The area on earth where plants can grow is limited. Even the ocean area that we can use wisely to grow brown algae or other biomasses is limited. Using finite resources makes mankind responsible for using them wisely and efficiently.

Compared to composting, mulching, incineration, or waste dumping, pyrolysis significantly increases carbon efficiency. However, when using primary biomass such as wood, pyrolysis is less C-efficient than its material use in buildings, infrastructure, furniture, composites, or textiles. Also, storage of compressed, dry biomass in controlled geological storage, such as salt domes or oil wells, could be more C-efficient, preserving close to 100 % of the biomass carbon for extended, though not geological, periods of time.

Depending on production parameters and feedstock, pyrolysis preserves about 30 to 60% of the biomass carbon in the biochar. When pyrolysis oil can also be sequestered, C-efficiencies of around 80% can be reached (Schmidt et al., 2018); with CO_2-CCS of the combusted pyrolysis gas, even higher C-efficiencies are possible.

If, in a pyrolysis process, only the biochar-C is preserved, the carbon efficiency is too low to aspire for large-scale negative emissions (Werner et al., 2018). For developing pyrolysis technology in the next decade, this might still be acceptable, but as long as biomass carbon is the principal source for carbon sinks, no carbon must be squandered.

The carbon efficiency of a pyrolysis facility is a measure of the part of biomass-carbon that is preserved by a technical transformation process as a potential C-sink. It is assessed at the factory gate of the pyrolysis facility independent of the further storage and use of the carbon products.

At the current stage of pyrolysis and other CDR technology development, imposing specific thresholds for C-sink efficiency would be overly restrictive. This is further emphasized by the increasing role that pyrolysis energy plays in providing process heat for industry and district heating while reducing reliance on fossil fuels. However, it is essential to have a clear objective of transforming a growing proportion of biomass carbon into carbon sinks. This also may comprise temporary C-sinks in rather short-lived products, e.g., from pyrolysis oil; and replacing crude oil products in everyday lives is also part of climate change mitigation. To achieve this, C-sink efficiency must be evaluated and used as a benchmark for progress. The carbon efficiency is not disclosed on the carbon sink certificate.

The C-sink efficiency of a biochar batch is calculated by dividing the total sequestrable pyrogenic carbon (biochar, pyrolysis oil, purified CO_2, and derived products) by the total biomass carbon used as feedstock for the entire batch. Only biochar, pyrolysis oil, and CO_2 that is or will be registered as C-sink are included. Biochar that is or will be sold as charcoal for barbecue, for the metal industry or other applications where the carbon is oxidized and reemitted to the atmosphere must not be included. The value is given as a percentage of initial biomass carbon.

To estimate the carbon efficiency, the pyrolysis company is requested to declare for what markets their products are intended. The carbon efficiency is calculated at the factory gate.

8.2 Energy Use Efficiency of Pyrolysis

The limited availability of biomass necessitates its efficient utilization. To address this, the standard incorporates two complementary strategies. While the C-sink efficiency discussed in the previous chapter is introduced for transparency purposes (customer information), there is a threshold value for energy efficiency that must be met in the production of each biochar batch for Global Biochar C-Sink certification.

The energy use efficiency provides the rate of how much of the energy contained in the biomass feedstock was transformed into usable energy and other beneficial products with a market value. The energy use efficiency does not express how beneficial and meaningful the different products are but provides a measure of how energy efficient the biomass carbon is used within the process. This may include the following uses on top of biochar production:

- Thermal and electric energy production to replace fossil fuel-derived energy, it avoids GHG emissions. Thermal energy can be used, e.g., in district heating or industrial processes.
- Thermal energy from combusting pyrolysis gas can be used to dry biomass feedstock for the pyrolysis plant itself, which would be accepted as a meaningful energy use.
- Charcoal is used for metallurgy to replace fossil carbon and thus reduces GHG indirectly. If it is used for barbecue or for other applications where it is oxidized and the carbon is reemitted as GHG to the atmosphere, it can still be seen as financially reasonable and climate-neutral carbon use.
- Pyrolysis oil can be used for the chemical industry or as fuel. Its carbon will, thus, be oxidized and returned as CO_2 back to the atmosphere within a relatively short time. Still, it will not cause more emissions than the biomass had removed from the atmosphere during its growth.
- Pyrolysis gas contains hydrogen and methane, that can be extracted.
- CO_2 can be extracted in pure form from the combustion of pyrolysis gas and pyrolysis oil for further use (i.e., carbon capture and use – CCU) or storage.

Therefore, if the non-biochar fraction of the pyrolysis products is used for energy production or as raw material for chemical or other industries, the biomass-carbon is considered as having been used meaningfully.

´

The energy use efficiency is calculated as follows (in kWh):

- The energy content of the feedstock is quantified as the lower heating value (LHV). If the feedstock is clearly defined, the LHV can be taken from the literature. Mixed and not clearly defined biomass and feedstock known for its high energy content variability (e.g., sieving residues from composting) must be analyzed in a laboratory endorsed by Carbon Standards. A list of endorsed laboratories is available on the Carbon Standard webpage.

- The energy content of the biomass processed for production of the batch is calculated by multiplying dry mass and lower heating value providing the parameter $E_{feedstock}$.
- The energy needed to produce the batch is quantified according to Chapter 4.1 ($E_{Expenditures}$)
- The energy content of the solid pyrolysis products (biochar, charcoal) is quantified as the LHV and multiplied by the total dry mass of biochar produced (E_{solid}). The LHV of the biochar and charcoal must be analyzed from the EBC/WBC certification sample.
- If pyro-oil is separated for storage or use, its LHV is quantified and multiplied by the total amount of pyro-oil co-produced with the biochar batch ($E_{pyrooil}$). The LHV of the pyro-oil must be analyzed in a laboratory endorsed by Carbon Standards. If different fractions of the pyro-oil are produced, the LHV of each fraction has to be analyzed.
- If thermal energy is used for drying biomass, 810 kWh per ton of evaporated water (2.44 kJ per gram of water + 20% margin) can be accounted for. The amount of evaporated water can be calculated based on the mass and moisture content of the biomass received and the achieved moisture content (e.g., 15% as required by most pyrolysis units) (E_{drying}).
- If thermal energy is supplied to district heating or industry, the actual amount used must be metered ($E_{thermal}$)
- If the pyrolysis gas is used to produce hydrogen, methanol, or other marketable fuels or chemicals, their energy content is to be provided as $E_{fuel\_products}$. If CO_2 is separated after oxidation of the pyro-gas, this can be accounted for with a maximum of 1000 kWh t^{-1} CO_2 which provides the parameter (E_{CO2pur}).

The total amount of used electrical and thermic energy, and the heating value of the marketed pyrolysis products is divided by the sum of the energy content of the biomass feedstock and the external energy used to produce the entire batch. The value is given as a percentage.

$$E_{eff} = \frac{E_{solid} + E_{pyrooil} + E_{fuelproducts} + E_{thermal} + E_{drying} + E_{electric} + E_{co2pur}}{E_{feedstock} + E_{expenditures}}$$

Equation 11: Calculation of the energy efficiency (E_{eff}) using the energy content of the biochar (E_{solid}), the pyrolysis oil ($E_{pyrooil}$), the fuels produced by the pyrolysis proces ($E_{fuelproducts}$), the produced thermal energy ($E_{thermal}$), the energy used for feedstock drying (E_{drying}), the electricity produced ($E_{electric}$), the energy value of separated CO2 from the flue gas (E_{CO2pur}), the higher heating value of the feedstock ($E_{feedstock}$), and the energy expenditures for the entire pyrolysis facility ($E_{expenditures}$).

In most cases of today's pyrolysis facilities, the calculation looks a lot simpler:

$$E_{eff} = \frac{E_{solid} + E_{thermal} + E_{drying} + E_{electric}}{E_{feedstock} + E_{expenditures}}$$

Equation 12: Simplified calculation of the energy efficiency to be used for most biochar production facilities.

For every batch of a certified pyrolysis unit, at least 60% of the sum of the energy contained in the biomass and all energy expenditures of the process must be used.

Box 5: Exemplary calculation of the energy use efficiency

Example for the calculation of the energy use efficiency of a wood gasification plant for one annual batch:

- **Input (feedstock):** Annual feedstock 4000 t of wood with a dry matter content of 65%, a carbon content of 48%, and a lower heating value (LHV) of 4 kWh/kg (@ 80% DM) representing (3250 t (@80% DM) * 4 MWh/t =) 13,000 MWh.
- **External energy input (consumption)**: Electricity consumption of the facility during the batch 375 MWh, 3 t LPG starter gas with 13 kWh/kg, 13 t diesel for feedstock preparation and transport with 11.8 kWh/kg representing (375 MWh + 3 t * 13 MWh/t + 13 t * 11.8 MWh/t =) 567.4 MWh
- **Output:** The unit produces per year 260 t biochar with LHV of 7.9 kWh/kg representing 2054 MWh, 5000 MWh of used heat, 2340 MWh electricity, and uses 800 MWh of the heat for feedstock drying representing (2054 MWh biochar + 5000 MWh used heat + 800 MWh drying + 2340 MWh electric =) 10,194 MWh.
- **Energy efficiency of batch**: 10,194 MWh / (13,000 MWh + 567.4 MWh) = 75.1%.

The 75,1 % energy efficiency is higher than the threshold of 60%, the facility can be certified.

9. Labeling of Biochar Properties for C-Sink Certification

9.1 EBC/WBC Labeling

If a pyrolysis plant is certified according to the EBC or WBC standard, the following information must be provided on each packaging and on delivery bills:

1. EBC or WBC certification is a prerequisite to Global Biochar C-Sink certification, so the QR code of the respective EBC or WBC batch must be printed on the delivery note and attached to each packaging unit. This QR code refers to the Global Biochar Tool, which documents the corresponding biochar batch's analytical data and production conditions.
2. Since the C-sink potential refers to water-free biochar, the dry weight of the biochar must be indicated for each packaging unit. The dry weight is the mass of the dry substance and is stated in tons or kilograms, rounded to 1% of the total weight. If the analysis of the dry weight results, for example, in 455.57 kg of 1000 kg fresh weight, the dry weight is rounded to 1% of the 1000 kg, i.e. to 10 kg. The dry weight would, therefore, be 460 kg.

The specifications for the labeling of products can be found in the Design Manual of Carbon Standards.

This QR code must also serve the dMRV system to track the biochar from the factory gate to its final use. The EBC/WBC and the Global Biochar C-Sink use the same QR code generated by the Global Biochar Tool. Alternatively, the dMRV provider may use its own QR code but must link then from the QR code landing page to the batch information provided by the Global Biochar Tool.

9.2 Dry Matter Content of Biochar: on-site measurement

The size of a C-sink is defined by its mass and carbon content. Mass here refers to dry mass, and it is a true challenge to measure it regularly onsite. The dry matter content of biochar cannot be measured directly but must be calculated from the fresh weight and the measured water content.

The water content of biochar can be subject to considerable fluctuations at the time of sale or even directly at the discharge of the pyrolysis plant. Reasons for this can be a fluctuating intensity of the quenching at the discharge, the absorption of air humidity, or air drying.

Therefore, it is impossible to determine the C-sink using the dry matter content analyzed once per batch during the annual EBC/WBC-accredited laboratory analysis.

Also, the bulk density, which is needed to calculate mass from a given volume, can vary significantly within a batch, mainly due to variations in the particle size distribution of the pyrolyzed biomasses and abrasion during the transfer and transport of the biochar. Thus, a volumetric determination of the dry weight of the produced biochar is also not appropriate.

Therefore, the reliable and regular determination of the dry matter (DM) content is a prerequisite to indicate the dry weight and, thus, the C-sink potential of a packaging unit of biochar. This is a considerable effort for biochar producers, which is, however, unavoidable to maintain verifiability and, thus, confidence in the Global Biochar C-Sink Standard.

For each sub-quantity of max. 10 m^3 of biochar, at least 20 individual sub-samples must be taken using a sampling stick. Combining a minimum of 20 sub-samples must yield at least a total sample volume of 10 liters of biochar. The individual sub-samples can be taken either from a collected pile or container of max. 10 m^3 of biochar or from each of several big bags presenting a total amount of max. 10 m^3. The combined sample is weighed using a skale with a precision of at least 1 gram. The biochar is then dried at 110 °C for at least 16 hours and weighed again. Weighing must be done immediately (max. 1 minute) after removal from the 110 °C drying oven. Otherwise, moisture may condense on the biochar and falsify the result. This method simplifies the usual DIN 51718 and ISO 589, which may also be followed.

$$\text{DM [\%]} = \frac{net\ weight\ after\ drying}{net\ weight\ before\ drying}$$

Equation 13: The dry matter content (DM) is calculated by dividing the net weight after drying by the net weight before drying.

If, for example, big bags (i.e., super sacks) of 1.3 m^3 are used for storing biochar, a maximum of seven big bags may be combined for one representative sample. At least three sub-samples from each of the seven big bags must be taken with a standard sampling drill stick. All 7x3 subsamples are then combined and weighed as described above, dried, and weighed again. If the 10-liter sample weighs 3.057 kg before drying and 2.139 kg after drying, the dry matter content is (2.139 kg / 3.057 kg =) 69.970%. This value is rounded to full percentages for further calculations (here: 70%). The DM content determined in this way must then be multiplied by each big bag's individually determined (fresh) weight (see example in Table 1). This results in each big bag's respective dry weight, with which each big bag must then be labeled. For instance, if a big bag weighs 200 kg (fresh weight, net weight) and has a determined DM content of 70%, the dry weight is (200 kg * 70% =) 140 kg. It is rounded to whole kilograms.

For the described DM determination via drying of a representative sample, a relatively large drying oven and correspondingly accurate scales are required. Still, the effort for 10 m^3 or seven big bags is manageable. Weighing of the big bags should be done on the same day as the sampling.

Deviations from the procedure described here can be regulated during the technical EBC/WBC audit, if, e.g., the dry weight is determined via a deviating method. If a producer can prove that the dry matter content does not change by more than ±2% over extended periods and production quantities, larger intervals between measurements can be authorized. If biochar with a particle size of more than 30 mm is produced, the subsamples' volume must be increased accordingly.

Table 2: Example of calculation of dry weight of a series of seven big bags.

Serial number of big bag	Volume	Weighed weight	Dry matter content	Dry weight
Big bag 2020-490	1,3 m3	195 kg	70%	137 kg
Big bag 2020-491		200 kg		140 kg
Big bag 2020-492		200 kg		140 kg
Big bag 2020-493		210 kg		147 kg
Big bag 2020-494		195 kg		137 kg
Big bag 2020-495		200 kg		140 kg
Big bag 2020-496		200 kg		140 kg

10. Post-Production dMRV: transport, processing, and tracking of biochar

10.1 Biochar dMRV System

From the moment a packaging unit filled with biochar (e.g., a big bag = super sack or a container) leaves the EBC or WBC certified factory site, many things can happen that may reduce or eliminate the potential C-sink of the traded biochar. The biochar may be burned, for example, as charcoal, processed into activated carbon, or used as a reducing agent in steel production, a significant amount of carbon would be lost to the atmosphere. Also, fossil fuels may be burned for the transport of biochar, and/or electricity may be consumed during pelleting or any other post-pyrolytic treatment. All resulting emissions must be compensated for.

Thus, biochar must be tracked by a digital Monitoring, Reporting and Verification (dMRV) system. The dMRV systems track the transport of each packaging unit from the factory gate to the C-sink and assess the related emissions. These emission data are either added to the emission portfolio of the respective biochar batch and must be offset by the biochar producer or become part of the emission portfolio of the processor, trader, or C-sink owner who are then responsible for offsetting them.

The dMRV system is usually provided by an external MRV system provider. External MRV systems and tools must be endorsed by Carbon Standards annually.

For as long as the packaging unit is stored closed on the factory premises and is protected from wind, rain, gases, and unauthorized diminution of stock, the C-sink potential remains unchanged. If the biochar is stored for more than one year, it can be registered as a temporary C-sink for the time of storage (cf., Chapter 12.5).

Once the biochar leaves the producers' premises, further emissions must be tracked. For this purpose, every packaging unit containing more than 1 t CO_2e of biochar must be labeled with a scannable identification code (i.e., usually a QR code, cf. Carbon Standards design manual). The label accompanies the product on all transports and must provide the following information:

- Batch ID
- Link the EBC/WBC biochar analyses
- Date of production
- Year of CO_2 removal
- Owner of C-sink material
- Point of departure (GPS) for biochar transports

- Amount of biochar in dry matter tons.
- Biochar C-content
- Link to the emission portfolio

It is not necessary that all these information are accessible to the buyer of the biochar or biochar product, but the dMRV provider must make it accessible to the certifier and to Carbon Standards.

Packaging units smaller than 1 m^3 biochar may be grouped into a larger unit (e.g., 20 bags of 50 l packed on a palette) where the larger unit is labeled with the scannable ID / QR code, given that all smaller units have the same destination.

The tracking tool accompanies the cargo on its way. At the destination where the packaging unit is discharged, the packaging unit must be scanned and the new location registered to calculate the traveling distance and the CO_2e footprint of the transportation means. If the product changes ownership, it must be technically transferred to the new product owner. The new product owner confirms the transfer request online, and with this step, the seller and the buyer confirm the transfer of ownership.

When the biochar or biochar product is applied to soil, the landowner or tenant must agree explicitly to provide the soil plot as the entry point of the biochar carbon to geological storage (i.e., to the lithosphere and thus the slow carbon cycle). The landowner or tenant agreement can, e.g., be part of the general terms and conditions or the invoice for the purchased biochar product. The landowner does not necessarily become the C-sink owner as the biochar carbon will enter the commons (migrate from private property) once applied to soil.

When substantial amounts of biochar are integrated into materials to become a temporary C-sink (e.g., a building made of biochar-containing concrete), the material owner (e.g., the building owner) must be registered as C-sink owner and becomes the responsible entity for the maintenance of the temporary C-sink.

To ensure that the MRV system works without leakage and that only high-quality, verifiable C-sinks are sold as a climate service, Carbon Standards endorses the external MRV software tools. Endorsed dMRV providers may use their own Carbon Standard endorsed MRV Tool to track biochar along the supply chain on behalf of the C-sink owner.

10.2 Biochar Processor

If the biochar is delivered to a processing company that makes new biochar-based products from the biochar, the receiving company must be EBC or WBC certified as a processing company and/or trader. All processing steps must be recorded with their CO_2e footprint. The annual EBC/WBC audit controls that the processing company supplies the data into the MRV system regularly for each batch that was handled. Once the products are repackaged, they must be registered as new product and C-sink unit providing the following information:

- Product processor
- Biochar production batch ID and/or QR code to access EBC/WBC biochar analysis.
- Date of biochar production
- Year of CO_2 removal
- Owner of C-sink material
- Point of new departure (GPS)
- Biochar C-content of product
- C-sink matrix, if mixed to one
- Emission that occurred during processing
- Link to the emission portfolio of the C-sink unit and/or company

If the biochar was mixed into a C-sink matrix and the packing unit contained less than 1 t CO_2e biochar carbon, it can be registered as a diffuse C-sink. In the latter case, the collection of the above information is not required. However, several packaging units with less than 1 t CO2e may be grouped under one new C-sink ID and delivered to and applied at one C-sink location to be registered as described above.

10.3 Biochar Trader

All biochar traders that trade C-sink units containing > 1 t CO_2e must be registered at Carbon Standards and receive their company ID and access to the MRV tool for trader. Biochar traders that only sell diffuse C-sinks do not need to register.

Biochar traders who do not repack the packaging units only need to scan the ID and add the storage location and date of arrival to the registered data. Once it leaves the premises again, the date of departure must be registered.

If the biochar is repackaged, the new packaging units must be registered and linked to the former registered packaging unit and all material and transportation data.

If the new packaging units contain less biochar carbon than 1 t CO_2e, they cannot be registered as C-sink units except when grouped to a new unit (e.g., a palette) of > 1 t CO_2e.

If the biochar is mixed into a C-sink matrix establishing a new C-sink unit containing > 1 t CO_2e, the trader must register as biochar processor with Carbon Standards.

11. Geo-Localized and Diffuse C-Sinks

11.1 Geo-Localization of C-Sinks

The geo-localization of biochar C-sinks must be registered for all C-sinks containing more than 1 $tCO2_e$.

When biochar is applied to soil, the carbon sink must be registered with at least one GPS point situated within the land where the biochar is applied. The landowner or tenant must grant the right of passage to geology for the applied biochar carbon that thus returns to the slow carbon cycle (Schmidt and Hagemann, 2024). The landowner does not become the carbon sink owner by simply owning the soil but only by producing or purchasing the biochar, including its C-sink value. Biochar can be traded with or without its C-sink value.

Once the biochar carbon is applied to the soil, the property rights of the carbon expire and are transferred to the commons. Also, the farmer cannot be made legally responsible for preserving and maintaining the C-sink. The farmer or landowner may claim a unique financial compensation for granting the right of passage to geology but not for providing stewardship to the land where the biochar was applied. The activities of carbon removal, pyrolytic transformation, and eventual application to soil are climate services to be remunerated as climate action independently from private or communal land property. The eventual C-sink will eventually transfer far below and away from the initial soil in the lithosphere, waterways, and sediments, where no private property rights are granted.

The case is diametrically different for temporary C-sinks. Here, the biochar-carbon is part of a material matrix that is owned by a legal entity, and the C-sink cannot be dissociated from the imbedding material such as thermoplastics, textiles, carbon fiber composites, asphalt, or concrete. Here, the owner of the material is also the owner of the C-sink and must be registered. When biochar finds application in large materials such as constructions for residential, infrastructural, or road-related purposes, registration of the geolocation is required.

Recording the ownership and location of temporary C-sinks is essential for subsequent monitoring of their fate and maintenance.

11.2. Diffuse C-Sinks

C-sink materials and packaging units containing biochar or biochar-based products representing less than 1 $tCO2_e$ of biochar and which are not grouped into products or deliveries with a total amount exceeding 1 $tCO2_e$ of biochar may be registered as diffuse C-sinks.

The C-sink matrix positive list (see Carbon Standards' website) classifies and specifies all permissible C-sink materials and applications that can be used to establish diffuse C-sinks. A distinction is made between biochar-containing products that will eventually be applied to soil (e.g., compost, liquid fertilizers, manure additives, potting soil, feed) and industrial or consumer materials where waste treatment or disposal is the expected end-of-life scenario.

If biochar was mixed at a volume ratio of at least 1 to 1 with compost, manure, feed, liquid fertilizer, rock powder, clay, lime, or ash, the spontaneous combustion or decomposition of the biochar and, thus, the loss of carbon can be practically excluded. Given the biochar-containing product is labeled and marketed as a soil amendment, feed product, potting soil, or manure additive, an eventual soil application can be expected, and the resulting C-sink may be registered as a geological C-sink.

If an agricultural biochar-based product contains, e.g., 20 m^3 compost and 1 $tCO2_e$ biochar for a total volume of 22 m^3 biochar-compost, it must be registered with geographic localization and the signed consent of the landowner or tenant. If the total volume of the biochar-compost is, e.g., 6 m^3 containing only 0.4 $tCO2_e$ biochar, the biochar-compost can be considered a diffuse C-sink.

Biochar products not intended for soil application may have shorter or longer lifetimes but will eventually end up in waste incineration or recycling processes, releasing carbon as a greenhouse gas back into the atmosphere. For those products, either a control period (to check if the carbon product is still in use) or the average lifetime of the product is applied to define the lifetime of the C-sink. If the biochar carbon contained in the C-sink materials represents less than 1 t CO_2e, no geo-localization is needed for the individual products.

It can be expected that CO_2 capture from waste incineration plants will become obligatory until 2050 and that the biochar-carbon of those industrial or consumer materials will never be released back into the atmosphere. However, as long as CO_2 capture from incineration and thermal waste treatment are not yet state-of-the-art, only the average lifecycle of the C-sink products can be registered.

When biochar is distributed in small amounts over a large number of serial products (e.g., several grams of biochar in a million pairs of skies), the registration of the temporary C-sink lies with the producer using the average lifetime of the products, and no C-sink location is required. In those specific instances where marginal quantities of biochar are applied or utilized in products, the registration of **diffuse carbon sinks** is permitted.

Diffuse C-sinks may present a risk of double counting if, e.g., the biochar-based product (e.g., a 30-l biochar-compost bag or the 25 kg bag of biochar clay plaster) was certified as a diffuse C-sink by the processor while the client thinks to compensate for some of its own global warming effects when using the biochar product in a garden or for the renovation of a house. To avoid such misunderstandings, diffuse C-sinks that are already registered as such must be labeled as a C-sink product, informing the buyer that the C-sink of the product is already registered and cannot be claimed for other emission compensations. This reference must at least be made by printing the following Carbon Standards registered seal: "Registered C-Sink" and a QR-Code with the web link to more detailed information about the C-sink registration and use. Further details can be found in Carbon Standard’s Design Manual.

If a biochar-based product is used in a garden as a diffuse C-sink and the gardener applies for soil organic carbon certification ("humus certificates"), double accounting could theoretically occur because the usual measurements used to quantify soil carbon will account for biochar as soil organic carbon. However, as there are no humus certificates for gardeners and as diffuse C-sinks are limited to 1 t CO_2e of biochar, and as such small amounts are hardly measurable using common methods for measuring soil carbon, the risk of double certification can be considered inexistent (Rathnayake et al., 2023a). Moreover, as Rathnayake et al. (2023) recommended, certification of soil organic carbon (SOC) requires declaring any biochar application and deducing it from certified SOC.

12. Approved Biochar Uses for C-sinks

Biochar that is mixed into a C-sink matrix listed in the C-sink matrix positive list (c.f., Carbon Standards' website), can be registered a C-sink, given the conditions marked in the C-sink matrix positive list are met. The following subchapters provide a complementary orientation for general categories of biochar C-sinks.

When biochar or biochar-based products arrive at the site where the C-sink will be established (e.g., a farm, a construction site, a composite factory), the GPS coordinates of the location and date of arrival must be registered in the MRV tool. Any further onsite transformation, such as mixing to a C-sink matrix such as compost, animal feed, or concrete must be documented. When the biochar or biochar-based product is applied to a defined field or site, a GPS point situated within the field or plot of application must be registered. A photo showing bulk applications with date and geolocation should be uploaded to the MRV system. Further documentation may be required depending on the site and application type, as further detailed in the following subchapters.

12.1 Soil Application

Mixing with soil or another eligible C-sink matrix (c.f., matrix positive list) at a portion of at least 50:50 (vol/vol) must be guaranteed, which is fulfilled in most cases of agricultural biochar application. Biochar depositions at a lesser mixing proportion are considered temporary biochar storages (c.f., Chapters 2.4 & 12.5)

12.2 Application in Animal Farming

If the biochar is first applied as feed, bedding, or manure additive, the biochar becomes blended with a C-sink matrix and is thus eligible as C-sink. However, the location of the eventual C-sink must still be registered. If the biochar containing animal manure or compost is spread or incorporated on-farm, the entire farm can be considered as C-sink location.

If the biochar containing manure or compost with a biochar C-sink unit size above 1 t CO_2e biochar is sold or provided to another farm or company, the biochar-compost-producing farm must be registered as a biochar processor. However, in most cases the biochar containing manure or compost will not be transported in packaging units to adjacent farms but rather as bulk material, and it may become impractical to create new packaging unit IDs. Depending on the individual systems in place, appropriate tracking of the biochar containing manures, composts, or digestates to other farms and thus C-sink sites will be developed during the technical audit of the biochar manure processor. For C-sink units below 1 t CO_2e of biochar, the biochar-manure substrate may be considered a diffuse C-sink (c.f., chapter 10.7).

12.3 Concrete Construction Materials

Biochar incorporated into cement-, lime-, clay-, or geopolymer-based construction materials is considered a carbon sink.

Structures like the Roman Colosseum, the Egyptian pyramids, and the old city of Fulda show that buildings may last longer than empires and constitutions. However, the average life cycle of reinforced cement-based concrete constructions is specified by various standards and publications, such as LEED v4.1 and Minergy/SNBS, to be approximately 60 years (20 years for logistic and production structures). These relatively short life cycles are primarily due to steel corrosion and urban planning. While extending the lifetime of these materials is both possible and desirable, given the current state of the global building industry, an average lifespan of 60 years for buildings and urban infrastructures and 20 years for logistics and production facilities is representative.

During the building's existence, the concrete matrix protects the biochar, e.g., from water, air, and chemicals, so it does not decay. For the duration of the average construction life cycle of 20 to 60 years, depending on the construction type, the carbon sink can be registered with 100% carbon persistence. No biochar carbon is lost when incorporated into the construction material for as long as the building exists. This holds true regardless of the binder used in the construction material, whether cement, lime, clay, or geopolymers.

While the preservation of biochar carbon during a building's lifetime is undisputed, the end-of-life scenario becomes crucial for certifying it as a permanent carbon sink. Different scenarios must be considered at this stage:

1) **Landfill**: Demolished building materials are often deposited in landfills and, thus, indirectly applied to the soil or at least exposed to conditions that are comparable to those in the soil, especially concerning moisture and biological activity. Still, concrete fragments are typically relatively large (centi- to decimeters), and the biochar particles within these pieces remain protected from microbial and chemical attacks for many decades to centuries. However, depending on the soil's pH, the biochar carbon will eventually be exposed to environmental conditions. Thus, the standard decay curve

of soil-applied biochar applies once the rubble is deposited in a landfill, with the year of landfill deposition marking the starting point of the biochar decay curve.

2) **Conventional concrete recycling**: Demolished concrete is increasingly recycled into new construction materials or fillers. To achieve this, the rubble must be crushed. During the crushing process, the biochar remains within the resulting pebbles. Depending on the size and quality of the crushed materials, these pebbles are used as filler, such as in road construction, or as aggregate for new construction materials. Both scenarios are distinguished in regard to the C-sink registration:

   2.1 When used as filler for roadbeds, retaining walls, or landscaping gravel where no binder is applied, the biochar carbon remains protected within the crushed concrete matrix for many decades. However, it will eventually be released into the soil matrix. The application of the filler material is considered the entry point to geology and marks the starting point of the decay curve for soil-applied biochar.

   2.2 When used as aggregate for new construction material, i.e., the aggregate is mixed with a binder, a new life cycle as building material begins, with an average lifetime of 60 years and no decomposition of biochar carbon (100% persistence during the second use as construction material). This cycle of reuse in building materials can continue many more times before reaching its end-of-life as filler in roadbeds (scenario 2.1) or landfills (scenario 1).

3) **Thermo-oxidative cement recycling:** A new process developed at laboratory scale aims to recycle cement from concrete materials and reuse it as a cement binder. To do this, the concrete is ground very finely and sieved to separate the used binder (fine material) and aggregates (oversized particles). The sieved oversize can be reused as aggregate, which is particularly important as sand is a non-renewable, limited resource (Wang et al., 2021). The fines, i.e., hydrated and aged cement, can then be reactivated by thermal treatment at 600 to 1400 °C under an oxidative environment (Bogas et al., 2022, 2021; Carriço et al., 2020; Dunant et al., 2024; Mostazid and Sakai, 2023). It can be assumed that biochar would predominantly end up with the fines and thus would be oxidized during the thermal treatment.

   While this procedure is theoretically possible, thermo-oxidative cement recycling is unlikely to be implemented at scale and thus not become an end-of-life scenario for biochar-amended concrete. Lab experiments demonstrated that the reactivation of recycled cement may require less energy as conventional cement production from limestone (Real et al., 2022). However, recycled cement past present significant lower purity and homogeneity and thus quality than limestone (Bogas et al., 2022) that is abundantly available in the earth's crust, is inexpensive and its use and quality assurance is well established. Cement-based concrete captures significant amounts of atmospheric CO_2 during aging, transforming it into highly stable carbonates. When concrete or recycled cement paste is deposited in non-acidic landfills, these carbonates form a very stable, long-term carbon sink. Aged concrete contains more than 20 kg CO_2e per m^3 in the form of carbonates formed with CO_2 captured from the atmosphere and/or industrial sources (Monkman and MacDonald, 2017; Pae et al., 2024; Zhao et al., 2024), which may even have been certified as a carbon sink (Puro Earth, 2022). If biochar were added as a cement additive or sand replacement, the carbon content could exceed 10% (m/m).

If the cement paste were thermo-oxidatively recycled, the captured and concrete-sequestered carbon would be released as CO_2. Given that by 2050, all industrial emissions must be equipped with CCS, the additional cost of recycling cement paste would make it comparatively more expensive than sequestering the cement paste in a soil matrix and producing new cement from limestone with CCS already in place. Maintaining the carbon sink long-term by sequestering hydrated and aged cement without thermal treatment is the most sustainable and economical recycling option.

Dunant et al. (2024) investigated combining steel and cement recycling by using recycled cement paste as flux in the melting of waste steel. Although this approach appears promising, many questions remain regarding the industrial scale-up with highly heterogeneous cement pastes. While steel melting does not cause major CO_2 emissions if conducted in electric furnaces, the thermo-oxidative treatment of carbonate and biochar-containing cement pastes would release significant amounts of CO_2. This would necessitate CCS, further increasing recycling costs.

If human civilization succeeds in limiting climate change, which is the primary goal of establishing the carbon sink economy, it is clear and unavoidable that by 2085—sixty years from now and the average life cycle of concrete buildings—no industrial CO_2 emissions will enter the atmosphere but will instead be recycled for carbon materials or sequestered geologically. Given that CCS of emissions from industrial processes will become legally mandatory in the coming decades, conventional limestone-based cement companies will not only produce cement but also purified CO_2 for the carbon cycling economy (Schmidt and Hagemann, 2024). Cement production will become carbon neutral by then.

As landfill application of waste cement paste is accepted as carbon sequestration (for both carbonate and biochar carbon contained in the paste), recycling the heterogeneous paste with mandatory CCS would clearly be at an economic, energetic, and environmental disadvantage compared to its carbon-sequestering landfill application and fresh cement production with CCS.

> It can thus be concluded that thermo-oxidative cement recycling is highly unlikely to develop due to both economic and physical considerations. According to the EU definition of permanent carbon removal as *any practice or process that, **under normal circumstances and using appropriate management practices**, captures and stores atmospheric or biogenic carbon for several centuries* (Eur-Lex, 2024). Under normal circumstances, thermo-oxidative cement recycling can be excluded as an end-of-life scenario for biochar-containing concrete materials. However, the evolution of the recycling technology will be closely observed, and if the recycling technology develops unexpectedly into a scaling solution, the present standard will adapt in due time.

Biochar applied in construction materials, such as buildings, urban constructions, and infrastructure, is typically pre-mixed at a processor's site. In most cases, these pre-mixed materials are transported as bulk material, measured by weight or volume, rather than in packaging units. Depending on the individual systems in place, appropriate tracking of the materials to the construction site, and thus to the carbon sink site, must be developed and submitted to Carbon Standards for approval. Only when the tracking to the construction site is verified, and the building itself is registered as the carbon sink location can the biochar carbon sink be registered. Here, the PAC fraction is registered as persistent for > 1000 years, while the SPC fraction is registered without decay for the expected average lifetime of the construction and potentially longer if material use in new constructions is tracked (c.f., scenario 2.2), followed by the SPC decay function (c.f., equation 4) starting with the year of the demolition of the construction (c.f., figure 3).

Given the complexity of tracking the biochar from the production of biochar-based building materials to the construction site, a transition period until 31st December 2026 is granted. During the transition period, biochar C-sinks in construction materials may be registered like diffuse construction C-sinks without leakage over the average life cycle of 60 years, followed by the SPC decay function (c.f., equation 4) starting with year 60 after its production (c.f., figure 3).

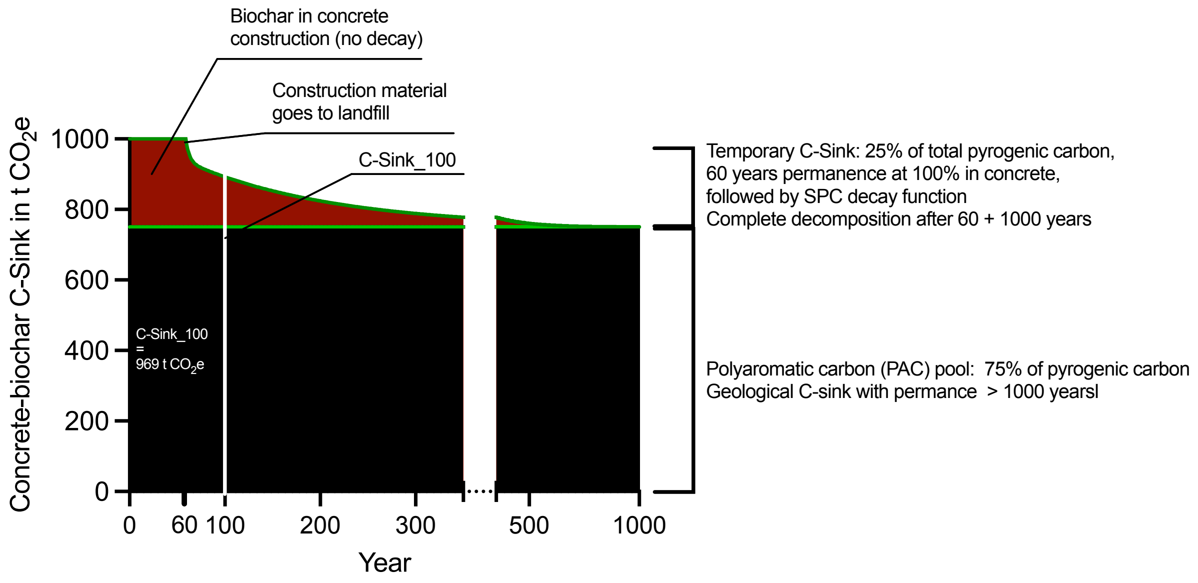


Figure 3: C-sink curve of concrete embedded biochar with an H/Corg ratio < 0.4. The PAC fraction is registered with a persistence of > 1000 years. The SPC fraction is registered without decay for 60 years, which is the average lifecycle of a concrete building. If the existence of the building cannot be proven after the control period of 60 years, the SPC fraction is considered as being applied to soil following the demolition of the construction and decays following the SPC decay curve of soil-applied biochar with an H/Corg ratio < 0.4. The C-Sink_100 of this construction C-sink is 969 t CO_2e (PAC + 60 years SPC + 40 years SPC decay). The C-Sink could also be divided into C-Sink_1000+ of 750 t CO_2e (i.e., the PAC fraction) and a C-Sink_100 of 219 t CO_2e (the SPC fraction).

For diffuse C-sinks of < 1 t CO_2e, tracking from the concrete mixing site to the construction site is not required. Biochar contained in the concrete at quantities of less than 1 t CO_2e is registered without degradation over the average life cycle of 60 years, followed by the SPC decay function (c.f., equation 4) starting with year 60 after its production (c.f., figure 3).

The packaging/delivery note of the diffuse C-sink material must clearly state that the biochar contained in the concrete material has already been registered as C-sink and must not be registered again as part of a construction or any other use.

12.4 Application in Composite Materials

Biochar can be used as an additive or filler to a multitude of composites, thermoplastics, textiles, organic or mineral fibers, paper, filters, metal, electronic, and other materials. Most of these materials are of small size, have a relatively short lifetime of a few years, but exist in thousands to millions if not billion replicates. It is impossible to register each individual product (e.g., the handle of a hammer, the housing of a watch, a T-shirt, or a sewage pipe).

To register the carbon of such products, the average lifetime of the product must be assessed. A monitoring plan to verify and, where necessary, correct the average product lifetime must be submitted to Carbon Standards. Depending on the size of production, the monthly (> 1000 t CO_2e per month), quarterly (> 1000 t CO_2e per quarter) or annual (≤ 1000 t CO2e per quarter) production of one product type at one production site must be registered as a C-sink unit in the Global C-Sink Registry. Annual global cooling services can be traded for periods given by the average lifetime of the product.

The application of biochar in asphalt roads must be tracked and registered with the road location.

12.5 Temporary Biochar Storage

It is possible to store carbon temporally in geological sites such as salt domes, crude oil wells, coal mines, or even in silos. For as long as the biochar is stored under controlled conditions and with regular verification, protected from water and from biologically active matrices, it can be considered a temporary C-sink during the controlled storage time. The control is usually assured remotely with continuous measurements of temperature, humidity, and CO_2 concentration. The monitoring plan must be approved by Carbon Standards.

The biochar carbon can be registered as total stored carbon, and the amount of stored carbon must be updated annually in the Global C-Sink Registry. Annual global cooling services of stored carbon can be traded only one year in advance. This means that the Global Cooling Services compensate the global warming effect of past emissions for the coming year.

12.6 Other Forms of C-Sink Establishments

Carbon Standards may approve other application and storage methods not mentioned or covered in the C-sink matrix positive list. A request for approval, including a detailed description of the new method, must be submitted to Carbon Standards.

13. Registration of the C-Sink

The Global Biochar C-Sink certification is the prerequisite for generating marketable C-sink certificates. However, before the climate effect of C-sinks can be traded and used to achieve climate change mitigation targets of individuals, companies, organizations, regions, or nations, they must be registered in the Global C-Sink Registry.

The following information are registered for biochar carbon sinks:

1. C-sink owner (owner of the material that contains the biochar, or producer of biochar containing products).
2. A GPS point of the land or area where the C-sink was established.
3. For soil application: Consent of the landowner or tenant to accept the biochar application to his soil (usually part of the purchase contract).
4. Date of C-sink establishment.
5. Year of CO_2-removal (date of carbon uptake of biomass that was pyrolyzed).
6. EBC/WBC batch number.
7. Biochar analysis - can be linked with the Carbon Standard Biochar Tool
8. Type of C-sink (geo-localized or diffuse).
9. C-sink matrix.
10. Amount of biochar in dry tons.
11. Amount of carbon in CO_2e.
12. Persistence curve of C-sink (depending on C-sink matrix).
13. Controlling period (depending on C-sink matrix).
14. C-sink project documentation
15. Report of the verification and validation body
16. Confirmation of the compensation of the emission portfolio of the biochar

This information is collected by the biochar producer, processor, trader, C-sink owner, and/or dMRV provider at the various stages of the biochar and C-sink life cycle using dMRV. The C-sink owner must ensure the completeness and correctness of the data, which is controlled by the verification and validation body.

The C-sink project documentation contains different documents. Project Design Document (PDD), Monitoring report, Validation report and Verification report will be published in the Global C-Sink Registry together with the C-sinks.

The right to use the "registered C-Sink" seal, owned by the Global Carbon Register Foundation, is acquired by registration of the corresponding C-sink in the Global C-Sink

Registry. All logos can be downloaded from the Carbon Standards International website (www.carbon-standards.com).

registered
C-SINK

Manufacturers of EBC/WBC certified biochar are advised to sell the registered C-sink effects only through Carbon Standards' endorsed C-sink traders. This is the only way to guarantee that exactly the amount of carbon actually removed from the atmosphere in the form of CO$_2$ and the respective global warming effects are certified and sold.

Biochar producers may equally become endorsed as C-Sink Traders and thus sell C-sink effects (global cooling services or CO$_2$e offsets) to third parties or offset their own emissions.

For more detailed information, please refer to the Global Carbon Register Foundation (www.global-c-registry.org). Carbon Standards collaborates with the Global Carbon Register Foundation. Carbon Standards' C-sink tools provide direct data exchange with the Global C-Sink Registry and support its methodology. However, Carbon Standards and its standards are free to collaborate also with other registries given they provide the same data security and science-based calculations of annual cooling and warming effects.

14. Quoted Literature

Aamaas, B., Berntsen, T.K., Fuglestvedt, J.S., Shine, K.P., Bellouin, N., 2016. Regional emission metrics for short-lived climate forcers from multiple models. Atmos Chem Phys 16, 7451–7468. https://doi.org/10.5194/ACP-16-7451-2016

Allen, M., Fuglestvedt, J., Shine, K., et al., 2016. New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nature Clim Change 6, 773–776.

Ascough, P.L., Bird, M.I., Brock, F., Higham, T.F.G., Meredith, W., Snape, C.E., Vane, C.H., 2009. Hydropyrolysis as a new tool for radiocarbon pre-treatment and the quantification of black carbon. Quat Geochronol 4, 140–147. https://doi.org/10.1016/j.quageo.2008.11.001

Ascough, P.L., Meredith, W., Bird, M.I., Large, D., Snape, C., Tilston, E., 2012. Evaluating hydropyrolysis as a method for quantification and characterisation of Black Carbon in environmental matrices 14, 5975.

Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2009. Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use.

Azzi, E.S., Li, H., Cederlund, H., Karltun, E., Sundberg, C., 2024. Modelling biochar long-term carbon storage in soil with harmonized analysis of decomposition data. Geoderma 441, 116761. https://doi.org/10.1016/J.GEODERMA.2023.116761

Balcombe, P., Speirs, J.F., Brandon, N.P., Hawkes, A.D., 2018. Methane emissions: choosing the right climate metric and time horizon. Environ Sci Process Impacts 20, 1323–1339. https://doi.org/10.1039/C8EM00414E

Bogas, J.A., Carriço, A., Real, S., 2022. Thermoactivated Recycled Cement. London.

Bogas, J.A., Carriço, A., Real, S., Bogas, J.A., Carriço, A., Real, S., 2021. Thermoactivated Recycled Cement. Sustainability of Concrete With Synthetic and Recycled Aggregates. https://doi.org/10.5772/INTECHOPEN.98488

Bowring, S., Jones, M., Ciais, P., Guenet, B., Abiven, S., 2020. Fire as carbon sink? The global biome-dependent wildfire carbon balance. https://doi.org/10.21203/RS.3.RS-127629/V1

Bowring, S.P.K., Jones, M.W., Ciais, P., Guenet, B., Abiven, S., 2022. Pyrogenic carbon decomposition critical to resolving fire's role in the Earth system. Nature Geoscience 2022 15:2 15, 135–142. https://doi.org/10.1038/S41561-021-00892-0

Camps-Arbestain, M., Amonette, J.E., Singh, B., Wang, T., Schmidt, H.-P., 2015. A biochar classification system and associated test methods, in: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management. Routledge, London, pp. 165–194.

Carriço, A., Bogas, J.A., Guedes, M., 2020. Thermoactivated cementitious materials – A review. Constr Build Mater 250, 118873. https://doi.org/10.1016/J.CONBUILDMAT.2020.118873

Dunant, C.F., Joseph, S., Prajapati, R., Allwood, J.M., 2024. Electric recycling of Portland cement at scale. Nature 2024 629:8014 629, 1055–1061. https://doi.org/10.1038/s41586-024-07338-8

Eur-Lex, 2024. EUR-Lex - 52022PC0672 - EN - EUR-Lex [WWW Document]. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0672 (accessed 6.30.24).

Ferrero, F., Malow, M., Noll, M., 2011. Temperature and gas evolution during large scale outside storage of wood chips. European Journal of Wood and Wood Products 69, 587–595. https://doi.org/10.1007/s00107-010-0512-0

Fuglestvedt, J.S., Berntsen, T.K., Godal, O., Sausen, R., Shine, K.P., Skodvin, T., 2003. Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. Clim Change 58, 267–331. https://doi.org/10.1023/A:1023905326842

Howell, A., Helmkamp, S., Belmont, E., 2022. Stable polycyclic aromatic carbon (SPAC) formation in wildfire chars and engineered biochars. Science of The Total Environment 849, 157610. https://doi.org/10.1016/J.SCITOTENV.2022.157610

IPCC, 2022. IPCC sixth assessment report (AR6) - Working group III contribution, UNEP.

IPCC, 2019. Method for estimating the change in mineral soil organic carbon stocks from biochar amendments: basis for future methodological development, in: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, p. Ap4.1.

IPCC, 2013. Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge. ed. Cambridge.

Jaeckel, U., Thummes, K., Kaempfer, P., 2005. Thermophilic methane production and oxidation in compost. FEMS Microbiol Ecol 52, 175–184. https://doi.org/10.1016/j.femsec.2004.11.003

Jeltsch-Thömmes, A., Joos, F., 2019. The response to pulse-like perturbations in atmospheric carbon and carbon isotopes 1–36.

Juhrich, K., 2016. CO2-Emissionsfaktoren für fossile Brennstoffe. Berlin.

Kadiyala, A., Kommalapati, R., Huque, Z., 2016. Evaluation of the Life Cycle Greenhouse Gas Emissions from Hydroelectricity Generation Systems. Sustainability 2016, Vol. 8, Page 539 8, 539. https://doi.org/10.3390/SU8060539

Kuzyakov, Y., Bogomolova, I., Glaser, B., 2014. Biochar stability in soil: Decomposition during eight years and transformation as assessed by compound-specific 14C analysis. Soil Biol Biochem 70, 229–236. https://doi.org/10.1016/j.soilbio.2013.12.021

Lehmann, J, Abiven, S., Kleber, M., Pan, G., Singh, B.P., Sohi, S.P., Zimmerman, A.R., 2015. Persistence of biochar in soil, in: Lehmann, Johannes, Joseph, S.D. (Eds.), Biochar for Environmental Management. Routledge, London, pp. 235–299.

Lehmann, Johannes, Abiven, S., Kleber, M., Pan, G., Singh, B.P., Sohi, S.P., Zimmerman, A.R., 2015. Persistence of biochar in soil, in: Lehmann, J., Joseph, S.D. (Eds.), Biochar for Environmental Management. New York, pp. 235–282.

Lehmann, J., Hansel, C.M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S., Nunan, N., Reichstein, M., Schimel, J.P., Torn, M.S., Wieder, W.R., Kögel-Knabner, I., 2020. Persistence of soil organic carbon caused by functional complexity. Nat Geosci 13, 529–534. https://doi.org/10.1038/s41561-020-0612-3

McBeath, A. V., Wurster, C.M., Bird, M.I., 2015. Influence of feedstock properties and pyrolysis conditions on biochar carbon stability as determined by hydrogen pyrolysis. Biomass Bioenergy 73, 155–173. https://doi.org/10.1016/J.BIOMBIOE.2014.12.022

Meredith, W., Ascough, P.L., Bird, M.I., Large, D.J., Snape, C.E., Sun, Y., Tilston, E.L., 2012. Assessment of hydropyrolysis as a method for the quantification of black carbon using standard reference materials. Geochim Cosmochim Acta 97, 131–147. https://doi.org/10.1016/J.GCA.2012.08.037

Monkman, S., MacDonald, M., 2017. On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete. J Clean Prod 167, 365–375. https://doi.org/10.1016/J.JCLEPRO.2017.08.194

Moosmann, L., Herold, A., 2023. Metriken für Methan-Emissionen. Freiburg.

Mostazid, M.I., Sakai, Y., 2023. Thermal treatment of recycled compacted concrete: Effects on physical properties and hydration characteristics. Journal of Building Engineering 78, 107707. https://doi.org/10.1016/J.JOBE.2023.107707

Myhre, G.D., Shindell, F.M., Breon, W., Collins, J., Fuglestvedt, J., et al., 2013. Anthropogenic and Natural Radiative Forcing, in: Stocker, T., Qin, D., Platner, M., et al. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, New York, p. 712.

Nugent, D., Sovacool, B.K., 2014. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. Energy Policy 65, 229–244. https://doi.org/10.1016/J.ENPOL.2013.10.048

Pae, J., Kim, W.K., Moon, J., 2024. Mineral carbonation performance of wollastonite-blended cementitious composites through in-situ CO2 mixing. Constr Build Mater 438. https://doi.org/10.1016/j.conbuildmat.2024.137160

Petersen, H.I., Lassen, L., Rudra, A., Nguyen, L.X., Do, P.T.M., Sanei, H., 2023. Carbon stability and morphotype composition of biochars from feedstocks in the Mekong Delta, Vietnam. Int J Coal Geol 271, 104233. https://doi.org/10.1016/J.COAL.2023.104233

Pier, P.A., Kelly, J.M., 1997. Measured and estimated methane and carbon dioxide emissions from sawdust waste in the Tennessee Valley under alternative management strategies. Bioresour Technol 61, 213–220. https://doi.org/10.1016/S0960-8524(97)00064-3

Pipatti, R., Silva Alves, J., et al., 2006. Biological treatment of solid waste, in: IPCC Guidelines for National Greenhouse Gas Inventory.

Prather, M.J., Holmes, C.D., Hsu, J., 2012. Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry. Geophys Res Lett 39, n/a-n/a. https://doi.org/10.1029/2012GL051440

Puro Earth, 2022. Carbonated Materials Methodology for CO 2 Removal [WWW Document]. URL https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Carbonated%20Materials%20Methodology.pdf (accessed 6.30.24).

Rathnayake, D., Schmidt, H.P., Leifeld, J., Mayer, J., Epper, C.A., Bucheli, T.D., Hagemann, N., 2023. Biochar from animal manure: A critical assessment on technical feasibility, economic viability, and ecological impact. GCB Bioenergy 00, 1–27. https://doi.org/10.1111/GCBB.13082

Real, S., Sousa, V., Meireles, I., Bogas, J.A., Carriço, A., 2022. Life Cycle Assessment of Thermoactivated Recycled Cement Production. Materials 2022, Vol. 15, Page 6766 15, 6766. https://doi.org/10.3390/MA15196766

Sanei, H., Rudra, A., Przyswitt, Z.M.M., Kousted, S., Sindlev, M.B., Zheng, X., Nielsen, S.B., Petersen, H.I., 2023. Assessing biochar's permanence: An inertinite benchmark. Int J Coal Geol 104409. https://doi.org/10.1016/J.COAL.2023.104409

Schmidt, H., Abiven, S., Hagemann, N., Meyer zu Drewer, J., 2022. Permanence of soil applied biochar. The Biochar Journal 1, 69–74.

Schmidt, H., Hagemann, N., 2024. Fossil C - The Legacy Bloodline. The Biochar Journal 1, 81–85.

Schmidt, H.P., Anca, A., Nikolas, C., Werner, C., Gerten, D., Lucht, W., Kammann, C., 2018. Pyrogenic carbon capture and storage 1–19. https://doi.org/10.1111/gcbb.12553

Schmidt, H.P., Hagemann, N., 2024. Planetary Carbon Recycling - Global Cooling with Temporary C-Sinks. the Biochar Journal 16, 75–80.

Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. Nature 478, 49–56. https://doi.org/10.1038/nature10386

Song, J., Chen, C., Zhu, S., Zhu, M., Dai, J., Ray, U., Li, Yiju, Kuang, Y., Li, Yongfeng, Quispe, N., Yao, Y., Gong, A., Leiste, U.H., Bruck, H.A., Zhu, J.Y., Vellore, A., Li, H., Minus, M.L., Jia, Z., Martini, A., Li, T., Hu, L., 2018. Processing bulk natural wood into a high-performance structural material. Nature 554, 224–228. https://doi.org/10.1038/nature25476

Song, X.-P., Hansen, M.C., Stehman, S. V, Potapov, P. V, Tyukavina, A., Vermote, E.F., Townshend, J.R., 2018. Global land change from 1982 to 2016. Nature. https://doi.org/10.1038/s41586-018-0411-9

Wang, B., Yan, L., Fu, Q., Kasal, B., 2021. A Comprehensive Review on Recycled Aggregate and Recycled Aggregate Concrete. Resour Conserv Recycl 171, 105565. https://doi.org/10.1016/J.RESCONREC.2021.105565

Werner, C., Schmidt, H.-P., Gerten, D., Lucht, W., Kammann, C., 2018. Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °c. Environmental Research Letters 13. https://doi.org/10.1088/1748-9326/aabb0e

Whitman, T., Lehmann, J., 2015. A dual-isotope approach to allow conclusive partitioning between three sources. Nat Commun 6, 8708. https://doi.org/10.1038/ncomms9708

Whittaker, C., Macalpine, W., Yates, N.E., Shield, I., 2016. Dry Matter Losses and Methane Emissions During Wood Chip Storage: the Impact on Full Life Cycle Greenhouse Gas Savings of Short Rotation Coppice Willow for Heat. Bioenergy Res 9, 820–835. https://doi.org/10.1007/s12155-016-9728-0

Zhang, W.-F., Dou, Z.-X., He, P., Ju, X.-T., Powlson, D., Chadwick, D., Norse, D., Lu, Y.-L., Zhang, Y., Wu, L., Chen, X.-P., Cassman, K.G., Zhang, F.-S., 2013. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. Proc Natl Acad Sci U S A 110, 8375–8380. https://doi.org/10.1073/pnas.1210447110

Zhao, Y., Cui, K., He, J., Zheng, Y., Shen, P., Poon, C.S., Peng, G., Guo, R., Xia, D., 2024. An innovative strategy for maximizing CO2 reduction in concrete through preparing carbon sequestration precursors by accelerated carbonation. Cem Concr Compos 152. https://doi.org/10.1016/j.cemconcomp.2024.105618

Zimmerman, A.R., Gao, B., 2013. The Stability of Biochar in the Environment, in: Ladygina, N., Rineau, F. (Eds.), Biochar and Soil Biota. Boca Raton, pp. 1–40.