Support to the development of methodologies for the certification of industrial carbon removals with permanent storage

Review of carbon removals through biochar

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Review of carbon removals through biochar

A report submitted by ICF S.A.

In association with Cerulogy & Fraunhofer ISI

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Contents

Executive summary

Biochar has been identified as a potentially promising route to deliver carbon removals with potential to deliver significant co-benefits. Biochar produced by heating biomass in a low oxygen environment can be incorporated into soils or integrated in materials, and depending on the characteristics of the produced char the carbon may remain in storage in those soils/materials for decades, centuries or even millennia. This scoping paper provides a brief discussion of approaches to estimate the long-term carbon storage in biochars and a review of existing standards to certify biochar use as a carbon removal activity, and identifies some key issues to be considered in the development of a biochar certification methodology as part of the EU carbon removals framework.

Biochar consists primarily of carbon, hydrogen and oxygen, along with other trace elements. Some of the constituent molecules of a biochar can be relatively easily mineralised in the environment (i.e. their carbon can be oxidised to carbon dioxide and released); these are sometimes referred to as a labile fraction. Other molecules are less likely to be mineralised in the environment, with the most inert constituents of biochar having expected lifetimes of thousands or even millions of years in normal soil conditions; these are sometimes referred to as a recalcitrant fraction. Biochars produced at higher temperatures are expected to have a larger recalcitrant fraction and smaller labile fraction.

In 2019 the IPCC published a methodology for estimating long-term carbon storage in biochars for national carbon inventories. Values for the fraction of carbon in a biochar that is expected to remain after one hundred years are tabulated for biochars produced at three temperature levels. These values are based on the results of incubation experiments in which samples of soil and biochar are incubated at a constant temperature and moisture for one or more years – an exponential decay relationship with two terms (one representing the labile fraction and one the recalcitrant fraction) is fitted to the results of a number of such studies.

The IPCC method is based on the assumption that the calculation will be undertaken at the national level with limited data available about specific biochars, but operators of carbon removal projects have access to the biochar and are able to take advantage of a more detailed characterisation of the biochar and the conditions in which it will be used. A paper by Woolf et al. (2021) builds on the IPCC work and provides an estimated biochar permanence relationship based on the ratio of hydrogen to carbon atoms in the biochar (H/C_{org} ratio, a property that can easily be measured) and on the average temperature of the soil in which the biochar will be incorporated, for time periods of 100, 500 and 1000 years. This relationship has been adopted as the basis for estimating carbon storage in biochar after 100 years by several existing certification standards.

While the Woolf et al. (2021) results have been adopted by several standards, new incubation results and additional analysis of incubation results could allow better estimates of the real permanence relationships to be developed. For example, a study by Azzi et al. (2024) provides analysis of an expanded set of incubation results and provides a discussion of alternative functional forms that could be fitted to those results, in particular presenting the results of fitting a 'power model' as an alternative to exponential decay functions. In physical terms, the power model can be understood as representing biochar as being constituted of a large number of components each with greater permanence than the last, while the exponential functions represent biochar as constituted of one, two or three pools of material where each pool has a uniform rate of decay. There is not yet consensus in the literature about whether an exponential model or power model is expected to give a better characterisation of real biochar behaviours.

An alternative to using permanence functions derived from incubation results is to directly assess the chemical structure of a biochar sample to identify a fraction that is believed to be relatively permanent under normal conditions. Sanei et al. (2024) provides an example of this type of assessment based on the identification of 'inertinite macerals' in the biochar. Sanei et al. (2024) argues that carbon in inertinite macerals can be expected to be permanent on timescales of millions of years, and could therefore be treated as fully permanent on any timeframe relevant to carbon removal certification. The inertinite content of a biochar sample can be assessed using a random reflectance test.

An EU certification methodology for biochar as a carbon removal activity could assess permanence based on an estimated decay function and a minimum expected carbon residence period, or based on assessing the inertinite fraction in a biochar sample, or could allow a choice between these approaches, or could be based on an alternative approach not discussed in detail in this paper.

This review goes on to detail five active certification approaches for carbon removals with biochar (European Biochar Certificate C-sink, Puro.earth, VCS, Riverse and C-Capsule), two biochar product standards (the European Biochar Certificate and International Biochar Initiative), one inactive carbon removal certification methodology (ACR) and one carbon credit rating approach for biochar (Sylvera).

In addition to questions around assessing the permanence of biochar, the following further issues are identified as important to consider in the development of an EU biochar certification methodology:

1. Co-products. Most biochar production systems produce other saleable products in addition to biochar, such as pyrolysis oil. It may be appropriate to allocate emissions associated with the biochar production process between co-products.
2. Albedo. Some studies have suggested that biochar incorporation in soils or products can lead to increased absorption of solar irradiation (reduced albedo) and that this could reduce the net climate benefit offered by biochar use.
3. Activity penetration testing. Several existing certification standards require the level of penetration of the biochar activity in a given region to be considered when assessing whether biochar projects are additional. Activity penetration testing could inform the consideration of a standardised baseline for biochar projects.
4. Avoided decomposition emissions. Some standards allow the possibility of claiming additional GHG benefits due to avoided methane emissions from feedstock that would otherwise decompose. Such avoided emissions would not be treated as additional permanent carbon removals under an EU certification methodology, but could potentially be offset against production emissions.
5. Potential reversals. When biochar is incorporated into soils it is not practically possible to monitor the biochar in situ to identify reversals, as it is not possible to accurately measure how much biochar carbon remains in field conditions. If it is used in materials such as concrete, however, it would be possible in principle to record the location of use and monitor the materials for any reversals, for example due to incineration at end of life.
6. Contaminants in biochar. When biochar is used in agricultural contexts in particular it is important that it should not contain significant amounts of heavy metals or other

toxicants. The European Biochar Certificate Guidelines for a sustainable production of biochar include thresholds for various toxicants that could inform sustainability requirements in an EU certification methodology.

7. Soil incorporation. The agricultural co-benefits of biochar may be improved by incorporating biochar in soils rather than applying it to the soil surface only. It may be appropriate to set a requirement for incorporation in an EU certification methodology.
8. Maximising co-benefits. An EU certification methodology could set additional requirements relating to best practice in biomass use, either as a minimum requirement or as part of an assessable co-benefit.
9. Feedstock eligibility for biochar and biomass energy. Several existing standards set feedstock limitations for biochar certification that are more restrictive on feedstock choice than the sustainability rules set under the RED III.
10. End use verification. Several existing standards have a light-touch approach to demonstrating the use of biochar (e.g. allowing offtake agreements to be used as evidence of the end use). Consideration must be given to whether monitoring requirements on biochar utilisation would be necessary for an EU certification methodology.

Glossary

Abbreviations

ACR – American Carbon Registry

BECCS – Bioenergy with carbon capture and storage

CDM – Clean Development Mechanism

CDR – Carbon dioxide removal

CH_4 – Methane

CO_2 – Carbon dioxide

CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation

CRCF – Carbon Removal Certification Framework

DACCS – Direct air capture with carbon storage

EBC – European Biochar Certificate

FSC – Forestry Stewardship Council

GHG – Greenhouse Gas

GPS – Global Positioning System

GWP – Global warming potential

IBI – International Biochar Initiative

IPCC – Intergovernmental Panel on Climate Change

ISCC – International Sustainability and Carbon Certification

ISO – International Standards Organisation

LCA – Lifecycle analysis/assessment

LULUCF – Land use, land use change and forestry

MRV – Monitoring, reporting and verification

N_2O – Nitrous oxide

RED III – Renewable Energy Directive (Directive (EU) 2018/2001 of the European Parliament and of the Council as amended by Directive (EU) 2023/2413)

SDG – UN Sustainable Development Goals

TRL – Technological Readiness Level

UNFCCC – United Nations Framework Convention on Climate Change

VCS – Verified Carbon Standard

Terms

Co-products are outputs of a process that constitute the main aim of the process, as distinct from **residues** which are produced by a process but are not a primary aim of the production process.

Biomass gasification is defined as a high-temperature process (generally > 700 °C) that involves the partial oxidation of biomass in the presence of a controlled amount of oxygen (or air) and a gasification agent (e.g. steam). The main product is syngas consisting of hydrogen and carbon monoxide, with biochar and ash as residues and produced carbon dioxide being vented or captured.

High carbon fly ash from biomass is a residue of biomass energy recovery in a boiler. A fraction of this material may have the properties of biochar. It is common practice that high-carbon fly ash would be recirculated for combustion, resulting in loss of the carbon from the ash, but if it is non recirculated the biochar can be recovered.

Pyrolysis is defined as a medium-temperature process (generally 400 to 800 °C) that involves the thermal breakdown of biomass in the absence of oxygen. Pyrolysis produces pyrolysis oil, pyrolysis gases and biochar, as well as heat. The yield of these three products varies depending on the biomass used and the process conditions. The oil can be upgraded to a transport fuel, while the gases are often combusted for on-site energy.

1 Introduction and context

On 30 November 2022, the European Commission adopted a proposal for Regulation establishing a first European Union (EU)-wide voluntary Carbon Removal Certification Framework (CRCF)[1] to reliably certify high-quality carbon removals. A provisional agreement on the final text of the Regulation was reached between the EU institutions on 20 February 2024[2]. The proposed regulation aims to boost innovative carbon removal approaches and sustainable carbon farming solutions, and contribute to the EU's climate, environmental and zero-pollution goals. It should significantly improve the EU's capacity to quantify, monitor and verify carbon removals. Higher transparency will ensure trust from stakeholders and industry, and prevent greenwashing. Moving forward, the Commission, supported by experts, will develop tailored certification methodologies for carbon removal activities delivering on climate and other environmental objectives.

To ensure the transparency and credibility of the certification process, the proposal sets out rules for the independent verification of carbon removals, as well as rules to recognise certification schemes that can be used to demonstrate compliance with the EU framework. To ensure the quality and comparability of carbon removals, the proposed regulation establishes four QU.A.L.ITY criteria:

1. Quantification: Carbon removal activities need to deliver unambiguous benefits for the climate and be measured, monitored, and reported accurately;

2. Additionality: Carbon removal activities need to go beyond existing practices and what is required by law;

3. Long-term storage: Certificates are linked to the duration of carbon storage and should ensure long-term storage;

4. Sustainability: Carbon removal activities must contribute to sustainability objectives such as climate change adaptation, circular economy, water and marine resources, and biodiversity.

The Commission's proposal for the certification framework anticipates an EU standard for the certification of robust high quality carbon removals, implemented through certification methodologies for specific carbon removal activities.

One carbon removal approach that has been identified as potentially interesting is the long-term sequestration of carbon in biochar.

Biochar is produced by heating biomass in a low oxygen environment leading to carbonisation (production of charred residual materials with an increased elemental carbon content). The level of carbonisation in the produced biochar is strongly affected by the temperature of the reaction. Biochar is primarily produced by pyrolysis, in which case the solid char is co-produced with gaseous materials (such as methane (CH_4), hydrogen and carbon monoxide) and liquid materials (such as pyrolysis oil and tar), which have a higher ratio of hydrogen atoms to carbon atoms (H/C_{org} ratio). Biochar can also be produced as a by-product of higher-temperature gasification processes, where the higher process temperatures lead to greater thermal decomposition to maximise production of hydrogen and

[1] COM (2022) 672 final: Proposal for a Regulation on an EU certification for carbon removals

[2] https://www.consilium.europa.eu/en/press/press-releases/2024/02/20/climate-action-council-and-parliament-agree-to-establish-an-eu-carbon-removals-certification-framework/

carbon monoxide at the expense of eliminating production of hydrocarbon gases and liquids, and reducing the amount of biochar produced.

Torrefaction and hydrothermal carbonisation also produce carbonised forms of biomass, but these processes operate at lower temperatures and the outputs are often not treated as ‘true’ biochars – for example, the European Biochar Certificate defines biochar as being produced at temperatures above 350 °C. Some pyrolysis processes are optimised to produce liquid pyrolysis oil that can be upgraded into transport fuels, others are optimised to maximise the biochar yield.

There is evidence that biochar with the correct characteristics can be stable in the environment for hundreds, thousands or even millions of years, with higher levels of carbonisation being associated with greater carbon permanence.

Biochar can be applied to agricultural soils, and has been identified as potentially beneficial to various soil properties and as potentially able to boost agricultural yields. It can also be used as an additive in materials such as concrete, allowing those materials to act as a carbon storage vector and potentially allowing the improvement of some material properties.

Biochar can be treated as a carbon removal approach because it allows carbon absorbed by plants from atmospheric CO_2 to be stored in soils or materials on a long-term basis.

2 Review of relevant literature on the estimation of long-term carbon storage in biochar

2.1 Approaches to assessing the durability of biochar

A key question for the certification of biochar as a long-term carbon removal approach is how long the carbon in biochar can be expected to remain sequestered, and how this may differ between soil applications and material applications (such as the use of biochar as an additive in concrete or polymers).

The durability of biochar can be investigated through three basic approaches.

Firstly, biochar residence times in soil can be studied directly through **field experiments**. The fundamental challenge to this sort of experiment is that it is difficult, if not impossible, to distinguish between biochar loss through degradation and mineralisation of carbon to CO_2, and biochar loss by transportation, for example through vertical movement in the soil column and by wind and water erosion. Biochar that is lost from soil through transportation may well continue to sequester carbon for as long or longer than biochar that remains in situ (van Oost et al. 2007[3]). Field experiments have therefore not been considered an accurate basis to assess the durability of carbon storage in biochar, and we have not reviewed data from field experiments in the discussion below.

It is also possible to assess biochar degradation in a more controlled environment through **incubation studies** performed in a laboratory setting. Incubation studies involve mixing a biochar sample with a chosen soil, moistening the samples and placing them in an incubation bath at a constant temperature for a chosen experimental duration. Respired CO_2 from the sample is captured, and the proportions of carbon released from the biochar sample and from the soil can be identified using carbon isotope analysis. A mathematical function for the expected ongoing rate of biochar carbon loss (for example an exponential decay function) can be fitted to the experimental data. With data from experiments at different temperatures, it is also possible to develop transformation functions to infer the expected rate of carbon loss for that sample if it had been kept at a lower or higher temperature. Because the incubation experiments are based on a closed system there is no risk of biochar loss through transportation. Results from incubation experiments and the associated process of fitting mathematical models to the observed carbon loss rates are discussed in sections 2.3 and 2.4 below, which cover the findings from academic reviews of biochar incubation studies by respectively Woolf et al. (2021) and Azzi et al. (2024). Such results are also the evidentiary basis for the IPCC's method for considering biochar in national emission inventory, which is discussed in section 2.2.

Finally, it is possible to assess biochar durability by **analysing the properties of the constituent molecules** in a biochar sample, presuming that information is available about the durability characteristics of those particular types of molecule. In the case of biochar, it is expected that durability will increase with greater 'aromaticity'. Aromaticity is a chemical property associated with organic compounds that are relatively unreactive, and which is related to the configuration of carbon atoms in rings that often feature alternating single and double carbon-carbon bonds. In particular, some biochars consist of a high fraction of 'inertinite macerals', which consist of molecules with a high degree of aromaticity and are considered to be highly inert in the natural environment (hence the name). These macerals

[3] https://www.science.org/doi/abs/10.1126/science.1145724

are also present in coal, and flakes of inertinite can be found in sedimentary rocks. It has been suggested that if a fraction of a biochar sample can be identified as inertinite through chemical analysis then it can be concluded that that fraction of the material will experience essentially no degradation in an agricultural or material environment on the timescales relevant for carbon removals. This is further discussed in section 2.5 below, with reference to the results of academic research by Sanei et al. (2024).

The following four sections elaborate on methods for estimating biochar durability identified in the existing literature.

2.2 IPCC Sixth Assessment Report and Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments

Biochar is discussed in Chapter 7 of the 2022 Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, henceforth 'the AR6 report'. The IPCC has also produced a 'Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments' as part of the 2019 updates to the national GHG inventory reporting guidelines, henceforth the 'IPCC biochar method'. This method is not framed as final but rather as a 'basis for future methodological development'.

2.2.1 Quantification

The AR6 report states that "When applied to soils, biochar is estimated to persist from decades to thousands of years, depending on feedstock and production conditions". This is referenced to papers by Singh et al. (2015)[4] and Wang et al (2016)[5].

The IPCC biochar method provides an equation to estimate carbon stock increase (i.e. the fraction of applied carbon that remains) after 100 years in cropland and grassland soils receiving biochar additions. The method is identified as "not applicable for application of biochar to soils in forest land, settlements, other lands or wetlands". It is not framed as applicable to non-soil applications of biochar.

$$\Delta BC_{Mineral} = \sum_{p=1}^{n} \left(BC_{TOT_p} * F_{C_p} * F_{perm} \right)$$

$\Delta BC_{Mineral}$ is the change in persistent (100 year) carbon stocks.

p is an index across types of biochar applied (up to n types).

BC_{TOT} is the quantity of biochar applied.

F_{C_p} is the carbon fraction in each type of biochar.

F_{perm} is the fraction of biochar carbon that is expected to remain after 100 years.

Default values for F_{C_p} are tabulated by feedstock and production process (pyrolysis or gasification). The carbon content for biochar from pyrolysis is assumed to be higher (for some feedstocks several times higher) than in biochar from gasification.

[4] https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0141560

[5] https://onlinelibrary.wiley.com/doi/epdf/10.1111/gcbb.12266

Default values for F_{perm_p} are tabulated by biochar production temperature, divided into three regimes (350-450 °C, 450-600 °C and > 600 °C). Higher temperatures are associated with a higher remnant fraction, 0.89 for higher temperature biochars against 0.65 for lower temperature ones. It is explained that the relationship between recalcitrance and production temperature is not believed to be linear, and this is why the method considers three discrete processing-temperature regimes rather than proposing a temperature-parameterised function.

The calculation of F_{perm_p} is based on a 'double exponential' model of biochar carbon decay, whereby a function that is the sum of two exponential decay curves is fitted to experimental biochar durability datasets from incubation experiments. This 'two pool' model is predicated on the idea of biochar consisting of a labile fraction and a recalcitrant fraction that have different rates of carbon decay, both of which are constant over time. The decay defaults are considered conservative as they are based on an ambient soil temperature of 20 °C, against a global average of 10 °C.

The IPCC biochar method uses processing temperature as the sole parameter for the calculation of F_{perm_p}. This is explained on the basis that processing temperature may be more readily characterised at the national level than other potential indicators of recalcitrance (the IPCC method is focused on national inventory reporting rather than project level reporting). The IPCC biochar method identifies the H/C_{org} ratio or the O/C_{org} ratio as properties that could potentially be used as parameters instead of processing temperatures, and that in principle these properties could be combined with information on local soil temperatures and moisture in making the assessment of expected biochar permanence, but notes that those properties are not considered in the proposed method.

2.2.2 Co-benefits

The AR6 report identifies several potential co-benefits from the use of biochar to deliver carbon removals. It states that additional carbon benefits for biochar application in soil can be delivered: by 'negative priming', whereby biochar stabilises soil carbon and rhizodeposits[6]; by reductions in nitrous oxide (N_2O) emissions from soils, compost, and rice paddies; by reduced CH_4 emissions from compost application and from rice paddies; and by co-generation of bioenergy as part of the biochar production process. The AR6 report also notes that biochar used in soils may deliver pollution benefits by absorption of organic pollutants and heavy metals and that it may improve agricultural yields and improve water use efficiency. The report further notes that when fed to ruminant animals biochar may help reduce enteric fermentation CH_4 emissions.

The AR6 report notes that biochar application is not uniformly associated with benefits, stating that "Studies report a range of biochar responses, from positive to occasionally adverse impacts, including on GHG emissions, and identify risks", and that responses to biochar application will depend on biochar type and site characteristics. The report states that, "Mitigation through biochar will be greatest where biochar is applied to responsive soils (acidic, low fertility), where soil N_2O emissions are high (intensive horticulture, irrigated crops), and where the syngas co-product displaces fossil fuels."

[6] Carbon released into soil through root systems.

2.3 'Greenhouse Gas Inventory Model for Biochar Additions to Soil', Woolf et al. 2021[7]

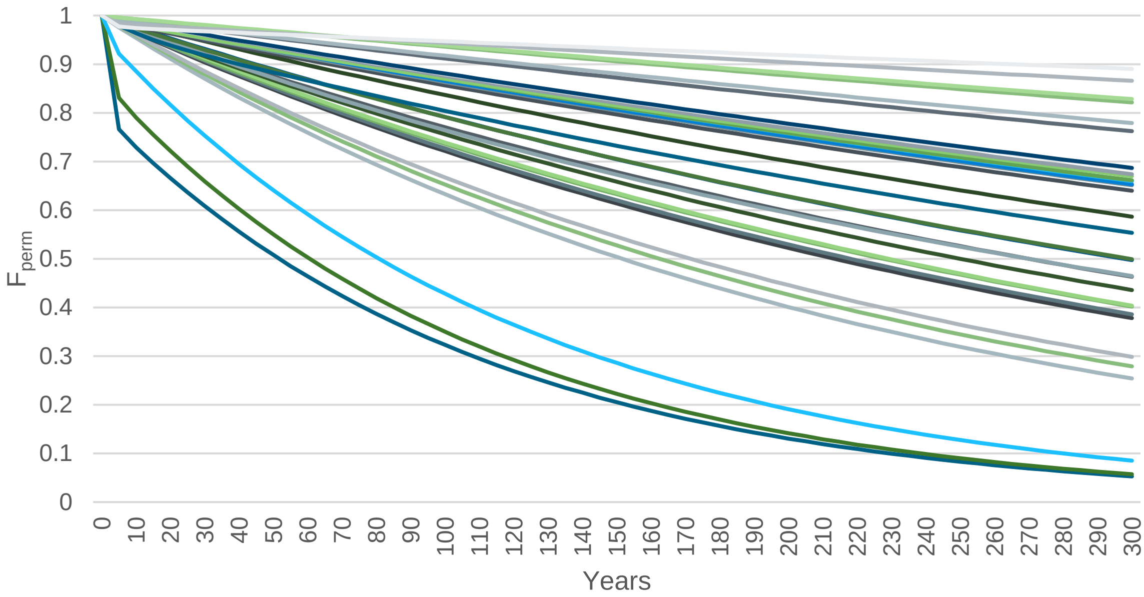
The 2021 study by Woolf et al. (2021) aimed to "further develop the IPCC biochar method" by providing a more detailed analysis of the background scientific work and by adding additional parameterisation options for the durability function in the case that more detailed biochar information is known. The central exercise in the paper consists of meta-analysis and curve fitting using incubation study results from the literature. Woolf et al. (2021) is referenced on biochar permanence by several existing biochar certification approaches (including Puro.earth, VCS and Riverse).

Woolf et al. (2021) discusses the high durability in the environment of biochar compared to untreated biomass, noting that, "Biochar typically decomposes at least 1−2 orders of magnitude more slowly in soil than the biomass from which it was made." Woolf et al. (2021) discusses the idea that biochar can be understood as "a complex mixture of both aliphatic and aromatic organic compounds, with the larger aromatic structures typically being more persistent than the other compounds. As such, biochar decomposition is best described using a multipool decay function rather than a single pool model." The meta-analysis of incubation results therefore models biochar decay rate using a two-pool exponential model where one fraction of the material (presumed to correspond to the labile/aliphatic pool) has a higher decay rate and the other fraction (presumed to correspond to the recalcitrant/aromatic pool) has a lower decay rate. There is also a subset of results for which a three-pool exponential model was applied (this applied to only six sets of observations from two studies). In these cases, the additional pool could best be understood as an intermediate pool (i.e. the calculated decay coefficients for the most labile and most recalcitrant pools were comparable to those from observations fitted with the two-pool model, and the third pool had intermediate decay coefficients).

Even for biochars produced at relatively high temperatures (≥ 550 °C) and with an H/C_{org} ratio ≤ 0.7 there is a considerable range in the carbon loss rates implied by the fitted curves, as shown in Figure 2.1 (these curves are not corrected for incubation temperature, and include observations of incubations from 19 to 40 °C).

[7] *Greenhouse Gas Inventory Model for Biochar Additions to Soil* https://pubs.acs.org/doi/10.1021/acs.est.1c02425

Figure 2.1 Fitted exponential biochar carbon decay functions for observations on biochars with pyrolysis ≥ 550 °C and H/C_{org} ratio ≤ 0.7



Source: Woolf et al., 2021, supplementary information.

The data were transformed to a consistent soil temperature basis using the Q_{10} relationship described by Lehmann et al. 2015[8], which is also discussed further below (see section 2.4.3), and then average relationships were assessed between the pyrolysis temperatures and H/C_{org} ratio and the permanence of the biochar to form the basis of the inventory approach.

2.3.2 Scope

The analysis includes biochar produced by pyrolysis processes and gasification processes. Torrefaction and hydrothermal carbonisation processes were excluded from Woolf et al. (2021) on the basis that these processes typically use temperatures below 350 °C and that because the process temperature is lower than is typical for pyrolysis the material thereby produced shows a relatively low persistence. The dataset did however include four measurements for pyrolytic biochars produced at temperatures below 350 °C. The dataset covers a range of feedstocks including woody material, leaves, agricultural residues, grasses, cow manure, poultry litter and paper mill sludge. The dataset was limited to studies with at least one year of decay data.

2.3.3 Quantification

Woolf et al. (2021) provides the following inventory equation for GHG impact of biomass additions to mineral soils:

$$GHG_{bc} = M_{bc} \cdot F_C \cdot F_{perm} \cdot 44/12 + 0.23 \cdot n \cdot GWP_{N_2O}$$

[8] https://www.routledge.com/Biochar-for-Environmental-Management-Science-Technology-and-Implementation/Lehmann-Joseph/p/book/9780367779184

In this equation, $\mathrm{M_{bc}}$ is the mass of biochar added to soil, $\mathrm{F_C}$ the organic carbon fraction in the biochar, $\mathrm{F_{perm}}$ the fraction of biochar carbon remaining after a defined time period (with the default being 100 years), n the baseline annual N_2O emission on an area to which at least ten tonnes of biochar is applied per hectare.

Other possible GHG effects are excluded either because they are handled in other parts of the GHG inventory system (e.g. changes in biomass carbon stocks on land are estimated in the LULUCF inventory) or in order to be conservative (e.g. negative priming).

2.3.3.1 Organic carbon fraction

The $\mathrm{F_C}$ value can either be directly measured for the specific biochar produced or can be estimated. Organic carbon content on a 'dry ash-free' basis can be estimated:

$$F_{C,daf} = 0.93 - 0.92e^{-0.0042T}$$

where T is the pyrolysis temperature. Calculating the carbon fraction in the whole biochar requires also considering the ash content (see the Woolf et al., 2021, paper for details).

$$F_{a,bc} = \frac{F_{a,bm}}{F_{a,bm} + Y_{bc}}$$

where the biochar yield (fractional) is on a 'dry ash free' basis and is modelled as a function of temperature and lignin content:

$$Y_{bc} = 0.1261 + 0.5391\, e^{-0.004T} + 0.002733L$$

Ash and lignin content are to be taken from the Phyllis2 database, and a summary set of values is tabulated in Woolf et al. (2021).

2.3.3.2 Permanence

Tabulated permanence coefficients $\mathrm{F_{perm}}$ are provided for a set of soil temperatures, times, and pyrolysis temperature ranges. Some example coefficients are tabulated in Table 2.1 for time periods of 100 and 500 years.

Table 2.1 Examples of tabulated F_{perm} values from Woolf et al. (2021).

Time period	Soil temperature	F_{perm}		
		350–450 °C	450–600 °C	≥ 600 °C
100 years	5 °C	0.84	0.89	0.94
	10 °C	0.72	0.79	0.88
	20 °C	0.57	0.67	0.79
500 years	5 °C	0.55	0.66	0.78
	10 °C	0.30	0.44	0.57
	20 °C	0.15	0.26	0.37

Notice that the $\mathrm{F_{perm}}$ values given in Woolf et al. (2021) for 20 °C soil temperature and 100-year residence are not identical to the values given in the earlier IPCC method – the values include in Woolf et al. (2021) are somewhat lower (0.57 versus 0.65, 0.67 versus 0.80, 0.79 versus 0.89 for low, medium, and high pyrolysis temperatures respectively).

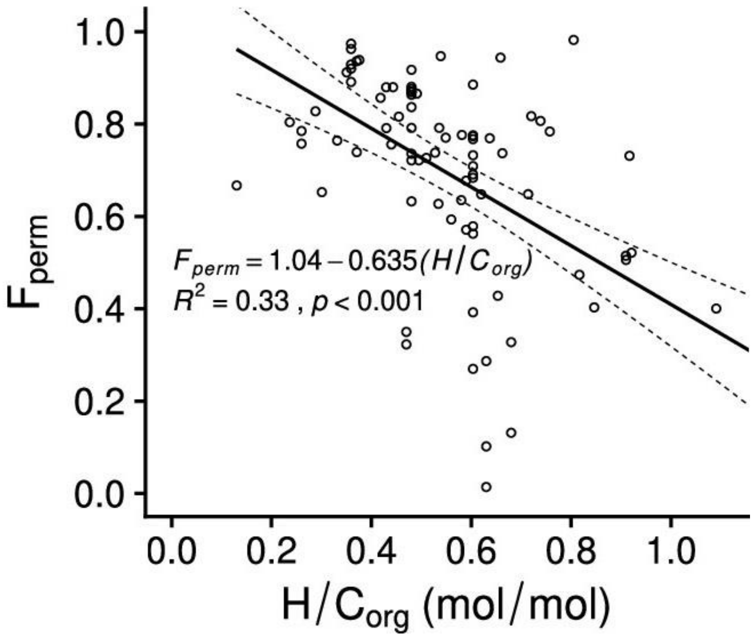
It is also noteworthy that, for higher soil temperatures in particular, the Woolf et al. (2021) functions imply very significant carbon losses for biochar resident in soil for 500 years or longer – even for high temperature biochar, the $\mathrm{F_{perm}}$ value is less than 0.5 at 20 °C. This result is not consistent with the view that a large fraction of the carbon in such biochar is essentially inert at plausible soil temperatures.

Woolf et al. (2021) also provides regression coefficients $\mathrm{c_{hc}}$ and $\mathrm{m_{hc}}$ for these time periods and soil temperatures to allow the permanence fraction to be estimated from the H/C_{org} ratio, instead of with reference to the pyrolysis temperature:

$$F_{perm} = c_{hc} - m_{hc}(H/C_{org})$$

Woolf et al. (2021) notes that H/C_{org} has been used in preference to O/C_{org}. The use of H/C_{org} rather than O/C_{org} is explained by reference to the potentially significant inorganic oxygen in the ash for some biochars, saying that the choice “becomes especially important when considering biochar with a high ash content such as that produced during gasification and/or derived from ash-rich feedstocks.” It should be recognised that the relationship in the incubation data between H/C_{org} and F_{perm} is not a precise linear correspondence, but a best fit regression to data with significant variation. This is illustrated in Figure 2.2 below, taken from Woolf et al. (2021), which shows the distribution of H/C_{org} ratio against estimated 100-year biochar permanence for the incubation studies considered (where H/C_{org} ration was known), as well as the fitted linear regression.

Figure 2.2 Distribution of H/C_{org} ratio against estimated 100-year biochar permanence



Source: Woolf et al. (2021) Figure 1

2.3.4 Co-benefits

The paper identifies a number of potential co-benefits from biochar use in agricultural soils:

- Potential reduction of soil CH_4 and N_2O emissions (but it notes that N_2O impacts may decrease over time, and "there is little consensus on which conditions correspond to increased or decreased net [CH_4] emissions or uptake"). The overall GHG inventory equation given includes a one year 23% assumed N_2O reduction on top of the carbon storage from the biochar.
- Avoided CH_4/N_2O from biomass decomposition (if the biochar feedstock would have decomposed naturally in a counterfactual scenario).
- Improved agricultural yield/net primary productivity.
- Potentially reduced rate of mineralisation of soil organic carbon ('negative priming'). The paper notes, however, that "the net negative priming was not significant at $P < 0.05$ in currently available meta-analyses."[9] The inventory equation therefore conservatively excludes a term for negative priming even though the studies considered, "all support the expectation that priming will become increasingly negative rather than positive over a period of several years". The paper further notes that these results relate only to mineral soils, there is a dearth of results for organic soils or for forest soils with substantial organic horizons, and that, "One study on priming of forest soil organic horizons found substantial losses of carbon over a ten-year period with charcoal additions" – but this study was unable to distinguish carbon mineralisation from leaching.
- Reduced fertiliser requirements in agriculture due to improved nutrient efficiency.

2.3.5 Sustainability risk

The paper also identifies some sustainability risks:

- Release of CH_4/VOCs during poorly controlled pyrolysis;
- Loss of vegetative carbon stock; and,
- Biomass production emissions.

2.4 'Modelling biochar long-term carbon storage in soil with harmonized analysis of decomposition data', Azzi et al. 2024

Azzi et al. (2024)[10], in work sponsored by the Swedish Energy Agency, provides a more recent meta-analysis of data from biochar incubation studies, reproducing and going beyond the analysis presented by Woolf et al. (2021). As well as considering a slightly expanded set of biochar observations to the set considered in Woolf et al. (2021), Azzi et al. (2024) provides a much more detailed discussion of the curve fitting methodology than is available in the Woolf et al. (2021) work, and considers an additional functional form for the decay rate. Azzi et al. (2024) argues that the transparency of some previous studies was limited by a lack of documentation of curve fitting algorithms, "Curve fitting is an optimisation problem that does not always have a unique solution, and which can be sensitive to both irregularities in

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[9] P here refers to the probability of observations being reported if the null hypothesis (no causal relationship of the variables) was true – not being significant at $P < 0.05$ means that there was a greater than 5% chance that the reported results were observed despite there being no actual negative priming effect.

[10] https://www.sciencedirect.com/science/article/pii/S001670612300438X

experimental data and assumptions made." The Azzi et al. (2024) paper therefore includes a link to a data repository, where it is possible to review (and in principle to rerun) the computer code used for curve fitting. We are also grateful to the authors of Azzi et al. (2024) for sharing additional data on best fit curve parameterisations with us.

In addition to considering single-, double- and triple-pool exponential models for biochar carbon decay, Azzi et al. (2024) also considers a power model as an alternative functional form, following Zimmerman (2010)[11]. Whereas an exponential model assumes that the decay rate of each pool of material in the biochar is constant over time, the power model is consistent with a decay rate that decreases over time. Zimmerman (2010) explains the relevance of such a model by suggesting that, "Reactivity continuously and exponentially decreases as more labile or, perhaps, more physically accessible organic compounds oxidize, leaving behind a progressively more refractory or more physically inaccessible residue."

The mathematical form of the double exponential function is:

$$\mathrm{BC(t)} = \mathrm{c_1}\exp(-\mathrm{k_1} * \mathrm{t}) + (100 - \mathrm{c_1})\exp(-\mathrm{k_2} * \mathrm{t})$$

for constants $\mathrm{c_1}$, $\mathrm{k_1}$ and $\mathrm{k_2}$ established through the curve fitting procedure.

The mathematical form of the power function is:

$$\mathrm{BC(t)} = \mathrm{c_0}\left(1 - \frac{\exp(\mathrm{b})}{\mathrm{m}+1}\,\mathrm{t}^{\mathrm{m}+1}\right)$$

for constants $\mathrm{c_0}$, b and m established through the curve fitting procedure[12].

In practical terms, the main difference with the power model is that the modelled biochar decay over 100 years tends to be slightly reduced and the longer-term modelled biochar decay tends to be significantly reduced, although there are cases (typically for biochars with a lower permanence) where the power model predicts a more rapid decay than the exponential model.

2.4.1 Scope

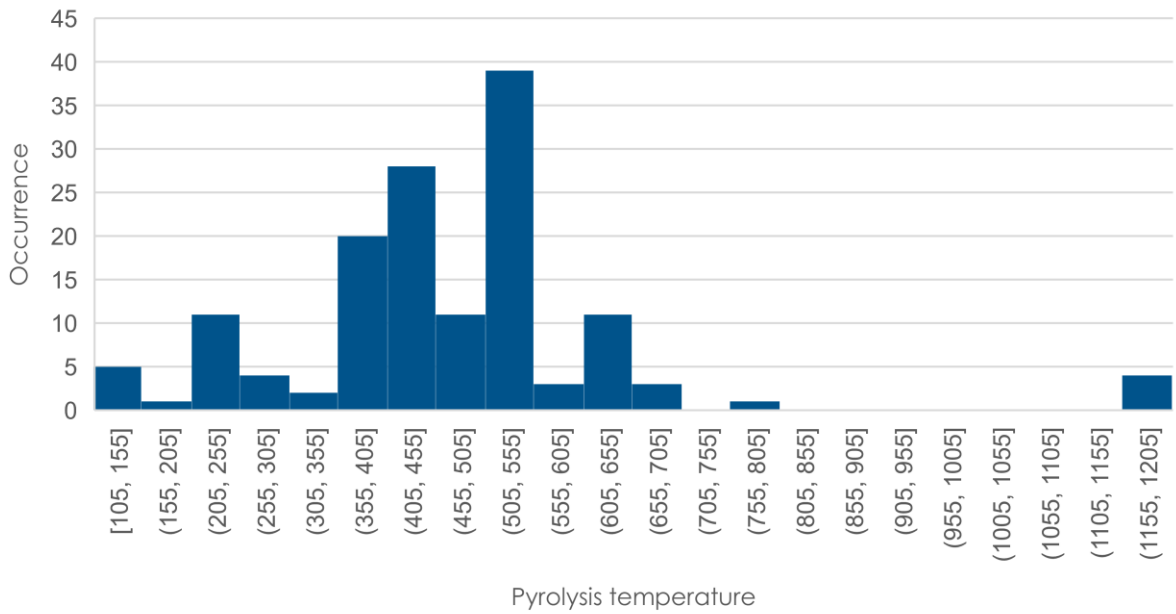
Most of the observations in the Azzi et al. (2024) dataset are from slow pyrolysis (95%) with only a few reflecting gasification, hydrothermal carbonisation, or flash carbonisation. Most results were for laboratory scale biochar production (rather than commercial production) and most biochars were produced with peak temperature between 350 and 650 °C (see Figure 2.3). A range of soils was represented, but most soils were characterised as sandy and few as clay rich. Most of the studies considered were based on laboratory incubations, but 8 out of 129 results were based on studies in the field. Most incubation studies used temperatures between 20 and 35 °C. Slightly over half of the considered biochars were produced from woody feedstock, a quarter from crop residues, a sixth from grasses and the remainder from manure, leaves and biosolids. H/C_{org}[13] ratios ranged from 0.13 to 1.4, with a median of 0.54.

[11] https://pubs.acs.org/doi/10.1021/es903140c

[12] Strictly speaking this form of the power model is only applicable for values of $m > -1$, but this is the relevant regime for the observations assessed. The Azzi et al. (2024) supporting information gives a full function including specification at $m = -1$ and $m < -1$.

[13] Note that Azzi et al. (2024) reports that several studies assume that $C_{org} = C_{tot}$ – where it was not possible to identify C_{org} separately Azzi et al. (2024) used C_{tot} as a substitute.

Figure 2.3 Histogram of treatment temperatures in Azzi et al. (2024) dataset



Source: Own analysis on data from Azzi et al. (2024)

Azzi et al. (2024) states that the main data gaps in the dataset relate to:

1. Biochar produced above 600 °C;
2. Biochar with very low H/C ratio (<0.1);
3. Studies in field conditions;
4. Incubation in soil temperatures below 10 °C; and,
5. Characterisation of biochar samples using chemical and optical indicators of stability (Azzi et al., 2024, suggests that in principle it may be possible to undertake characterisation of remaining samples of biochar from previous experiments).

2.4.2 Quantification

The Azzi et al. (2024) data confirm results from previous studies the biochar decay rates in incubation experiments reduce over time, and that after initial periods decay rates are several orders of magnitude below those for fresh biomass. The paper notes that in some studies with longer incubation times the measured decay rates on biochar became comparable to those for lignite coal. Cumulative carbon loss in the incubation experiments varied from 0.02% to 22.6%, with a median of 1.4%.

Best fit curves for each set of observations were assessed based on four ‘strategies’ as follows:

1. Best fit considering the double-pool exponential function is constrained so that the sum of the two pools is equal to 100% of the carbon in the sample;
2. Best fit considering single-, double- and triple-pool exponential functions, considering also functions where the pools did not add to exactly 100% of the carbon in the sample;
3. Best fit considering only the power model formulation; and,

4. Best fit across all exponential functions and the power model.

Azzi et al. (2024) notes that previous studies have tended to assess the best curve fit based on the R^2 coefficient of determination statistic, but argues that this is not recommended for non-linear curve fitting. The fitting algorithms used by Azzi et al. (2024) instead rely on Bayesian information criteria (BIC). Azzi et al. (2024) notes that this meant that different best fits were identified than would have been chosen with R^2 as the sole determinant, but that in all cases the selected curves still had $R^2 > 0.9$. Azzi et al. (2024) notes that 'irregularities' in the data from some observations (such as periods in which the decay rate was observed to increase) could lead to results that are inconsistent with theoretical expectations, and therefore that visual inspection of the selected best fits is important. Azzi et al. (2024) suggests that there may be a case to exclude observations that include these sorts of irregularities if developing persistence correlations.

Under the curve fitting strategy that included all exponential models as options, the triple-pool exponential model delivered the best fit in slightly more cases than the double-pool exponential model. A small number of observations delivered best fits with the single-pool exponential model, but this was associated with datasets containing 'irregularities'.

Under the curve fitting strategy that considered all of the exponential models and the power model, best fits for similar numbers of observations were found with the power model and the double-pool exponential model, with slightly fewer cases being best described by the triple-pool exponential model and only a couple of observations finding a best fit with the single-pool exponential model. As expected, the power model generally predicted longer-term biochar persistence than the exponential models.

Azzi et al. (2024) also assessed which biochar parameters were the most relevant to consider as the basis of persistence estimates. Correlations were identified for elemental composition/molar ratios, fixed carbon, volatile organic matter content, pH, pyrolysis char yield and pyrolysis temperature. Correlations to the H/C_{org} ratio were assessed using both linear and power models, and were assessed for the full dataset and for reduced datasets excluding 'singular' observations and outliers, using the exponential-model fits and the power-model fits. For soil at 20 °C on the reduced dataset, Azzi et al. (2024) finds the following linear relationship for 100-year biochar permanence (BC_{100}) when correlating to the exponential model fits:

$$\mathrm{BC}_{100} = 1.18 - 0.752 * \mathrm{H/C_{org}}$$

which is similar to the relationship estimated by Woolf et al. (2021):

$$\mathrm{BC}_{100} = 1.01 - 0.65 * \mathrm{H/C_{org}}.$$

When correlating to the power-model fits, Azzi et al. (2024) gets the relationship:

$$\mathrm{BC}_{100} = 1.30 - 0.696 * \mathrm{H/C_{org}}.$$

The power model curve fits for the H/C_{org} relationship are:

$$\mathrm{BC}_{100} = 0.930 - 0.491 * \left(\mathrm{H/C_{org}}\right)^{1.98}.$$

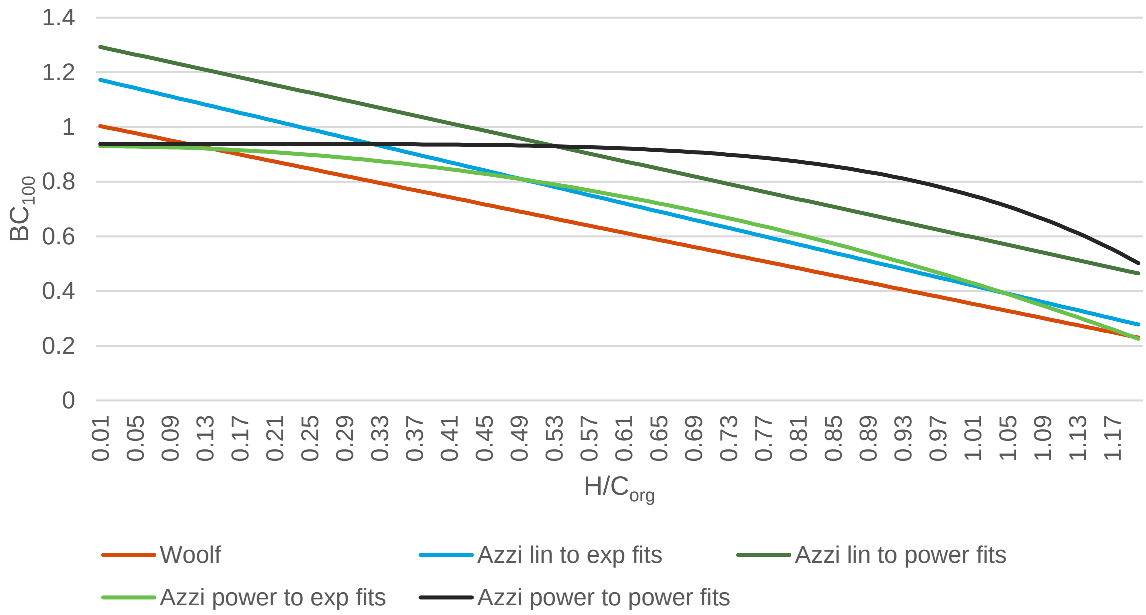
and

$$\mathrm{BC}_{100} = 0.938 - 0.180 * \left(\mathrm{H/C_{org}}\right)^{4.85},$$

assessed against the exponential- and power-model fits respectively.

It can be seen in Figure 2.4 that there are meaningful differences between the results from these different correlation equations. All of the Azzi et al. (2024) correlations generally predict a higher BC_{100} than the Woolf et al. (2021) relationship. The Azzi et al. (2024) linear correlations give a BC_{100} greater than 1 for the low H/C_{org} regime ($H/C_{org} < 0.24$ or 0.44 depending on the model) whereas the Woolf et al. (2021) function goes above 1 only for $H/C_{org} < 0.02$. The power model for the correlation against the power model curve fits in particular predicts significantly higher BC_{100} for relatively high values of H/C_{org}.

Figure 2.4 Correlations for H/C_{org} to 100-year biochar permanence from Azzi et al. (2024), compared against the relationship from Woolf et al. (2021)



Azzi et al. (2024) suggests that “the use of power regressions is preferred over linear regressions, for describing 100-year biochar persistence as a function of the H/C ratio”, but also notes that, “data selection, curve fitting, and soil temperature adjustment procedures significantly affect the persistence predictions”.

2.4.3 Temperature normalisation

Incubation studies are performed at a constant temperature, generally above a standard ambient soil temperature as the experiments aim to accelerate decomposition compared to real conditions. Results from experiments at different temperatures are only comparable if some sort of transformation can be applied from temperature A to temperature B.

Azzi et al. (2024) compares three soil temperature adjustment methods:

1. The ‘Q_{10}’ method that has been proposed based on previous work;
2. A stepwise Q_{10} method that makes the transformation as the product of a series of steps instead of as a single step; and,
3. An exponential method.

The Q_{10} transformation is defined:

$$\frac{k_b}{k_a} = \frac{1}{T_b - T_a}\int_{T_a}^{T_b}\left(1.1 + 12e^{-0.19T}\right)dT$$

Azzi et al. (2024) notes that the Q_{10} method as a functional model can be seen to be limited, because transforming the decay rate between temperature A and temperature B directly yields a different answer than making the transformation in two steps, via temperature C. The second, stepwise, approach resolved this mathematical property by defining the transformation as the product of small steps:

$$\frac{k_b}{k_a} = \prod_{i=0}^{n-1}\frac{1}{s}\int_{T_a+i*s}^{T_a+(i+1)*s}\left(1.1 + 12e^{-0.19T}\right)dT$$

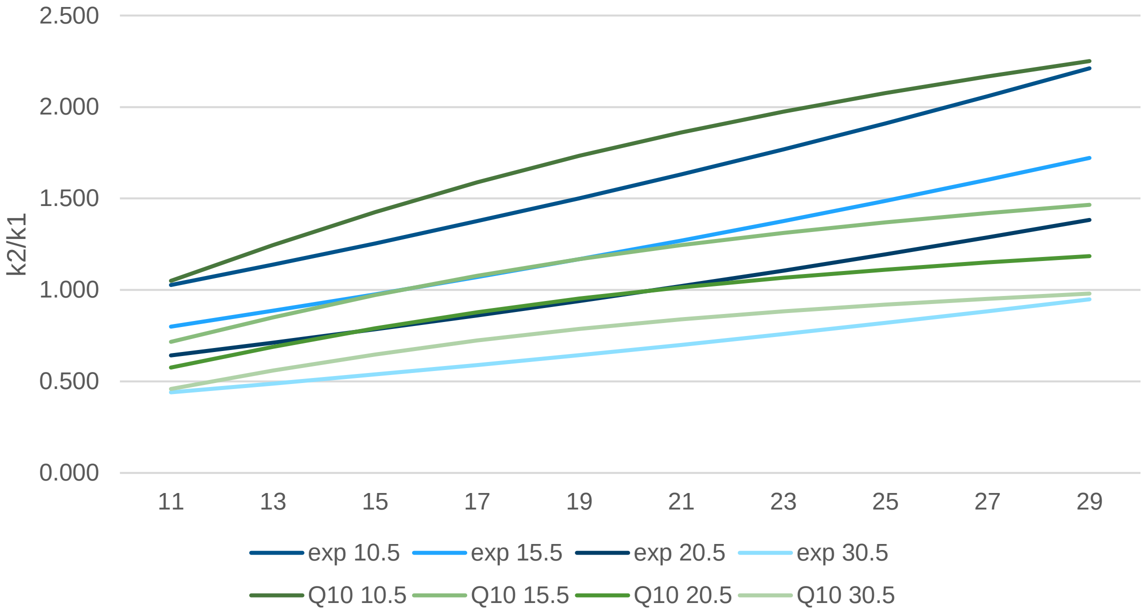
The ‘exponential’ method is derived from the data in Azzi et al. (2024) for experiments with H/C < 0.7 and pyrolysis temperature above 400 °C.

$$\frac{k_b}{k_a} = \frac{0.9e^{0.02T_b} - 0.7}{0.9e^{0.02T_a} - 0.7}$$

Azzi et al. (2024) states that the existing Q_{10} method may overestimate stability at low soil temperatures, and argues that the stepwise Q_{10} method or exponential method may give better results in this lower temperature regime. Azzi et al. (2024) notes that even with the exponential approach fitted to the data considered, the model was not well calibrated to convert from high temperature (>40 °C) incubations to standard soil temperatures. Several observations from higher temperature incubations were therefore treated as ‘singular’ and excluded from the main analysis.

We note that for the temperature regimes that are not considered poorly calibrated, the functions considered depart only slightly from linearity, and that the Q_{10} and exponential functions are concave and convex respectively in this regime (see Figure 2.5). Azzi et al. (2024) uses the exponential functional form to transform the incubations considered in the study.

Figure 2.5 Comparing the Q10 and exponential temperature correction functions, for four different values of T1, from Azzi et al. (2024)



2.5 'Assessing biochar's permanence: An inertinite benchmark', Sanei et al. 2024

Sanei et al. (2024)[14] approaches the question of biochar permanence by directly considering the constituents of biochar, and in particular the 'inertinite maceral'. The term maceral is used to describe organic material in coal and oil shales, and is used analogously to the term mineral for inorganic content. Sanei et al. (2024) argues that the petrology literature in reference to inertinite macerals has been overlooked in much of the discussion of biochar permanence (as soil scientists are typically not familiar with this literature), but that it is exceedingly relevant to biochars that consist of macerals very similar to those found in coal.

2.5.1 Inertinite

Inertinite macerals are found naturally not only in coal, oil shales and in biomass char, but also as a constituent of sedimentary rocks. Sanei et al. (2024) quotes an estimate of 15 million gigatonnes total carbon storage in inertinites in sedimentary rocks. The presence of inertinites in sedimentary rocks of geological ages demonstrates that inertinites *can* be very stable in at least some conditions. It is generally understood that higher degrees of aromatisation in hydrocarbons are associated with greater recalcitrance. Higher aromatisation is correlated to lower hydrogen fraction (and therefore low H/C_{org} ratio) and Sanei et al. (2024) shows that inertinite content as measured through random reflectance (this measurement is discussed further in section 2.5.2) in a biochar is inversely correlated to H/C_{org} ratio. Sanei et al. (2024) presents oxidation reaction kinetic modelling and states that the results are consistent with an oxidation half-life of 100 million years for a biochar sample

[14] https://www.sciencedirect.com/science/article/pii/S0166516223002276

maintained at 30 °C, but this modelling does not directly consider more complex potential degradation pathways such as enzymatic action.

Sanei et al. (2024) argues that biochar incubation experiments may not have been well designed to capture the high recalcitrance of inertinites where permanence is estimated through fitting a two-pool decay rate to observations. Most biochars contain some amount of condensates, as well as the 'true' biochar – this is material that could in principle have been evaporated off at biochar production temperatures, but that has remained attached in the vacuoles to the other more recalcitrant biochar fractions during the pyrolysis process. These condensates are relatively easily biodegraded, and therefore the most labile pool in a two-pool exponential fit reflects the low-permanence of these condensates. The second more recalcitrant pool reflects a combination of more recalcitrant materials, including inertinite and the semi-inertinite macerals. Sanei et al. (2024) argues that the decay rate estimated on this amalgamated recalcitrant pool will therefore tend to underestimate the permanence of inertinites (while implicitly overestimating the permanence of the other somewhat-recalcitrant fraction). In principle, one might expect that a triple-pool exponential model could avoid this problem, but in practice the curve fitting process for triple-pool models appears to tend to split the more labile pool into two sub-pools rather than disaggregate the recalcitrant pool, and therefore this approach does not resolve the problem.

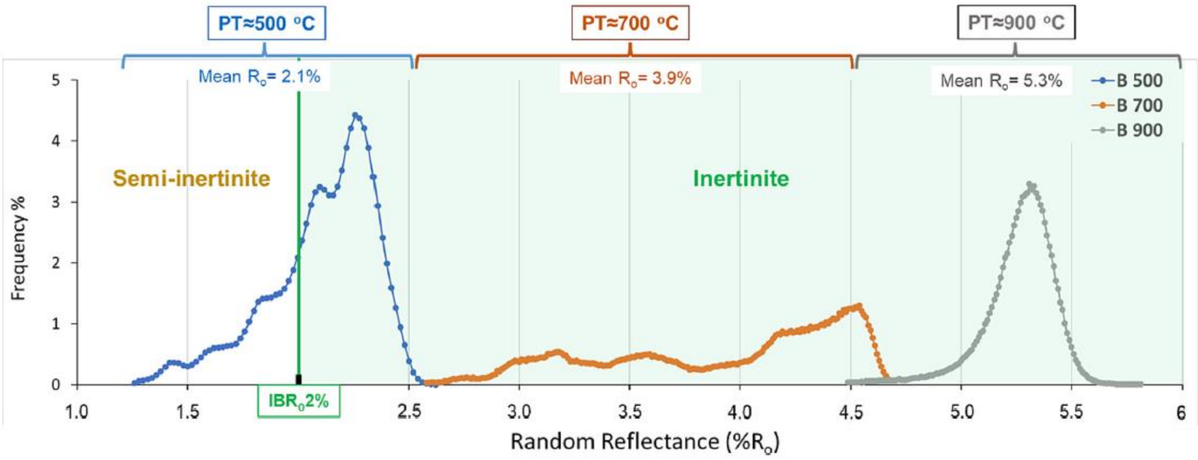
2.5.2 Quantification

Rather than proposing a permanence function in the manner of the IPCC approach, Sanei et al. (2024) suggests that biochar permanence could be assessed by direct assessment of the inertinite fraction. This can be experimentally achieved, according to Sanei et al. (2024), by assessing the 'R_o random reflectance'. The distribution of R_o can be assessed across the surface of a polished sample containing an organic carbon particle. This is an established technique for the characterisation of macerals in coal[15].

Sanei et al. (2024) states that inertinites are associated with a R_o value greater than 2%, while R_o values of 1.3-2% are associated with 'semi-inertinites' and lower values are associated with liptinites. Sanei et al. (2024) argues that if the R_o frequency distribution for measurements on hundreds of macerals across a representative biochar sample shows values consistently higher than 2%, then that sample can be understood as consisting solely of inertinite macerals plus any attached condensates (up to about 2%). For example, Figure 2.6 shows the R_o profile for biochars produced at 700 °C and 900 °C respectively being consistent with 100% inertinite content. This can be considered a benchmark for biochars with maximal permanence. Sanei et al. (2024) argues that "in order to consider biochar as a permanent CDR method, the industry should focus on production of pure inertinite".

[15] See e.g. https://www.uky.edu/KGS/coal/coal-analyses-vitrinite.php

Figure 2.6 R_o profile for bamboo biochar samples produced at three pyrolysis temperatures



2.5.3 Permanence indicators

While the central proposal in Sanei et al. (2024) is that biochar permanence can be assessed by R_o measurement, the paper also discusses the potential role of other biochar characteristics as proxies to indicate permanence.

As discussed above, the H/C_{org} ratio has been identified in some previous work (e.g. Woolf et al. 2021) as an appropriate parameter for estimation of F_{perm}. Sanei et al. (2024) argues that “the correlation between the most commonly used proxy, H/C molar ratio and the F_{perm} is not strong” and argues that the hydrogen index (HI) “is a more suitable aromatization proxy than the H/C ratio.” The hydrogen index is a measure of the prevalence in the biochar of liptinites, which are relatively hydrogen rich macerals with lower recalcitrance. Liptinites have $0.2 < R_o < 1.2\%$.

2.6 Summary – options and challenges for characterising biochar permanence

When assessing biochar as a carbon removal approach, the duration of carbon storage by the biochar is a central question in determining how many carbon removal units should be issued. It is generally agreed that it is not possible to accurately assess ongoing carbon storage by biochar in soils by direct monitoring, due to issues of uneven biochar distribution and transport of biochar beyond the area of application. In the case of biochar in materials, the likelihood of biochar transport out of the material is very low, but there is still a possibility of uneven distribution which would make precise assessment very difficult, and there is a fundamental problem that methods of testing for carbon in biochar are likely to be destructive to the materials in question.

Existing standards for carbon removals through biochar therefore rely on predictions of the long-term rate of loss of carbon from biochar, based on consideration of the results of incubation tests, in which samples of biochar in soil are kept at a constant temperature in moist soil for a period of a year or more and the rate of carbon loss is observed.

Such results from incubation tests informed the estimated values for biochar permanence that are included in the IPCC’s 2019 ‘Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments’, as discussed in section 2.2. This method is intended to provide a basis for the inclusion of carbon removals through biochar in national GHG inventory accounting, and therefore it assumes that the reporting party (the national inventory compiler) is not able to test biochar samples directly. The IPCC results are based on fitting a two-pool exponential model to available data, i.e. a model that assumes that biochar consists of two fractions, associated with two different exponential decay rates.

Woolf et al. (2021) presents an approach based on a slightly expanded analysis and that provides for a more precise estimate where the user has access to additional data to characterise the biochar. In particular, Woolf et al. (2021) provides a linear regression of the carbon permanence factor after 100, 500 or 1000 years against the ratio of hydrogen to organic carbon (H/C_{org}) in the biochar, a property that can be directly measured by sending biochar samples for laboratory analysis. The H/C_{org} ratio is an indicator of the degree of carbonisation and aromatisation of the biochar – a lower ratio is associated with a greater biochar permanence. It is generally agreed that H/C_{org} is a good practical indicator of biochar permanence, but it should be noted that there are several outlying observations that are not consistent with the calculated relationship.

Azzi et al. (2024) builds on the work of Woolf et al. (2021) by further extending the dataset of observations considered, by providing a more detailed discussion of curve fitting strategies for the available data and by systematically considering both exponential and power model fits to the available data. It is shown that for some sets of observations the power model provides a better fit than an exponential model, but there is no clear conclusion as to whether the power model is fundamentally more useful. From the point of view of certifying expected carbon storage after centurial timeframes, the major difference between the exponential model and power model fits is that the power models predict less carbon loss on long timescales. A power model will therefore be more likely than an exponential model to overestimate long-term carbon storage, while an exponential model will be more likely than a power model to underestimate long-term carbon storage.

Sanei et al. (2024) suggests an alternative approach to assess biochar permanence, based on identifying the fraction of a biochar sample that consists of inertinite macerals – a form of carbon with a low H/C_{org} ratio that is understood to be highly inert. It is suggested that the inertinite fraction of a given biochar could be treated as permanent on the timescales relevant to the CRCF, and therefore that if the inertinite fraction can be demonstrated it would not be necessary to refer to a decay function for that fraction.

The issues associated with these approaches (from the point of view of carbon removal certification under the CRCF) are summarised in Table 2.2 below.

Table 2.2 Summary of issues in modelling of biochar permanence

Approach	Advantages	Issues
100-year permanence fractions based on pyrolysis temperature (IPCC, 2019)	IPCC represents a credible official source The IPCC approach is simple	The IPCC approach is not intended for use at the project level, and assumes limited access to biochar data The IPCC approach is not intended to be final, but is presented as a "basis for future methodological development" Reports 100-year permanence only

Approach	Advantages	Issues
Permanence fractions based on exponential decay functions (e.g. Woolf et al., 2021, Azzi et al., 2024)	Builds on the IPCC work Woolf et al. (2021) reports permanence coefficients for 100, 500 and 1000 years – coefficients for other periods could be derived Can parameterise the relationship by H/C_{org} ratio The Woolf et al. (2021) relationship is already referenced in several standards Less risk of overestimating permanence on long periods than a power model	Treats the more-recalcitrant part of biochar as having a uniform decay rate If applied over several hundred years, the exponential decay functions can imply rates of carbon loss that are inconsistent with a view of a large fraction of some biochars being essentially inert Need to choose which of the calculated exponential relationships to use
Permanence fractions based on power model (e.g. Azzi et al., 2024)	Builds on the IPCC work Can parameterise the relationship by H/C_{org} ratio Azzi et al. (2024) reports permanence coefficients for 100 year period, coefficients for other periods could be derived The power model gives long-term results that are more consistent with the hypothesis that a significant fraction of biochar is highly inert	Unclear whether a power model is preferable to an exponential model Not currently used by any standards More risk of overestimating permanence on long periods than an exponential model
Inertinite assessment (e.g. Sanei et al. 2024)	Based on chemistry principles Testing identifies inertness directly rather than using H/C_{org} ratio as a proxy measure	Sample testing may be more expensive than current testing requirements There is not (yet) a clear consensus in the scientific community that inertinites can be treated as having a zero decay rate Does not provide a permanence estimate for biochars with lower inertinite content

3 Existing standards for certification of carbon removals through biochar

While the principle of the addition of biochar to soils is ancient, with the practice of charcoal addition to soils dating back thousands of years in the Amazon basin[16], the practice of biochar use as a carbon removal is recent. This section presents a review of certification methodologies for carbon removal through biochar addition that have been developed by private standards engaged with the voluntary market for carbon removals:

1. European Biochar Certificate (EBC) C-Sink
2. International Biochar Initiative (IBI)
3. Puro.earth
4. Verified Carbon Standard (VCS)
5. Riverse
6. C-Capsule distributed biochar
7. American Carbon Registry (ACR)
8. Sylvera (carbon credit ratings)

The description of each initiative includes a short introduction and (except in the case of Sylvera which is a rating approach rather than a certification approach, and the IBI which provides a production standard rather than removal certification) a discussion of the way that the standard handles quantification, indirect emissions and leakage, additionality and baselining, long-term storage and liability, sustainability, and MRV.

3.1 European Biochar Certificate C-Sink

The European Biochar Certificate (EBC) is a project developed by the Ithaka Institute for Carbon Strategies and operated by Carbon Standards International. Carbon removals certified by EBC are referred to as 'certified C-sinks'. Here we have reviewed version 2.1 (1 February 2021) of the "EBC-Guidelines for the Certification of Biochar Based Carbon Sinks" (henceforth the '*C-sink guidelines*') and version 10.3E (5 April 2023) of the "EBC Guidelines for a sustainable production of biochar" (henceforth the '*EBC Production Guidelines*').

The EBC allows a 'packaged unit' of biochar to be assessed against the *C-Sink Guidelines* and to be identified as a 'potential' certified C-sink at the factory gate prior to shipping for use in an agricultural or industrial application. Full certification of carbon removals requires an 'EBC accredited C-sink broker' to adjust the final C-sink value of a batch based on emissions and losses incurred during transport and use, after which the certified C-sink is created.

The EBC considers two biochar production processes to be eligible – pyrolysis and gasification. This echoes, for example, the IPCC guidelines.

The *EBC Production Guidelines* allow biochar to be identified into several certification classes depending on the use category. The main use categories are animal feed, agricultural soil enhancement, urban soil enhancement, consumer materials and basic materials. Slightly different requirements are placed on biochars certified for each of these

[16] https://en.wikipedia.org/wiki/Terra_preta

uses. For example, the feedstock for biochar for feed applications must be 100% plant matter.

The EBC defines six eligible categories for biomass:

1. Agricultural biomasses;
2. Organic residues from food processing;
3. Wood from landscape conservation, short rotation plantations, arable forestry, forest gardens, field margins, and urban areas;
4. Biomass from forest management;
5. Wood waste; and,
6. Other biogenic residues.

The EBC publishes a positive list of eligible feedstocks within these categories[17], but this list is relatively inclusive – for example, it includes all biomass from annual or perennial energy crops including food crops.

The sustainable production standards set rules on maximum allowable contamination in different applications. For example, biochars for soil use must be free of any contamination with paint residue or solvents, and are permitted a maximum 1% contamination with plastic and/or rubber waste. Biochar to be used as a feed additive may not be produced from animal by-products.

There are several requirements on the operation of the pyrolysis unit:

- Other than pre-heating, fossil fuels must not be used for heating the pyrolysis reactor;
- Produced pyrolysis gases must be recovered or burned;
- The facility must comply with local emissions regulations; and,
- Heat from gas combustion must be utilised with an efficiency of at least 70%.

The following properties must be declared for certified biochars:

- Fractional organic carbon content;
- Molar H/C_{org} ratio, which must be less than 0.7, or less than 0.4 for feed applications;
- Molar O/C_{org} ratio, which must be less than 0.4;
- Thermogravimetric analysis of volatile organic compounds – this is only required to be assessed in the first year of operation of a pyrolysis plant;
- Content of nitrogen, phosphorus, potassium, magnesium, calcium, and iron;
- Conformance with requirements on maximum heavy metal content, excepting the case of ‘EBC-basic materials’ (i.e. non-agricultural uses not in consumer products) for which there are no limits;
- pH, salt content, bulk density, and water content;
- Water holding capacity;
- Electrical conductivity; and,

[17] https://www.european-biochar.org/media/doc/2/positivlist_en_2022_1_v10_1.pdf

- Conformance with maximum limits on polychlorinated biphenyl (PCB) and polychlorinated dibenzo-p-dioxins and dibenzofuran (PCDD/Fs) content – this is only required to be assessed in the first year of operation of a pyrolysis plant.

There is also a recommendation to report specific surface area and pore size, but this is not made mandatory as it is considered potentially costly.

3.1.1 Quantification

3.1.1.1 Quantity of biochar applied

The *C-sink guidelines* are primarily concerned with managing the production of biochar up to the point that it leaves the factory gate as a packaged unit, at which point the unit has C-sink potential, but a full C-sink certificate is not generated until the final use of the biochar is identified. The *C-sink guidelines* state that the carbon sink may be considered to have been created at the point that the unit of biochar is put into a final storage site (e.g. soil or concrete) or is incorporated into a substrate "such as compost, litter, feed, fertilizer or cement, sand, clay, and lime", as after this incorporation it is no longer practical to combust the biochar. The *C-sink guidelines* anticipate the introduction of a central C-sink registry where information would be recorded including the owner and location of the site at which final storage is reached. The guidance suggests that this should include the GPS coordinates of the piece of land on which biochar was applied or the building in which biochar-enriched concrete was used. This is not mandatory in v2.0 of the guidelines, however.

The carbon content in a batch of biochar must be determined according to the EBC method.

3.1.1.2 Quantity of biochar considered stored on long-term basis

Long-term storage is to be estimated based on the expected carbon storage in biochar 100 years after its application.

For biochar with an H/C_{org} ratio of less than 0.4, the EBC certification assumes an annual degradation rate of 0.3% when used in agricultural soils. At his degradation rate, 74% of biochar carbon would remain sequestered after 100 years, 41% after 300 years. Based on previous meta-analysis, this is characterised as a conservative estimate, on the basis that some other studies have suggested significantly lower degradation rates.

For biochar with an H/C_{org} ratio between 0.4 and 0.7 a degradation rate must be applied that is parameterised by the H/C_{org} ratio, that is based on the IPCC guidelines or the book chapter "A biochar classification system and associated test methods"[18], and that is not less than 0.3% per year.

In the case of biochar incorporated into building materials (concrete, mineral plasters, gypsum, clay) a permanent sink may be assumed.

In the case of biochar used in other non-agricultural applications such as asphalt and plastic, the standard states that, "it can be assumed that the biochar persists and remains a C-sink for as long as the material itself persists", and therefore the duration of carbon storage must be assessed based on some form of monitoring of the proportion of the material that will not

[18] https://www.taylorfrancis.com/chapters/edit/10.4324/9780203762264-8/biochar-classification-system-associated-test-methods-marta-camps-arbestain-james-amonette-balwant-singh-tao-wang-hans-peter-schmidt

have been combusted after a given time. This may be assessed through “statistically validated lifetime averages”.

3.1.1.3 Other lifecycle analysis rules

Any emissions of CH_4 and/or N_2O are to be converted into CO_2e on a 20 year Global Warming Potential (GWP_{20}) basis. CH_4 emissions are to be offset by surrendering short term C-sink certificates[19]. This is not allowed for nitrous oxide as the warming from nitrous oxide emissions is persistent on a comparable timeframe to CO_2 emissions.

A standard factor of 1 tCO_2e per 100 kg applied nitrogen is applied to calculate GHG emissions associated with nitrogen fertiliser use. A standard default emission value of 94 $kgCO_2e$ per hectare of application is used for pesticides. Any fuel combustion associated with cultivation and harvest of biomass must also be accounted, using a standard emission factor of 3.2 $kgCO_2e$ per litre of diesel (about 89 gCO_2e/MJ, similar to but slightly lower than the lifecycle emissions value assumed for fossil diesel in the RED III, for example). Other cultivation and harvest emissions are not to be calculated directly, but rather are assumed to be covered by a 10% ‘margin of safety’ that is applied to the considered GHG emissions.

The *C-sink guidelines* note that storage of large quantities of biomass in moist conditions can lead to material degradation, including anaerobic formation of CH_4. These CH_4 emissions may be treated as zero if at least one of the following practices is followed:

- Biomass is chipped at most four weeks before pyrolysis; and/or,
- Biomass is dried to a moisture content of no higher than 25%; and/or,
- Biomass is pelletised; and/or,
- Biomass is stored in ventilated containers such as lattice boxes that prevent anaerobic decomposition.

If these practices are not followed, then in the case of woody material it must be assumed that 2.5% of the biomass carbon is degraded per month, of which 20% is assumed to form CH_4, of which 25% is assumed to be released to the atmosphere. In the case of non-woody material it is to be assumed that 0.25% of the stored carbon is converted to released CH_4 every month. These emissions must be accounted from the second month of storage onwards (the first month’s emissions are assumed to be covered by the safety margin).

Electricity consumed in biomass treatment and pyrolysis is to be accounted at the regional average grid electricity GHG intensity. If the pyrolysis plant exports at least as much electricity as it consumes, however, the electricity emissions are to be set to zero.

The *C-sink guidelines* also address the formation of CH_4 during the pyrolysis process and the risk that this CH_4 could be emitted and undermine the GHG performance of the project. The guidelines propose that the costs of actively monitoring CH_4 emissions from a pyrolysis unit to the appropriate efficiency would be prohibitively high, and therefore instead of setting a measurement requirement for all projects the guidelines require certification of the equipment type, which should be based on measurement of CH_4 from at least three operational examples of the equipment type.

The *C-sink guidelines* adopts what it refers to as a ‘margin of safety’ approach as an alternative to requiring LCA of feedstock production. The standard treats the emissions from

[19] The premise being that as the warming effect of methane emissions is relatively short lived, it is acceptable to offset them with short term emissions reductions/removals

most feedstock cultivation and collection as out of the scope for assessment, instead adding a safety margin term to the emissions that is equal to an additional 10% on the in-scope emissions. The exception are terms for any nitrogen fertilisation for transport of biomass from the point of origin to the pyrolysis plant, which must be explicitly characterised.

3.1.2 Indirect emissions and leakage

There is no consideration of indirect land use change emission or of emissions associated with the displacement of biomass resources from existing uses.

3.1.3 Additionality and baselining

The C-sink standard does not require any demonstration of additionality for biochar projects and does not require any explicit baseline assessment.

3.1.4 Long-term storage and liability

There is no requirement for long-term monitoring of biochar in situ and no accommodation for biochar producers to be made liable for later reversals.

3.1.5 Sustainability

Several sustainability principles are expressed in relation to biomass supply, but it is not always clear whether and how compliance with these principles is to be assessed during the certification process. For example, the standard says in relation to agricultural residues that, “it has to be ensured that the removal of harvest residues does not decrease soil organic carbon stocks”, but there are no specific certification requirements stated to ensure this principle is observed.

In the case of wood harvested from “forest gardens, orchard meadows, tree lines, and hedges” the certification requirements state that “the amount of wood removed per unit area does not exceed the amount of the annual regrowth”, but again there is no specific guidance on how to assess this.

In the case of plantation forestry for biomass production, there is a requirement that “it must be ensured that biomass production is maintained on the corresponding area either through new planting or rejuvenation”.

In the case of biomass from forest management the requirements are more detailed. There is a requirement stated that forest should be considered in hundred-hectare units, and that the annual wood harvest must be balanced by new growth on each forest unit. The canopy cover in the unit must not fall below 75%, and at most 80% of the wood harvested should be removed from the forest (i.e. 20% should be left for nutrient cycling and to support biodiversity). These requirements at the forestry unit level were effectively temporarily suspended, however, pending the reform of the LULUCF Regulation (this revision was passed in 2023, cf. https://climate.ec.europa.eu/eu-action/land-use-sector_en). Pending the next revision of the EBC rules, biomass harvested from a forest that can demonstrate that growth exceeds removals at any larger scale (e.g. of the order of 10,000 hectares) is to be treated as eligible. It is therefore unclear whether and in which cases the principle of assessing one hundred hectare forest units will be operationalised.

Other wood wastes and biogenic residues are generally to be treated as carbon neutral resources, although in the case of new categories of biogenic residue the certification guidance calls for assessment during certification.

3.1.6 MRV

The EBC includes a system for registering and tracking batches of produced biochar. All batches must be registered on the EBC website and assigned an ID number and corresponding QR code. Each production batch must share (up to a defined tolerance) a single production temperature and a single feedstock mix. A single batch may include biochar produced over a period of up to one year.

Each biochar production company must adopt a sampling plan which is to be agreed during the initial audit. Samples must be taken by an accredited sampler, but it should be noted that accreditation is available to representatives of the biochar producing companies and so the accredited sampler need not be independent. Samples are to be sent to an accredited laboratory. The accredited inspection company (bio.inspecta/q.inspecta) is also entitled to “take additional samples at any time”. Further, daily one litre samples of the produced biochar must be taken, aggregated over a month, and stored in dry conditions for two years.

EBC inspections are to be carried out once a year by the accreditation company bio.inspecta (also trading as q.inspecta).

3.1.7 EBC Global Artisan C-Sink

In addition to the *C-sink guidelines*, Carbon Standards International offers bespoke guidelines for ‘artisan’ small-scale biochar production in low income, lower middle income, and higher middle income countries[20] (‘*Global Artisan C-Sink - Guidelines for Carbon Sink Certification for artisan biochar*’)

production. These are targeted at either farmers producing up to 100 cubic metres of biochar per year for application on their own farms (‘C-Sink farmers’), or small-scale producers of up to 1500 cubic metres per year for sale (‘Artisan Pro’). Other than scale, the main difference between the industrial and artisan guidelines is that artisan producers are expected to use ‘Kon Tiki kilns’ rather than industrial pyrolysis facilities.

The production of biochar in small-scale kilns is often associated with release of pyrolysis gases including CH_4, and uncontrolled release of these pyrolysis gases can cancel out the climate benefit of carbon storage in biochar. The artisan guidelines therefore only certify biochar production technologies such as the Kon Tiki kiln that are designed to minimise uncontrolled off-gassing. The Kon Tiki kiln was developed by the Ithaka Institute and is a type of kiln that uses ‘flame curtain pyrolysis’ to reduce emissions of pyrolysis gases – the idea is that the pyrolysis gas is oxidised as it rises into the flame curtain. A Kon Tiki kiln is intended to deliver persistent biochar temperatures of over 400 °C. Avoiding CH_4 emissions is not only a question of kiln design, but also of managing the charring process. The guidelines note that, “If the feedstock is not layered with care and the flame curtain is disrupted, smoke may arise from the kiln and within the smoke CH_4. For that reason, the training and proof of expertise of the artisan biochar producers are of utter importance.”

Even a well operated Kon Tiki kiln is still associated with a residual level of CH_4 emissions, with the average emissions reported as 30 kg CH_4 per tonne of biochar produced. As in the

[20] As defined by the World Bank.

main *C-sink guidelines*, this should be accounted as a GHG emission on a 20-year GWP basis, as opposed to the 100-year GWP accounting that is standard in UNFCCC inventory accounting and in much lifecycle analysis. The choice of a 20-year GWP is explained on the basis that most of the warming effect of CH_4 emissions occurs within the first 20 years after emission. With a 20-year GWP of 86, 30 kg of CH_4 emission is equivalent to 2.6 tCO_2 emissions. The guidelines require these CH_4 emissions to be offset through temporary carbon removal by tree planting – the carbon sequestration in biomass over twenty years of tree growth must deliver 2.6 tonnes of temporary CO_2 removal for every tonne of biochar produced.

The artisan guidelines state that biochar produced in a Kon Tiki kiln following the training given to operators should reach temperatures of over 650 °C and achieve an H/C_{org} ratio < 0.4. Artisan operators are not required to undertake biochar testing, but Artisan Pro operators are required to test for H/C_{org} ratio. The guidelines set a standard assumption of 26% biochar degradation over 100 years, i.e. 74% of the biochar is treated as long-term storage. The degraded 26% may be treated as short-term storage with a mean residence of 50 years, and the guidelines permit this to be offset against CH_4 emissions, reducing the tree planting requirements.

3.2 International Biochar Initiative

The International Biochar Initiative (IBI) is a membership organisation that describes itself as providing, “a platform for fostering stakeholder collaboration, good industry practices, and environmental and ethical standards to support biochar systems that are safe and economically viable”. IBI does not provide a carbon removal certification; rather it sets biochar product definition and specification standards. Here we have reviewed version 2.1 of the standard, dated November 2015[21].

The standard does not address issues of feedstock sustainability, which are taken as out of scope, but it does impose some basic feedstock restrictions.

The standard sets a maximum 2% limit on ‘contaminants’ in the feedstock, where contaminants are defined as “An undesirable material in a biochar material or biochar feedstock that compromises the quality or usefulness of the biochar or through its presence or concentration causes an adverse effect on the natural environment or impairs human use of the environment”, and include fossil fuels, fossil derived chemical compounds such as plastics, glass, and metal objects. Contaminants exclude non-biomass ‘diluents’, which include soil, clay, and gravel and which are not carbonised by heat treatment in the same way as biomass. If feedstock is grown on contaminated soil it must be subject to toxicity assessment, and municipal waste is not eligible as feedstock if it contains hazardous materials.

The IBI standard requires testing for a range of properties. All biochars must be tested for ‘basic utility properties’ and for toxicants, and an additional set of optional tests is available to assess properties primarily relating to soil enhancement value. The basic utility properties are:

- Moisture content;
- Organic carbon content;
- H/C_{org} ratio;
- Total ash;

[21] https://biochar-international.org/standard-certification-training/biochar-standards/

- Total nitrogen;
- pH;
- Electrical conductivity;
- For alkaline biochars, liming (% $CaCO_3$); and,
- Particle size distribution.

The maximum allowable H/C_{org} ratio is 0.7.

The IBI standard details expectations for the conduct of biochar sampling and testing and for the qualifications of laboratory testers and accreditation of laboratories.

Testing of basic utility properties must be performed at least annually, and test results must be updated following any ‘material change’ in feedstock or in processing parameters. A material change in feedstock is defined as a change affecting 10% of more of the feedstock base. Feedstock is grouped by type, so that for instance a shift from maize stover to wheat straw would be counted as a feedstock change, but a change between stover from two different varieties of maize would not count as a change. A material change in process is a change of at least ±50 °C in process temperature of a change of at least 10% in processing time.

Testing of toxicants must be performed annually except for ‘unprocessed’ feedstocks[22], for which testing once every three years is permitted. Again, retesting is required if there is any material change in feedstock or process.

In the case that biochar is stored uncovered outside after testing and is subjected to precipitation, the batch must be retested. Any biochar batch that is subject to precipitation prior to testing must be thoroughly mixed before sampling.

Ash from bioenergy production may be assessed against the IBI standard and potentially treated as biochar providing it is produced by combustion of ‘clean cellulosic material’ only, i.e. cellulosic material that has not been contaminated (such as treated wood) or sourced from a secondary waste stream (such as municipal waste). In addition to the normal sampling and testing requirements a sample of each batch of biomass ash produced must be taken, and one per quarter a composite sample must be tested for identified toxicants.

The standard requires biochar manufacturers to keep records of feedstock use including chain of custody records, and of test results for at least seven years.

3.3 Puro.earth biochar methodology

Puro.earth’s biochar methodology is advertised as being the first carbon removal crediting standard for biochar brought to the voluntary carbon market. It was first introduced in 2019 and later updated in 2022, presenting its second version. It is due for another review in 2024. Puro.earth states that the methodology is aligned with the IPCC definition of carbon removals.

The methodology is based off a Life Cycle Assessment (LCA) approach which includes an assessment of the entire project’s emissions from cradle-to-grave, i.e. infrastructure, production, transportation, and biochar application-related emissions. The LCA approach is aligned with the principles of ISO 14040/44 and includes emissions from:

- production and supply of the biomass (section 4.3 of the methodology);
- biomass conversion to biochar (section 4.4 of the methodology); and,

[22] Identified as residues of agricultural and forestry operations.

- biochar distribution and use (section 4.5 of the methodology).

The use of fossil fuels for ignition or heating of the pyrolysis reactor is permitted. However, the simultaneous firing of fossil fuels and biomass in the same reaction chamber is not permitted, as it could lead to fossil carbon being mixed into the produced char. The emissions associated with any use of fossil fuels during the production process are accounted for in the LCA.

Biochar production can lead to the generation of combustible gases including CH_4, and therefore there is a requirement in place for emissions control. For example, gases resulting from the pyrolysis process are treated and CH_4 is reduced to negligible amounts.

There could be several co-products resulting from the pyrolysis process such as excess heat, electricity, or bio-oil:

- If the pyrolysis co-products represent high-value products or a large share of the initial biomass energy content, then an energy allocation between the biochar and the co-products must be applied. Puro.earth is not prescriptive about whether this should be done on a lower or higher heating value basis (unlike, for example, the Renewable Energy Directive (RED III) which requires all allocations to be made on a lower heating value basis).
- If the pyrolysis co-products are not deemed to be “important”, then all the burdens are allocated to the biochar production (allocation factor of 100%).

The scope of the methodology includes applications which preserve carbon storage for at least 100 years. Applications for biochar that would result in carbon being returned to the atmosphere are out of scope e.g. fuel or reductant[23] uses. Eligible applications include (non-exhaustive list):

- Soil additives/amendments;
- Horticultural substrates;
- Feed and manure additives;
- Contaminated soil remediation;
- Filter materials;
- Wastewater treatment;
- Construction material; and,
- Landfill/mine absorber.

The biochar must meet any legal quality requirements for the relevant application that are in place in the jurisdiction where it is used. In jurisdictions where there are not any specific quality requirements, the biochar must meet quality thresholds as defined in either the International Biochar Initiative (IBI) Certification Program[24] or the *EBC Production Guidelines.* The methodology does not address what must be done in the case that local legal requirements are significantly weaker than the IBI or EBC requirements – as written, this may represent a limitation in the oversight. The methodology allows for deviations from the IBI/EBC quality standards, provided these deviations from threshold values are justified, are approved by Puro.earth, and are made public.

The methodology states that “biochar must be produced from sustainable biomass”. The standard refers to the lists of biomass types given by the IPCC Method for Estimating

[23] E.g. for reducing iron ore.

[24] See section **Error! Reference source not found.**, https://biochar-international.org/standard-certification-training/certification-program/

Change in Mineral Soil Organic Carbon[25] (see section 2.2 above) and the positive list of biomass feedstock of the EBC[26].

The IPCC list includes:

- Animal manure;
- Wood;
- Herbaceous (grasses, forbs, leaves);
- Rice husk and rice straw;
- Nut shells, pits, and stones; and,
- Biosolids (paper sludge, sewage sludge).

The EBC positive list of biomass feedstock includes:

- **Agriculture:** biomass from agricultural farms, including both residues and biomass deliberately cultivated for biochar production;
- **Forestry and wood processing**: Natural bark and wood, untreated or mechanically treated, from forestry operations, sawmills, or similar operations;
- **Landscape management**: Residues generated by municipalities, landowners, landscaping contractors, NGOs active in nature conservation;
- **Recycling economy**: Residual biomass, organic residues, and wastes from industrial processes ("defined source") or from collection/separation by specific recycling companies;
- **Kitchen and canteen waste**;
- **Food processing residues on vegetable basis**, from food industry and manufactures, food wholesale, supermarkets, convenience stores etc.;
- **Water maintenance & vegetal marine biomass**;
- **Textiles**;
- **Anaerobic Digestion**; and,
- **Sludges from wastewater treatment**.

Other eligible biomass would be "invasive species" causing environmental harm i.e. plants that are not native to the region. The following criteria for invasive species are to be followed:

- The species are recognised by an appropriate state or national authorities;
- The carbonisation of the cleared waste is not mandated or legally required by relevant authorities; and,
- The CO_2 removal supplier has procedures in place to differentiate the invasive species from other local species, and to avoid unplanned clearing of current native vegetation within the project area.

Finally, the biochar produced must have a molar H/C_{org} ratio lower than 0.7.

[25] 19R_V4_Ch02_Ap4_Biochar.pdf

[26] https://www.european-biochar.org/media/doc/2/positive-list_en_v10_3.pdf

3.3.1 Quantification

3.3.1.1 Quantity of biochar applied

The quantity of biochar produced must be documented through continuous documentation of the biochar production for each production period. Additionally, some form of documentation to establish a use in which carbon is sequestered on a long-term basis must be provided. This evidence may include, “an offtake agreement, documentation of the sale or shipment of the product, indicating the intended use of the product.” As we understand it, there is no provision for further verification of the use to which the biochar is put, and therefore the Puro.earth rules would not identify cases where, for example, biochar initially marked for soil use is instead supplied for a combustion or reductant application.

The amount of Carbon Removal Credits (CORCs) generated is calculated as equal to the amount of CO_2 sequestered by the biochar over a 100-year time horizon, minus life-cycle emissions from the pyrolysis process, the biomass provision, and the biochar use, following this equation[27]:

$$CORCs = E_{stored} - E_{biomass} - E_{production} - E_{use}$$

Where:

$CORCs$ is the amount of net CO_2e removed over 100-year period by the biochar production activity.

E_{stored} is the amount of CO_2 sequestered over a 100-year time horizon by the amount of biochar produced over the reporting period.

$E_{biomass}$ is the lifecycle GHG emissions arising from the production and supply of biomass to the production facility, including direct land use changes.

$E_{production}$ is the lifecycle GHG emissions arising from the transformation of the biomass into biochar, at the producing facility.

E_{use} is the lifecycle GHG emissions arising from the use of biochar, including its distribution up to the point of final use.

The unit for all terms is measured in tonnes CO_2e (metric tonnes i.e. 1000kg).

3.3.1.2 Quantity of biochar considered stored on long-term basis

Puro.earth requires the biochar carbon content determination to be accomplished via laboratory analysis. The analysis should determine the total organic carbon content and total hydrogen content and therefore allow calculation of the molar hydrogen to organic carbon ratio in the biochar.

The term E_{stored} is defined as the amount of CO_2 estimated to be sequestered over a 100-year time horizon by the amount of biochar produced over the reporting period. E_{stored} is to be calculated based on results published by Woolf et al. (2021) (see also section 2.3 above).

The Puro.earth biochar methodology uses the following biochar carbon sequestration equation to calculate E_{stored}:

[27] Puro.earth Standard, Biochar Methodology, Edition 2022 Version 2

$$E_{stored} = Q_{biochar} \times C_{org} \times F_p^{TH,T_s} \times \frac{44}{12}$$

Where:

$Q_{biochar}$ is the amount of biochar produced over the reporting period expressed in dry metric tonnes of biochar. It is very important to account for any moisture in the biochar produced, as failure to exclude the mass of water in the biochar would lead to overestimation of carbon storage.

C_{org} is the fractional organic carbon content of the biochar produced expressed in dry weight of organic carbon over dry weight of biochar.

$F_p^{TH,Ts}$ is the permanence factor of biochar organic carbon over a given time horizon TH in a given soil temperature T_S. It is also known as biochar carbon stability (%). The permanence factor is a linear function of the molar hydrogen to organic carbon ratio H/C_{org} of the biochar,

$$\mathrm{F_p^{TH,T_s} = c + m \times H/C_{org}}$$

where *m* and *c* are determined solely by the mean soil temperature and are to be sourced from a lookup table provided by Puro.earth, based on Woolf et al. (2021). In other words, the ratio H/C_{org} is the indicator of biochar stability. The methodology states that the produced biochar must have H/C_{org} <0.7. Materials with H/C_{org} <0.2 are classified as "hardly degradable in the environment"[28].

The factor $\frac{44}{12}$ is the ratio between the molar mass of carbon dioxide and the molar mass of carbon. This factor converts an amount of carbon to the corresponding amount of CO_2.
The methodology must be applied for a mean annual soil temperature representative of the climate[29] where the biochar is distributed and used. The global mean soil temperature of 14.9 °C can be used as a default value when a region cannot be defined.

3.3.2 Indirect emissions and leakage

Indirect land use changes are outside the scope of the Puro.earth assessment. The Puro.earth biochar project brochure states that projects are required to demonstrate that they "will not displace activities that create significant emissions outside the boundaries of the project", but it is not clear to us how this requirement is implemented in the biochar methodology.

3.3.3 Additionality and baselining

Projects are required to demonstrate the need for carbon finance to make them more financially attractive compared to the alternative of leaving biomass to decompose. Financial additionality is measured via investment analysis. Puro.earth also notes that "Even with substantial non-carbon finance support, projects can be additional if investment is required, risk is present, and/or human capital must be developed."

[28] One Step Forward toward Characterization: Some Important Material Properties to Distinguish Biochars - Schimmelpfennig - 2012 - Journal of Environmental Quality - Wiley Online Library.

[29] The global mean annual cropland temperature is about 14.9 °C but can vary between 5 °C and 25 °C between world regions. Please refer to Table 1 of the Puro biochar methodology for regression coefficient for estimating biochar stability at various soil temperatures.

The financial test requires "full project financials and counterfactual analysis based on baselines that shall be project-specific, conservative and periodically updated."

Suppliers must also show that the project is not required by existing laws, regulations, or other binding obligations, referencing the "Microsoft criteria for high-quality carbon dioxide removal"[30].

The default baseline emission scenario is set at zero and it does not account for CH_4 emissions from the decay of manure or combustion of waste biomass. However, there is an option to submit a non-zero baseline emission scenario if there is enough evidence that can be reviewed and accepted by Puro.earth.

3.3.4 Long-term storage and liability

The methodology specifies lifetime of carbon storage of 100 years, "with virtually no risk of reversal". It also accounts for local climatic conditions for the areas where biochar is applied in the calculation of carbon storage permanence. This relationship is based on the analysis in Woolf et al., 2021, which found a connection between biochar decomposition and soil temperature. There is no requirement for ongoing verification of carbon storage in biochar after initial certification.

3.3.5 Sustainability

As noted above, the Puro.earth requirements state that biomass must be produced from 'sustainable biomass'. The requirements for audit of the production facility state that, "The CO_2 Removal Supplier shall be able to demonstrate Environmental and Social Safeguards and that the Production Facility activities do no significant harm to the surrounding natural environment or local communities". Sustainability should be evidenced through an environmental impact assessment, environmental permit or 'other documentation' approved by the issuing body. Where other documentation is provided to support sustainability claims, it is required to "consider, where applicable, effects on human health, biodiversity, fauna, flora, soil, water and air, inter alia". It is not clear to us precisely what threshold level of environmental impact could be considered acceptable.

There are three additional sustainable biomass sourcing principles identified in section 1.1.2 of the Puro.earth methodology, but it is not entirely clear whether these are to be understood as hard requirements or as examples of systems to be considered sustainable:

1. For agricultural waste collection, it is required that 30% of residues are left on the field to maintain the health of the soil and crop levels;
2. Timber that has been damaged by a natural disaster and cannot be economically recovered or used as originally intended; and,
3. Invasive species cleared by an appropriate authority, where carbonisation of the waste is not required by existing regulation and where measures are in place to differentiate the invasive species from local species.

Additional biochar properties may need to be assessed as per the quality requirements of each type of biochar application (e.g. testing for polycyclic aromatic hydrocarbons and heavy metal contents). For example, the EBC positive list of biomass feedstock identifies cases in which particular attention should be paid to potential heavy metal contamination.

[30] Criteria for High-Quality Carbon Dioxide Removal (microsoft.com)

Beyond carbon removal, biochar projects are identified[31] as having potential to further contribute to up to 12 of the 17 UN SDGs:

- No poverty (SDG #1);
- Zero hunger (SDG #2);
- Good health and well-being (SDG #3);
- Clean water and sanitation (SDG #6);
- Affordable and clean energy (SDG #7);
- Decent work and economic growth (SDG #8);
- Industry innovation and infrastructure (SDG #9);
- Sustainable cities and communities (SDG #11);
- Climate action (SDG #13);
- Life below water (SDG #14);
- Life on land (SDG #15); and,
- Responsible consumption and production (SDG #12).

3.3.6 MRV

The biochar output from a production facility is determined as eligible for issuance of carbon removals only after a third-party audit and verification against the methodology is completed in a "periodic Output Report".

The producer of biochar is required to supply the following:

- Proof of origin and sustainability of the biomass feedstock with special certificate requirements for forest biomass (e.g. FSC, SFI, PEFC etc.);
- For non-forest waste biomass, certificates are not required, but raw material must be sustainably sourced;
- LCA data for the biomass production and supply;
- Documentation on the amount of biochar produced for the whole period, including any changes in production and calculation of the dry mass of the biochar produced;
- Evidence that the laboratories where analyses are conducted comply with national and international testing requirements;
- Evidence of a protocol in place to ensure both representative sampling[32] and appropriate testing frequency[33];
- Compliance with local environmental regulations[34] and an evaluation of emissions of pollutants to air, water, and soil supported with existing measures to limit negative impact and a commitment to improve environmental performance every year;
- Proof that the end-use of the product does not cause CO_2 to return to the atmosphere, i.e. documentation that it is not used as a fuel or reductant. As we understand the methodology this condition would be treated as automatically satisfied in the case of

[31] Puro.earth biochar brochure, https://carbon.puro.earth/biochar

[32] Biochar sent for analysis is representative of the batch produced.

[33] Biochar is sent for analysis as often as needed to reflect variability and seasonality in biomass feedstock and production conditions.

[34] "For instance, in the EU, biochar facilities above a certain size must comply with either the Industrial Emissions Directive (2010/75/EU) or the Medium Combustion Plants Directive (2015/2193/EU) (https://ec.europa.eu/environment/industry/stationary/index.htm"

biochar used in soil or construction applications, without any requirement for in situ monitoring. This proof could include offtake agreements of documentation of sale, and therefore as we noted in section 3.3.1 there is no active check to ensure that biochar is used in the stated application. The requirements state that the amount of biochar that is likely to end up in waste incineration at end of life is to be excluded, but it is not explicit how this fraction is to be identified for non-soil applications of biochar;

- Justification on the T_s chosen for the biochar carbon sequestration calculation.

3.4 VCS biochar methodology

The 'Verified Carbon Standard (VCS) has an active Methodology for Biochar Utilization in Soil and Non-soil Applications (VM0044, version 1.1[35]) which was released in July 2023 and falls under VCS Sectoral Scope 13 (i.e. waste handling and disposal of waste biomass). The methodology is claimed to be based on CDM methodologies and tools, as well as on the following:

- Intergovernmental Panel on Climate Change (IPCC) (2019) Appendix 4: Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development;
- International Biochar Initiative (IBI) Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil, v2.1; and,
- *EBC Production Guidelines*, v10.1.

The methodology is applicable to the production of biochar from waste biomass in a pyrolysis process or gasification process, or to the extraction of biochar from high-carbon fly ash generated as a by-product of a biomass boiler. The biochar may be used in a soil or non-soil application. Biochar produced from torrefaction and hydrothermal carbonisation is ineligible.

The expected permanence of the produced biochar is calculated for a 100-year period. The produced biochar must be utilised within soil or non-soil applications within the first year of its production.

For soil applications, biochar is used as a soil amendment on lands such as cropland, grassland, vegetated urban soils and forests, but not wetlands. It can be applied either to the soil surface (mixed with other substrates) or subsurface (as a unique soil amendment or with other substrates).

For non-soil applications, biochar must be produced in a "high technology production facility", i.e. a facility where all produced CH_4 is recovered or combusted, where the process heat is utilised, where appropriate pollution controls are in place and where production temperature is measured and reported. Any end-use applications where long-term storage of the biochar is possible to achieve are eligible. Similar to Puro.earth's biochar methodology, applications where the biochar produced is burned as a fuel and/or used as a reductant are not eligible.

The methodology includes a 'non-exhaustive' list of eligible waste biomass feedstock which includes:

- Agricultural waste biomass;
- Food processing residues;
- Forestry and other wood processing;
- Recycling economy;

[35] https://verra.org/methodologies/vm0044-methodology-for-biochar-utilization-in-soil-and-non-soil-applications/

- Aquaculture plants;
- Animal manure; and,
- High-carbon fly ash (HCFA) from biomass[36].

The methodology requires feedstock to be:

- "Biogenic waste biomass and not purpose-grown";
- Destined for decay or be combusted for purposes other than energy production in the absence of project activity;
- Not imported from another country;
- Compliant with sustainability criteria for the relevant feedstock category as listed in the VCS methodology in *Table 1: list of Eligible Feedstocks for Biochar Production)*[37];
- Compliant with the latest version of the *IBI Biochar Testing Guidelines* or the *EBC Production Guidelines*.

The biochar produced must have a molar H/C_{org} ratio lower than or equal to 0.7, must meet the *IBI Biochar Testing Guidelines* or the *EBC Production Guidelines* if it will be applied to soil, and must be used within a year of production.

3.4.1 Quantification

The quantification section of the methodology is developed as a framework to allow for inclusion of more feedstocks and other biochar end uses in the future.

The GHG emission removals during the biochar production stage are calculated based on the below formula. This calculates the difference between the organic carbon content in the biochar produced and the project emissions at production stage (i.e., pre-treatment of feedstocks and emissions from the production facility).

$$ER_{PS,y} = \sum_t \left(\left(\sum_k CC_{t,k,y} \times \frac{44}{12} \right) - \left(\sum_p PE_{PS,t,p,y} \right) \right)$$

Where:

$ER_{PS,y}$ are the GHG emissions removals at production stage in year *y* (tCO_2e).

$CC_{t,k,y}$ is the organic carbon content on a dry weight basis for biochar type *t* used for application type *k* in year *y* (tonnes).

$PE_{PS,t,p,y}$ are the project emissions at production stage *PS* for production of biochar type *t* at production facility *p* in year *y* (tCO_2e).

$\frac{44}{12}$ is the coefficient to convert organic carbon to tCO_2e.

Biochar properties and relevant parameters are influenced by the type of feedstock and the technology used, and any fossil fuel inputs used to create the final product. The methodology provides two types of calculation aiming to accommodate the parameters for two types of

[36] A by-product of biomass-based energy production, whereby the by-product is usually reinjected into the process. High-carbon fly ash from biomass is typically produced using boiler systems at lumber and other forestry-related facilities.

[37] Section 4, bottom of page 9.

production facility i.e. high and low technology facilities (see section 3.4.1.3 below). Furthermore, the different biochar applications (soil and non-soil) bring different decay rates into consideration for the corresponding amount of biochar used.

The methodology supplies a calculation for determining GHG emissions associated with processing and utilisation of biochar at the application stage and excludes emissions related to the production of materials with which the biochar is mixed (for non-soil applications). Processing of biochar includes activities before final end-use application, such as grinding, sifting and other mechanical biochar treatments. In cases where the processing of biochar is absent, the emissions are set at zero. As for emissions associated with the utilisation of biochar, emissions from fuel combustion or mixing of biochar with fertilisers are considered insignificant, and are therefore set at zero, as per *CDM AR-ACM0003 Afforestation and reforestation of lands except wetlands.*

The methodology accounts for emissions from transportation (distance >200km) of waste biomass at the different stages of the biochar lifecycle, i.e. from sourcing to the production facility and final transportation from the production facility to the end-use application location. The latter can consist of two transportation activities:

- Transportation from production facility to processing facility and from processing facility to the end-use site; or,
- Transportation from production facility to end-use site only.

Emissions from transportation are calculated as per *CDM Tool 12: Project and leakage emissions from transportation of freight.*

3.4.1.1 Quantity of biochar applied

The geographic location of the site where the biochar was applied (soil and non-soil) must be provided. For soil applications, at least one geodetic coordinate must be provided for each field where biochar was used, thus enabling sampling by the validation and verification bodies when required. For non-soil applications, similarly at least one geodetic coordinate of the place where biochar was applied or mixed to is required. However, for this end-use, the proof of application ends when biochar is converted into a “long-lived” material. The latter is monitored via “statistically validated lifetime averages” to ensure that the used biochar is not released back into the atmosphere.

The application of biochar (whether soil or non-soil) must be verified using chain of custody records, which link the biochar production to the biochar utilisation, although it is not entirely clear to us how the veracity of this chain of custody information is to be established.

3.4.1.2 Quantity of biochar considered stored on long-term basis

The methodology requires evidence that the biochar produced (and any final products) are “long-lived” via “lab results, peer reviewed literature or any other third-party evaluation of product assessment e.g. decay rate analysis”. For soil end-uses, the methodology offers what are described as ‘conservative defaults’ for 100-year biochar permanence fractions: 0.89 for processing temperatures > 600 °C; 0.8 for temperatures of 450 – 600 °C; and 0.65 for temperatures from 350 – 450 °C.

For non-soil applications, the information required must include the duration for which biochar is stored, i.e. the lifetime of the final product, as well as its compliance with applicable standards and specifications (e.g. for concrete). In the absence of application specific permanence data, the permanence fractions for soil applications may be used.

3.4.1.3 Production emissions

Project emissions during the biochar production stage are calculated based on the technology of the production facility, as described in section 3 of the methodology. High technology production facilities must fulfil the following criteria:

- meet the requirements of the *EBC Production Guidelines*;
- GHG emissions from the pyrolysis process must be either recovered or combusted;
- at least 70% of the generated heat is used;
- appropriate pollution controls must be applied; and,
- production temperatures must be measured and reported.

If any of these conditions are not met, the production facility is considered a low technology production facility.

Emissions from high technology facilities:

The first part of the calculation is to estimate organic carbon content of biochar (**$CC_{t,k,y}$**): the value is based on the mass of the biochar, its organic carbon content, and the decay rate[38] of organic carbon in the biochar over a 100-year period.

$$CC_{t,k,y} = \sum_{p} \left(M_{t,k,p,y} \times F_{Cp,t,p} \times PR_{de,k} \right)$$

Where:

$CC_{t,k,y}$= Organic carbon content on a dry weight basis for biochar type t used for application type k in year y (tonnes). Biochar type is based on the feedstock used to produce the biochar.

$M_{t,k,p,y}$= Mass on a dry weight basis of biochar type *t* for application type k produced at the production facility p in year y (tonnes).

$F_{Cp,t,p}$= Organic carbon content of biochar type t produced in production facility p per tonne of biochar, taken on a dry weight basis (percent). For high technology production facilities, this is defined through laboratory material analysis of biochar.

$PR_{de,k}$= Permanence adjustment factor due to decay of biochar per application type *k* (dimensionless). It is defined for soil or non-soil applications. The former is established via default values based on production temperatures (T_{prod}) (high, medium, and low temperature pyrolysis), referencing IPCC (2019) and Woolf et al. (2021). For non-soil applications, the project proponent provides the permanence values which must be supported by credible evidence[39].

The second part of the calculation is to estimate project emissions ($PE_{PS,p,y}$)

$$PE_{PS,p,y} = \left(P_{ED,p,y} + P_{EP,p,y} + P_{EC,p,y} \right) \times \frac{\sum_t \sum_k M_{t,k,p,y}}{M_{p,y}}$$

[38] For soil applications, the methodology supplies default decay values. For non-soil applications, the project proponent provides the permanence values or uses default soil decay values.

[39] The supporting evidence must meet the requirements for default factors established in Section 2.5.2 of the latest version of the VCS Methodology Requirements.

Where:

$PE_{PS,p,y}$ = Project emissions at the production stage for production of biochar at production facility p in year y (tCO_{2e}).

$P_{ED,p,y}$ = Emissions associated with the pre-treatment of waste biomass at production facility p in year y (tCO_{2e}). Pre-treatment of feedstock includes preparation (e.g. agglomeration, homogenisation, pelletizing etc.) and drying of feedstock. $P_{ED,p,y}$ is set at zero when a renewable energy source is used. In all other cases, it is calculated as the sum of the emissions associated with use of grid-connected electricity and emissions associated with combustion of fossil fuels utilized for pre-treatment of waste biomass. These are calculated as per the provisions of *CDM Tool 05: Baseline, project and/or leakage emissions from electricity consumption and monitoring of electricity generation* and *CDM Tool 03: Tool to calculate project or leakage CO_2 emissions from fossil fuel combustion,* respectively.

$P_{EP,p,y}$ = Emissions associated with the conversion of waste biomass into biochar at production facility p in year y (tCO_{2e}). These are the emissions resulting from the pyrolysis process which for high technology production facilities are considered "de minimis" and therefore set at zero.

$P_{EC,p,y}$ = Emissions due to the utilization of auxiliary energy for the purpose of pyrolysis at production facility p in year y (tCO_{2e}). $P_{EC,p,y}$ is set at zero when a renewable energy source is used, otherwise it is calculated as the sum of the emissions associated with use of grid-connected electricity and emissions associated with combustion of fossil fuels utilized for starting the reactor at a high technology production facility. These are calculated as per the provisions of *CDM Tool 05: Baseline, project and/or leakage emissions from electricity consumption and monitoring of electricity generation* and *CDM Tool 03: Tool to calculate project or leakage CO_2 emissions from fossil fuel combustion,* respectively.

$M_{t,k,p,y}$ = Mass on a dry weight basis of biochar type t for application type k produced at production facility p in year y (tonnes).

$M_{p,y}$ = Total mass of biochar on a dry weight basis produced in production facility p in year y (tonnes).

Low technology production facilities are usually deployed in smallholder and farm level settings and do not meet the requirements defined under the high technology production. These may be compared to the 'artisan' biochar production processes discussed in sections 3.1.7 and 3.6. GHG removals at production stage are calculated in a similar way to high technology production, but with some adjustments for low technology production.

The organic carbon content of biochar ($CC_{t,k,y}$) is similarly estimated based on the mass of the biochar, its organic carbon content, and the decay rate of organic carbon in the biochar over a 100-year period. The organic carbon content of biochar type t produced ($F_{Cp,t,p}$) is established via laboratory material analysis of biochar following the *IBI Biochar Testing Guidelines* or *EBC Production Guidelines*. However, in cases where this is not a viable option, default values are used as per the type of feedstock used[40] as per IPCC (2019) or Woolf et al. (2021). If a combination of feedstocks is used, then the more conservative value is used. Regarding the permanence adjustment factor due to decay of biochar ($PR_{de,k}$), it is

[40] Feedstock types include animal manure, wood, herbaceous (grasses, forbs, leaves, excluding rice husks and rice straw), rice husks and rice straw, nutshells, pits, and stones and biosolids (paper sludge).

often the case that low technology production facilities would not measure the production temperature, therefore a default value of 0.56[41] is used.

As for the second part of the calculation of biochar for low technology production facilities, project emissions ($PE_{PS,p,y}$) are determined in a similar way, including emissions associated with the pre-treatment of waste biomass, the conversion of waste biomass into biochar, and emissions due to the utilisation of auxiliary energy for the purpose of pyrolysis.

Emissions associated with the conversion of waste biomass into biochar at low technology production facility are calculated either via direct emission measurement or inserting data from peer-reviewed papers in a separate formula (they are not set at zero as in the high technology production calculation), containing average CH_4 emissions from producing one tonne of biochar (tCH_4/tonne) and global warming potential of CH_4 as per the VCS Standard.

3.4.2 Indirect emissions and leakage

The methodology states that emissions due to activity-shifting leakage or biomass diversion are considered zero, as currently only waste biomass is eligible for biochar production.

3.4.3 Additionality and baselining

The baseline scenario is the case of waste biomass left to decay or combusted for purposes other than energy production. The default net GHG emissions are set at zero. The methodology requires evidence to demonstrate the baseline scenario in the form of annual government records, or records of a waste disposal or production facilities. If relevant documentation is not available, data can be obtained either from existing literature and surveys of similar industry as a proxy, or through carrying out own surveys. Appendix 2 of the VCS methodology provides further guidance on how project proponents can demonstrate the fate of waste biomass in the absence of biochar production.

Additionality is demonstrated via an activity method and eligible biochar activities are placed on a ‘positive list’, meaning that they are treated as inherently additional. The methodology notes that an ‘activity penetration’ test has been undertaken for biochar: “the total mass of waste biomass converted to biochar amounts to five percent or less of the total mass of waste biomass available worldwide.” We note that in our previous review of carbon removal certification approaches[42] we commented that, “it is not obvious to us that this comparison of existing production versus global technical potential represents a useful metric for quantitative assessment” of additionality, but that the “broader qualitative conclusion that biochar production and application has a low market penetration compared to its potential is fair”. The activity penetration test is to be reassessed as per the *VCS Methodology Development and Review Process.* The activity method also requires a regulatory surplus test which follows the rules of the latest version of the *VCS Standard and VCS Methodology Requirements*.

[41] Value of 0.56 is used where the temperature of pyrolysis is not measured, recorded, and reported. Default value taken from Figure 4Ap.1(b) in IPCC (2019) Appendix 4: Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development. Available at https://www.ipccnggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Ap4_Biochar.pdf

[42] https://climate.ec.europa.eu/document/download/28698b02-7624-4709-9aec-379b26273bc0_en?filename=policy_carbon_expert_carbon_removals_with_permanent_storage_en.pdf

3.4.4 Long-term storage and liability

The methodology has a reversal risk mitigation section. This identifies purposeful combustion as a fuel source as a permanence risk, but argues that that risk is wholly mitigated by the requirement that biochar should only be used in approved applications with end-use monitoring.

The methodology also refers to natural and non-natural risks of reversal during and after use in approved applications. The methodology lists possible transport mechanisms (floods, wind, precipitation) that could take biochar outside the project boundaries and out of control of the project proponent. It concludes, however, that it is unlikely that transport will lead to carbon sequestration loss (as, for example, biochar can be deposited in sediments in water bodies where its persistence is expected to be no less than in the soil where it was originally applied).

Fire is identified as a more serious risk, as it could lead to immediate loss of carbon sequestration, but the VCS standard notes that combustion of material integrated into the soil sub-surface is unlikely as the temperature due to wildfires declines rapidly with depth. The standard therefore requires either that the biochar should be mixed into the soil, “ideally to a minimum of 10 cm depth”, or if surface applied that it should be intermixed into some other substrate, such as manures or composts (although there seems to be some confusion in the cross-referencing on this point, as it is linked to an applicability condition that appears unrelated).

In the case of biochar use for non-soil applications, natural risks are considered minimal and reversal due to combustion is “nearly impossible”. Non-natural risks are those related to and not limited to project management, financial viability, government policies, or community and stakeholder resistance. The methodology concludes that given the required mitigation actions the reversal risk is minimal.

3.4.5 Sustainability

The feedstock specific sustainability criteria listed in VCS’s Table 1 include the following:

- For agricultural waste biomass, documentation that removals do not lead to reduction in soil carbon stock or crop productivity, or else that in the baseline residues would have been burned, or else demonstration that not more than 50% of material is collected;
- For food processing residues, there is a requirement that residue production must not have been increased specifically to supply biochar feedstock (although it is unclear how this would be documented/identified as a concern);
- For forestry residues, demonstration that the forest stand is certified by a relevant forestry sustainability programme or has a sustainable management plan approved by a local authority;
- For non-forestry wood residues, material must not include residues of paint, solvents, or other potentially toxic material;
- For materials from the ‘recycling economy’ feedstocks must meet either the IBI or EBC threshold requirements on heavy metals and/or other contaminants;
- For plants from aquaculture, the feedstock must be a by-product of aquaculture undertaken for another purpose, and project proponents must demonstrate that invasive species were not purposefully introduced in order to qualify as biochar feedstock; and,
- Several specific requirements are placed on high-carbon fly ash (HCFA) as feedstock.

Biochar utilised for soil application must comply with biochar standards (*IBI Biochar Testing Guidelines* or *EBC Production Guidelines*) to prevent the transfer of unwanted heavy metals and organic contaminants to soil.

Waste biomass sustainability can be demonstrated via:

- Biomass certification schemes such as Roundtable on Sustainable Biomaterials (RSB);
- International Sustainability and Carbon Certification (ISCC); and,
- Any other certification scheme approved by a relevant legislative body or international body such as the European Union, CORSIA, and national/state governments.

The wider technological scope of the methodology includes a health and safety programme for workers to be in place to protect them from airborne pollutants and other hazards.

3.4.6 MRV

The monitoring and accounting practices revolve around three stages: sourcing, production, and application. The monitoring plan is developed according to the requirements of ISO 14064-2. The methodology provides a list of resources for monitoring, but a strict requirement for a monitoring system is outside the scope of the methodology. The methodology states that the project proponent is required to demonstrate that the biochar in non-soil applications is not combusted at the end-of-life of the product in which the biochar is used, it is our understanding that this does not imply a requirement for active monitoring of biochar in situ until end of life, but rather that this requirement would be satisfied by showing that the biochar is to be used in an application where combustion at end of life is unlikely.

Monitoring is required for emissions from the baseline and project scenarios. It includes tracking and documentation from the sourcing stage to the application stage. At the production stage, biochar production variables are monitored, i.e. production temperature and biochar material properties; and in some cases, default values are used. The methodology presents a list of data and parameters available at validation and those that are monitored at a given frequency.

Data and parameters at validation include:

- Organic carbon content of biochar for each biochar type on a dry weight basis (%) (obtained from material analysis or default values);
- Permanence adjustment factor due to decay of biochar (dimensionless) to be defined for application type;
- Global warming potential of CH_4;
- Average CH_4 emissions from producing one tonne of biochar in year *y* in a low technology production facility; and,
- Category and source of feedstock, fate in the absence of project activity, documentation to prove sustainability criteria compliance.

Data and parameters to be monitored include:

- Total mass on a dry weight basis of biochar produced in production facility;
- Mass on dry weight basis of biochar type and application type produced at production facility;

- Organic carbon content of biochar for each biochar type produced in production facility per tonne of biochar, taken on a dry weight basis (material analysis or default values for low technology facility);
- Average annual production temperature during pyrolysis (for low technology facility default values are used);
- Ratio of hydrogen to organic carbon (H/C_{org} of less than 0.7) (derived by laboratory analysis); and,
- Fraction of total waste heat utilised at biochar production facility (to qualify a high technology production facility).

3.5 Riverse biochar and BECCS methodology

Riverse describes itself as an 'impact certification platform', which issues credits for CO_2 avoidance or removal in the Riverse Registry. There is a common set of rules (the *Riverse Standard Rules*) applicable to all activities certified by Riverse, and Riverse's sector-specific methodology *"Pyrolysis of biomass for bioenergy with carbon capture storage"* allows certification of pyrolysis and gasification facilities used to produce some combination of syngas, bio-oil, and biochar. Version V1.0 of the methodology (version V1.0), published in September 2023, was the one reviewed in this paper.

The methodology covers the production of biochar by pyrolysis or by gasification. For the purposes of this paper, the focus is on the part of the methodology which refers to projects that produce biochar for carbon removals. Under the methodology, the biochar produced is limited to application to agricultural soils (unlike the EBC, VCS and Puro.earth standards, which allow both soil and non-soil applications).

The *Riverse Standard Rules* include 14 eligibility criteria for projects:

- C1 – Measurability;
- C2 – Real;
- C3 – Additionality;
- C4 – Permanence;
- C5 – Unicity[43];
- C6 – Co-benefits;
- C7 – Substitution;
- C8 – Environmental & social do no harm;
- C9 – Leakage;
- C10 – Rebound effects;
- C11 – Technology Readiness Level (TRL);
- C12 – Targets alignment;
- C13 – Minimum impact; and,
- C14 – Independently validated.

Prospective projects are required to provide responses to questions and support evidence for each eligibility requirement. As part of the eligibility criteria, projects are required to demonstrate they can achieve at least 40% reduction in GHG emissions when compared to the baseline scenario. Furthermore, there is a minimum-impact criterion of at least 1,000 tCO_2e avoided over a 5-year crediting period.

[43] No double counting of carbon credits

Feedstocks must be listed on the EBC's positive list of biomass feedstocks[44]. This list is rather broad, but Riverse also requires project developers to describe management strategies for sustainability issues associated with certain specific feedstocks (see also sections 3.5.2 and 3.5.5).

3.5.1 Quantification

A comparative LCA is conducted to calculate the amount of CO_2 that the biochar removes from the atmosphere. The life cycle stages in the methodology include:

- Sourcing, transport, and preparation of feedstock;
- Pyrolysis and gasification;
- Product upgrading and transport (for syngas and bio-oils products, not for biochar);
- Biochar soil amendment (i.e., biochar soil application); and,
- Infrastructure and machinery (assumed lifetime of 25 and 5 years respectively with option for project developer to suggest otherwise).

The biochar soil amendment stage includes the transportation of biochar from the production site to the application site. The calculation requires: (1) the distance between both locations; (2) specific geo-locations of the application sites; (3) the amount of biochar produced (dry mass); and (4) the organic carbon content of biochar and hydrogen content of biochar.

3.5.1.1 Quantity of biochar applied

The standard expects that all biochar that is counted as a carbon removal shall be used in soil applications. It asks producers to indicate where biochar will be applied to the soil with GPS coordinates, but it is unclear what verification would be required that biochar has actually been used in this way.

3.5.1.2 Quantity of biochar considered stored on long-term basis

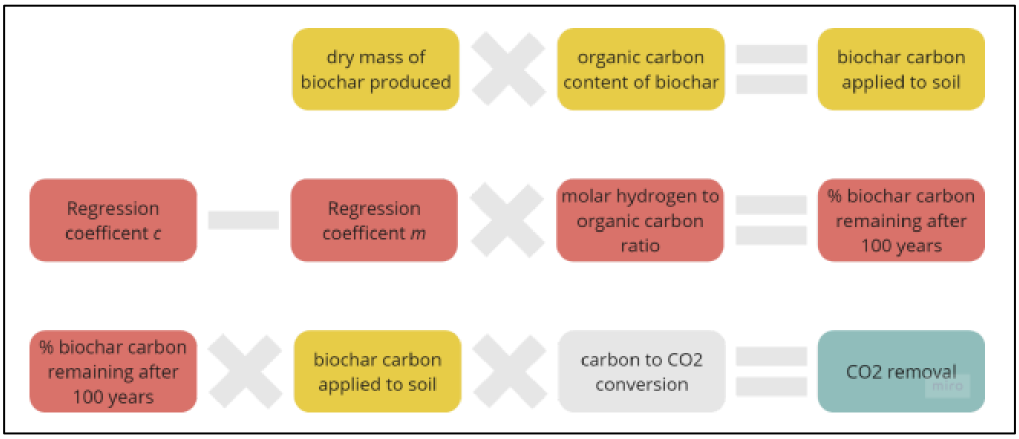
Carbon removals over a 100-year period are calculated using the models presented in Woolf et al. (2021) (Figure 3.1 below presents a schematic of the calculation. The calculation is based on the H/C_{org} ratio which is measured via a laboratory chemical analysis:

> *"The model calculates the percent of biochar carbon remaining after 100 years, using a regression equation for a given soil temperature and H/C_{org}. This percent is then multiplied by the amount of carbon applied in biochar, using the mass of biochar and the carbon content, to determine the amount of biochar carbon stored in soils after 100 years. This is converted to CO_2e using the molar mass ratio of carbon to CO_2."*[45]

[44] https://www.european-biochar.org/media/doc/2/positivlist_en_2022_1_v10_1.pdf

[45] BECCS and Biochar. Pyrolysis of Biomass for bioenergy with carbon capture and storage, Sector-specific framework, version V1.0, September 2023 https://drive.google.com/file/d/1cCuenUtSyd_8lm70OSr0ZKrIgSWiQGqA/view?usp=sharing

Figure 3.1 The calculations for determining the CO_2 removed from biochar. Regression coefficients are taken from Table 3 in Woolf et al. (2021)



Source: BECCS and Biochar. Pyrolysis of Biomass for bioenergy with carbon capture and storage, Sector-specific framework, version V1.0, September 2023

3.5.1.3 Other lifecycle analysis rules

The treatment of wastes (residues and ash from pyrolysis/gasification) is excluded from the methodology on the basis that it is a minor GHG emission source.

3.5.2 Indirect emissions and leakage

The methodology states "the project's avoided GHG emissions should not be indirectly transferred elsewhere." It identifies the risk of displaced fossil-based energy offsetting the net emissions reduction from bioenergy, but it states that this is outside the scope of the methodology. The methodology acknowledges the risk of rebound effects[46], but identifies this as something to be assessed by Riverse at the sector scale. It is unclear to us in what circumstances Riverse would identify the rebound risk as being so great that a project should be prevented from being certified.

3.5.2.1 Indirect land use change

The methodology identifies the following as major risks that could impact "local and far-off land use":

- Use of dedicated crops, competition for food and agricultural land; and,
- Deforestation from use of forestry products as feedstock.

Project developers are expected to describe how they will manage these risks, but it is unclear what would constitute a failure to provide adequate assurance.

[46] If the additional supply of bioenergy does not replace fossil energy on a 1:1 basis, but contributes to increased overall energy consumption.

3.5.2.2 Displacement from existing uses of waste/residual materials

The standard also identifies the risk of negative sustainability impact from excessive removals of residues from fields and requires operators to describe how this risk will be managed. Again, it is unclear what would constitute a failure to provide adequate assurance.

3.5.3 Additionality and baselining

3.5.3.1 Additionality

Projects are required to demonstrate regulatory and either financial or 'prevalence' additionality.

Regulatory additionality ensures that there is no local regulation that already mandates the project activity.

Financial additionality can be demonstrated based on satisfying one of the following conditions:

- Projects require financial funding to be operational or are operating at a financial loss, demonstrated by audited accounting documents which state negative financial state or an increase in the working capital.
- Projects require funding for technology improvements, demonstrated by a description of the improvements required, justification and rationale why these are needed, estimated cost and a description of restrictions in funding from other sources.
- Projects need funding for the development of a new additional site, demonstrated by a business plan showing reliance on revenue from the sale of carbon credits.

Prevalence additionality resembles the VCS's activity penetration test for converting waste biomass into biochar. The project must prove that it is not well established on the marketplace and that the funding would be utilised to subsidise or improve the project technologies to reach higher adoption and market penetration levels. It is unclear what proof of this point should be provided by the applicant.

3.5.3.2 Baseline

Under the methodology, the baseline scenario depicts the conditions in the absence of the project activity. For biochar only projects, the baseline is set at zero and there are no avoided emissions.

3.5.4 Long-term storage and liability

Eligible biochar projects are required to calculate carbon sequestered over a 100-year period and include it in a comparative LCA.

The permanence of the biochar is assessed by measuring the carbon and hydrogen content via a laboratory chemical analysis. The biochar produced must have a molar H/C_{org} ratio lower than 0.7 (the same as in the Puro.earth and VCS standards). The methodology is based on calculation models by Woolf et al. (2021), considering soil temperature, hydrogen, and organic carbon content, to estimate the amount of carbon stored in the soil in 100 years' time.

Regarding the issue of double-counting of carbon removals, the methodology states the usual provisions of counting only once, i.e. ensuring that removals are not registered in multiple registries or that they are being double-claimed (e.g. by the credits seller and buyers). There is an additional clause for a signed agreement between the biochar producer and farmers to prevent the user of biochar from claiming carbon credits.

3.5.5 Sustainability

The standard states that there is a 'strict limit' on the source of biomass feedstock, but feedstock eligibility is primarily determined by inclusion on the EBC positive list, which (as noted above) is a fairly comprehensive list of potential biomass sources that includes all energy crops. The feedstock eligibility is cross-referenced against a set of potential sustainability problems associated with feedstock sourcing:

- Use of dedicated crops leads to competition for food and agricultural land;
- Deforestation from use of forestry products as feedstock; and,
- Collection and export of organic matter from agricultural fields disrupts soil organic matter.

It is not clear how these feedstock risks are to be managed – the standard refers states that feedstocks must be waste products or sourced from sustainable production, but no definition of sustainable production is included beyond the requirement for inclusion on the EBC positive list.

"Heavy metal or other pollutants in biochar applied to agricultural soils" is one of the risk areas listed as part of the identified environmental and social risks to be considered by project developers. It is allocated a Major severity level. It must meet strict pollutant thresholds as per the *EBC Production Guidelines*, proven with a laboratory chemical analysis and a sampling protocol including sampling frequency, volume, composite and retention sampling and random sampling.

The methodology states that projects must provide at least two co-benefits from the UN SDGs. For biochar projects, a common co-benefit is *"15.1 Ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services",* which can be evidenced with contracts, invoices, receipts of sale of biochar to farmers.

The methodology presents a list of environmental and social risks which must be considered, but these can be expanded on a project-specific basis. The project developer must explain how each identified risk is managed. The Riverse team would use the provided information to complete a risk assessment matrix with allocated the likelihood and severity level (e.g. negligible, minor, moderate, major, and catastrophic) of each risk.

3.5.6 MRV

The monitoring plan, together with the LCA and detail project description, are required to be independently audited.

Projects are required to demonstrate a Technology Readiness Level (TRL) of at least six (TRL 6 - Technology demonstrated in relevant environment[47]). The project developer must

[47] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

supply proof of technological progress and/or production capacities either in an operational environment or a laboratory. Biochar projects that are already operational can demonstrate that they meet this TRL requirement by supplying receipts of biochar sales.

Key Impact Indicators (KIIs) are measured by the project developer on an annual basis and reported in the monitoring plan. KIIs are provided as part of the LCA including proof, source of proof and update frequency. For biochar projects, the functional unit which is used for comparison between baseline and project scenarios is the production and application of 1 tonne of biochar. Impacts per functional unit are calculated by dividing annual impacts by the annual energy production of the site.

3.6 C-Capsule distributed biochar

The C-Capsule carbon removal system has one approved carbon removal methodology, and it applies to ‘distributed biochar’ projects, i.e. projects producing biochar in small batches from non-industrial biochar kilns. The scope is somewhat similar to the EBC Artisan Biochar certification. Unlike the EBC Artisan standard though, the C-Capsule standard requires active digital MRV in relation to kiln operations, including real-time monitoring of weight and temperature data from each kiln.

Eligible feedstocks are restricted to:

- Animal or human manure/sewage;
- Invasive bush species;
- Agricultural processing residues;
- Staple crop residues; and,
- Forestry and wood processing residues.

Eligible biochar uses for removal certification are application to soils (either directly or via animal feed use) and non-agricultural uses, including blending with cement/concrete, blending with asphalt for road paving, geological sequestration, and any other application where long-term storage is demonstrated.

3.6.1 Quantification

3.6.1.1 Quantity of biochar applied

The number of certificates to be awarded are determined by the amount of biochar produced and its carbon content. Proof of biochar utilisation in an eligible use must be provided. This could take the form of:

- Computerised tracking of GPS location coordinates and chain of custody to the point of use;
- Photographic evidence of local use; and,
- An offtake agreement of documentation for the sale or shipment of the biochar to an end user.

The standard recognises the risk that proof of appropriate biochar utilisation could be falsified. This risk is to be managed by:

- Allowing certification issuance to be halted if the certifier, issuer, or operator has reason to believe that the biochar is being used in an ineligible way;

- The issuer 'satisfying itself' with the proof of end use, and being able to appoint a verifier for local investigation; and,
- Requiring certification to be stopped if an investigation concludes that biochar has been used outside the eligible uses.

The effectiveness of these risk management tools is likely to depend on how active the certifier/issuer is in monitoring risks of ineligible use.

3.6.1.2 Quantity of biochar considered stored on long-term basis

The C-Capsule methodology calculates biochar 100-year permanence based on the IPCC method, but substituting measurement of H/C_{org} ratio for reporting of pyrolysis temperature (so that a biochar with H/C_{org} ratio < 0.2 is estimated to have 89% permanence after 100 years, biochar with H/C_{org} ratio between 0.2 and 0.4 is estimated to have 80% permanence after 100 years and biochar with an H/C_{org} ratio between 0.4 and 0.7 is estimated to have 65% permanence after 100 years). The biochar carbon expected to be lost over 100 years is referred to as the 'leakage buffer'.

3.6.1.3 Other lifecycle analysis rules

An emissions inventory is to be developed describing emissions from feedstock transport, and from biochar production, transport, and use. Emissions from feedstock production are considered out of scope, but so are any avoided CH_4 emissions due to utilisation of biomass that may otherwise be allowed to decay.

For the Kon Tiki kiln a default CH_4 emission rate is set of 60 gCH_4/kg biochar, to be included in the calculation on a GWP_{100} basis (1.632 $kgCO_2e$/kg biochar), unless lower emissions can be demonstrated by emissions monitoring. The default value is considered conservative as it reflects the high end of emissions identified in an experimental assessment.

3.6.2 Indirect emissions and leakage

There is no consideration of land use change or of potential indirect emissions from feedstock displacement, although the risk of feedstock displacement emissions is somewhat managed through restricting the eligible feedstock list.

3.6.3 Additionality and baselining

Additionality shall be demonstrated through a regulatory surplus test and by an activity penetration test. The latter test is that less than 5% of the feedstock type in a given country is processed to produce biochar. This activity penetration test is likely to be met by all projects in the near term.

3.6.4 Long-term storage and liability

Storage is estimated on a 100-year time horizon. As we understand the standard there is no requirement for ongoing monitoring of biochar in-use beyond the point of certification, and therefore no liability in the case of later reversals.

3.6.5 Sustainability

The utilised feedstocks must be certified sustainable by 'any certification scheme approved by a relevant legislative of international; body'. For crop residues, the maximum sustainable removal rate is defined as 50%. Where invasive species are harvested, the facility must have procedures in place to differentiate invasive species from other local species. An issuer is entitled to determine that a given category of feedstock identified as generally eligible shall not be eligible for a specified location if the issuer "has reasons to believe the described Feedstock will not be available in sufficient quantity to allow sustainable production of Biochar without significant Environmental, Social and Governance (ESG) risks."

3.6.6 MRV

As noted above, the standard requires ongoing digital monitoring of the weight of material in each kiln and its operational temperature. Produced biochar must also be tested for H/C_{org} ratio on at least three samples. The sample results are considered valid for the rest of the audit period of three years (after the audit period ends a new audit must be performed).

3.7 ACR inactive methodology

In 2013 the American Carbon Registry (ACR) made a draft biochar methodology available for public comment (Methodology for Biochar Projects, v1.0[48]), and submitted it for scientific peer review[49]. Following this process the methodology was rendered inactive, and ACR does not currently have an active protocol for certification of biochar projects. In this section we briefly outline the proposed methodology, and details some of the key concerns that were expressed in the scientific review process and led to the methodology not being adopted.[50]

Eligibility was to be constrained to biochars that meet the biochar product definition that was set by the IBI in 2012 and the list of biomass residues set by the IBI (referring to IBI documents from 2012 and 2013). The only eligible use was to be as a soil amendment.

3.7.1 Quantification

3.7.1.1 Quantity of biochar applied

The quantity of biochar produced must be monitored, and the end-use of the biochar should be demonstrated through:

- 'Agricultural records';
- Indication that biochar has been mixed with other soil amendments prior to supply;
- Proof that at least two of the following conditions are met when the biochar is supplied:
  - Particles < 2 inches in longest dimension (based on the premise that sales of larger particles may make fuel use more likely/soil use less likely);
  - Demonstration that the price of the biochar would make it uncompetitive as an energy source;

[48] https://acrcarbon.org/wp-content/uploads/2023/03/Biochar-Methodology-Public-Comment-Draft.pdf

[49] https://acrcarbon.org/wp-content/uploads/2023/03/Biochar-Methodology-Scientific-Peer-Review-Comments-and-Response.pdf

[50] Cf. https://acrcarbon.org/methodology/inactive-biochar-projects/

– Demonstration that the biochar is marketed as a soil amendment.

3.7.1.2 Quantity of biochar considered stored on long-term basis

The proposed methodology predates the 2019 IPCC reporting guidelines and Woolf et al. (2021), and therefore proposes a different approach to characterising biochar stability than the other standards discussed here. A sample of the biochar must be analysed to establish C_{org} content and the H/C_{org} ratio – a detailed description of sampling and test procedures is provided. The 100-year carbon storage is then to be calculated based on the IBI report *Biochar Carbon Stability Test Method: An Assessment of Methods to Determine Biochar Carbon Stability*[51]. The 100-year carbon storage (BC_{+100}) is then assigned a value of 70% for an H/C_{org} ratio < 0.4, and a value of 50% for 0.4 < H/C_{org} ratio < 0.7. Biochar with an H/C_{org} ratio above 0.7 are not eligible.

ACR summarises that the scientific peer reviewers on this methodology concluded that, “the scientific literature does not provide sufficient evidence of the stability of soil carbon sequestration in fields treated with biochar using H/C_{org} ratio correlations as cited in the IBI’s Standard Test Method for Estimating Biochar Carbon Stability”. The fundamental difference of opinion between the peer review and the methodology developers appears to relate to the potential for biochar decomposition by non-microbial mechanisms. The peer reviewers in particular pointed to physical degradation mechanisms and to the possibility of UV photo-oxidation. The methodology developers agreed that there were mechanisms that would lead to reduction in biochar particle sizes over time, and that this could lead to increased movement of biochar and potentially dissolution into watercourses, but disputed that there was any evidence that this would lead to increased rates of oxidation to CO_2. The methodology developers similarly disputed whether there was scientific evidence of significant photo-oxidation of biochars, noting that biochars incorporated into soils would be largely protected from solar irradiation and that biochar has been demonstrated to be resistant to photo-oxidation. Several other issues were raised in the review, but the fundamental issue that prevented adoption of the methodology appears to have related to the scientific robustness of the proposed relationship between H/C_{org} ratio and biochar durability.

3.7.1.3 Other lifecycle analysis rules

Emissions from the implementation of the project were to be calculated as the sum of emissions from: feedstock transportation; feedstock processing and drying; combustion of auxiliary fuel to activate the pyrolysis process; consumption of electricity; pyrolysis of any non-biogenic material; and the processing and use of bio-oil/syngas.

Bio-oil and syngas produced as co-products of pyrolysis were to be accounted through a system expansion approach, with emissions from combustion of the equivalent amounts of fossil liquid fuels/fossil gaseous fuels added to the baseline emissions.

3.7.2 Indirect emissions and leakage

There is no mention of indirect land use change emissions, though the eligible feedstock list should have reduced the risk of indirect land use change by restricting the feedstock base to residues. The draft standard included combustion of the biomass with energy recovery in the

[51] https://biochar-international.org/wp-content/uploads/2018/06/IBI_Report_Biochar_Stability_Test_Method_Final.pdf

default baseline scenario. Any reduction in production of electricity/heat as a result of transitioning from a bioenergy-focused facility to a pyrolysis facility were to be included as a leakage emission, with the emission factor for reduced electricity output based on the regional grid average GHG intensity and the emission factor for heat based on “the most carbon intensive fuel that could reasonably be used to replace this biomass heat”.

Project operators would be permitted to propose an alternative baseline scenario (based either on natural decomposition of the material or on combustion without energy recovery). In order to use an alternative baseline the operator must demonstrate that “this is the most reasonable and credible baseline for each individual feedstock processed” by using the CDM combined tool for baselining and additionality. In the case that the baseline did not include energy recovery and the project was a net electricity/heat exporter, then credit would be given by including the emissions for alternative energy generation as part of the baseline.

Biogenic CO_2 emissions from combustion are treated as zero, but the baseline and project emissions calculation would have included terms for the CH_4 and N_2O emissions associated with biomass combustion or decomposition.

3.7.3 Additionality and baselining

In addition to following the rules for baseline-setting that were briefly described in the previous section, the methodology would have required that additionality should be demonstrated using the most recent version of the CDM “Combined tool to identify the Baseline Scenario and determine additionality”.

3.7.4 Long-term storage and liability

The ACR methodology assesses carbon expected to be stored for at least 100 years, using the estimation rules discussed above. The standard would not require soil sampling to verify ongoing carbon storage.

3.7.5 Sustainability

Feedstock sustainability was to be assessed based on compliance with the following criteria:

- The feedstock must be a biomass residue, by-product or waste meeting the feedstock expectations of the IBI biochar standards (2013 edition).
- There must have been no land use change within the previous seven years (presumably this criterion would not have applied to residues from industrial biomass processing).
- The Project Proponent must ensure that carbon stocks and other critical soil and ecosystem attributes are not depleted or negatively impacted by residue harvests, including assessing sustainable residue removal rates, with a minimum of 25% of residues left in-situ.
- There should be a management and monitoring plan with measures to avoid overharvesting, soil erosion/compaction and water pollution.
- Forest residues must be accompanied either by proof of sustainable harvesting through either certification of the forest to the Forestry Stewardship Council (FSC) standard or by a verification statement from an independent third-party professional.
- Agricultural residues may only be used if evidence can be provided to show that harvesting in that region would not lead to soil carbon depletion or to erosion or

compaction of the soil, either through certification to an approved standard, independent verifiers statement or by reference to peer reviewed scientific articles relevant to that region and feedstock.

The standard stated that biochar producers would be, “periodically and randomly evaluated for adhering to the document collection requirements and feedstock suppliers for meeting the qualification criteria”, with assessment at least every five years.

3.7.6 MRV

The standard required ‘continuous’ monitoring of feedstock consumption, and regular monitoring of feedstock composition. Biochar production must be monitored continuously in line with ‘industry best practice’. Organic carbon content of the biochar and H/C_{org} ratio must be confirmed annually, and reassessed any time that feedstock type or production process changes ‘materially’.

3.8 Sylvera

Sylvera presents itself not as a carbon removal certification standard or carbon removal registry, but as a provider of ‘carbon credit ratings’, which can be used to inform company decision making when buying carbon credits. Sylvera compares a company’s analysis of its project (potentially as mediated by a certification scheme) against Sylvera’s own assessment. In 2023 Sylvera published a ‘carbon credit framework for biochar projects’[52] “to help biochar project developers and buyers understand how we would approach assessing biochar projects”. It is our understanding that Sylvera has not yet gone through the process of fully rating any biochar projects.

Sylvera’s carbon credit ratings scores are based on consideration of ‘carbon score’, ‘additionality score’, ‘permanence score’ and ‘co-benefits score’.

In assessing the carbon score Sylvera would compare the claimed permanence of carbon storage in a biochar project against the estimated 100-year storage permanence calculated based on the IPCC method and the relationship from Woolf et al. (2021).

The additionality score would be based on considering regulatory surplus, financial additionality and whether a practice is already common.

The permanence score is based on considering the risk of reversals (i.e. reversals beyond the modelled carbon losses for the biochar over 100 years of use). Biochar is identified as having a low permanence risk compared to nature-based removals. Sylvera states that the end use of the biochar “must be traceable and monitored to quantify reversal risk”, and notes that reversal risk can be reduced by incorporating biochar in to the subsurface.

Finally, the co-benefit rating is an assessment of the project impact on biodiversity (this is limited to whether the biochar facility is located in a conservation area) and the ‘community impact’ which is informed by consideration of the UN SDGs.

[52] https://www.sylvera.com/blog/sylveras-approach-to-biochar-ratings

4 Issues in relation to carbon removals through biochar

4.1 Quantification and boundaries

4.1.1 Permanence assessment

As discussed in section 2, there is a degree of scientific uncertainty as regards the rate of carbon loss from biochar when used as a soil amendment or in materials. The current set of active standards have adopted 100-year permanence functions, based in general on the IPCC inventory accounting method (2019) and/or the results of the meta-analysis of incubation studies provided by Woolf et al. (2021). The IPCC method is explicitly intended for national accounting and is predicated on not having a precise characterisation of the characteristics of the biochars produced, therefore basing a permanence estimate on pyrolysis temperature groupings, rather than on more detailed biochar characterisation. A certification methodology can set requirements for testing of samples of utilised biochars, and therefore a function can be parameterised by a characteristic of the biochar itself, rather than of the production process e.g. H/C_{org} ratio rather than pyrolysis temperature.

It has been argued that the exponential decay rates for biochars, which have been calculated based on incubation experiments, may give an underestimate of long-term carbon storage; and we discussed in section 2.5 Sanei et al. (2024)'s suggestion that if a fraction of a biochar can be identified as entirely constituted of inertinites, then it would be possible to conclude that this fraction would experience no significant carbon loss over centurial timeframes. While there is supporting evidence for this view, there remains a lack of consensus in the community about whether there could still be decay paths for inertinite material. Sanei et al. (2024) suggest that a biochar may be identified as being entirely composed of inertinite, ash and condensates if the distribution range of R_o random reflectance is entirely over 2%. This 'inertinite benchmark' (coupled with analysis of condensate and ash content) could be adopted as a basis to identify carbon storage in biochar as permanent as an alternative to the calibrated permanence functions provided by studies such as Woolf et al. (2021).

4.1.2 Accounting for co-products

Pyrolysis processes produce not only biochar, but also gases including CH_4 (sometimes referred to as syngas) and pyrolysis oils. The syngas is often combusted locally for energy but could in principle be cleaned and supplied as biogas. If processes are optimised for liquids production the oil can be upgraded through hydrogen addition and used as a biofuel (subject to feedstock, a biofuel from upgraded pyrolysis oil is counted as an advanced biofuel under the RED III, and therefore eligible to contribute to targets under REFuelEU and FuelEU Maritime). In the case of biochars from gasification, the biochar tends to be a relatively minor product stream compared to the produced syngas, which may be used as a basis to produce hydrogen or reacted to produce liquid fuels (such as methanol or drop-in transport fuels). Biochar producing processes may also result in the export of heat and/or electricity.

In the RED III lifecycle accounting rules, emissions from processes that generate co-products are generally to be allocated between the co-products by energy content (unless a co-produced substance is of low value or produced in low quality, in which case it is classed as a residue and no emissions from the production process are allocated to it). It is also possible to account for co-products using an LCA technique sometimes referred to as 'system expansion'. In system expansion, a product of interest is identified (in this case biochar) and rather than allocating emissions from the process to the co-products, all emissions are allocated to the biochar, but offsetting 'credits' are given based on the emissions intensity of the products that no longer have to be produced because the co-products are available. This accounting system for pyrolysis oil and syngas was in the proposed ACR accounting framework (section 3.7), for instance. This system expansion approach is often preferred in LCA guidelines over the approximation provided by allocation approaches, but it is more appropriate when considering a product that is clearly the main product produced by a process. In the case that the product of interest is produced in relatively low quantity compared to the co-products, system expansion can lead to distortive results.

4.1.3 Albedo

Biochar is a characteristically dark material, and therefore the application of biochar in the topsoil could decrease the albedo of treated fields (i.e. increase the amount of solar irradiation that is absorbed as heat rather than reflected upwards). For example, Verheijen et al. (2013)[53] reported albedo reduction by around 20% for application of 50 tonnes biochar per hectare integrated into the top 15 cm of soil. The impact of biochar incorporation on albedo will be mitigated by the canopy cover from crop production – the less the soil is exposed to the sunlight the less impact biochar will have on annual average albedo. For example, Meyer et al. (2012)[54] suggested a reduction in net climate benefit by 13-22% due to albedo change in a field producing wheat and rapeseed in rotation, although these results reflect relatively high rates of biochar application (up to 100 tonnes per hectare) and relatively shallow tilling (10 cm). With lower application rates the albedo change would be reduced – but if the albedo change is proportional to the biochar application rate and therefore to the amount of carbon stored, it may still have a significant impact on net climate benefit even for lower applications. The IPCC AR6 Working Group III report concluded that "biochar could decrease soil albedo (Meyer et al. 2012), though this is insignificant under recommended rates and application methods".

The question of albedo change is not addressed in the certification approaches reviewed in section 3 (except that it was raised during the scientific peer review of the inactive ACR standard, cf. section 3.7). Albedo impact would be largest in the case that biochar was applied to the soil surface without being dug in, and therefore one option would be to include a requirement in the certification methodology on the way that biochar is integrated into the soil (see also section 4.4.2). It may be possible to set a requirement for biochar incorporation in soils that is also consistent with agricultural best practice and therefore would enhance agricultural co-benefits (cf. section 4.4.2).

Albedo reduction could also be a potential result of biochar addition to material such as concrete (Winters, Boakye and Simske, 2022) if the materials are used in applications where they are exposed to sunlight.

[53] https://iopscience.iop.org/article/10.1088/1748-9326/8/4/044008/pdf

[54] https://pubs.acs.org/doi/full/10.1021/es302302g

4.2 Additionality and baselining

4.2.1 Activity penetration testing

Several existing standards suggest the use of an ‘activity penetration test’ alongside a regulatory surplus test as a basis to identify the additionality of biochar production activities. This may be suggested either as an alternative to or complement to financial additionality testing. Activity penetration tests are predicated on the idea that an activity should be considered additional if its penetration is still well below its theoretical maximum rate of application.

Biochar differs from some carbon removal approaches (such as DACCS) in that there is a market value to the biochar produced (whether as a soil or feed amendment or as a material additive), and it is plausible that this value could be enough on its own to support biochar projects. This is doubly likely in the case of biochar produced as a co-product to transport fuels, as those transported fuels are already strongly supported within the RED III. It is therefore at least plausible that in some cases biochar production projects would be economically viable without the value of carbon removal credits, and would therefore not pass a financial additionality test. The use of an activity penetration test allows projects that would not pass a financial additionality test to be credited, but we discussed in our earlier review of carbon removals certification methodologies and relevant legislation[55] that the quantification on activity penetration tests can potentially be seen as somewhat arbitrary.

4.2.2 Avoided decomposition emissions

Some standards allow for the consideration of emissions avoided due to preventing anaerobic decomposition in residual feedstocks that might otherwise have led to CH_4 emissions. Puro.earth, for example, allows in principle for a non-zero baseline to be set, if the “supplier could submit non-zero baseline emission claims if sufficient scientific demonstration is provided”. Avoided emissions of this sort should not be conflated with delivered carbon removals, but could be offset against emissions associated with biochar production – for example, it would be possible to argue that fugitive CH_4 from the pyrolysis process could be offset against avoided CH_4 due to preventing residual feedstock from decomposing in situ. It can be difficult, however, to verify claims about counterfactual CH_4 emissions. The Innovation Fund, for example, explicitly precludes such avoided CH_4 emissions from being included in calculation of project emissions avoidance.[56]

4.3 Long-term storage and liability

4.3.1 Potential reversals

As noted above, most existing approaches assess long-term storage in biochar based on some sort of 100-year permanence function, and impose no further requirement on monitoring biochar in situ. In the case of biochar in soil applications, this is partly justified by reference to the difficulty of accurately assessing the amount of carbon remaining in biochar

[55] https://climate.ec.europa.eu/document/download/28698b02-7624-4709-9aec-379b26273bc0_en?filename=policy_carbon_expert_carbon_removals_with_permanent_storage_en.pdf

[56] https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/innovfund/guidance/ghg-emission-avoidance-methodology_innovfund_en.pdf

that was previously applied to soil. Biochar can be transported up and down the soil column, as well as into water courses and by the wind, and therefore it is generally accepted that it is not possible to accurately verify ongoing carbon storage from a biochar after e.g. 20 years following application.

In materials applications, in contrast, permanence may be determined not only by the properties of the biochar (H/C_{org} ratio etc.) as by the duration of the use of that material. It is assumed in some existing certifications that once biochar is integrated into the material structure ongoing monitoring would be redundant. One exception to this assumption would be the case of materials that may be sent for incineration at the end of their useful life. If biochar is used in building materials, such as concrete, the first major risk of reversal may come at the point of destruction of the building. If biochar is used in materials for consumer products (such as polymers) then disposal of those products by incineration would represent a reversal risk[57]. The VCS methodology approaches this reversal risk by requiring "statistically validated lifetime averages" for the lifetimes of the materials in question, but determining statistically validated product durations may be challenging for novel products. Consideration needs to be given both to likely material lifetimes and to the risk of reversal at end of life. It must also be determined whether active monitoring of end of life for the materials will be required by a certification methodology.

4.4 Sustainability

4.4.1 Use of biochar in soils: heavy metals and other toxicants

Biochars can contain toxicants including heavy metals if these were present in the biomass feedstock. This is a particular risk for biochar produced from 'biosolids', which is an alternative term for sewage sludge. These toxicants can be problematic if applied to agricultural land in significant concentrations. The EU Fertilising Products Regulation[58] excludes biochar produced from municipal waste, sewage sludge, industrial sludge, dredging sludge and animal by-products from being categorised as fertilising products. A review by Sobol, Dyjakon and Soukup (2023)[59] found that biochars produced by pyrolysis at temperatures greater than 400 °C are expected to be safer in terms of produced dioxins and furans than lower temperature biochars and thus better suited as soil amendments. The *EBC Production Guidelines* set testing requirements for biochar and maximum threshold values for a range of contaminants, distinguishing between soil and non-soil applications. It may be appropriate for an EU certification methodology to echo the quality testing requirements of the EBC.

There may be cases in which pyrolysis and biochar production may be used as part of a treatment strategy for contaminated materials, in which case it might be possible to identify a co-benefit under the pollution prevention and control sustainability objective.

4.4.2 Application approach for soil incorporation

The way in which biochar is applied to agricultural soils will affect the co-benefits that can be delivered by biochar utilisation, and may affect albedo and permanence. The existing standards are generally non-prescriptive about the way that biochar should be used in the

[57] Cf. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9863687/

[58] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02019R1009-20230316

[59] https://link.springer.com/article/10.1007/s10311-023-01600-7

agricultural context. One view would be that farmers have a built-in incentive to use biochar in the most effective way possible (i.e. in a way that enhances soil quality and allows a reduction in fertiliser application and hence fertiliser cost) and therefore that guidance on good practice can be expected to be followed without requirements and monitoring being imposed through carbon removal certification. On the other hand, it is expected that not all farmers will yet be familiar with best practices for biochar use and that the optimal approaches will vary for different soil types and crops, and therefore there is clearly a risk that some potential co-benefits could be missed through sub-optimal application strategies. It is also likely that guidance on best practices in biochar application will evolve as the practice becomes increasingly widespread and additional data becomes available.

It may be possible for a co-benefit against the climate change mitigation sustainability objective to be defined for cases where biochar is applied to soils in a way that supports increases in non-biochar soil organic carbon.

4.4.3 Maximising co-benefits

Biochar can deliver co-benefits in a number of uses, from crop yield improvement to reductions in some agricultural emissions to reduced nutrient leeching to improved material characteristics. The CRCF states that, “The certification methodologies shall incentivise as much as possible the generation of co-benefits going beyond the minimum sustainability requirements.” It would therefore be appropriate to consider whether some carbon removal certification for biochar should be restricted to a subset of potential applications that have greater co-benefits. The delivery of co-benefits could also be improved by setting requirements on the agricultural context in which biochar is applied as a soil amendment, targeting areas where the potential benefits would be greatest. On the other hand, additional regulation of end-uses may be seen as an administrative burden for biochar producers, and could prevent certification of some uses even when they deliver carbon removals.

4.4.4 Feedstock eligibility for biochar and biomass energy

Some existing standards restrict the eligible list of biochar feedstocks to only residues and waste materials, whereas others include farmed grasses and wood. Under the RED III, pyrolysis-based advanced biofuels can be produced from any feedstock that satisfies the RED III sustainability criteria, which can include farmed wood and other farmed cellulosic crops.

It should be noted that any differences in eligibility criteria between the advanced biofuel rules in the RED III and the biochar certification rules under the CRCF could lead to a two-tier market for co-product biochar. One possible route would be to allow the use of specific feedstocks identified as having enhanced sustainability characteristics to be reported as a co-benefit.

4.5 MRV

4.5.1 End-use verification

As discussed in section 3, several of the existing biochar standards have a relatively light touch approach to demonstrating end-use of biochar, requiring for example evidence of off-take agreements rather than tracking of biochar to the point of use (although some such as VCS require reporting of the geographical coordinates of the site of end-use). In the absence of direct monitoring of biochar use, there is a risk that biochar registered as a carbon removal could end up being used in a combustion application (for example as a coal substitute in steel making). As was noted in the draft ACR biochar standard, this risk is greatest if the retail price of biochar is close to or below the retail price of comparable fuel materials, such as charcoal or coal. Currently, it is our understanding that quality biochar marketed for agricultural applications retails at a significantly higher price than coal for energy, but it is conceivable that the value of carbon removal certification combined with increased availability of biochar could reduce or eliminate this price differential. Consideration must be given to whether monitoring requirements on biochar utilisation would be proportionate and would significantly reduce the risk of reversals due to misreporting of biochar use.