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Biochar: accounting for carbon benefits of production and use

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Executive Summary

Carbon removals play a significant role in many modelled pathways to limit global warming to 2 °C. One potential carbon removal technology that has attracted considerable interest and market growth recently is biochar production, which delivers long-term carbon storage in soils or material products. By transforming 'labile' (easily decomposed) carbon in biomass into 'recalcitrant' (long-lived) carbon, biochar offers an alternative to geological CO_2 storage. Unlike geological CO_2 storage, biochar use presents potential economic and environmental co-benefits, such as increased agricultural productivity in some contexts, and the potential to alleviate non-CO_2 forms of pollution (e.g. by improving nitrogen fertiliser use efficiency in agriculture). However, biochar use also carries some environmental risks that are not associated with geological storage, such as the potential accumulation of contaminants in soil, and the disruption of existing soil biodiversity and ecosystem functions.

Biochar's carbon storage potential can be recognised and incentivised across multiple policy contexts. Certification systems for permanent carbon removals can issue credits based on an estimation of the long-term carbon storage that biochar use will deliver, and these credits can be sold on voluntary carbon markets. This estimation is calculated based on the physical characteristics of the biochar that indicate the level of carbonation it has experienced, and therefore how resistant to decomposition it will be. Approaches use parameters including the molar ratio of hydrogen to carbon in the biochar (H/C_{org}), the temperature at which the biochar was produced, or the fraction of the biochar consisting of 'inertinite' macerals.

Carbon in biochar can also be recognised by systems that quantify the amount of organic carbon in soil. With standard measurement approaches it is difficult to experimentally distinguish biochar carbon from other forms of soil carbon, and therefore approaches that offer incentives based on directly measured soil carbon may be unable to avoid giving credit to any contained biochar. One application in which this is relevant is the assessment of soil carbon formation due to improved agricultural practices in biofuel feedstock cultivation. Similarly, soil carbon measurement may be part of the assessment of direct land use changes associated with biofuel production. Indeed, given that biochar can be produced as a co-product or residue of some biofuel production processes, the policy and economy of biofuel and biochar may well be tightly interwoven in the coming years.

There are compelling reasons for the assessment of carbon in biochar in permanent carbon removals schemes to be based on modelling and first principles, and for the assessment of soil carbon change at the farm level to be based on measurement. However, this inconsistency creates the possibility that the benefit of the carbon stored in biochar could be counted under multiple frameworks.

If carbon storage is recognised twice towards the same goal, this can be referred to as double counting and is prohibited by most climate policies and certification systems. If carbon benefits are recognised twice under different goals, however, this is sometimes considered acceptable – indeed, there are many places in climate policy, including in biofuel policy, in which 'stacked incentives' are considered an important tool to drive investment, in particular in hard to decarbonise areas. For example, in the United States a single batch of biofuel can simultaneously qualify as a climate change mitigation technology under the federal Renewable Fuel Standard, state clean fuel standards, and receive favourable tax treatment at the federal and or state level.

In this report, we draw a distinction between stacked incentives, which we define as forms of multiple recognition that are intended by policy makers, and double crediting, which we define as forms of multiple recognition that are not intentional. Double crediting can undermine the integrity of climate change policy by giving a misleading sense of the rate of overall progress. It can also lead to inefficient allocation of capital by distorting the playing field between different decarbonisation approaches.

This report identifies several ways in which biochar could receive multiple recognition, some of which might be seen as double crediting or even as double counting. For example, we sketch out a case in which the carbon storage in biochar could potentially be recognised twice under the CORSIA instrument for aviation decarbonisation (once as an offset and once in an aviation fuel LCA), which would represent double counting. A similar case could see carbon in biochar recognised both through credits on the voluntary carbon market and in the LCA of biofuels used in the EU or UK through the 'e_{sca}' term, which represents soil carbon accumulation due to improved agricultural practice and can be assessed by measurement. Although this is not technically double counting because the biofuel targets and voluntary market are separate, but it could be perceived as double crediting.

We also highlight the sustainability risks, that if biomass harvesting for biochar significantly reduces standing carbon stocks, the nominal carbon storage from biochar could be entirely offset (and more). This emphasises the need for strict sustainability governance for biochar feedstocks.

To effectively manage these challenges as the biochar sector expands, we recommend:

1. **Transparent recognition**: Opportunities for multiple recognition of benefits from biochar should be explicitly and transparently acknowledged, and that policymakers should ensure that any multiple recognition is aligned with broader policy and climate goals.

2. **Chain of custody measures**: Tracking biochar from feedstock through production to end-use will ensure accurate carbon accounting.

3. **Post-application monitoring**: As the market develops, post-application monitoring of biochar's long-term impacts should be undertaken to improve our understanding and to support farmers to use biochar in the most effective way.

Contents

1. Introduction

Biochar is a carbonised form of biomass produced through thermal decomposition in a low-oxygen environment, a process that inhibits full combustion and results in a stable, carbon-rich material (Jiao et al., 2021; Lehmann et al., 2006). Its resistance to biological and chemical degradation under ambient conditions makes biochar an appealing tool for carbon sequestration. By stabilising biomass carbon that would otherwise return to the atmosphere as CO_2 (Osman et al., 2022), biochar has the potential to serve as a durable carbon sink. While there is no universally agreed definition distinguishing biochar from other charcoals, it is often characterised as material processed at temperatures above 350°C, with an elemental hydrogen-to-carbon (H/C_{org}) ratio below 0.7, reflecting a high degree of carbonisation and stability (Malins et al., 2024).

In its 2022 report on mitigating climate change, the United Nations Intergovernmental Panel on Climate Change (IPCC) identified biochar as one of eight carbon dioxide removal (CDR) technologies with a Technology Readiness Level above six, highlighting its potential as an industrially viable climate solution. Biochar carbon removal (BCR) was listed alongside approaches like afforestation/reforestation, soil carbon sequestration in croplands and grasslands, direct air carbon capture and storage (DAC or DACCS) and bioenergy with carbon capture and storage (BECCS) (Shukla et al., 2022).

Beyond carbon storage, biochar can offer co-benefits across agriculture, industry and environmental restoration. In agriculture, biochar has been shown to enhance water retention (Omondi et al., 2016; Osman et al., 2022), nutrient use efficiency and crop productivity (Blanco-Canqui, 2021; Lehmann et al., 2006, 2021), particularly in soils with low cation exchange capacity (CEC)(Jeffery et al., 2017; Woolf et al., 2016). Emerging applications of biochar include water treatment, construction materials, and industrial processes, underscoring its versatility. However, biochar's performance is dependent on feedstock properties, production processes and intended applications (Fawzy et al., 2021; R. Singh et al., 2015; Wang et al., 2016; Zygourakis, 2017), and some cases show negative instead of positive agricultural impact (Brtnicky et al., 2021; Joseph et al., 2021).

Biochar can also be a co-product of biofuel production, such as in cellulosic biofuels via gasification or fast pyrolysis and can also be used as an input to improve soil carbon during biofuel feedstock cultivation. This means that biochar can appear at multiple stages within a biofuel's lifecycle analysis (LCA), influencing its overall greenhouse gas (GHG) emissions performance.

However, biochar's multi-sectoral applications can introduce challenges for its integration into carbon crediting systems (Rathnayake et al., 2024). Biochar can be produced as a primary product, co-product or by-product, and its carbon benefits may be claimed across multiple crediting pathways, such as soil carbon sequestration, avoided GHG emissions, or industrial offsets. This raises concerns about the possibility of double-counting carbon credits and misalignment between regulatory and voluntary frameworks, whilst highlighting the need for robust accounting methodologies to ensure biochar's climate integrity.

This report explores some of these interconnected issues, focusing on biochar application to agricultural soils, where measurement challenges are most complex, and where biochar's CO_2 benefits may also have relevance to the biofuel lifecycle. The report also examines policy overlaps, potential market distortions caused by crediting the same benefits multiple times, and whether such double counting should be considered problematic or avoidable.

We begin with an overview of biochar production processes and feedstock considerations.

1.1. Biochar production processes

Biochar can be produced naturally, e.g. through wildfires, but is predominantly manufactured through controlled thermal processes. These processes differ in temperature ranges and heating rates, residence times, and primary outputs, all of which influences the resulting biochar's properties and suitability for specific applications (Zilberman et al., 2023).

1.1.1. Pyrolysis

Pyrolysis is a process that drives the thermal decomposition of biomass into solid, liquid and gaseous fractions, with the yields and uses of these fractions varying depending on the process conditions and intended outputs. Pyrolysis is the process that occurs at the head of a match, where heat causes the release of gases that can be seen combusting in the flame, while the body of the match becomes charred.

Pyrolysis can be divided into "slow" and "fast" processes:

- Slow pyrolysis operates at temperatures between 350-700°C with a slower rate of heating and prolonged residence times of the biomass in the reactor, from tens of minutes to an hour or more. Slow pyrolysis optimises biochar yields at the expense of other products such as pyrolysis gases and liquids. Biochar yields typically range from ~25-50%, depending on feedstock and temperature. For example Weber et al. (2018) reported mass yields around 30% for slow pyrolysis up to ~600 °C of forest residues, bark, and walnut shells.

- Fast pyrolysis uses higher temperatures (500-950°C) with rapid heating rates (10-200°C/s) and shorter residence times, and is generally optimised for producing pyrolysis oil (Tripathi et al., 2016). Biochar yields by mass are lower than for slow pyrolysis, typically between ~15-25% (Mašek et al., 2013; Mullen et al., 2010; Tripathi et al., 2016; USDA, 2025). For example, a study for the US National Renewable Energy Laboratory (Wright et al., 2010) reported an example biochar mass yield of 16% for fast pyrolysis, with the majority of the output as pyrolysis oil (60%) and with smaller quantities of combustible gases (7.5%), CO_2 (5.4%) and water (11%). While the higher temperatures typical in fast pyrolysis can promote the formation of more aromatic and stable carbon structures, the shorter residence times may slightly reduce carbon stability in some cases. The stability is determined by the interplay between pyrolysis temperature and residence time, as well as feedstock properties (S. Li et al., 2019; Zimmerman, 2010).

All other things being equal, biochar yields decrease as pyrolysis temperature increases, as more carbon is volatised into syngas and bio-oil fractions. S. Li et al. (2019) suggest a mathematical model of exponential reduction of biochar mass yield with processing temperature for a given pyrolysis residence time. Figure 1 shows mass yield of biochar produced from wood falling from over 40% when processed for an hour at 350 °C to below 20% when processed for an hour at 700°C.

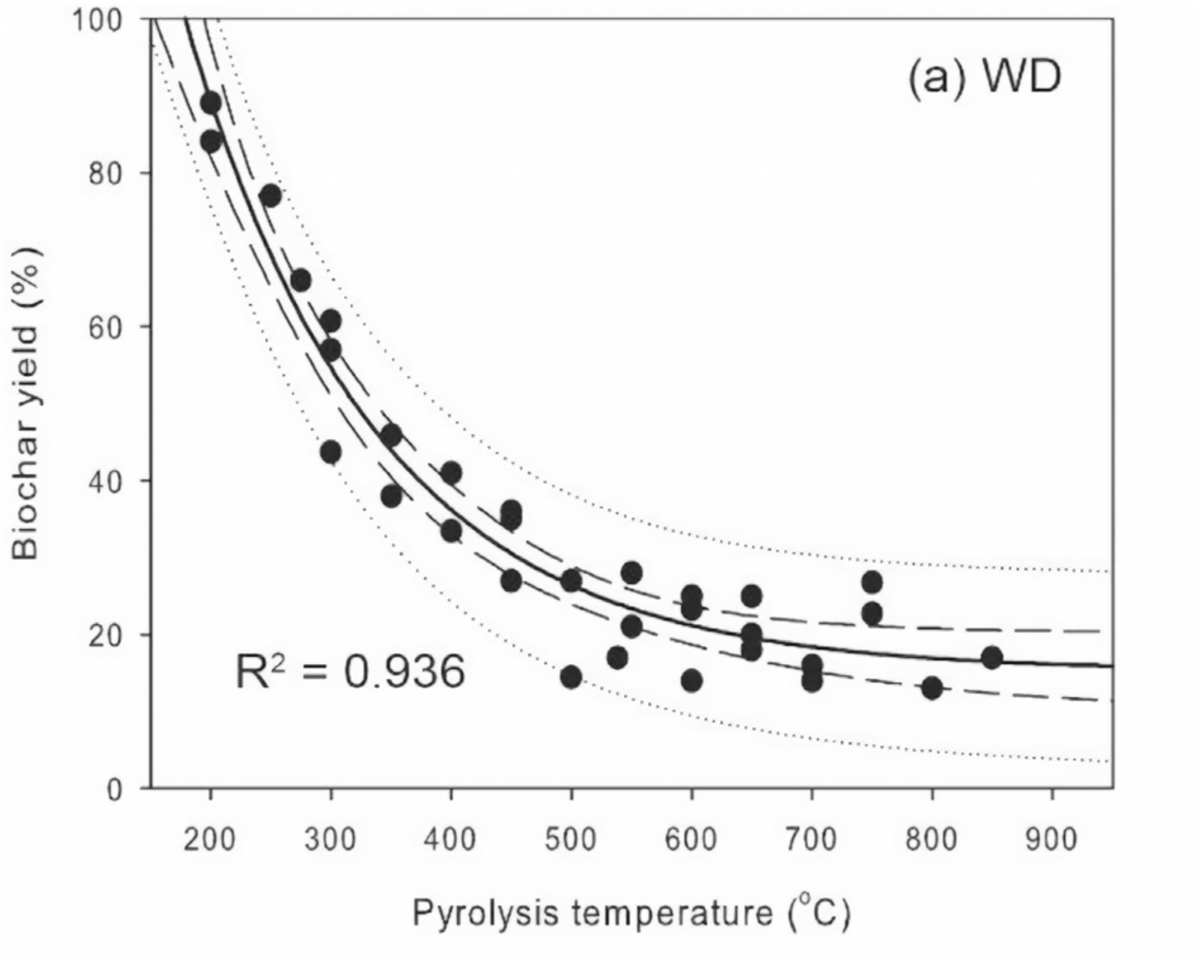

Figure 1 Graph of solid mass yield against pyrolysis temperature showing experimental data points (circles) and modelled exponential decay curve (fitted curve, 95% confidence intervals, 95% prediction intervals)

Source: S. Li et al. (2019)

Note: The y-axis is labelled 'biochar yield', but for lower temperature processes (below 350 °C) the solid output fraction would not meet standard definitions of biochar, perhaps better being described as charcoal; the residence time is reported as 60 minutes in "many studies", and presumably varies from that for some of the reported measurements.

1.1.2. Gasification

Gasification involves treating biomass at very high temperatures (~1,000°C) to produce 'syngas', consisting primarily of hydrogen and carbon monoxide, with biochar generated as a by-product. The syngas can be combusted for electricity or potentially be converted into advanced biofuels, for example via the Fischer Tropsch process. Gasification is optimised for energy production, and biochar yields are generally lower than in pyrolysis pathways. Gasification typically results in around 85% gaseous products, 10% biochar and around 5%

liquid bio-oil (Tripathi et al., 2016). Since biochar is a minor product in gasification pathways, emissions from biochar are often not allocated separately under LCA rules (Malins et al., 2024).

Beyond these primary biochar production pathways, lower temperature processes, such as torrefaction and hydrothermal carbonation, produce chars with lower degrees of carbonisation. These materials generally do not meet the criteria to be considered biochars, and often exhibit higher H/C_{org} ratios (above 0.7), meaning they tend to be more labile and decompose more readily in soil environments, making them less suitable for durable carbon storage.

The classification of biochar as a co-product, by-product or residue depends on its relative contribution to energy output and economic value. According to Malins et al. (2024), the EU's RED III LCA rules allocate emissions to co-products based on energy content, meaning that if biochar accounts for at least 15% of a system's total energy output, it is considered a co-product rather than a by-product. In slow pyrolysis, where biochar yields are highest (~30-50% or more), it is often considered as a co-product alongside syngas and bio-oil, meanwhile in fast pyrolysis and gasification, where biochar yields are lower (~10-25%), it may be treated as a by-product of bio-oil or syngas production.

1.2. Application and integration into carbon crediting systems

Biochar applications span agriculture, industry, and environmental remediation. In agriculture, biochar has been shown to have the potential to improve soil health and fertility by enhancing water retention, nutrient availability, and microbial activity particularly in degraded or sandy soils (Blanco-Canqui, 2021; Osman et al., 2022; Razzaghi et al., 2020). It can also be used in industrial applications, such as a coal substitute in steel production, an additive in cement or asphalt, and a filtration medium for water treatment, where it can adsorb pollutants like heavy metals (e.g., El-Naggar et al., 2019; Silvani et al., 2019). Additionally, biochar is being explored as a component in plastic composites (Bartoli et al., 2022), and has been applied in habitat restoration, where it has been shown to improve germination rates for native vegetation (cf. oak and mahogany species, Drake et al., 2015).

Perhaps biochar's most significant role in the coming decades lies in its ability to sequester carbon for long periods (potentially thousands of years), by stabilising organic carbon that would otherwise return to the atmosphere at CO_2. This durability makes biochar a valuable tool for climate mitigation, serving as both a carbon removal tool (by storing atmospheric CO_2) and a carbon reduction tool (reducing emissions in various processes, such as when substituting fossil fuels in energy applications or fossil-based products in materials applications).

Reflecting this potential, biochar is increasingly being integrated into carbon crediting systems, where it can generate carbon credits based on its long-term carbon stability and emissions reduction benefits (Rathnayake et al., 2024). Carbon credits are tradable units representing either the avoidance of CO_2 emissions or the creation or enhancements of carbon sinks, thereby reducing net atmospheric CO_2 concentrations (Salma et al., 2024). The production and application of biochar can serve as a basis to generate such credits, with its carbon benefits recognised across both regulatory frameworks and voluntary carbon markets.

Biochar can be recognised in biofuel lifecycle analysis (LCA), both as a co-product of biofuel production and as a soil amendment applied to biofuel feedstock-cultivation systems, for example under the EU's Renewable Energy Directive (currently in its third iteration, RED III).

Certification schemes, such as the European Biochar Certificate's (EBC) C-sink, allow biochar to be recognised as a CDR activity in the voluntary carbon markets. Additionally, biochar is also under consideration for recognition as an eligible activity to generate carbon removal units in the EU's Carbon Removal Certification Framework (CRCF) (Malins et al., 2024).

LCA can provide a framework for accounting all of the emissions associated with biochar, from feedstock sourcing and pyrolysis conditions, through to biochar's final application – whether it is used as a soil amendment, energy source, or industrial input. One key consideration with LCA is how the system boundaries are defined, as this directly influence the calculated lifecycle emissions. The system boundaries determine which stages of biochar's lifecycle are included in the emissions calculations (demonstrated in Table 2), whether the biochar is considered a primary product or a co-product (e.g. biofuel production), how emissions are allocated (between biochar and other products in multi-output systems) and what baseline assumptions are made regarding avoided emissions (e.g. whether biomass feedstocks would have decomposed or been burned otherwise).

If biochar is treated as a co-product, such as in biofuel production systems, it may be allocated a share of the production process emissions. This allocation approach is widely used in biofuel policy across various jurisdictions where biofuels must demonstrate lower lifecycle emissions compared to fossil fuel alternatives. For example, in California and Germany, support for biofuels is proportional to the GHG reduction achieved compared to a benchmark or fossil fuel comparator. These methodological choices impact how biochar is classified within different LCA frameworks, influencing whether it qualifies as a negative emissions technology and how its carbon crediting potential is assessed.

Because of biochar's multi-sectoral applications and potential to generate credits through various regulatory frameworks and voluntary carbon markets, there is a risk of double-counting (or perhaps even triple-counting), where the same carbon benefits are credited under separate but overlapping systems, inflating biochar's perceived climate contributions (Rathnayake et al., 2024). For systems that are handling and crediting biochar, robust monitoring, reporting and verification (MRV) frameworks are needed to ensure that biochar's benefits are accurately accounted for, and not over-credited across multiple markets and regulatory schemes. Addressing these challenges will be critical for improving transparency, maintaining creditability and integrity as biochar's role within sustainability framework and voluntary carbon markets continues to grow.

1.3. The biochar market

Based on the results of its 2023 global market survey, the International Biochar Initiative (IBI) and U.S. Biochar Initiative (USBI) estimated global biochar production to be at least 350,000 metric tonnes (t) in 2023, representing over 600,000 t of BCR (IBI, 2024). According to CDR.fyi, an open registry of 100-year plus carbon removals, BCR credits reportedly accounted for around 7% of CDR credit sales in 2023, but represented more than 90% of delivered carbon removals registered on the platform in 2023 (CDR.fyi, 2024; IBI, 2024). The difference between purchased and delivered carbon removals demonstrates biochar's significant role in delivering CDR in the voluntary carbon markets, which is likely due to biochar's relatively short production and verification cycles, compared to methods like DAC with longer lead times.

The IBI/USBI survey results also indicate that biochar is primarily produced from residual agricultural and forestry biomass (IBI, 2024), but the extent to which it is generated as a primary product versus a co-product is unclear. A cautious conclusion can be drawn that most biochar is custom-produced rather than an incidental by-product of other processes. Only a small number of producers reported using pyrolysis liquids for fuel (7.7%), and there is limited evidence of large-scale transport fuel production via pyrolysis that could generate substantial volumes of biochar as a by-product. All of which suggests that the biochar market is presently led by biochar-focused production, rather than being driven by energy-sector applications. If, for example, pyrolysis-derived biofuels were scaled up to produce a billion litres per year, this would generate biochar volumes roughly comparable to current global production – reinforcing the view that biochar is unlikely to be dominated by co-product production in the near term.

Barriers to scaling the biochar market also remain significant. Gwenzi et al., (2015) identified constraints such as insufficient investment, limited large-scale production facilities, high production costs at small scale and a lack of agreement on approaches to monitoring, reporting and verification (MRV). In 2023, only about half of biochar production was reported as having been supported by the generation of BCR credits (IBI, 2024). However, access to carbon removal markets is expected to accelerate industry growth, as demand for high-integrity carbon removals increases (Chiaramonti et al., 2024; Salma et al., 2024; Zilberman et al., 2023). Given the 90% compound annual growth rate (CAGR) since 2021 (IBI, 2024), the biochar market is expanding rapidly, which means that the role of carbon crediting in supporting future production is also likely to grow.

2. Biochar durability and measurement

2.1. Biochar as a vector for long-term carbon storage

Biochar production involves heating biomass to high temperatures, resulting in the emission of biogenic CO_2. Unlike combustion, which converts nearly all of the biomass carbon into CO_2, biochar production releases only a small fraction. But still, we might ask: how can a process that emits CO_2 be considered a form of CDR?

The answer lies in biochar's durability in the environment. When biomass decomposes naturally, its carbon is gradually released back to the atmosphere as CO_2 through natural decomposition processes. Small biomass fragments like leaves and straw will decompose quickly, whereas larger pieces like branches and logs can take decades, depending on environmental conditions. Biochar cannot store more carbon than its biomass source, but it decomposes much more slowly, extending carbon storage over the longer-term despite the release of process emissions.

Biochar's stability results from the carbonisation process, which transforms part of the biomass into a recalcitrant form of carbon that resists microbial and chemical degradation (Lehmann et al., 2006, 2021). In soil, biochar is more stable than organic matter, which typically degrades over years to decades, whereas depending on the feedstock, production method, and resulting characteristics, biochar is believed to have mean residence times ranging from hundreds to thousands of years (Wang et al., 2016; Y. Zhang et al., 2022).

Biochar occupies an intermediate position on the 'carbon storage continuum'. At one end, activities such as 'carbon farming', afforestation and the use of harvested wood products provides short-term storage but are susceptible to reversal (e.g., soil organic carbon loss due to changes in farming practices, wildfire, or demolition and incineration of wooden buildings) (Smith et al., 2020). At the other end, geological carbon storage offers near-permanent sequestration, keeping CO_2 out of the atmosphere for tens of thousands of years if leaks are prevented. Biochar falls in between, with soil-applied biochar expected to decompose gradually but retain some of its carbon for centuries or longer (Woolf et al., 2010), and for this retained carbon to be resistant to reversal.

On human timescales, and from a climate change mitigation perspective, storing carbon for hundreds or thousands of years may be seen as equally beneficial as geological storage, as the goal is to stabilise atmospheric CO_2 levels long before then. In the context of the EU's CRCF, storing carbon for at least 'several centuries' would qualify as permanent carbon removal. As such, biochar production has been identified alongside biomass use with carbon capture and storage (BioCCS) as a candidate for permanent carbon removal certification (Malins et al., 2024).

2.2. Carbonation as an indicator of durability

To determine how much of a given biochar will remain in the environment over longer timescales, it is important to identify the durable fraction for specific biochars. Researchers have studied the characteristics and behaviour of biochar, and have proposed a number of ways to estimate the fraction of a given biochar that will remain in different applications after a given amount of time has passed, considering factors such as variations in soil type, climate and other environmental factors (Malins et al., 2024). For example, the EBC's C-Sink framework assumes that biochar degradation depends on site-specific conditions. Similarly, carbon crediting methodologies, such as those used by Verra's Verified Carbon Standard (VCS) and Puro.earth assess carbon storage in biochar over 100 years, factoring in local soil properties and climatic conditions.

A commonly used indicator to distinguish longer-lived from shorter-lived biochars is the elemental H/C_{org} ratio. Biochars with a H/C_{org} ratio value below 0.7 are generally considered to have high durability (Budai et al., 2013; Sanei et al., 2024; Woolf et al., 2010). The H/C_{org} ratio reflects the degree of carbonation of the biochar or, conversely the extent to which hydrogen has been driven off during the heat treatment. A lower H/C_{org} ratio indicates a higher degree of carbonisation, and generally a greater resistance to decomposition. However, it is important to note that biochar properties do not abruptly change at any particular H/C_{org} value, and the threshold of 0.7 is a practical classification tool used to guide technical discussion and policy decisions, rather than an absolute cut off.

Another indicator of biochar durability is the temperature at which biochar is produced. Higher-temperatures lead to greater degrees of carbonisation, resulting in a more recalcitrant, long-lived form of biochar (Enders et al., 2012; L. Leng et al., 2019). This is why some standards use production temperature as a durability criterion, alongside the H/C_{org} ratio.

While the H/C_{org} ratio and production temperature are useful indicators of biochar's durability, its long-term stability is influenced by a broader range of factors. These include the type of biomass used as feedstock and its characteristics, the specific pyrolysis conditions, and environmental variables at the application site, such as soil properties, climate, and microbial interactions (Fang et al., 2019; Zimmerman & Ouyang, 2019). Because of this complexity, accurately predicting biochar's long-term behaviour requires a somewhat holistic understanding of how these factors interact.

2.3. Studying biochar durability in the laboratory and the field

One of the primary methods used to study and characterise the rate of carbon loss from biochar is through incubation in laboratory conditions. Incubation experiments typically involve measuring changes in biochar samples kept in moist soil at a constant temperature over extended periods. By manipulating factors such as temperature, moisture, and microbial activity, laboratory studies provide controlled insights into biochar's degradation processes (Adhikari et al., 2024). Often, higher temperatures are used to accelerate decomposition, enabling short-term studies (generally between 1 and 10 years) to provide indications of biochar's possible long-term decay rates.

Meta-analyses of incubation studies have been used to model biochar decomposition over extended timescales. Woolf et al. (2021) conducted a comprehensive meta-analysis of published incubation results and developed exponential decay functions that account for time, soil temperature and either biochar production temperature or H/C_{org} ratio. These models typically utilise either a two- or three-pool approach, categorising the biochar into distinct fractions. Most of the biochar is grouped into a highly stable ('recalcitrant') pool, while smaller fractions (typically no more than 10%) are classified as less stable ('labile') and are expected to decompose more rapidly.

A potential limitation of this type of analysis is that because only a very small part of the recalcitrant carbon is expected to decay during an incubation experiment, and a small amount of noise in the data can have a disproportionate impact on the calculated results. Some analysts (e.g. Sanei et al., 2025), argue that these exponential decay functions may overestimate the decomposition rate of the recalcitrant fraction. Alternative models, such as power functions, have been suggested to provide a better fit for observed decay rates (Azzi et al., 2024; H. Li et al., 2024). As research in this area continues, debates over the most appropriate functional model for biochar decomposition are likely to persist.

While laboratory studies provide valuable insights, these controlled studies cannot fully replicate the dynamic environmental processes that could affect biochar decomposition in natural settings, such as temperature fluctuations, physical fragmentation, and complex interactions with soil biota. It would therefore be useful to be able to compare 'real-world' evidence from long-term field studies to the results of incubation experiments and associated functional fitting. Unfortunately, long-term field studies are challenging to conduct, in part due to the lengthy timescales involved, as well as the practical difficulties in accurately measuring the carbon loss in an open field experiment.

Field studies introduce other complexities, including the vertical and lateral movement of biochar within soil profiles, which can be facilitated by soil biota like earthworms or transported by wind or water. Reliably distinguishing between biochar decomposition and physical redistribution is not considered practically possible in field trials, contributing to uncertainties in assessing biochar's longevity in field conditions and its sequestration potential (Blanco-Canqui, 2021; Lehmann et al., 2006, 2011).

An alternative approach to studying biochar durability is to analyse its fundamental physical characteristics and develop a theoretical framework justifying treating certain biochar fractions as highly recalcitrant on relevant time scales. One such approach involves analysing the 'macerals' in biochar, which are microscopic components analogous to the minerals that occur in inorganic material. Sanei et al. (2024) suggests that many biochars are predominantly composed of 'inertinite macerals', a category of carbonised organic material originally identified in coal. Carbon in inertinites is considered highly resistant to decomposition, and therefore 'permanent' on the timescales relevant to carbon removal certification (Malins et al., 2024).

The end-use of biochar significantly influences its durability, and as Table 1 demonstrates some voluntary market methodologies distinguish between biochar used in soil amendments, livestock feed, or construction materials (Malins et al., 2024). For example, under the Puro.earth methodology, biochar used in construction materials, such as asphalt or concrete, is exposed to far fewer environmental factors that could cause decomposition compared to soil applications (such as microbial activity, oxidation and leaching). Similarly, the EBC's C-Sink methodology notes that biochar embedded in composites (e.g. cement, plastics, or insulation materials) has a near-permanent carbon storage potential (Malins et al., 2024).

Different carbon crediting standards adopt varying methodological approaches to assess and report biochar's durability. Many of the existing standards, including those considered briefly in Table 1, utilise the decay function from Woolf et al. (2021), or other similar approaches, to estimate biochar degradation over time. These methodologies incorporate multiple factors influencing biochar's durability, however, the assumptions and parameters used in these models vary between standards, and may influence the credited amount of CDR.

Table 1 An overview of five biochar standards

Standard	Scope and focus	Durability approach	Measurement and accounting
European Biochar Certi-fication (EBC) C-Sink **C-Sink guidelines Version 2.1, February 2021**	A biochar-specific carbon removals certification managed by Carbon Standards International, covering agricultural, industrial, and consumer applications.	Estimates carbon storage 100 years post-application. Biochars with H/C_{org} ratios <0.4 are assumed to degrade at 0.3% annually; those with H/C_{org} ratios between 0.4 and 0.7, follow parameterised degradation rates based on IPCC (2019) guidelines but are not less than 0.4% per year.	Excludes emissions from feedstock cultivation and collection in LCA, and instead uses a 10% safety margin above other LCA emissions. No long-term in-situ monitoring but requires batch tracking via QR codes and ID numbers. Annual inspections are conducted.
Puro.earth **Biochar Methodology, Version 2, Edition 2022**	A voluntary carbon removal crediting standard for biochar aligned with IPCC carbon removal definitions. Eligible applications include soil amendments, feed, waste-water treatment, construction materials and more.	Assumes 100 years carbon storage for eligible uses but does not verify end-use compliance. Uses lab analysis and Woolf et al. (2021) to calculate CO_2 sequestration durability, adjusting for local climate conditions.	Carbon removal credits are issued based on CO_2 sequestered over 100 years minus lifecycle emissions. LCA includes biomass sourcing (from sustainable sources), biochar production emissions, allocation of energy among biochar co-products, and end-use emissions. Requires third-party verification but no ongoing monitoring post-certification.
Verified Carbon Standard (VCS) – Verra **VM0044, Version 1.1, July 2023**	A widely used GHG crediting programme with an active methodology for biochar covering both soil and non-soil applications.	Assesses 100-year permanence using a discount factor based on IPCC (2019)and Woolf et al. (2021). Biochar must be used within a year of production. The methodology also acknowledges reversal risks from environmental factors but concludes that these are unlikely to cause carbon sequestration loss.	Requires monitoring of sourcing, production and application, including sustainability criteria for feedstocks (limited to wastes and residues). Quantifies emissions from biochar production. No post-application monitoring, but chain of custody tracking from sourcing through to application, for which geo-location is required.
Riverse **Standard Rules, Version 1.0, September 2023**	A European registry certifying biochar as part of BECCS, limited to agricultural soil applications.	Uses Woolf et al. (2021) model to estimate 100-year carbon storage, adjusting for soil temperature and the H/C_{org} ratio (<0.7), which is determined via lab analysis.	Requires a comprehensive LCA covering feedstock sourcing through to soil application, including infrastructure and machinery emissions. Monitoring is independently audited, and geo-location is required for application sites.

American Carbon Registry (ACR) **Methodology for biochar projects, Version 1.0, 2013**	A U.S. based registry that developed a draft biochar methodology in 2013, which was never adopted due to concerns expressed during a scientific review process. The only eligible use was to be as a soil amendment.	Proposed H/C_{org} -based storage factors, with 70% storage assumed for an H/C_{org} ratio < 0.4, and 50% for 0.4 > H/C_{org} < 0.7. Biochars with H/C_{org} ratios above 0.7 were not eligible. The methodology predates the IPCC (2019) reporting guidelines and Woolf et al. (2021).	The LCA excluded feedstock cultivation and final application, though co-products of pyrolysis were to be accounted through a system expansion approach. Soil sampling was not required. The methodology remains inactive.

Note: The information presented in this table is drawn from Malins et al. (2024)(pg. 26 – 58), which reviews the certification methodologies for biochar developed by private standards engaged with the voluntary market for carbon removals.

2.4. Priming effects and soil carbon dynamics

Priming effects occur when biochar influences microbial activity in soil, leading to changes in the decomposition rates of soil organic carbon (SOC). The effects can either enhance or supress SOC mineralisation[1]. If biochar addition to soil reduces the rate of SOC mineralisation, leading to greater carbon storage over time, this is referred to as negative priming. Conversely, if biochar stimulates microbial activity and accelerates the rate of SOC mineralisation, reducing carbon storage over time, this is known as positive priming. These interactions are highly context-dependent and influenced by biochar's properties, soil type, microbial communities, and environmental conditions (Blanco-Canqui et al., 2020; Ding et al., 2018). For example, there is evidence that applying biochar produced at high temperatures to temperate soils can reduce SOC mineralisation rates, though further research is needed to fully understand the mechanisms involved (J. Chen et al., 2021; Weng et al., 2022; Yang et al., 2022)

Positive priming occurs when biochar stimulates microbial activity, leading to accelerated decomposition (mineralisation) of native SOC. This can happen, for example, when nutrient-rich biochar is applied to nitrogen-limited soils, enhancing microbial respiration (Y. Zhang et al., 2022) and potentially undermine the carbon sequestration benefits of biochar application (B. P. Singh & Cowie, 2014). In contrast, negative priming occurs when biochar stabilises SOC, either by physically adsorbing SOC onto its surfaces, making it less accessible to microbes, or by promoting microbial communities that are less efficient at decomposing organic matter (Budai et al., 2016; Ding et al., 2018; Wang et al., 2016; Y. Zhang et al., 2022; Zheng et al., 2018).

The balance between positive and negative priming is influenced by numerous variables, including biochar composition, pyrolysis conditions, soil type, and application rates, and there is no scientific consensus at this time on the prediction of the priming that may be associated with biochar application at a given location (Purakayastha et al., 2024). This uncertainty

1 Mineralisation refers to the transfer of carbon to inorganic molecules – in this case the conversion of carbon in SOC into CO_2. It should be noted that mineralisation processes are not always associated with CO_2 emission. For example, the formation of carbonates in concrete by absorption of carbon from atmospheric CO_2 is also referred to as mineralisation but is associated with reductions in atmospheric CO_2.

complicates predictions about biochar's net impact on soil carbon dynamics, underscoring the need for site-specific studies that consider variations in soil properties, climatic conditions and biochar characteristics, though it is clear that priming effects can influence the durability of biochar's carbon sequestration potential in soils.

2.5. Measuring biochar in soil

Current carbon removal certification frameworks for biochar rely on measuring the amount of biochar that is applied and estimating the fraction of carbon that will remain stored over a specified period. An alternative approach is to measure the biochar present in situ, focusing on the actual carbon stored at the time of measurement rather than projecting its durability over time. This approach is embedded in the EU's RED III through the term for soil carbon accumulation (e_{sca}).

However, just as there are challenges in accurately predicting the durability of biochar, accurately measuring biochar-derived carbon in a given land area presents significant challenges. This could be particularly relevant in frameworks like the International Civil Aviation Organisation's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), where multiple land management practices may be credited simultaneously. In such cases, isolating biochar's effect on SOC from other practices (e.g. cover cropping, compost application, or reduced tillage) is difficult, raising concerns around attribution and the potential for double-counting.

Standard soil carbon measurement methods, such as dry combustion, measure total soil carbon without distinguishing biochar-derived carbon and other SOC pools. This limitation is particularly problematic when assessing changes over time, as observed gains or losses could result from various factors unrelated to biochar application, or even possibly through unforeseen priming effects. Consequently, these methods cannot accurately attribute carbon storage to biochar alone.

Advanced techniques, including stable isotope analysis and spectroscopic methods such as Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and nuclear magnetic resonance (NMR) can help differentiate biochar carbon from other sources. However, these methods can be costly, complex, and labour-intensive, limiting their practical application in biochar crediting schemes (Adhikari et al., 2024).

Biochar's physical movement within soil profiles further complicates carbon accounting. Studies have shown that biochar particles can migrate vertically or laterally due to soil biota activity, water movement, or wind erosion. Consequently, carbon assessments based on soil sampling could underestimate sequestration (if biochar moves out of the sampled area) or overestimate it (if biochar is disproportionately concentrated in the sampled area) (Blanco-Canqui, 2021). Uneven application of biochar across fields adds another layer of variability (Lotz et al., 2024).

The EU's Soil Monitoring Directive, currently in the trilogue process of negotiation between the European Institutions, proposes a standardised approach to assessing SOC stocks across EU Member States as part of broader soil health monitoring. Although the directive mandates regular SOC measurements, it does not provide a framework for differentiating biochar-derived carbon from other forms of SOC. This limitation makes it difficult to interpret data on biochar's impact on soil health and carbon sequestration. Nevertheless, the directive could provide a valuable baseline for monitoring SOC changes associated with biochar applications.

Adapting the Soil Monitoring Directive to directly address the unique dynamics of biochar addition would require further research and innovation in sampling and analytical techniques. However, by leveraging the directive's framework, policymakers and researchers will be better placed to address these knowledge gaps, ensuring that biochar's role in soil carbon sequestration is credible and that its ecological impacts are fully understood. This integration could provide crucial insight for regulatory and voluntary crediting systems to align their methodologies for accounting for biochar's carbon durability with the latest scientific understanding.

3. Co-benefits and sustainability risks

Studies have shown that biochar can deliver a range of potential co-benefits beyond carbon sequestration, making it an appealing tool for addressing climate change while contributing to broader sustainability goals. In addition to CDR and the potential negative priming of SOC (as discussed in section 2.4), biochar may deliver mitigation benefits by reducing soil nitrous oxide (N_2O) emissions (Borchard et al., 2019; Cayuela et al., 2014; Song et al., 2016; Verhoeven et al., 2017), lowering nitrogen fertiliser requirements due to reduced nitrogen leaching and volatilisation (Borchard et al., 2019; Q. Liu et al., 2019) and reducing GHG emissions from co-applied compost (Agyarko-Mintah et al., 2017; H. Wu et al., 2017). There is also emerging evidence that using biochar as a feed additive in livestock diets could reduce enteric methane emissions from ruminant animals, though results reported in the literature are mixed (Saleem et al., 2018; Schmidt et al., 2019; Winders et al., 2019).

However, delivering these potential co-benefits depends on the application context, and biochar can also pose risks and challenges that require careful management to ensure its benefits are realised without unintended consequences (Brtnicky et al., 2021; Joseph et al., 2021). This section explores biochar's agricultural and environmental co-benefits, biodiversity and ecosystem impacts, and potential sustainability risks.

3.1. Agricultural co-benefits

Biochar's most documented benefits relate to its potential for enhancing soil health. Its highly porous structure and large surface area can improve water retention, particularly in coarse-textured soils prone to moisture loss (Blanco-Canqui, 2021). However, in finer-textured soils such as clays, biochar's impact can be more variable, with some studies suggesting it may, in certain conditions, reduce water availability by altering soil pore distribution (Brtnicky et al., 2021).These dynamics are context-depending, highlighting the importance of site-specific assessments.

Biochar may also enhance agricultural resilience by increasing SOC and supporting microbial communities that promote nutrient uptake and pathogen resistance (Y. Zhang et al., 2022). Studies have also suggested that biochar can enhance nutrient cycling by improving the retention, transformation, and availability of essential nutrients like nitrogen (N), phosphorous (P), and potassium (K), reducing leaching and improving fertiliser efficiency (Q. Liu et al., 2019). Biochar can also buffer soil pH, creating optimal conditions for nutrient solubility, which is particularly valuable in dry or degraded soils (Smith, 2016). Studies have also demonstrated increased crop productivity in biochar-amended soils, which may be attributed to enhanced water availability, nutrient retention, and improved soil structure (Blanco-Canqui, 2021; Lehmann et al., 2006, 2021).

Despite these potential benefits, it remains challenging to develop a predictive model for the impact of biochar on yield for a given crop in a given context (Kumar et al., 2021; Osman et al., 2022). In some cases higher application rates (> 50 t ha^{-1}) have been shown to impair soil microbial communities, reduce soil fertility or inhibit plant productivity (Joseph et al., 2021), whereas low application rates (~1 t ha^{-1}) have been found to enhance fertiliser efficiency and reduce nutrient losses, particularly when biochar is blended with compost or other materials (such as zeolites or clay minerals) (Joseph et al., 2021). Field data to determine whether applying a large initial dose of biochar or yearly administrations at lower rates are preferable are generally lacking (Oelbermann et al., 2020).

3.2. Reductions in CH_4 and N_2O emissions

Biochar can help mitigate GHG emissions in agriculture, particularly methane (CH_4) and nitrous oxide (N_2O), the latter of which is a particularly potent GHG with a global warming potential nearly 300 times that of CO_2 (Domeignoz-Horta et al., 2018; Osman et al., 2022). Experiments have suggested that biochar combined with fertilisers can reduce N_2O emissions, for example, one experiment in China reported reductions by 30–40% per unit of produced maize compared to chemical fertilisers alone (Niu et al., 2017). It may also help reduce CH_4 formation, for instance a study by Liu et al. (2011) suggested that adding biochar to rice paddy soil could significantly reduce CH_4 emissions under certain conditions. Rice paddies are a major source of CH_4 emissions, highlighting the potential of biochar as a mitigation tool in this context, but while promising these studies were derived from incubation studies, and their applicability to real-world settings requires further investigation.

Biochar's inclusion in livestock feed has been suggested as a potential pathway to mitigate CH_4 emissions from enteric fermentation (Schmidt et al., 2019), potentially through altering methanogenesis pathways in the rumen (R. A. Leng, 2014; Saleem et al., 2018). However, the results of such studies remain mixed, with some showing no significant difference in enteric emissions following biochar feed supplementation (Winders et al., 2019). Therefore, further research is needed to confirm these effects under varying feed compositions and animal species. Beyond this, biochar addition to animal feed has been associated with additional benefits such as improved weight gain (Mirheidari et al., 2020), animal health (Talaş et al., 2021) and detoxification of contaminants (Schmidt et al., 2019).

Biochar-containing manures also have higher plant-available nutrient content, which could reduce reliance on fertilisers and enhance crop productivity (Schmidt et al., 2019). However, these benefits are context dependent, influenced by factors such as soil type, biochar properties, and application rates. While some studies report promising results, others highlight inconsistencies or limited benefits under certain conditions, underscoring the need for further research (Lehmann et al., 2021).

In Europe, the use of biochar as a feed ingredient is subject to feed quality rules under EC Regulation 178/2002, and in the case of organic systems to the regulations for organic livestock feed under EC Regulation 834/2007, all of which is regulated under the Food Safety Authority (Gerlach & Schmidt, 2014). A summary of the characteristics and safety limits for feed-grade biochar is provided in Table 4 of Osman et al. (2022), relating directly to the animal feed threshold values established under the EBC. Though certification under the EBC is generally voluntary, in Switzerland for example, it is obligatory for all biochar sold for use in agriculture (Gerlach & Schmidt, 2014; Osman et al., 2022).

Biochar may also be able to help mitigate CH_4 emissions from landfill sites. Research has suggested that when biochar is mixed into landfill soil covers, it can enhance the activity of methanotrophic microbes, and reduce CH_4 emissions by more than traditional soil covers alone (Chetri & Reddy, 2022; Osman et al., 2022). Advanced biochar formulations that are pre-loaded with methanotrophs have shown even greater CH_4 mitigation potential, which may in the future offer pathways for generating CH_4 avoidance credits in waste management systems (Huang et al., 2019).

3.3. Environmental co-benefits

Beyond agriculture, biochar may offer environmental benefits such as improved water quality and ecosystem restoration. Its high adsorption capacity can reduce nutrient leaching into waterways (thereby mitigating eutrophication risks) and enhance water filtration systems (El-Naggar et al., 2019; Osman et al., 2022). Biochar's ability to adsorb heavy metals and organic pollutants also makes it a potentially valuable tool for land remediation and soil rehabilitation, including restoring degraded or contaminated soils for crop cultivation (Chiaramonti & Panoutsou, 2019; Hilber et al., 2017; Ji et al., 2022; S. Wu et al., 2017).

Biochar also has applications in industrial decarbonisation, where it can be incorporated into traditional production methods, either as a fossil fuel substitute, or as a material enhancer. In construction, biochar additives have been shown to enhance the mechanical properties of materials such as cement and asphalt, improving compressive strength, flexibility and durability (Fawzy et al., 2021). However, further studies are needed to optimise biochar application in these various contexts (Osman et al., 2022).

3.4. Biodiversity and ecosystem impacts

Biochar interacts with soil biodiversity and ecosystem function in complex ways that influence its long-term stability and ecological outcomes. Its porous structure creates microhabitats for soil microorganisms, and can foster greater microbial diversity, and support fungal and bacterial communities involved in nutrient cycling and carbon stabilisation (Lehmann et al., 2011; Y. Zhang et al., 2022). However, a clearer understanding of the context and conditions in which these positive interactions can occur is needed to ensure biochar application contributes to soil biodiversity and improved ecosystem resilience, particularly in degraded and agricultural landscapes.

Despite the potential benefits, the broader biodiversity impacts of biochar are poorly understood, particularly outside of agricultural contexts. Research on biochar's effects in ecosystems, such as forests and grasslands remains limited (Brown et al., 2023; Bruckman & Pumpanen, 2019). Some evidence indicates that biochar application can reduce species richness among soil fauna, such as earthworms and other invertebrates, in certain contexts (Brtnicky et al., 2021; Rice-Marshall et al., 2024). These changes may also alter ecosystem services associated with key soil organisms, affecting nutrient cycling, decomposition rates, and food web interactions (Briones et al., 2020; Wang et al., 2024). Given that soil invertebrates play a fundamental role in soil structure, aeration and ecological stability, further research is needed to clarify the conditions under which biochar supports or disrupts soil biodiversity.

3.5. Sustainability risks and challenges

Despite biochar's potential to deliver multiple co-benefits, its widespread adoption introduces several sustainability risks that should be carefully considered. First, climate policy frameworks tend to prioritise GHG mitigation, sometimes at the expense of biodiversity and ecosystem resilience (Pettorelli et al., 2021). This is particularly relevant given that soil biodiversity is significantly and positively associated with soil ecosystem functioning (Delgado-Baquerizo et al., 2020). To achieve truly sustainable outcomes, policies and crediting frameworks must integrate biodiversity safeguards, ensuring that climate mitigation strategies do not compromise ecosystem health (Courvoisier et al., 2018; Phillips et al., 2024; Urban, 2024). Although some biochar certification schemes include basic environmental safeguards, these vary and are not standardised across voluntary or regulatory carbon markets.

Scaling biochar production without sustainable feedstock sourcing also poses significant risks. Increased demand for biomass feedstocks could exacerbate land-use pressures, particularly if feedstock sourcing leads to deforestation or unsustainable agricultural practices. Competition for biomass resources is expected to intensify in the future, underscoring the importance of prioritising residues and waste materials as feedstocks. The Working Group III contribution to the IPCC's sixth assessment report warns that, "afforestation or production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure" (Shukla et al., 2022). Biochar feedstock sourcing could also create unintended trade-offs, where shifting readily decomposable organic inputs from one location to others that receive more recalcitrant inputs, could alter soil carbon dynamics, potentially undermining ecosystem health and contributing to land degradation (Whitman et al., 2010).

Another risk arises from the presence of trace contaminants in biochar, particularly when derived from feedstocks such as sewage sludge, industrial wastes, and biogas production residues. These contaminants, including heavy metals like Cadmium, Copper, and Nickel, can pose risks to soil and human health, particularly if the biochar is used in agricultural applications. To mitigate these risks, stringent quality standards are necessary. The IBI for example, has set permissible limits for heavy metals in biochar, including Cadmium, Copper, and Nickel, at 1.4–39 mg/g,143–6,000 mg/g, and 47–420 mg/g respectively (see Table 1, Hilber et al., 2017).

The co-benefits of biochar are likely to raise interest in crediting schemes beyond GHG emissions. Existing crediting frameworks tend to focus primarily on carbon sequestration and emissions reduction, although there is potential in the future to expand methodologies to account for additional benefits such as improved water quality or land restoration. However, this would require standardised metrics and transparent reporting mechanisms. As environmental crediting schemes continue to evolve, and as scientific understanding of biochar's long-term impact on ecosystems advances, it's possible that new or existing crediting frameworks will credit additional co-benefits. However, further research and policy deliberation would be needed to explore the feasibility and implications of these approaches.

4. Biochar, LCA and carbon crediting

Biochar offers several potential routes for delivering CO_2 benefits, creating opportunities for recognition under various carbon accounting systems. This versatility allows biochar to generate carbon credits in both regulatory and voluntary markets, while influencing lifecycle emissions calculations for other products. However, this flexibility also presents challenges, including the risk of double counting, policy misalignment, and market distortions, all of which could undermine biochar's credibility and effectiveness as a climate mitigation strategy.

As illustrated schematically in Figure 2, biochar production is associated with a number of potential CO_2 sources and sinks, which must all be considered in assessing the net emissions consequence of biochar production and use.

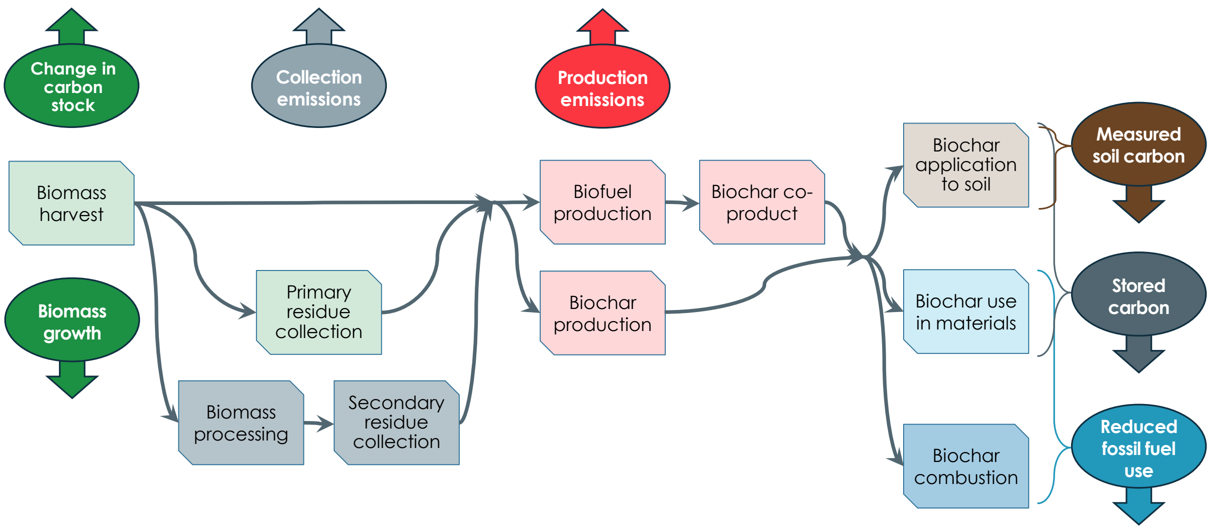

Figure 2 Schematic outline of the processes and associated carbon sources and sinks in biochar production

As highlighted in section 3.5, the delivery of biochar's carbon benefits depends on the sustainability of its feedstock source since upstream biomass production impacts net GHG reductions (Bergman et al., 2016). If biochar were produced using primary forest biomass as feedstock, this could negate potential emissions benefits, particularly if the biochar were later used for energy recovery rather than long-term carbon sequestration. Crediting schemes and LCA rules must therefore strive to prevent any mischaracterisation of biochar's environmental performance.

This section gives an overview of how different LCA approaches influence biochar's carbon accounting before reviewing the ways that biochar is recognised and/or credited in existing accounting schemes.

4.1. The role of LCA in biochar carbon crediting

LCA provides a framework for evaluating biochar's GHG emissions, energy use, product yields, carbon removal potential, and co-benefits potential across its lifecycle. In recent years, the body of work conducting LCAs on biochar's various applications has grown (Azzi et al., 2022; Bergman et al., 2016; L. Chen et al., 2022; J. Li et al., 2024; Matuštík et al., 2020; Patel & Panwar, 2023). Such evaluations are essential for ensuring accurate carbon accounting, especially as biochar use expands. Several CDR certification schemes, including EBC's C-Sink, Puro.earth and VCS, require an assessment of biochar's lifecycle emissions to ensure that carbon benefits are properly accounted for (Malins et al., 2024). However, there is variability as to what is included in methodology calculations across these schemes (see Table 1).

Table 2 Biochar LCA stages and system boundary considerations

LCA Stage	Description	System boundary			
		Cradle-to-gate	Gate-to-gate	Cradle-to-grave	Cradle-to-grave with system expansion
Biomass collection	Harvest / collection (agricultural and forestry residues, animal manure, sewage sludge etc.), transport from farm or field to the processing plant.	✓		✓	✓
Biomass pretreatment	If biomass is pretreated (e.g. shredded, ground, dried, washed with acid) to prepare for pyrolysis or thermochemical conversion.	✓	✓ (if pre-treated at plant)	✓	✓
Pyrolysis or Thermochemical conversion	Conversion of biomass into biochar, bio-oil, and syngas via pyrolysis / other pathways.	✓	✓	✓	✓
Biochar trans-portation	Biochar is packaged and transported to final use.			✓	✓
Biochar application	Biochar is applied to soil or used in other applications (e.g. construction, industrial processes, or waste systems).			✓	✓
Avoided emissions from co-product	Biochar and other pyrolysis co-products (pyrolysis oil and syngas) replace fossil-based alternatives.				✓

Note: Informed by biochar LCA system boundary approaches presented in Bergman et al. (2016), J. Li et al. (2024), Matuštík et al. (2020), Patel & Panwar (2023), and Roberts et al. (2010).

LCA methodologies differ depending on the chosen system boundary, which defines the emissions sources and activities that are included in the analysis (Patel & Panwar, 2023). System boundary choices also affect whether biochar is classified as a co-product, by-product or residue (Malins et al., 2024). As shown in Table 2, the key system boundary choices include cradle-to-gate (ends at biochar production), gate-to-gate (production only), cradle-to-grave (ends at biochar application). It is also possible to adopt a 'system expansion' approach to bring emissions changes associated with co-products within the system boundary, as an alternative to allocating system emissions between the produced products. For example, this could lead to calculating a 'credit' for a co-product based on the fossil-based alternative products that it could displace (Yu et al., 2022).

4.2. Biochar carbon removal (BCR) crediting

Biochar is recognised as a viable carbon removal approach because it allows carbon absorbed by plants from atmospheric CO_2 to be stored in soils or other materials on a long-term basis (Malins et al., 2024). By stabilising carbon in recalcitrant forms, biochar can store carbon for thousands of years, making it a 'permanent'[2] form of carbon removal under several CDR certification frameworks (e.g. the EBC's C-Sink, Puro.Earth, VCS, and Riverse, see Table 1). Biochar can also contribute to temporary carbon removal pathways by enhancing SOC storage, although this is more dependent on application methods and environmental conditions (see sections 2.4 on priming effects and soil carbon dynamics).

Permanent carbon removals are credited by these voluntary carbon removal certification schemes through the issuance of carbon removal 'units', each representing a tonne of CO_2[3] certified as removed from the atmosphere by the project activity. These units are typically traded on the voluntary carbon market, where companies purchase them to offset emissions as part of their corporate social responsibility activities and climate commitments. In the EU, regulation of these units is being developed under the Carbon Removal and Carbon Farming (CRCF) certification framework[4].

The number of units issued by these schemes is based on the amount of biochar produced and used in eligible applications (e.g. soil amendments, construction materials) multiplied by the carbon content of the biochar, then converted from mass of carbon to mass of CO_2 using a factor of 44/12. This is further multiplied by the fraction of the carbon expected to be stored for a minimum period, often 100 years, with GHG emissions that arise from biochar production and use being subtracted. Table 1 provides a brief overview of how some different CDR certification schemes currently approach calculating biochar's durability. It should be noted that the assessment of biochar permanence is still an evolving field, and thus it may be expected that emerging scientific results will lead to changes in these approaches over time.

4.2.1. Biochar carbon storage crediting in biofuel policy

Under the EU's RED III, biochar could be credited as an agricultural input (see section 4.3), and/or as a co-product of the biofuel production process, with an allocation of process emissions (see section 4.5). However, there is no direct mechanism under RED III to credit for the permanent carbon content in co-produced biochar.

In California, biochar carbon sequestration could potentially be recognised as a form of CCS and supported under the LCFS. Although not yet accepted by the California Air Resources

2 There is no universally accepted definition of the duration of carbon storage that may be treated as permanent – several existing standards for biochar certification treat the quantity of biochar expected to remain after 100 years as the 'permanent' fraction, and the EU's CRCF specifies that permanent storage must last for 'several centuries'.

3 Units could be issued in other denominations than a tonne of CO_2, but a tonne is standard.

4 https://climate.ec.europa.eu/eu-action/carbon-removals-and-carbon-farming_en

Board (CARB), the idea signals another pathway to valorise biochar from biofuel production systems. The LCFS operates by assigning lifecycle carbon intensity (CI) values to transport fuels, allowing credit generation for those with lower CIs than the set targets. In 2018, amendments to the LCFS expanded the scope of CCS projects eligible for LCFS credits, provided that they comply with CARB's CCS Protocol[5].

Currently, the CCS protocol allows LCFS credits to be generated for CO_2 captured from specific facilities (e.g. oil and gas production, refineries, ethanol plants) that supply transport fuel to California, as well as direct air capture projects globally (Townsend & Havercroft, 2019). However, the protocol only credits geological carbon storage, thereby excluding biochar. The California Governor's Office has suggested expanding CCS provisions to include biochar, although no regulatory action has been taken yet (Assefa, 2024).

ICAO's CORSIA framework aims to reduce the net emissions from aviation growth by supporting sustainable aviation fuels (SAFs) and carbon offsetting mechanisms. Currently, soil carbon credits are eligible under CORSIA's offsetting scheme, but biochar's potential for soil carbon sequestration during biofuel feedstock cultivation is not yet included within its fuel LCA methodologies (i.e. there is no term equivalent to the 'e_{sca}' term seen in the EU and UK fuel policy frameworks). However, a methodology for including soil carbon in CORSIA is in development, and if adopted, could expand ICAO's existing land management practice system to recognise biochar's potential for sequestering carbon in soils.

In addition, biochar could be integrated into CORSIA through the Fischer-Tropsch Gasification pathway, though the LCA methodologies (ICAO, 2022) primarily focus on syngas production, cleaning, and upgrading into liquid hydrocarbons, without acknowledging biochar or other solid carbonaceous residues as co-products. Nevertheless, the flexibility of CORSIA's methodology to approve new pathways suggests potential for the future inclusion of biochar into aviation fuel LCAs.

4.3. Biochar as an input to biofuel production: e_{sca} and climate smart agriculture

Biochar application as a soil amendment has demonstrated the potential to enhance soil carbon storage and provide other functional benefits for overall soil health in agricultural systems (Matuštík et al., 2020). As discussed in Section 2, biochar application can increase carbon stocks through two primary mechanisms. Firstly, it directly introduces carbon into the soil – some of which is recalcitrant, with an expected long residence time, while the labile fraction degrades over years to decades. Secondly, biochar application may reduce the mineralisation rate of existing non-biochar carbon (i.e. native SOC) in the soil, promoting its accumulation (see discussion of priming effects in section 2.4). Both mechanisms could be quantified using soil carbon measurement on the land to which the biochar is applied, although challenges exist in isolating biochar's specific contribution from other potential drivers of SOC change (see section 2.5 on the challenges of distinguishing biochar derived soil carbon from other soil carbon pools).

5 https://ww2.arb.ca.gov/resources/documents/carbon-capture-and-sequestration-protocol-under-low-carbon-fuel-standard

4.3.1. The EU and UK, e_{sca}

The EU's RED III includes specifications for the LCA of transport biofuels and biomass fuels. Suppliers of transport biofuels or bioenergy to the EU market must report GHG intensity values for their fuels following the RED III's LCA rules. These lifecycle emissions values are crucial, as the RED III sets maximum allowable thresholds on lifecycle GHG emissions intensity[6]. Biofuels or bioenergy that exceed the threshold are ineligible to receive financial support under Member State schemes. In some biofuel support schemes that use a GHG intensity standard, which includes some EU Member States, the lifecycle emissions savings attributable to biochar could be significant to a given fuel's policy value because biofuels are incentivised proportionally to their reportable lifecycle emissions savings.

Within the RED III lifecycle accounting rules, suppliers are allowed to include an emissions saving term for 'soil carbon accumulation via improved agricultural management', abbreviated to e_{sca}. This term allows biomass producers to report and receive credit for an increase in soil carbon on agricultural land, plantations, or harvested forest areas where biomass is produced. A similar e_{sca} term may be applied under the UK's Renewable Transport Fuel Obligation (RTFO), which follows LCA rules that are largely based on the EU system.

In both frameworks, biochar is explicitly recognised as a qualifying practice. The RED implementing regulation[7], lists biochar among accepted improved agricultural management practices, alongside compost, digestate and manure fermentation. Similarly, RTFO guidance[8] includes biochar as a method to maintain or enhance soil carbon as part of a broader soil management plan. As such, biochar is one of several practices that can contribute to increases in soil carbon. and the measurement process estimates the overall net change in soil carbon after the practices are applied (Chiaramonti et al., 2024). These methodologies for calculating soil carbon accumulation rely primarily on direct field-based soil-carbon measurements, supplemented with soil-carbon modelling. There are no specific rules within the e_{sca} term calculation for isolating biochar's contribution to soil carbon.

To claim the e_{sca} credit, producers must establish a baseline of SOC stocks before the biochar application and measure subsequent SOC changes at regular intervals, not more than five years apart. Between these measurement points, soil carbon increases may be estimated using representative experiments or soil carbon models (as allowed by the biofuel certifying bodies), but new direct measurements override modelled estimates, and models must be calibrated to the observed field data.

The RED III methodology for calculating e_{sca} is outlined in Annex V of Implementing Regulation 2022/996, with the following equation:

$$e_{sca} = (CS_A - CS_R) \times 3{,}664 \times 10^6 \times \frac{1}{n} \times \frac{1}{P} - e_f$$

Where:

6 These thresholds are expressed as minimum required carbon savings, but because these carbon savings are calculated against fixed comparison values this is functionally the same as a maximum intensity threshold.

7 Commission Implementing Regulation (EU) 2022/996

8 Renewable Transport Fuel Obligation: Compliance Guidance

- CS_R is the mass of soil carbon stock per unit area associated with the reference crop management practice in Mg of C per ha.
- CS_A is the mass of soil estimated carbon stock per unit area associated with the actual crop management practices after at least 10 years of application in Mg of C per ha.
- 3,664 is the quotient obtained by dividing the molecular weight of CO_2 (44,010 g/mol) by the molecular weight of carbon (12,011 g/mol) in g CO_2eq/g C.
- *n* is the period (in years) of the cultivation of the crop considered.
- *P* is the productivity of the crop (measured as MJ biofuel or bioliquid energy per ha per year).
- e_f is the emissions from increased fertiliser or herbicide use, where relevant.

The baseline carbon stock, CS_R, is measured at the farm level before the adoption of improved practices. The carbon stock after adoption of improved practices, CS_A, is measured at intervals of not less than every five years. The farm is only allowed to claim an e_{sca} credit where a specified improved agricultural management practice is applied – these could include reduced or zero-tillage, improved crop rotation, cover cropping, crop residue management, and the use of organic soil improvers like biochar. The maximum threshold for the e_{sca} credit is normally 25 gCO_2/MJ taken away from the other lifecycle emissions of the biofuel or bioenergy pathway, but where biochar has been used the cap on the allowable credit increases to 45 gCO_2/MJ.

To improve accuracy, at least 15 well-distributed soil samples per five hectares (or per field, if smaller) must be taken before and after biochar application, either in spring before cultivation and fertilisation, or in autumn, post-harvest, to a depth of 30cm. The soil carbon measurement systems that are likely to be used would not be able to distinguish between carbon from the recalcitrant part of the added biochar, carbon from the labile part, and carbon from other soil carbon pools.

Certification bodies must verify e_{sca} claims and document the results in audit reports. One key example is the International Sustainability and Carbon Certification (ISCC) voluntary scheme, which provides further guidance for operators by integrating soil sampling with models such as RothC, Century or Daycent to estimate changes in SOC between measurements.

For biochar-specific applications, Pulcher et al., (2022) modified the RothC model to include two biochar pools and incorporated a constant negative priming effect on SOC. This modification was calibrated using data from a field study by Ventura et al. (2015), which found that biochar application reduced SOC degradation by 16% annually over a three-year period. While the modified model was able to simulate observed SOC dynamics over the eight-year field experiment, the authors caution that the results are site-specific, and that the underlying mechanisms of priming remain poorly understood. As such, the model's ability to predict priming effects beyond this context was deemed limited.

A study by Oelbermann et al., (2023), assessed the Century model in predicting changes in SOC after biochar application under a commercial farming system in Ontario, Canada. Baseline soil samples were taken prior to application, followed by repeated sampling after harvest across several growing seasons. The model was calibrated using this field data under different combinations of biochar and manure application. The Century model's

SOC predictions aligned closely with field measurements (within -1% to +9%), demonstrating a degree of accuracy after baseline soil sampling and calibration. However, the authors emphasised that the model's apparent accuracy may be partially due to the relatively straightforward nature of modelling direct carbon inputs from organic amendments. They also noted several key limitations, including the model's assumption of fixed soil bulk density, its inability to account for biochar ageing or leaching, and its restriction to the top 20cm of soil. These limitations suggest that while calibration can improve short-term model performance, longer-term carbon sequestration dynamics may still be underestimated or misrepresented, especially in systems with more complex biochar-soil interactions.

4.3.2. U.S. climate smart agriculture policies

In the U.S., biochar crediting is influenced by a diverse portfolio of policies including the federal Renewable Fuel Standard (RFS), state-level policies such as California's LCFS, the Washington, Oregon and New Mexico Clean Fuel Standards (CFS), as well as federal tax credits that offer a set financial benefit for supplying certain categories of renewable fuels.

Under the Inflation Reduction Act (IRA), the '45Z' biofuel tax credit[9] (effective 2025 to 2027) applies to alternative fuels supplied for both aviation and non-aviation applications. It assigns a value per gallon of fuel based on the reportable carbon intensity (CI) of the fuel. For aviation fuels, the value of the credit increases linearly from $0 to $1.75 per gallon as the reportable CI of the fuel goes down from the maximum allowable value (47 gCO_2e/MJ[10]) to zero. This is equivalent to a carbon price of about 280 $/t$CO_2$e for 'climate smart agriculture' (CSA) practices. It is our understanding that the 45Z credit can go beyond $1.75 per gallon for fuels that report a negative carbon intensity, and therefore that the emissions benefit of a CSA practice would always be fully rewarded.

The 45Z credit recognises emission reductions due to CSA practices, which are defined as agricultural practices that can reduce GHG emissions or increase soil carbon sequestration[11]. Currently, the crops eligible to report the use of a CSA practice are corn, soybeans and sorghum. While biochar is not explicitly recognised as a CSA practice, its inclusion could allow SAF producers to increase the value of the credit when using feedstock grown on biochar-treated fields.

The U.S. Department of the Treasury has indicated an intention to propose CSA rules under the 45Z credit[12], but no final guidance has been issued on what will be permitted. An earlier notice[13] created a 'safe harbor' for biofuel producers using feedstock produced under the USDA CSA Pilot Program. This safe harbor provision means that the Treasury has committed to recognising the emissions reductions calculated for feedstocks produced under that program when the full final rules are established. The CSA Pilot Program requires three practices for corn (no till, cover crops, enhanced efficiency nitrogen fertilisation) and two for soy (no till and cover cropping).

9 Notice 2025-11 https://www.irs.gov/pub/irs-drop/n-25-11.pdf

10 Expressed in the tax code as 50 kgCO_2e/mmBTU.

11 https://www.usda.gov/sites/default/files/documents/7CFR2100_FINAL_1_15.pdf

12 Notice 2025-10, https://www.irs.gov/pub/irs-drop/n-25-10.pdf

13 Notice 2024-37

Shortly after the Treasury confirmed its commitment to propose CSA rules, the USDA released an interim rule of its own outlining "Technical Guidelines for Climate-Smart Agriculture Crops Used as Biofuel Feedstocks". This rule does not directly apply to the calculation of the 45Z credit (at least not yet), rather it is more broadly framed as setting guidelines relating to "emerging environmental services markets". The eligible CSA practices under this rule are no or low till, cover crops, nitrification inhibitors, and practices relating to the timing of nitrogen application. Biochar application is not currently identified as a CSA practice. Unlike the calculation of the e_{sca} credit in RED III, emissions reductions from CSA practices (including soil carbon increase) are to be calculated entirely based on modelling approaches under the USDA guidelines. This means that biochar use could only be credited if it is reflected in the modelling. Currently, the model ("USDA FD-CIC"[14]) does not allow for biochar to be considered, and therefore biochar use will not be creditable within this framework unless it is actively added to the list of eligible practices.

4.3.3. Biochar in the calculation of direct land use change emissions

Biochar could also play a role in the calculation of emissions when biofuel production systems are associated with direct land use change (DLUC). Under the RED III, if the use of land used for producing biofuel feedstock has changed since 2008 then the producer must account for associated carbon stock changes. The soil carbon contribution to this change may be based on measurement, and therefore a soil carbon increase due to biochar application could be used to offset reductions in biomass carbon stocks associated with a land use change.

Similarly, biochar could affect calculated land use change emissions under ICAO's CORSIA methodology for calculating DLUC emissions, which follows IPCC guidelines for land use emission factors. While biochar is not explicitly mentioned in the text, the equation includes terms for SOC change (ICAO, 2024), and under IPCC tier 3 rules for calculating land use change emissions if biochar is utilised as a soil carbon amendment after the land use change it could increase identified values of SOC and thus offset DLUC emissions.

4.4. Crediting biochar-associated soil organic carbon increase through carbon farming initiatives

Biochar has the potential to enhance SOC stocks and support climate-smart agriculture (CSA), contributing to both climate mitigation and adaptation goals (Chiaramonti et al., 2024). Studies indicate that biochar can improve soil resilience by enhancing water retention, nutrient cycling, and microbial diversity, particularly in degraded and dry soils (Blanco-Canqui, 2021; Smith, 2016). These effects have the potential to improve crop productivity and reduce reliance on synthetic fertilisers (Lehmann et al., 2021) (as discussed in section 3.1).

In voluntary carbon markets, biochar's contribution to SOC can be credited under methodologies designed to improve agricultural practices, for example, Gold Standard's "Soil Organic Carbon Framework Methodology"[15] allows SOC stock changes quantification using IPCC Tier 1 or 2 default approaches or on-site measurements. However, eligible practices

14 https://www.usda.gov/usda-fdcic

15 https://globalgoals.goldstandard.org/402-luf-agr-fm-soil-organic-carbon-framework-methodolgy/

must align with an existing 'activity-specific module', and currently, as in the case of the CSA rules in the U.S., biochar addition is not currently defined as a qualifying activity.

As noted previously, a key challenge for biochar crediting is the difficultly of distinguishing biochar-derived carbon from other SOC pools using standard measurement techniques. When applied alongside other SOC enhancement activities (e.g. reduced tillage), measured SOC increases reflect the combined effect of all practices. It is unclear whether verifiers under Gold Standard, or other similar standards, would accept this combined effect or require separate attribution for biochar-related SOC changes.

Soil carbon modelling may offer an alternative pathway for crediting biochar if models can be updated to include biochar application as a parameter. As described in section 4.3.1. the RothC model has been modified to include two biochar pools (labile and recalcitrant), along with adjustments for biochar's observed priming effects on SOC (Pulcher et al., 2022). However, it remains unclear whether verifiers would accept such modelling approaches.

To prevent double counting, Gold Standard rules ensure that if multiple SOC-enhancing activities are registered as separate projects, the combined effect is not credited twice. However, the framework does not explicitly address whether a soil carbon enhancement activity such as biochar application could also be used to generate permanent carbon removal credits. Given that Gold Standard is currently developing a dedicated Sustainable Biochar Methodology[16], clearer guidance on biochar's crediting pathways through soil carbon accounting and other applications can be expected.

4.5. Biochar as a co-product in biofuel LCA

Biochar can be produced as an additional output in biofuel production systems, particularly in pyrolysis or gasification processes (Buffi et al., 2024; De Corato et al., 2018; Kang et al., 2022). In the LCAs of these systems, emissions from the production and processing of feedstock are allocated between the more valuable outputs, thereby reducing the share of GHG emissions attributed to the biofuel products. Emissions would be allocated to biochar if it is treated as a co-product – but not if it is treated as a residue[17].

The classification of biochar as either a co-product or residue depends primarily on its economic significance within the production system. Outputs that generate significant revenue are considered co-products, while those with minimal revenue are classified as residues. However, the distinction is not always clear cut. For example, CORSIA states:

> *"Primary and co-products are the main products of a production process. These products have significant economic value and elastic supply, (i.e., there is evidence that there is a causal link between feedstock prices and the quantity of feedstock being produced)."*

Despite this, there is no firm numerical rule defining 'significant' value, or just how elastic an elastic supply is. Similarly, the RED III describes residues as products that are 'not a primary aim'

16 https://globalgoals.goldstandard.org/in-development/sustainable-biochar

17 The precise terminology varies between systems – for example in the RED III materials are classed as co=products, residues or wastes, while under CORSIA they can have those classifications but there is an additional category of 'by-products' between residues and co-products.

of a production process. In gasification systems, where biochar yields are typically low, we would not expect gasification biochar to be treated as a co-product. The situation is different for fast pyrolysis as the biochar yield is higher – for a process that does not consume the biochar for on-site energy, it seems likely that the biochar could be treated as a co-product to which emissions would be allocated.

Under the EU's RED III, allocation is based on the energy content of the outputs. If, for example, the biochar from a pyrolysis process contained 25 gigajoules of energy and the biofuel contained 75 gigajoules of energy, then 25% of the process emissions could be allocated to the biochar. Other policy frameworks, including the UK's RTFO, allow for emissions allocation to co-products in biofuel LCAs.

Similarly, this is understood to be possible under California's LCFS, where allocation reduces the reportable CI of fuels, and may also be applicable under other U.S. state policies modelled on the LCFS. This allocation mechanism allows biochar production to implicitly contribute to transport sector decarbonisation by lowering the reportable emissions of the produced biofuels.

4.6. CH_4 and N_2O avoidance due to biochar application

Carbon credits for CH_4 and N_2O avoidance can be generated under voluntary frameworks, such as VCS and Gold Standard, which credit reductions from waste and manure management, as well as livestock feed applications. While it is unclear whether biochar is currently recognised as a creditable practice under these different emissions reductions methodologies, their existence suggests a potential pathway for crediting biochar's use in these contexts.

For example, Gold Standard's methodology for reducing methane emissions from enteric fermentation in beef cattle[18] requires that feed supplements which are utilised can demonstrate emissions reduction efficacy from peer-reviewed scientific literature. Although it is unclear whether existing literature on enteric methane emission reduction through biochar as a feed additive would meet this requirement. Under the Gold Standard methodology, CH_4 emission reductions can be quantified through direct measurement or modelling. However, these reductions would not be creditable under permanent carbon removal schemes or in biofuel LCA and therefore avoid the risk of double crediting in this case.

4.7. Biomass-based fuel in industrial applications

Beyond its role in agriculture, biochar can be used as a biomass-based fuel or as an input in industrial processes, generating additional carbon reduction opportunities in hard-to-abate industries, such as steel making and cement production.

In the steel industry, biochar can replace coke or coal, reducing emissions associated with fossil fuel use (Meng et al., 2024). In the EU, replacing coke with biochar reduces the reportable emissions for steel producers under the EU's Emission Trading Scheme (ETS) and therefore delivers value by reducing the need to purchase ETS allowances.

18 https://globalgoals.goldstandard.org/standards/438_V1.0

Biochar can also be integrated into construction materials like cement and asphalt. In the best cases this enhances material properties while sequestering carbon (Lin et al., 2023) – in some applications biochar addition has been shown to be able to improve strength, soundproofing and thermal insulation while also reducing weight (Gupta et al., 2020; Lin et al., 2023). These applications are promising for generating long-term carbon credits, as biochar used in industrial processes is assumed to be shielded from decomposition, achieving equal or greater durability than the same biochar added to soil (Winters et al., 2022).

CDR credits can be generated for these applications under voluntary carbon market standards such as EBC's C-Sink, VCS and Puro.earth (see Table 1), which validate the emissions reductions and long-term sequestration potential through biochar's use in these industrial processes.

5. Coherent policy for crediting biochar

As discussed in the section above, biochar presents multiple opportunities for generating carbon credits or registering carbon benefits across a range of policy frameworks, including the voluntary carbon market, energy policy, and agricultural policy. This flexibility may enable biochar producers and users to couple multiple value streams to support the accelerated deployment of new biochar projects. However, this may also introduce challenges, such as risks of double-counting/double crediting[19] and methodology misalignment. There is also a risk of policy misalignment if the carbon storage delivered by using biochar is valorised, but there are no robust methods in place to prevent changes in standing carbon stock due to biomass harvesting.

This section explores some of these issues, using hypothetical project examples for illustration.

5.1. The challenge of complementary incentives

Multiple recognition of GHG benefits may occur when more than one entity claims the same GHG reductions or removals, or if a GHG reduction or removal is reported under more than one framework (ICVCM, 2024; Streck et al., 2023). Some forms of multiple recognition may be explicitly forbidden by the relevant frameworks, while other forms of multiple crediting may be normalised or even expected. There is no universally accepted terminology to distinguish between different forms of multiple recognition; here we draw a distinction between 'double counting', 'double crediting', 'double claiming' and 'stacking'. These terms are defined in Table 3 but caution is advised that other reports may use these terms differently.

The most problematic of these types of multiple recognition is double counting, as it undermines integrity by inflating perceived climate progress and can delay emissions reductions measures. Climate change policies and carbon reduction/removal certification schemes in the voluntary carbon market both generally have rules against double counting, and procedures to prevent it. In the case of biochar, we expect that GHG benefits would not be formally double counted unless these rules or procedures are broken. For example, in a very simple case a single biochar project could potentially be registered with two different carbon removal standards on the voluntary market, and claim removals from the same biochar batch under both. While it should not be taken for granted that this sort of double counting is effectively prevented in all cases, there are rules in place to address this, and therefore it is not our focus here.

The more nuanced area is the policy space that we are referring to as double crediting and stacked incentives. These are forms of multiple recognition that are not explicitly prohibited and may even be encouraged, but that could potentially distort the market. The biofuel market provides several examples of multiple recognition. For instance, a batch of aviation biofuel meeting the EU's sustainability requirements could: (1) count towards the Member State target for renewable energy in transport under the Renewable Energy Directive, (2) count towards the fuel supplier target for the supply of 'sustainable aviation fuel' under

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ReFuelEU Aviation, and (3) be treated as having zero combustion emissions when calculating the ETS obligations of the airline using it.

The EU has chosen to allow these incentives to be stacked. Similarly, in the U.S., a single batch of biofuel might be counted towards compliance with both a state renewable fuel policy such as California's LCFS, the Federal Renewable Fuel Standard, and also be eligible to receive support through tax credits – this full stack of incentives provides significantly more value than any individual one (cf. Malins & Sandford, 2022).

Table 3 Definition of terms related to multiple recognition of GHG benefits

Term	Definition
Double counting	A situation in which a single GHG emission reduction or removal is counted more than once towards achieving the same mitigation target or goal. This can happen through double issuance (more than one unit is issued for the same reductions or removals) or double use (the same units are used twice towards a single mitigation pledge). Double counting may occur indirectly, in the case that two distinct targets or goals are both meant to contribute to an overarching target or goal. For example, in inventory accounting, the EU and the aviation sector have separate inventories and emission reduction goals, but the two inventories are added together when considering progress against global goals, and therefore counting a GHG reduction in both the EU and aviation inventories would be double counting. Double counting of this sort is generally prohibited by the rules of the associated target or goal.
Double crediting	A situation in which a single GHG emission reduction is counted towards more than one different target or goal, without this being intended by those setting the targets or goals.
'Stacking' or stacked incentives	A situation in which a single project or activity receives multiple forms of financial or policy support from different mechanisms in relation to different targets or goals, and this is intended by the body or bodies setting those targets or goals. This might involve different forms of support recognising different characteristics of the project, such as GHG benefit and water quality (without necessarily double counting the same benefit) (Lankoski et al., 2015).
Double claiming	A situation in which responsibility for the same benefit is publicly claimed by more than one entity, but without double counting towards a target or goal. For example, if a forestry company supplying wood to a biochar plant, the biochar plant itself and the farmer applying the biochar all claimed in public statements to be delivering the carbon removals associated with the biochar, but carbon removal credits were issued only once.

An example of potential incentive stacking for biochar projects is provided by Chiaramonti & Panoutsou (2019), which examines the value available to a sunflower cropping system on marginal land if support was available for biochar use from both the EU's Common Agricultural Policy and from rewarding carbon storage in the biochar at the ETS price, and selling the sunflower oil into the aviation biofuel market with a sustainability premium.

This type of stacked support can be an effective tool to drive investment in low-carbon technologies that are expensive or seen as high-risk, and that would not attract investment if eligible for only one form of support. Therefore, stacked incentives for biochar production and use could accelerate market growth and innovation.

However, there is a risk that developing regulations could unintentionally make biochar eligible for forms of double crediting that would distort the market:

- Distortion of the carbon removals market: access to multiple incentives could unfairly favour biochar at the expense of other carbon removal technologies;
- Reduced net benefit: unintentionally counting the GHG benefits from biochar towards two different policy goals might reduce the net benefit from the two policies, compared to a scenario where double credited is not permitted.

If not properly acknowledged and addressed, double crediting of climate benefits risks creating an illusion of greater climate progress than has actually been achieved, thereby delaying further emissions reductions.

5.2. Examples

Biochar could potentially receive recognition across a range of policy contexts. This could be for its potential to deliver persistent carbon storage, its potential to replace fossil fuels, its potential to reduce emissions of CH_4 and/or N_2O, and for other environmental services, such as reducing nitrogen leakage and assisting with water quality management. Relevant policy contexts include:

- As a permanent carbon removal activity through certification for the voluntary carbon market;
- As a carbon removal activity through certification for regulated markets, such as ICAO's CORSIA for aviation;
- As a contributor to soil carbon formation that could contribute to temporary carbon removal crediting for carbon farming;
- As a biomass-based fuel for industrial applications, reducing obligations under emission trading schemes;
- As a low carbon-intensity alternative in materials applications, reducing obligations under emission trading schemes;
- As a co-product of biofuel production in biofuel LCA;
- As an agricultural practice supporting biofuel production through terms for soil carbon increase in biofuel LCA;
- As an agricultural emission reduction technology reducing enteric CH_4 emissions;
- As an agricultural emission reduction technology reducing N_2O emissions from fertiliser application;
- As a sustainable agricultural practice supported through agricultural policy;
- As a contributor to meeting soil carbon targets such as under the proposed EU Soil Monitoring Directive[20].

20 https://www.consilium.europa.eu/en/press/press-releases/2024/06/17/soil-monitoring-law-eu-on-

The following hypothetical cases sketch out circumstances in which biochar could be recognised in more than one way in policy, or in which a biochar-associated emission could be overlooked by policy, and discusses whether those potential overlaps could lead to double crediting or stacked incentives:

5.2.1. Case 1: biochar used in agricultural soil, generating both a carbon removal credit and e_{sca} credit

In this case, a biochar producer sells a batch of 1,000 tonnes of biochar as a soil amendment to a farm that supplies rapeseed to a local biofuel plant. The biochar was produced using a slow pyrolysis process operated at a peak temperature of 500°C, with 3 tonnes of biochar produced per 10 tonnes of biomass in. The biochar is applied to the soil at the farm across 100 hectares at a rate of 10 tonnes per hectare, and the biochar producer and the farmer coordinate to apply to a voluntary scheme to generate carbon removal credits. The farmer also reports the adoption of an improved agricultural practice and calculates an e_{sca} term for inclusion in the carbon intensity calculation for the biofuels produced using the rapeseed. This is shown schematically in Figure 3.

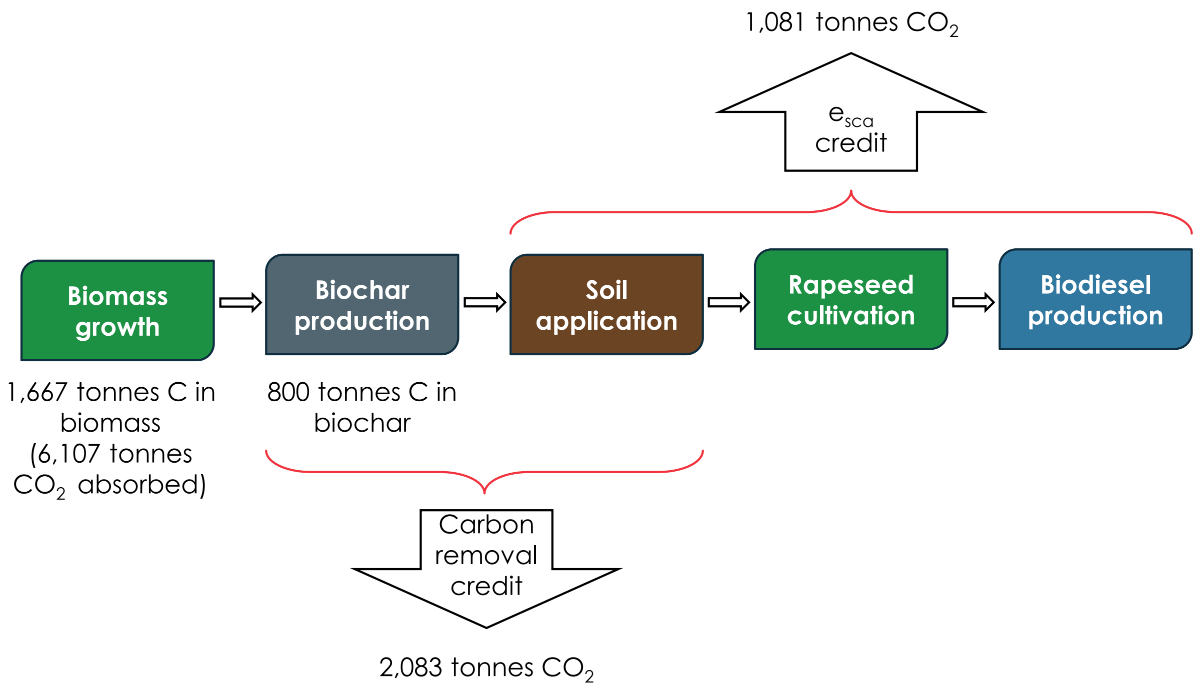

Figure 3 Schematic illustration of biochar generating both carbon removals and e_{sca} credit

The carbon removal crediting scheme asks operators to calculate the permanence fraction for the carbon in the biochar by applying the function in Woolf et al. (2021) for a one-hundred-year period. The average soil temperature at the location of application will be 15 °C, and cross-referencing soil temperature against pyrolysis temperature give a permanence fraction

the-pathway-to-healthy-soils-by-2050/

of 0.71. Analysis of the produced biochar shows that it is 80% carbon and therefore the project generates:

1,000	x	0.71	x	0.8	x	3.664	=	2,083
Tonnes of biochar		Permanence coefficient		Carbon fraction		Tonnes CO_2 per tonne C		Tonnes of CO_2 removal

Five years after the application of the biochar, the farmer undertakes soil sampling to identify the reportable change in soil carbon for the e_{sca} term. The farmer expects that at least 5.7 tonnes per hectare of recalcitrant carbon from biochar would still be in the soil if it has not been transported away, and that there may be additional soil carbon contributions from labile biochar carbon that has not yet decomposed and from any associated increases in other soil carbon. The measurements, which consider only the top 30 cm of the soil, identify an increase of 5 tonnes soil carbon per hectare. Without further analysis the farmer cannot be sure why the measurements give a slightly lower result than hoped for – whether some of the biochar has been moved below 30cm or whether there may have been an unexpected positive priming effect leading to a reduction in non-biochar carbon in the soil. In any case, the measurements have shown an increase compared to the baseline, and therefore an e_{sca} credit can be applied to the biofuels produced on the land. The farmer has chosen to spread the e_{sca} credit over 20 years of production and achieves a rapeseed yield of 4 tonnes per hectare, translating into 55,000 MJ of biofuel per hectare. 59% of the e_{sca} credit is allocated to the biofuel product, the rest to the co-products. The final e_{sca} credit for the biofuel is therefore calculated as:

5	x	3.664	x	10^6	x	1/20	x	1/55,000	x	59%	=	9.8
Tonnes of soil carbon per hectare		Tonnes CO_2 per tonne C		Tonnes to grams		Amortise over 20 years		Hectare per MJ biofuel		Allocation to biodiesel		gCO_2e/MJ

Multiplying back up by the quantity of biofuel that can be produced over twenty years and 100 hectares, the total carbon value of the e_{sca} term is 1,080 tonnes of CO_2.

In this case, a total of 3,163 tonnes of CO_2 benefits are recognised, 2,083 in the voluntary carbon market and 1,080 under the RED. This compares to a total of 2,900 tonnes of carbon stored in the biochar at the point of application. The sum of the identified carbon benefits is therefore greater than the sum of the recalcitrant and labile carbon in the biochar, although for this example only by 8%. Up to 1,080 tonnes of CO_2 benefits could be seen as having been double credited (being recognised as a benefit under both frameworks), although some of the biochar carbon detected during soil carbon measurement could be labile carbon excluded from the assessment of permanent carbon removal benefit, in which case the overlap would be less.

5.2.2. Case 2: biochar as output and input from the same biofuel production system

In this case, a biofuel facility produces biochar as a co-product of a fast pyrolysis process, using switchgrass as feedstock. One tonne of biochar is produced for every three tonnes of output biofuel, and the biofuel is supplied to the EU market. The produced pyrolysis gas is consumed for energy. The annual output of the facility is 120,000 tonnes of biofuel and 40,000 tonnes of biochar. The annual lifecycle carbon emissions from the facility are assumed to be 129,000 tonnes of CO_2. The biochar has a lower heating value of 25 MJ/kg, while the transport fuel has a lower heating value of 43 MJ/kg – the biochar therefore represents 16% of the output energy from the process. The biochar will then be supplied back to the switchgrass farm as an agricultural input. We consider what the implications would be of treating the biochar as leaving and re-entering the system boundary of the LCA, versus treating it as never leaving the system boundary – and whether adopting a different treatment would lead to significantly different results.

In one accounting approach, the biochar remains within the system boundary of the biofuel production. It would not be treated as a product, and therefore no emissions would be allocated to it. Allocating the full 129,000 tonnes of CO_2 emissions to the transport fuel gives a carbon intensity of 25 gCO_2e/MJ, before consideration of an e_{sca} credit.

We then assume that the produced biochar is sold back to the switchgrass farmer for use as a soil amendment. The biochar is applied to the fields on which the switchgrass is grown, and the farmer reports an improved agricultural practice and calculates an e_{sca} credit. The switchgrass is produced across 64,000 hectares with a yield of 8 tonnes per hectare, and the biochar is returned to this area at a rate of 0.625 tonnes biochar per hectare per year. Soil carbon measurement is undertaken after 5 years following the e_{sca} rules, and the measurement indicates an increase in total soil carbon by 2.7 tonnes per hectare. In this case, this is slightly more than the total carbon input to the soil as biochar (2.5 tonnes per hectare if the biochar is 80% carbon). Without further analysis the farmer cannot be sure why the measurements give a slightly higher result than may have been expected based on the carbon in the biochar alone – it may be due to negative priming, or to unrelated soil carbon development, or could reflect measurement uncertainty. In any case an e_{sca} credit can be applied to the biofuels produced on the land. The e_{sca} credit for the biofuel is calculated as follows:

2.7	x	3.664	x	10^6	x	1/5	x	1/80,625	x	100%	=	24.7
Tonnes of soil carbon per hectare		Tonnes CO_2 per tonne C		Tonnes to grams		Amortise over 5 years		Hectare per MJ biofuel		Allocation to biofuel		gCO_2e/MJ

Combining the e_{sca} credit with the rest of the lifecycle emissions gives a resulting carbon intensity for the biofuel of only 0.3 gCO_2e/MJ.Alternatively, the biochar could be treated as leaving the system as a co-product and re-entering the system as an input to the system. After allocating emissions by energy content to the biochar co-product, both the biochar and the fuel are assigned a carbon intensity of 21 gCO_2e/MJ[21], i.e. the carbon intensity of the biofuel is reduced by 4 gCO_2e/MJ. This is equivalent to allocating a total of 20,940 tonnes of CO_2 emissions to the 40,000 tonnes of produced biochar. The biochar leaves the system with this carbon 'burden'.

In this system the e_{sca} credit is allocated between the biofuel and the biochar, with the credit on the biofuel calculated as:

21 Ignoring for the sake of simplifying the example any emissions from the fuel upgrading process, which should be 100% allocated to the fuel product.

2.7	x	3.664	x	10^6	x	1/5	x	1/80,625	x	84%	=	20.7
Tonnes of soil carbon per hectare		Tonnes CO_2 per tonne C		Tonnes to grams		Amortise over 5 years		Hectare per MJ biofuel		Allocation to biofuel		gCO_2e/MJ

The carbon intensity of the biochar as an input must also be considered – the biochar had been allocated 20,900 tonnes of carbon burden, but this is offset by the part of the e_{sca} credit that is allocated to the biochar as a co-product, which is 20,650 tonnes – so the biochar ends up being treated as nearly carbon neutral as an input. Adding together the production emissions allocated to the biochar with the e_{sca} credit and the carbon intensity of the consumed biochar gives a final biofuel carbon intensity of 0.3 gCO_2e/MJ. This is the same number that was obtained when keeping the biochar within the system boundary.

This case shows that as long as the LCA rules are consistently applied, biochar could be recognised as both a co-product from a biofuel production system and as a soil amendment, without necessarily leading to double crediting.

5.2.3. Case 3: biochar from an unsustainable biomass source

A biochar producer operates a pyrolysis facility in a region where there is forest biomass locally. The facility produces 100 tonnes of biochar using slow pyrolysis at a peak temperature of 500°C. The producer sells the biochar as a soil amendment to local farmers and applies to a voluntary scheme to generate carbon removal credits. The crediting scheme uses the function from Woolf et al. (2021) to estimate a permanence of 0.75. The biochar is tested and determined to have an 85% carbon content and so the removal credit is:

100	x	0.75	x	0.85	x	3.664	=	234
Tonnes of biochar		Permanence coefficient		Carbon fraction		Tonnes CO_2 per tonne C		Tonnes of CO_2 removal

In this case, however, the woody biomass is sourced by clear cutting a local forest area without guaranteeing forest regrowth. The facility requires approximately 400 tonnes of dry biomass to reach its production target of 100 tonnes of biochar, assuming a 25% biochar yield from the pyrolysis process. Assuming that the local forest has standing woody biomass stock of about 130 tonnes per hectare. With some material being left behind during harvesting, clear cutting delivers 100 tonnes of biomass per hectare, and therefore the facility clears 4 hectares of forest to obtain the feedstock. Ignoring any associated changes in soil carbon, we can estimate that the carbon stored in biomass on these four hectares is reduced from 65 tC/ha[22] to 7.4 tC/ha (this latter is the typical vegetation carbon value for scrubland used to calculate land use change emissions in the RED III), a reduction of 57.6 tC/ha.

When the reduction in carbon in biomass is converted to CO_2 using a conversion factor of 3.664, about 211 tonnes of CO_2 per hectare is emitted. Across 4 hectares of deforestation, the total land use change emissions are 844 tonnes CO_2.

With this biomass harvesting system, 234 tonnes of durable CO_2 removal credits in biochar are delivered at the expense of the emission of nearly four times that amount of CO_2 from

22 About 50% of wood, by mass, consists of carbon, so 250 tonnes of biomass translates to 125 tonnes of carbon.

reductions in standing biomass carbon stocks. This biochar production model would result in a net carbon increase rather than a removal. In this case, the benefit of the biochar is not double credited, but an associated land use change emissions term is potentially not recognised.

Existing carbon removal certification standards look to prevent this type of outcome by putting requirements on the type of biomass that they allow as biochar feedstocks – for example the EBC's C-sink standard requires that, "it must be ensured that biomass production is maintained on the corresponding area either through new planting or rejuvenation". In the EU's RED III, there is a requirement that forest biomass harvested for energy use comes from areas where there are either binding laws or enacted forest management systems in place that require the regeneration of harvested areas.

If instead of being left as scrubland the standing carbon stock of the harvested forest area is returned to its original level, then the 844 tonnes of CO_2 are only temporarily emitted – but even a temporary increase in atmospheric CO_2 would reduce (and in the short-term reverse) the climate mitigation value of the biochar system.

5.2.4. Case 4: biochar carbon removal crediting without end use monitoring

A biochar producer in the EU sells a batch of 600 tonnes of biochar. The biochar was produced using a slow pyrolysis process operated at a peak temperature of 400°C. The biochar is packaged as a soil amendment and sold to a farmer. The biochar producer registers the use of the biochar with a carbon removal certification scheme to generate carbon removal credits. The carbon removal crediting scheme asks operators to calculate the permanence fraction for the carbon in the biochar by applying the function in Woolf et al. (2021) for a one-hundred-year period. The average soil temperature at the location of application will be 5 °C, and cross-referencing soil temperature against pyrolysis temperature give a permanence fraction of 0.84. Analysis of the produced biochar shows that it is 80% carbon and therefore the project generates:

600	x	0.84	x	0.8	x	3.664	=	1,477
Tonnes of biochar		Permanence coefficient		Carbon fraction		Tonnes CO_2 per tonne C		Tonnes of CO_2 removal

In this case, however, the farmer who has purchased the biochar changes their mind about using it as a soil amendment, and decides instead to sell the biochar batch on to a local steel mill as a coke substitute. Assume that the carbon removal certification scheme allowed a removal to be certified based on sale, and did not require monitoring of application.

The steel mill uses the biochar as a reducing agent instead of coal-based coke, and because it is a form of biomass fuel no ETS allowances need to be surrendered in relation to this use. For one-to-one substitution of carbon in coke by carbon in biochar, the steel mill avoids obligations to surrender 1,760 tonnes of CO_2 emission allowances. 1,477 tonnes of CO_2 benefit from the biochar have been double credited into both the ETS and the voluntary market; the reported CO_2 removal benefit is not really delivered.

5.2.5. Case 5: double counting biochar under CORSIA

A biochar producer sells 2,000 tonnes of biochar as a soil amendment to a farm that supplies switchgrass to a local aviation biofuel plant. The plant produces cellulosic ethanol, which is then converted to aviation fuel using an alcohol-to-jet process. The biochar was produced using a slow pyrolysis process operated at a peak temperature of 750°C. It has a carbon fraction of 84% and is applied to the soil at a rate of 5 tonnes per hectare across 200 hectares, where the average soil temperature is 15°C.

The biochar producer and the farmer coordinate to apply to a voluntary scheme to generate carbon removal credits, which are eligible as offsets under CORSIA. These credits will be sold to an airline to meet CORSIA obligations. The CO_2 removal is calculated as follows:

2,000	x	0.82	x	0.86	x	3.664	=	5,047
Tonnes of biochar		Permanence coefficient		Carbon fraction		Tonnes CO_2 per tonne C		Tonnes of CO_2 removal

Meanwhile, the aviation biofuel producer seeks to maximise the credit available for supplying the produced aviation biofuel under CORSIA by submitting an actual value calculation for the carbon intensity. According to the CORSIA LCA rules, replacing an annual crop with a perennial crop triggers a land use change, and therefore the actual value calculation will include working with the farmer to assess the soil carbon change on the affected fields, as part of the DLUC calculation (see section 4.3.3). However, this introduces the potential for double counting because the soil carbon increase associated with biochar use could be credited twice – once as a carbon removal credit under the offsetting scheme, and again through the DLUC calculation in the LCA of the aviation fuel.

Field measurements indicate a soil carbon increase of 6.5 tonnes per hectare, significantly more than the 3.4 tonnes per hectare of recalcitrant carbon that the farmer believes was applied as biochar, and presumably this includes a contribution from the labile fraction of the biochar and soil carbon gains associated with the transition from an annual crop to a perennial crop. The contribution of soil carbon to the pathway carbon intensity is calculated:

6.5	x	3.664	x	10^6	x	1/25	x	1/51,600	=	18.5
Tonnes of soil carbon per hectare		Tonnes CO_2 per tonne C		Tonnes to grams		Amortise over 25 years		Hectare per MJ biofuel		gCO_2e/MJ

Over 400 hectares of biofuel production and 25 years, this is equivalent to 9,500 of CO_2 credits.

Since it is difficult accurately disaggregate the contribution from the biochar to soil carbon from the contribution of other agricultural changes, it is not possible to exactly identify how many tonnes of CO_2 are double counted by contributing both to the offsetting side of CORSIA though credit generation and to the alternative fuels side of CORSIA through the calculation of an actual lifecycle emissions value. However, it is potentially the full 5,047 tCO_2 for which carbon removal credits are issued. This demonstrates a clear risk of double counting when both carbon removal credits and DLUC credits are claimed under CORSIA.

5.3. Managing multiple recognition

To mitigate the risks of double crediting, robust methodologies and frameworks are needed to align regulatory and voluntary systems while maintaining transparency and accountability. Given the diverse pathways for biochar credit generation, careful consideration is required to ensure that carbon benefits are appropriately allocated, and that if some of the carbon benefits of a given batch of biochar are rewarded under more than one framework this is done purposefully for clear policy reasons.

5.3.1. Market differences and value implications

The value of carbon credits or of enabling compliance with alternative fuel support mandates varies significantly across crediting frameworks. According to MSCI Carbon Markets, in 2023 biochar credits sold on the voluntary carbon market averaged 150 $\$/tCO_2e$ (USD per tonne of CO_2 equivalent), significantly surpassing the $5.80 average reported for 'generic' voluntary carbon credits, which includes more traditional credits such as those from afforestation projects (MSCI, 2024b). However, these prices for biochar credits remain lower than those seen in transactions for other emerging carbon removal technologies, such as direct air capture (DAC) ($680 £/$tCO_2e$) and ocean alkalinity enhancement (850 $\$/tCO_2e$) (Supercritical, 2024).

In compliance markets, credit prices also show variation. As of December 2024, the price of carbon credits or emissions allowances under the EU's ETS was over 70 €/tCO_2e (Sandbag, 2025), while, in the U.S., California's LCFS credit price was around 75 $\$/tCO_2e$ as of January 2025. Within all of these schemes, the value of credits has fluctuated over time. According to the latest credit transfer report from the State of Washington's Department of Ecology, the average price per fuel credit was $23.88 USD for November 2024, substantially lower than the annual average price per credit in 2023, which was $91.23 USD. The price of credits under ICAO's CORSIA has been projected to range from $18 - $51 per tCO_2e in Phase 1 (2024-2026), and increase to $27 - $91 per tCO_2e during Phase II (2027 – 2035) (MSCI, 2024a).

From an economic perspective, biochar producers must generate enough revenue from the combination of biochar sales and policy value to cover the production costs. Feedstock acquisition plays an important role in the overall profitability of biochar production, and studies have identified it as one of the most sensitive factors in biochar cost-benefit analyses (Zilberman et al., 2023). For feedstock available at $100 a tonne, with 30% moisture content and assuming a yield of 250 kg biochar per tonne of dry biomass, the feedstock cost alone would amount to $570 per tonne of biochar. There may be cases where utilising waste materials that would otherwise require disposal, such as municipal solid waste, may be acquired at lower cost, significantly improving the economics of biochar production (Zilberman et al., 2023) – but these waste resources are limited, and low-cost materials may produce lower quality biochar.

Biochar production costs will also vary by region and technology. In California, reported production costs range from $200 to $1,000 per ton, with an average of around $400 per ton, while market prices for biochar in the state range from $600 to $1,300 per ton, depending on intended end-use applications (Thengane et al., 2021). A review of biochar pricing by Zhang et al. (2021) recorded values ranging from $670 per tonne (produced from tea oil shells (*Camellia oleifera*)) to $17,800 per tonne (for virgin wood feedstock). However, the highest-end prices likely reflect small-scale sales to retail consumers rather than bulk production costs, given that the named sources include Amazon.com. While biochar prices to retail consumers and to agriculture can be relatively high while production is relatively low and produced material can be sold to niche markets, many studies suggest that carbon credit revenues will play a crucial role in allowing producers to reduce prices, allowing biochar use to scale more rapidly (Chiaramonti et al., 2024; Salma et al., 2024; Thengane et al., 2021; Zilberman et al., 2023). Biochar's financial viability is also influenced by its integration within biofuel pathways. Studies have indicated that biofuel production is most economically viable when biochar serves as a revenue-generating co-product (Campbell et al., 2018).

Taking the average biochar production cost reported by Thengane et al. (2021), and assuming very approximately that about two tonnes of CO_2 removals could be delivered for every tonne of biochar produced, then carbon removal units priced at $200 per tonne CO_2 would allow biochar-only businesses to fully cover the costs of biochar production. Receiving complementary stacked incentives from other policies, and income from the biochar sales, would further improve the financial outlook.

5.3.2. Policy implications

Coherent policy on biochar will be essential for ensuring that the industry balances its growth potential with transparent accounting practices, aligned monitoring protocols, and robust climate outcomes. Achieving this balance will require coordinated efforts between governments, certifiers and industry stakeholders to provide clarity on crediting mechanisms.

The EU's RED III and UK's RTFO already have a methodology to allow soil organic carbon (SOC) increases to be credited in biofuel LCA under the e_{sca} term, including when biochar contributes to these soil carbon gains. Expanding 'carbon farming' initiatives may further enable crediting of SOC gains outside of biofuel production systems. However, challenges remain, particularly regarding protocols for monitoring soil carbon changes, and the difficulty of attributing the relative SOC increase to specific interventions, such as biochar use versus other CSA practices (e.g. cover cropping, reduced tillage, and other organic amendments). Given that multiple carbon farming practices often work in combination, ensuring clear methodologies for attribution will be important for maintaining crediting integrity, and particularly to avoid the risk of over-crediting any carbon benefits that could be simultaneously claimed under different frameworks.

Meanwhile, permanent carbon removals with biochar can already be credited in the voluntary carbon markets, and a certification methodology for BCR may be adopted under the EU's CRCF. However, differences in approaches to soil carbon crediting may present a policy alignment challenge. The underlying methodologies for crediting permanent carbon removals by BCR versus the certification of e_{sca} credits or of SOC increase through carbon farming are quite different, which creates a risk of inconsistency at the interface. BCR certification is not predicated on direct soil carbon measurement because it is recognised that accurately quantifying rates of biochar decomposition in soil through field measurement is not feasible. In contrast, the e_{sca} methodology and carbon farming certification approaches rely on measurements of soil carbon change, from which it is difficult or impossible to exclude the contribution of biochar.

As illustrated with our 'case 1' example, it is already possible in principle for carbon stored in biochar to be credited under a voluntary carbon removal certification and also implicitly credited under the e_{sca} term of a biofuel LCA pathway. Policymakers must decide whether that it is an acceptable overlap (stacked incentive) or would be considered problematic (double crediting).

Under ICAO's CORSIA framework, it is our understanding that credits for BCR from biochar projects would be eligible to be claimed as offsets, enabling airlines to purchase biochar carbon credits as offsets as part of their compliance with CORSIA, providing that they are generated under schemes that have been identified as eligible, such as VCS and Climate Action Reserve. However, CORSIA presents distinct crediting risks compared to the EU's regulatory frameworks. One concern is that SOC benefits attributed to the production of biofuel feedstocks (which may already be credited within CORSIA's LCA methodology) could overlap with offsets from biochar projects, potentially allowing double counting towards the same emissions reduction target. It is also worth highlighting though that (as noted in section 5.3.1) the carbon price for CORSIA eligible offset credits is expected to be below the voluntary market price for carbon removals for the foreseeable future, which would reduce the likelihood of this form of double counting occurring in practice.

As discussed in section 5.3.1, biochar's financial viability is closely tied to policy support, particularly through carbon crediting schemes. Production costs vary depending on feedstock, processing technology and scale of production, with production estimates in California ranging from $200 - $1,000 per ton, and market prices varying between $600 - $1,300 per ton (Thengane et al., 2021). Carbon credit markets can provide additional revenue that help to offset production costs, and many studies highlight that these financial incentives will be critical to scaling the industry (Chiaramonti et al., 2024; Salma et al., 2024; Zilberman et al., 2023).

However, scaling biochar production without consideration of the potential long-term ecological impacts could also pose significant risk. The IPCC has identified biomass availability as a major constraint to biochar's scalability, warning that as demand for biomass grows, competition between biochar, biofuels, and other bio-based industries could intensify land-use pressures (Shukla et al., 2022). To mitigate this risk, policies must prioritise sustainable feedstock sourcing, and seek to avoid adverse land-use changes, deforestation, and other unsustainable practices.

Furthermore, as highlighted in section 3.4, the long-term ecological impacts of biochar's application remain understudied. While biochar can enhance soil health and biodiversity in some contexts, misuse could disrupt ecosystems or inadvertently favour invasive species and pathogens (Brtnicky et al., 2021; Joseph et al., 2021). Given that soil biodiversity is crucial for ecosystem resilience, it will be important for policy makers to continuously assess whether there is a need for biodiversity safeguards to ensure that biochar deployment is ecologically sustainable and that its climate benefits are not overshadowed by unintended environmental consequences.

5.4. Recommendations

Biochar holds significant promise as a carbon removal strategy, but delivering on its potential climate and ecological benefits depends on robust monitoring, clear accounting frameworks, and continued research to close remaining knowledge gaps. To address these challenges, we make the following recommendations:

1. **Identify opportunities for multiple recognition and assess their policy implications.** As discussed in this report, a single batch of biochar could be supported by more

than one policy framework. However, multiple recognition is not always problematic. Policymakers should distinguish between low-risk and high-risk cases, ensuring that multiple crediting is aligned with policy goals and does not lead to overestimated carbon reduction or unintended market distortions.

a. Multiple recognition should be seen as higher risk if: two or more incentives have a high value in comparison to biochar production costs; if the value of the incentives is so high that biochar producers could give the biochar away for free and still make a profit; if recognising the benefits of biochar in two policies will undermine other climate action in one or both of those contexts; if policy makers have intended to use a single incentive to create a level playing field for solutions in that policy space; if it causes policymakers or market actors to overestimate actual progress toward climate targets.

b. Multiple recognition should be seen as lower risk if: policy makers have explicitly recognised the availability of a stacked incentive in policy design and impact assessment; if one incentive is clearly the principle financial signal and any others are relatively small; if incentives relate to distinct environmental goals; if incentives relate to separate environmental services.

2. **Implement chain of custody tracking for biochar to enhance transparency in carbon removal crediting**. Establishing a chain of custody system for biochar, similar to feedstock tracking systems in biofuel and forestry sectors, would help ensure traceability from feedstock production to end use. This could include verified documentation of feedstock source, production process, and application site, enabling regulators to track carbon flows and identify multiple crediting. Digital tracking platforms could enhance transparency and accountability, for example by enabling real-time monitoring of crediting pathways and cross-checking claims across various regulatory and voluntary markets.

3. **Provide post-application monitoring and address knowledge gaps.** As the biochar industry expands, continued post-application monitoring of biochar in soils for research purposes will be essential to refine long-term carbon sequestration estimates and assess biochar's long-term impacts on soil health, biodiversity and ecosystem functions. Post-application monitoring of biochar can also help farmers understand in which contexts the benefits of biochar are greatest, and identify any cases where sought-after benefits have not been delivered. Monitoring may be a requirement under some crediting systems, and in other cases may be supported by research funding or may be seen as good practice by the farmers themselves. Biochar's interactions with soil-dwelling organisms, biogeochemical processes, and broader ecosystem dynamics remains understudied, presenting clear knowledge gaps (see Section 2.4 and Section 3.4). Integrating biochar monitoring with existing and developing soil health initiatives, such as the EU's Soil Monitoring Directive, could provide valuable data while enhancing policy coherence.

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