Biochar's long game:

Unraveling the science of carbon permanence

Updated: July 8, 2025

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Key conclusions

- A critical question when considering biochar carbon dioxide removal (CDR) is how much of the carbon stored in the biochar during production will remain stored over time, rather than being released back to the atmosphere as CO_2. Durability claims and permanence factors can vary widely across existing CDR protocols.
- Quantification of permanence typically relies on experiments and models to project permanence over meaningful CDR timeframes. While these experiments have significant limitations, they offer insights into decomposition dynamics and inform models.
- Recent research comparing permanence of biochar to coal (inertinite) through a random reflectance method is a significant departure from other estimates of biochar durability, and at odds with more conservative models.
- This coal-biochar analogy is inadequate because coal buried underground is not exposed to the same degradation conditions as biochar in soil and burial pressures significantly change physical properties.
- Based on available literature and evidence, Carbon Direct does not believe the random reflectance method is currently a conservative and rigorous approach to assessing biochar permanence because validation against more established methods has not yet been done.
- The most conservative approach would only credit the highly recalcitrant portion of biochar carbon that is expected to remain stored over 1,000 years or more. Approaches that differentiate by biochar composition are recommended, to avoid excessively undercrediting biochar CDR and thereby harming project financial viability.
- Biochar stability science will keep advancing. Research into biochar degradation pathways in soil will continue to refine permanence models and inform the relevance of coal analogues.
- As knowledge and protocols evolve, Carbon Direct cautions against excessively generous claims of biochar CDR durability, in both permanence fraction and time frame, given the important uncertainties we have outlined.

Introduction

Biochar's prominence in the voluntary carbon market is rapidly growing. Biochar is a charcoal-like material that has garnered much interest, investment, and offtake as a pathway to carbon dioxide removal (CDR) because of its near-term readiness, potentially low cost, and environmental co-benefits. Global biochar production was nascent (<10,000 tCO_2e/yr) until 2019. Commercial uptake of biochar has expanded dramatically since then due to the voluntary carbon market. As of March 2025, large corporate buyers and nonprofits have purchased over 1.3 million tCO_2e of voluntary carbon credits from over 77 biochar suppliers.[1] Established and emerging CDR registries have developed protocols and are certifying biochar carbon credits.

A critical question when considering biochar CDR is how much of the carbon stored in the biochar initially after production will remain stored over time, rather than being released back to the atmosphere as CO_2. This measure of durability is called the permanence factor, or just permanence. The permanence factor is a fraction of the biochar carbon that is projected to remain stored out of the atmosphere over a given timeframe.

Science on permanence is evolving. At the same time, biochar CDR credits are being issued and sold based on different permanence models that the various registries' methodologies use. A critical evaluation of these models and the body of work behind them is needed to give a buyer confidence that they are buying credits with reduced risk of overcrediting. This white paper is intended to help with this critical evaluation.

Are you new to biochar? If so, **box 1** introduces biochar, how it is made, and how it is used.

Box 1. An introduction to biochar
Biomass heated in an oxygen-deficient environment produces biochar, a solid, carbon-rich material. In the near or full absence of oxygen, that process is called pyrolysis. Gasification or combustion in a less oxygen-deficient environment can also produce biochar, but more of the biomass is lost to reactions with oxygen so the biochar yields are lower. Biomass used to make biochar can include various materials such as agricultural or forest residues, construction debris, organic waste, seaweed, and more. The biomass is subjected to high temperatures and converted to gases, liquids, and solid products—the solid product is biochar. Biochar can be added to soils (**figure 1**) for benefits such as improved water and nutrient retention, pH adjustment of acidic soils, and pollution remediation. Biochar is also gaining attention for its potential as an ingredient within engineered materials, such as cement.

[1] CDR.fyi. c2025. CDR.fyi Leaderboards. CDR.fyi. [accessed 2025 Mar 5]. https://www.cdr.fyi/leaderboards.

Figure 1. Biochar agricultural farming application.

How biochar achieves carbon removal

As plants grow, CO_2 is pulled out of the atmosphere. Without further intervention, the carbon from that CO_2 will stay stored for as long as the plant remains alive, after which the plant biomass will decompose cycling most of the carbon back into the atmosphere. Technological interventions in this carbon cycle, like pyrolysis, can store the carbon that nature captured. Such engineered CDR interventions generally seek to store carbon for hundreds or thousands of years so that CDR efforts will achieve long-lasting climate benefits. Pyrolysis converts some of the biomass carbon into chemical compounds with higher resistance to environmental degradation. How much of the carbon converts to these more recalcitrant forms depends on the type of biomass and the heating conditions, including temperature and time. After biochar production, the highly recalcitrant fraction of carbon can be considered stored for long periods of time—100 years or more—as long as the biochar does not combust. That fraction is quantified as the permanence factor. **Box 2** illustrates how permanence factor is used to calculate long-term storage of carbon in biochar.

Box 2. An example to illustrate how a permanence factor parameter is used to calculate long-term storage of carbon in biochar

Assume one tonne of biochar is produced that is 85% carbon by weight. First, we calculate how much CO_2 storage it embodies when formed. Then, we make an assessment of how much of that biochar's carbon will remain stored over a given time period in order to understand how much CDR it accomplishes over that time period. This is where we use models to calculate the permanence factor.

- One tonne of biochar that contains 85% carbon by mass stores 3.1 tonnes of CO_2 from the atmosphere at the time of its formation.
- The assessment of net CDR deducts all the fossil emissions that biochar production generates, such as diesel fuel for trucking biomass and biochar. For example, if the production of one tonne of biochar generates 0.6 tonnes of fossil CO_2, a representative number, the net CDR of the produced biochar is 2.5 tonnes of CO_2 removed.
- Given a 100-year permanence factor of 84% is used, then the net CDR accomplished by the formation of one tonne of biochar is 2.1 tonnes of CO_2 removed from the atmosphere for 100 years.

Quantifying permanence

Quantification of permanence relies on experiments and models to project permanence over meaningful CDR timeframes. Current models are attempting to predict permanence over 100-1,000+ years. There are a number of established and emerging approaches to evaluating biochar recalcitrance to chemical decomposition and permanence in storage. Most of these are based on short-term incubation experiments in laboratories, where scientists seal biochar in a container with other organic matter and measure it over a period of weeks to months.[2] These approaches typically treat biochar as having multiple "pools" of carbon that differ by their resistance to decomposition. For example, a two-pool model includes one fraction of carbon that breaks down quickly in months or years, and another that decomposes more slowly, over centuries or longer.

While these experiments offer insights into decomposition dynamics, they have two significant limitations. First, these approaches do not measure biochar decomposition and durability in the real-world (e.g., after biochar is applied to agricultural soils)—meaning these approaches do not capture the effects of actual soil and other environmental factors. Research has shown that different soils can strongly influence decomposition rates.[3] Second, the short duration of these experiments means there is significant potential for error in extrapolation to centuries and beyond.

So what is a typical permanence factor? It depends.

Biochar CDR certification methodologies use a range of approaches to quantify permanence. Most common is the use of biochar chemical composition, namely the hydrogen-to-organic-carbon ratio (H/C_{org}), and models that correlate H/C_{org} with projected permanence from multi-pool decay models applied to biochar decomposition experiments, in order to calculate a permanence factor. The parameterization of these correlations is imperfect, and the

[2] Adhikari S, Moon E, Paz-Ferreiro J, Timms W. 2024. Comparative analysis of biochar carbon stability methods and implications for carbon credits. Science of The Total Environment. 914:169607. https://doi.org/10.1016/j.scitotenv.2023.169607.
[3] Woolf D, Lehmann J, Ogle S, Kishimoto-Mo AW, McConkey B, Baldock J. 2021. Greenhouse Gas Inventory Model for Biochar Additions to Soil. Environ Sci Technol. 55(21):14795–14805. https://doi.org/10.1021/acs.est.1c02425.

focus of numerous analyses[4]. A significant body of work suggests that models should incorporate a correlation with soil temperatures in addition to H/C_{org}.[5,6] Various forms of correlations and data selection for fitting (examples of which are shown in **figure 2**) produce a wide range of correlation coefficients ("R^2 value") ranging from 0.37-0.91, which indicates significant potential for variation of actual results from the model.

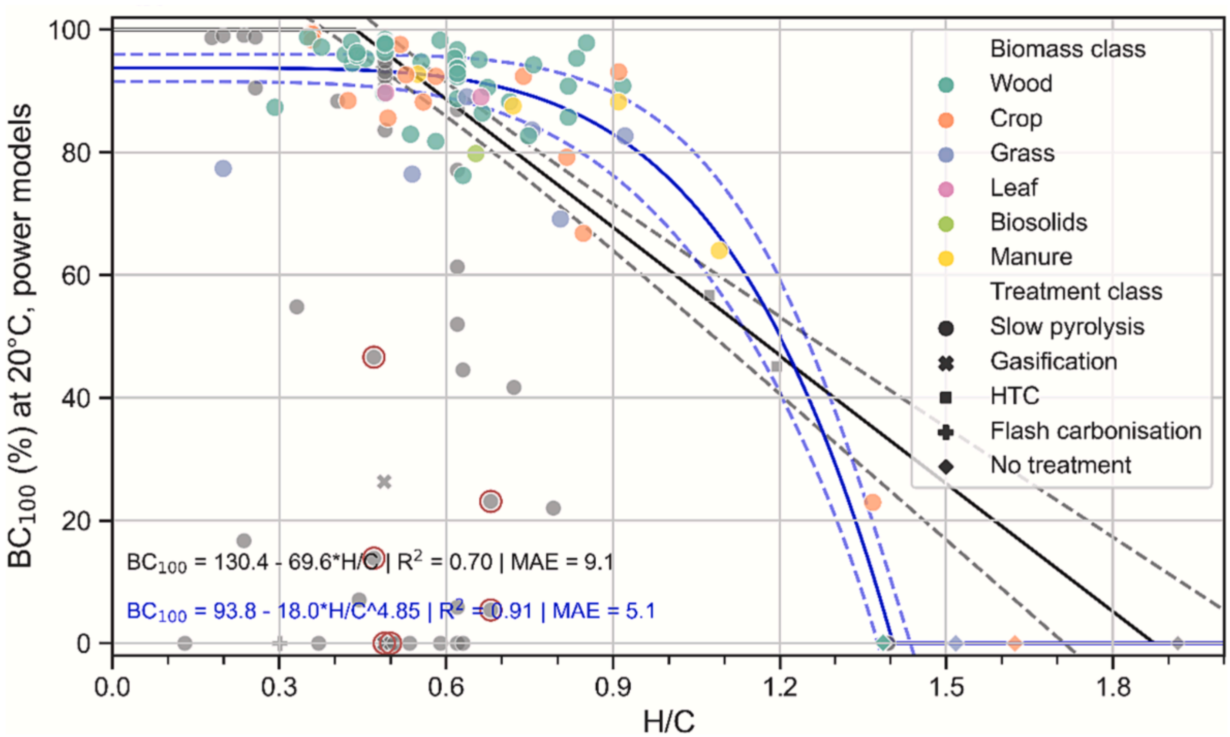

Figure 2. Fraction of biochar carbon remaining stored after 100 years (BC_{100}) for biochar applied to soil, as a function of biochar molar hydrogen-to-carbon ratio (H/C). MAE = mean absolute error. Source: Azzi et al. (2024) .[7]

A wide variety of feedstocks, residence times, production reactors, and operators who produced the biochar included in this data set are responsible for the scatter in the permanence data when plotted against H/C_{org} or temperature. This sensitivity of biochar composition and permanence to numerous variables supports a need for individual batch testing when producing biochar for CDR, and a conservative approach to permanence assessment that accounts for uncertainty.

The permanence values shown in **figure 2** are a snapshot in time of biochar carbon that is expected to remain stored 100 years after biochar production. However, similar correlations could

[4] Sanei, H., Petersen, H. I., Chiaramonti, D., & Masek, O. (2025). Evaluating the two-pool decay model for biochar carbon permanence. Biochar, 7(1), 1-7. https://doi.org/10.1007/s42773-024-00408-0
[5] Woolf et al., Greenhouse Gas Inventory Model for Biochar Additions to Soil.
[6] Azzi, E. S., Li, H., Cederlund, H., Karltun, E., & Sundberg, C. (2024). Modelling biochar long-term carbon storage in soil with harmonized analysis of decomposition data. Geoderma, 441, 116761. https://doi.org/10.1016/j.geoderma.2023.116761
[7] Azzi et al. Modelling biochar long-term carbon storage in soil with harmonized analysis of decomposition data.

be derived for 200 years, 1,000 years, or other durability terms. Permanence values will be lower over longer durability terms, as biochar is projected to continue decomposing and losing carbon, albeit at decreasing rates because as the remaining carbon is increasingly recalcitrant, over time.

Inertinite as a benchmark?

Recent research published in the International Journal of Coal Geology proposes a new approach to quantifying biochar durability.[8] The authors assert that random reflectance—a parameter developed in the field of organic petrology (the study of organic matter in rocks)—can be used to characterize durability. Using a component of coal (inertinite) as an analogue for biochar, they propose a benchmark random reflectance (Ro) of 2% as an "inertinite benchmark" for biochar. They argue that the entire fraction of biochar that meets that benchmark will degrade over approximately 100 million years. **This is a large departure from other estimates of biochar durability, and at odds with more conservative models.**

This coal-biochar analogy is inadequate because coal buried underground is not exposed to the same degradation conditions as biochar in soil. Underground coal has lower exposure to oxygen, water, and ultraviolet (UV) light, all of which are plentiful in surface soils. Each of these are associated with well-understood decay mechanisms. In water, both aerobic and anaerobic decay of biochar through microorganisms is possible. Water contact can also accelerate chemical degradation of biochar through physical processes like abrasion and dissolution. In the presence of oxygen, aerobic decay can occur; all forms of lignocellulosic biomass are vulnerable to aerobic decay. Too little is known about microbial-biochar interactions and their implications for long-term stability of biochar. Some soil microorganisms produce enzymes that are capable of breaking down biochar.[9] The final primary risk to the long-term stability of biochar surface storage is photodegradation. When biochar is exposed to sunlight, UV radiation can initiate photooxidation reactions, creating free radicals and peroxyl radicals that fragment and degrade the biochar structure over time.[10]

In addition, the process of geologic burial dramatically changes the physical structure of organic matter. Specifically, the pressure of burial reduces the porosity and permeability of organic matter as it forms lignite and coal. These structural changes affect water content and the ability of microbes and other degradational agents to access organic matter. Reflectance has not been demonstrated to capture the key structural or chemical characteristics that control degradation, such that a coal analogy to biochar can confidently be made.

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[8] Sanei H, Rudra A, Przyswitt ZMM, Kousted S, Sindlev MB, Zheng X, Nielsen SB, Petersen HI. 2024. Assessing biochar's permanence: An inertinite benchmark. International Journal of Coal Geology. 281:104409. https://doi.org/10.1016/j.coal.2023.104409.
[9] Feng J, Yu D, Sinsabaugh RL, Moorhead DL, Andersen MN, Smith P, Song Y, Li X, Huang Q, Liu Y-R, et al. 2023. Trade-offs in carbon-degrading enzyme activities limit long-term soil carbon sequestration with biochar addition. Biological Reviews. 98(4):1184–1199. https://doi.org/10.1111/brv.12949.
[10] Li N, Rao F, He L, Yang S, Bao Y, Huang C, Bao M, Chen Y. 2020. Evaluation of biochar properties exposing to solar radiation: A promotion on surface activities. Chemical Engineering Journal. 384:123353. https://doi.org/10.1016/j.cej.2019.123353.

The permanence factor that the reflectance method allows (readily up to 1.0, or 100% carbon retention over extremely long time scales) contradicts experimental evidence that some carbon loss will occur over years or decades. Incubation experiments are most useful for these time periods. Rectification of reflectance claims with the body of incubation-backed decay data is needed before reflectance should dictate permanence. There are also experimental techniques to chemically characterize the most recalcitrant carbon fractions that are likely to persist over centuries or millennia.[11] The reflectance method should be evaluated against these techniques to assess the reasonableness of permanence factor claims.

Summary of methodology approaches

Table 1 summarizes the current approaches that some biochar CDR methodologies use to quantify permanence factor. Methodologies diverge in their approaches and adoption of new techniques, such as the random reflectance method. The result of these different approaches can be significantly different permanence estimations for the same biochar. **When considering this uncertainty, the potential ramifications of error should be weighed: underestimation of credits may hurt project viability, while overestimation risks underachievement of climate targets.**

Table 1. Summary of select methodology approaches to quantifying permanence

Methodology	Approach	Durability claim	Data requirements
Puro.earth (Biochar Methodology - Edition 2025)	Model based on Azzi et al. 2024 and Woolf et al., 2021	200+ years	• H/C_{org} • Soil temperature
Isometric (Biochar Storage in Agricultural Soils v1.1)	Option 1: Woolf et al., 2021 Option 2: Sanei et al., 2024	200 years (Option 1) 1,000 years (Option 2)	• Soil temperature (Option 1) • H/C_{org} (Option 1) • Random reflectance of biochar (Option 2)
Verra (VM0044 Methodology for biochar utilization in soil and non-soil applications v1.1)	IPCC, 2019 and Woolf et al., 2021	100 years	• Organic carbon content • Production temperature or production process
Climate Action Reserve (U.S. and Canada Biochar Protocol v1.0)	Woolf et al.,2021	100 years	• H/C_{org} • Dry matter % • Organic Carbon % • Soil temperature
European Biochar Certificate (Global C-Sink Certificate Standard v1)	Schmidt et al., 2022	Flexible timeframe	• H/C_{org} • Organic Carbon %

Accounting for biochar permanence in CDR purchases

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

Durability claims and permanence factors can vary widely across existing protocols. The potential for overcrediting of CDR from biochar is large—a comparison of data from random reflectance models with H/C_{org} models suggests up to 10% or more. For this reason, shifts in crediting against new models should be done cautiously and conservatively, driven by compelling bodies of scientific evidence.

At present, the most conservative approach would only credit the highly recalcitrant portion of biochar carbon that is expected to remain stored over 1,000 years or more. This approach is most closely approached by Schmidt et al. (EBC Global C-Sink), applying a maximum permanence factor of 75% for 1,000 years of storage for biochar with adequately low H/C_{org}, although higher permanence factors can be credited over shorter time periods.[12]

While a conservative approach is expected to adequately safeguard against overcrediting, it may excessively undercredit biochar CDR and thereby harm project financial viability. The model of Woolf et al., for instance, takes a more nuanced approach that accounts for differences in H/C_{org} and soil temperatures to credit carbon storage based on elemental testing of produced biochar and a large body of biochar degradation studies.[13]

Common to the Schmidt et al. and Woolf et al. approaches is a strong tie to biochar characteristics that have been demonstrated to evolve with key pyrolysis parameters that determine biochar recalcitrance, such as pyrolysis temperature.[14, 15] At present, methodologies that rely on random reflectance do not incorporate these metrics and have not demonstrated a strong correlation of reflectance with permanence of biochar in soils. **As a result, based on available literature and evidence, Carbon Direct does not believe random reflectance methods are currently a conservative and rigorous approach to assessing biochar permanence.**

Biochar stability science will keep advancing. Research into biochar degradation pathways in soil will continue to refine permanence models and inform the relevance of coal analogues. Long-term field measurement studies with a high density of in-soil sampling to quantify persistence over time should be a near-term priority, and biochar CDR projects can contribute. Additional studies should investigate pathways to increase durability and rigorously develop modern isotopic, spectroscopic and chemical techniques for robust assessment of biochar's durability. Further studies should also incorporate a broader range of feedstocks, as most studies have focused on woody biomass.

Biochar certification protocols will need updating as well. Certifying bodies should strive to develop robust protocols governing biochar carbon removal. **As knowledge and protocols evolve, Carbon Direct cautions against excessively generous claims of biochar CDR durability, in both permanence factor and time frame, given the important uncertainties we have outlined above.** Protocols should not outpace science in terms of permanence assessment, and crediting should

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[12] Schmidt HP, Abiven S, Hagemann N, Meyer zu Drewer J. 2022. Permanence of soil applied biochar. Biochar Journal 2022. https://www.biochar-journal.org/en/ct/109.
[13] Woolf D, Lehmann J, Ogle S, Kishimoto-Mo AW, McConkey B, Baldock J. 2021. Greenhouse Gas Inventory Model for Biochar Additions to Soil. Environ Sci Technol. 55(21):14795–14805. https://doi.org/10.1021/acs.est.1c02425.
[14] Schmidt et al., Permanence of soil applied biochar.
[15] Woolf et al., Greenhouse Gas Inventory Model for Biochar Additions to Soil.

stay rooted in a science-backed understanding of what drives biochar permanence, including pyrolysis production conditions (e.g., high temperatures) and biochar composition (namely, low H/C_{org}). At a time when investment in biochar is booming and the science of biochar is evolving, the voluntary carbon market must keep pace.

Acknowledgements

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About Carbon Direct
Carbon Direct Inc. helps organizations go from climate goal to climate action. We combine technology with deep expertise in climate science, policy, and carbon markets to deliver carbon emission footprints, actionable reduction strategies, and high-quality carbon dioxide removal. With Carbon Direct, clients can set and equitably deliver on their climate commitments, streamline compliance, and manage risk through transparency and scientific credibility. Our expertise is trusted by global climate leaders including Microsoft, American Express, and Alaska Airlines, as well as by the World Economic Forum, which selected Carbon Direct as an Implementation Partner for the First Movers Coalition. To learn more, visit www.carbon-direct.com.

Disclosure of Interests
Carbon Direct provides carbon management services and scientific advisory to various stakeholders in the carbon removal ecosystem. This paper represents our scientific assessment based on available research and is not intended to favor any specific methodology or commercial approach. The authors have endeavored to present a balanced scientific analysis while acknowledging that scientific understanding in this field continues to evolve.