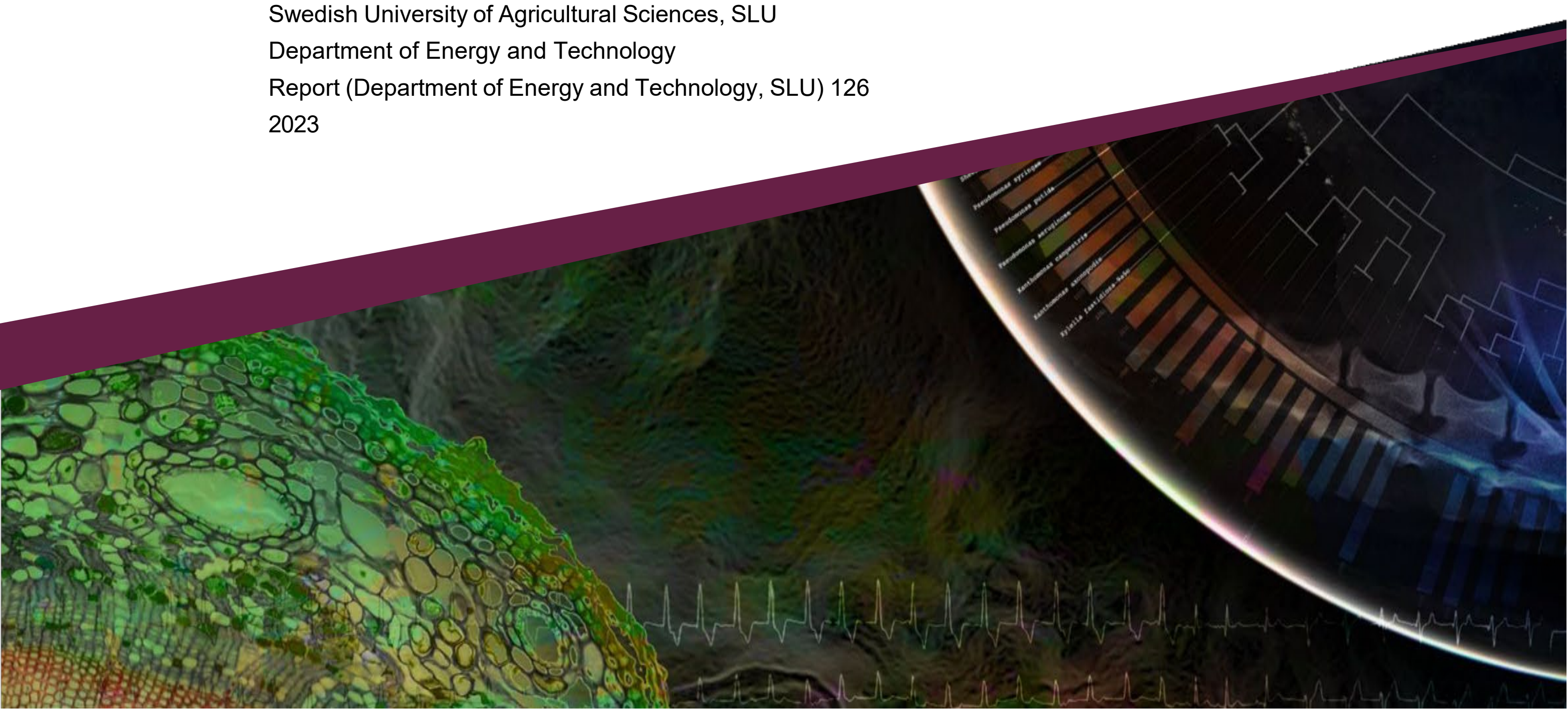
Guidelines for estimation of biochar durability

Background report

Elias S Azzi, Cecilia Sundberg, Helena Söderqvist, Tom Källgren, Harald Cederlund, Haichao Li

Swedish University of Agricultural Sciences, SLU
Department of Energy and Technology
Report (Department of Energy and Technology, SLU) 126
2023



Guidelines for estimation of biochar durability – Background report

Elias S Azzi	SLU, Department of Energy and Technology
Cecilia Sundberg	SLU, Department of Energy and Technology, cecilia.sundberg@slu.se
Helena Söderqvist	2050 Consulting AB
Tom Källgren	2050 Consulting AB
Harald Cederlund	SLU, Department of Molecular Sciences
Haichao Li	SLU, Department of Soil and Environment

Publisher:	Swedish University of Agricultural Sciences, Department of Energy and Technology
Year of publication:	2023
Place of publication:	Uppsala
Title of series:	Report (Department of Energy and Technology, SLU)
Part number:	126
ISSN:	1654-9406
ISBN (electronic)	978-91-8046-696-7
DOI	https://doi.org/10.54612/a.lkbuavb9qc
Keywords:	biochar, climate, persistence, permanence

Sammanfattning

Biokol produceras av biomassa som upphettas under begränsad syretillförsel. Rapporten behandlar biokols långsiktiga stabilitet i mark och hur detta kan hanteras i klimatberäkningar och klimatrapportering. Rapporten består av denna sammanfattning och fyra kapitel, vilka kan läsas fristående av varandra.

Begreppen inom området förändras. På engelska har forskare etablerat ”persistence of biochar in soil”, och inom kolinlagring används ”durability” av många. Vi har inte gjort någon försvenskning av dessa begrepp. På svenska har vi ordet ”kvar” som kan vara användbart i olika former (t.ex finnas kvar) och som vi föredrar i denna sammanfattning för att beskriva att kol inte har frigjorts till atmosfären i form av koldioxid.

Rapportens syfte är att presentera kunskapsläget om hur stor andel av kolet i biokol som blir kvar i mark över tid, och rekommendationer för hur detta kan beräknas. Det finns ett behov av att kunna beräkna hur stor andel av kolet i biokol som blir kvar i mark över tid i t.ex. nationell klimatrapportering, företags klimatrapportering, vid handel med kolkrediter och i livscykelanalyser för olika ändamål.

Om hur mycket biokol som är kvar

Hur mycket biokol som finns kvar efter en viss tid beror av biokolets egenskaper och av den miljö där det befinner sig. Nästan all forskning om hur mycket biokol som finns kvar över tid har handlat om placering av biokol i jordbruksmark.

Huvudanledningen till att biokol blir kvar länge i mark är att aromatiska stabila kolstrukturer bildas vid upphettning av biomassa genom pyrolys. En stor andel aromatiska kolföreningar gör att biokol blir betydligt mindre tillgängligt för nedbrytning av markmikroorganismer än obehandlad biomassa.

Olika biokol har olika egenskaper och detta har betydelse för hur länge biokol blir kvar i mark. För att få ett biokol med egenskaper som gör att det finns kvar i marken längre ska det produceras vid högre temperatur under tillräckligt lång tid.

Om hur man mäter och räknar hur mycket biokol som är kvar

Etablerade metoder för kvantifiering av hur mycket biokol som finns kvar efter 100 år (som t.ex. används i IPCC-riktlinjer och i frivilliga marknader för kolhandel, hittills) extrapolerar kortsiktiga nedbrytningsprocesser i jord, och beaktar inte till fullo de processer som skulle kunna förklara biokol som finns kvar i tusentals år.

Beräkningar för biokol har traditionellt använt 100 årsperspektivet för att beskriva mängden kvarvarande kol vid en viss tidpunkt. Att just 100 år används saknar vetenskaplig grund men har ansetts som ”tillräckligt långt” ur ett klimatperspektiv och tillräckligt nära för att modellering av mätdata kan anses meningsfull.

Ett aktivt forskningsområde relevant för förståelsen för hur mycket biokol som finns kvar med tiden är utvecklingen av avancerade analytiska karaktäriseringsmetoder för biokol som kommer möjliggöra mätning av den fysikalisk-kemiska heterogeniteten av de kolstrukturer som återfinns i biokol.

Ett annat område av fortsatt forskning är biokolsinkubation med fokus på fältförhållanden. Detta för att klargöra både skillnader mot laboratorieförhållanden och hur transportprocesser påverkar biokol i fält.

Rekommendation och slutsats

I projektet har tillgänglig forskningsdata aggregerats i en funktionell modell som beräknar hur mycket av kolet i biokol som finns kvar efter ett visst, justerbart antal år. Modellen baseras på H/C-kvoten hos det biokol som placeras i marken och årsmedeltemperaturen på platsen. Modellen

tillgängliggörs fritt[1] för att erbjuda biokolsintressenter bästa tillgängliga kunskap för beräkningar av hur mycket av biokolet som finns kvar efter en viss tid.

Befintliga forskningsresultat utgör ett tillräckligt bra underlag för att göra en konservativ bedömning för hur mycket biokol som kan förväntas finnas kvar över tid. Kommande forskningsresultat förväntas leda till utökad kunskap om bland annat nedbrytningsegenskaper hos biokol med mycket låg H/C-kvot, därför kommer denna rekommendation att revideras i samband med projektets slut 2025.

Nyckelord: *biokol, klimat, kolinlagring, permanens, stabilitet*

[1] https://biochar.systems/stability/guidelines

Abstract

Biochar is produced by heating biomass in the total or partial absence of oxygen. This report addresses the long-term persistence of biochar in soil and how this can be managed in climate calculations and reporting. The report consists of this summary and four chapters, which can be read independently.

Different terms have been used to describe the durability of biochar carbon storage, but also the physical presence of biochar in soils, e.g. persistence, permanence, recalcitrance, residence times, stability. Today, the term "durability of carbon storage" is preferred in policy contexts, but various academic disciplines such as soil science have other established terms like "persistence". Here, both durability and persistence are used, rather interchangeably. It is important to be aware of differences in meaning that exist between disciplines.

The purpose of this report is to present the state of knowledge regarding the proportion of carbon in biochar that remains in the soil over time and provide recommendations for calculating this. There is a need to calculate the persistence of biochar in soil for national climate reporting, corporate climate reporting, carbon credit trading, and life cycle assessments for various purposes.

On the persistence of biochar

The amount of biochar remaining after a certain time depends on the properties of the biochar and the environment in which it is located. Nearly all research on biochar persistence has focused on its application in agricultural soils.

The main reason for the high durability of biochar carbon storage is the formation of fused aromatic stable structures during biomass pyrolysis. A high degree of fused aromatic structures makes biochar much less prone to microbial decomposition than fresh biomass.

Different biochars have different properties, and this influences how long they persist in the soil. To achieve biochar with properties that provide higher persistence, it should be produced at higher temperatures for a sufficient duration.

Measuring and calculating biochar persistence

Established quantification methods of 100-year biochar persistence (e.g. referenced in IPCC inventory guidelines and used in voluntary carbon markets, to date) extrapolate short-term soil decomposition processes, and do not fully consider the processes that may explain millennial persistence.

Calculations regarding biochar persistence have traditionally used a time span of 100 years to describe the amount of remaining carbon after a certain time. The use of specifically 100 years lacks a well founded scientific reason, but has been regarded as "far enough" into the future from a climate perspective and close enough for modelling to be meaningful.

An active area of research relevant for the understanding biochar carbon storage durability is the development of advanced analytical characterisation methods of biochar that will enable measurement of the physicochemical heterogeneity in carbon structures present in biochar.

Another area of continued research is biochar incubation, with a focus on field conditions, to elucidate both differences from laboratory conditions, and how transport processes affect biochar in the field.

Recommendation and conclusion

In the project, available research data has been aggregated into a functional model that calculates how much of the carbon in biochar remains after a given number of years. The model is based on the H/C ratio of the biochar placed in the soil and the annual average temperature at the location.

The model is made freely accessible[2] to provide biochar market actors with the best available knowledge for estimating the durability of biochar carbon.

Existing research results provide a sufficient foundation for estimation of the amount of biochar expected to remain over time. Future research results are expected to lead to increased knowledge regarding the decomposition properties of biochar, in particular biochars with a very low H/C ratio. Therefore, this recommendation will be revised by the end of the project in 2025.

Keywords: *biochar, climate, permanence, persistence*

[2] https://biochar.systems/stability/guidelines

Table of contents

1 Introduction

Biochar is the carbon rich material obtained from biomass pyrolysis. Biochar is presented and increasingly recognised as a technique for carbon dioxide removal through storage of pyrogenic carbon in soils and products. Biochar systems, when adequately implemented, can have many positive social and environmental effects, beside its greenhouse gas mitigation impact of combined carbon dioxide removal and emission reductions (Azzi et al 2021, Celander och Söderqvist, 2021). That being said, we note that the rapid increase in commercial biochar projects worldwide, is to a large extent driven by the potential for carbon dioxide removal. The attention that biochar carbon storage is receiving highlights the need for improved understanding and knowledge dissemination around biochar carbon storage. Disseminating such knowledge is the overarching purpose of this report.

This chapter introduces the scope of the report. Chapter 2 introduces greenhouse gas accounting or management systems where biochar storage values can be used. In Chapter 3, the science of biochar persistence estimation is summarised. Chapter 3 is rather in depth, and is not necessary for understanding Chapter 4, which presents our current recommendations for estimation of biochar persistence at a project level.

1.1 Goal and scope

This report and its associated guidelines focus on what we **call the persistence of biochar carbon storage**. It can equally be referred to as e.g. biochar durability, or biochar carbon durability3. The persistence of biochar carbon storage refers to how much of the amount of carbon originally contained in a certain mass of biochar used in a given application that will remain in storage over time (i.e. not be returned to the atmosphere in the form of carbon dioxide). For a given time horizon and biochar use, we call the amount of biochar carbon remaining in storage the **carbon storage value** of biochar.

Fundamentally, biochar carbon storage and its persistence depend on the properties of the biochar and the environment to which the biochar is exposed.

- **The properties of biochar** are a function of the type of biomass used as feedstock, the pyrolysis conditions, and possible transformations post-production.

[3] We are following international terminology. Durability and persistence are preferred because they are not yes/no terms, but capture the gradients.

- **The exposure environment** corresponds to the type of application where biochar is used over its life cycle (e.g., soil, landfill, construction material), and to the processes that take place in these environments (e.g., microbial activity, photochemical exposure, mineral protection, transport) as affected by varying temperature and moisture.

Biochar carbon storage and its durability is only one component of the broader climate effect of biochar systems, but an important component. We distinguish two concepts:

- **The cycle of biochar carbon** starts with photosynthesis and plant growth which removes carbon from the atmosphere. Then, during pyrolysis of the biomass feedstock, a portion of the biomass carbon is turned into gases and liquids, while the fraction of carbon that remains in the biochar is thermochemically transformed, forming a highly stable organic material consisting mainly of aromatic structures. Carbon contained in the gases and liquids is returned to the atmosphere upon combustion of these products. Carbon-containing biochar is then placed into a soil (or another use) and is exposed through its lifetime to a various processes leading to physical degradation, chemical alteration, formation of soil-biochar aggregates, and macroscopic movements in the environment. Along those processes, some biochar carbon will be returned to the atmosphere as carbon dioxide. The biochar carbon storage value and the biochar durability are the combination of all these processes.
- **The life cycle of a biochar system** builds upon the biochar carbon cycle described above but adds the technical system around it. This includes the whole **biochar value chain**: activities for cultivating and harvesting biomass, activities for handling and transport of biomass and biochar, activities for operation and maintenance of a biochar production unit, and finally, activities for putting biochar to use and effects of biochar use. The life cycle of a biochar system also includes the **systemic effects** such as land use change, reference biomass fate, and substitution of other products (or multi-functionality). All these processes are associated with greenhouse gas fluxes.

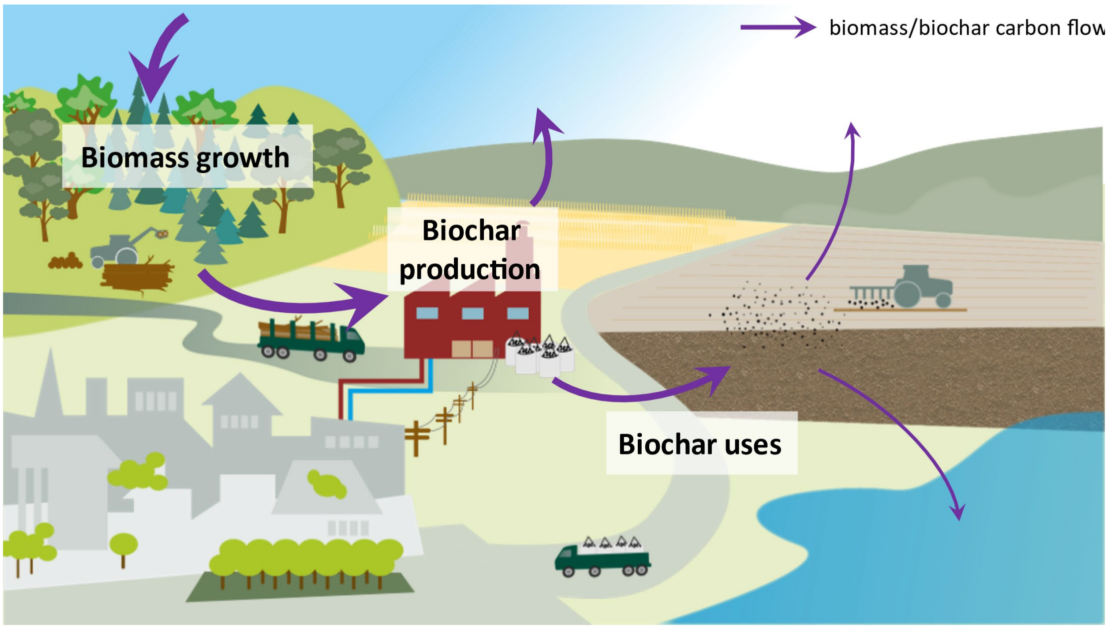


Figure 1. The cycle of biochar carbon and the lifecycle of biochar system. Arrows represent flows of carbon in biomass or biochar, from capture during biomass growth up to use in soil with potential re-emission and transport to other areas. Each step in the supply-chain is associated with greenhouse gas emissions, as well as systemic effects (e.g., land use change, product substitutions).

In practice, the bigger picture described above – comprised of the cycle of biochar carbon and the life cycle of biochar systems – translates differently depending on the accounting system that is used. These systems have different purposes and therefore different accounting rules (see section 2), but all require an understanding of **biochar** durability and a sound calculation approach for the **biochar carbon storage value**.

1.2 Intended audience of the report

This report is intended for anyone working within the value chain of biochar carbon removal or who is interested in interpreting a declaration of the duration of biochar carbon storage. For example: organizations that want to use the carbon storage value in their inventory report, carbon credit producers, brokers and buyers, investors or public authorities that want to quantify carbon sequestration as a decision basis for allocating financial support to projects and activities that incentivize biochar carbon removal or other policy instruments. The report is also intended for researchers who are not-biochar experts, as an introduction to principles of biochar durability.

1.3 The project

This report has been developed within the project Biochar stability - Supporting transparent & reliable carbon removal, funded by the Swedish Energy Agency

2022-2025[4]. The project aims at strengthening the knowledge of biochar durability in soils over long time frames. Field trials are established, laboratory incubations are performed, and a new analysis of the existing research data is done. This report is an early deliverable from the project, and it is planned to be updated at the end of the project.

[4] Formal name in English *Biochar stability validation - reaching a new level of understanding and transparency* and Swedish *Validering av biokols stabilitet - mot en ny kunskaps- och trovärdighetsnivå*, P2021-00117

2 The role of biochar durability in GHG accounting and life cycle assessment

The biochar carbon storage value is used in different ways in different types of greenhouse gas reporting and accounting systems. Four types will be introduced in this section: life cycle assessment, national greenhouse gas inventories, carbon trading, and organizational greenhouse gas accounting. Most accounting other than national greenhouse gas inventories are at project level, by which we mean a single production unit, its biomass feedstock, and produced biochar and its storage. The focus of this report is on project-level accounting of biochar durability.

The biochar carbon storage value is not equal to the climate change impact of biochar systems. The net climate impact of a biochar system depends on many other factors (Figure 1). Some of these will be mentioned in this chapter, but for a full introduction, see Azzi (2021).

2.1 Life cycle assessment of biochar

Life cycle assessment (LCA) is a method for quantifying potential environmental impacts of product-systems. LCA is widely used in both research and industry, for various purposes. The way an LCA is performed must always be in line with its goal, and this affects the conclusion that can be drawn. Below, two cases of LCA with different goals are presented. Both cases are limited to climate impact measured in carbon dioxide equivalents.

2.1.1 Type 1: LCA of a biochar supply-chain for calculation of product climate footprint

The goal is to quantify the climate footprint of a given biochar supply-chain in a given context, to understand what the main sources of greenhouse gas emissions and removals are. Here, the functional unit is set to the production of 1 dry tonne of biochar at the gate of the factory.

The above system can be described with the flowchart in Figure 2a, and the outcome of such an LCA can be visualized with bar charts as in Figure 2b (fictional example). Here, knowledge on biochar durability is needed to quantify the amount of biochar carbon stored in a 100-year time perspective.

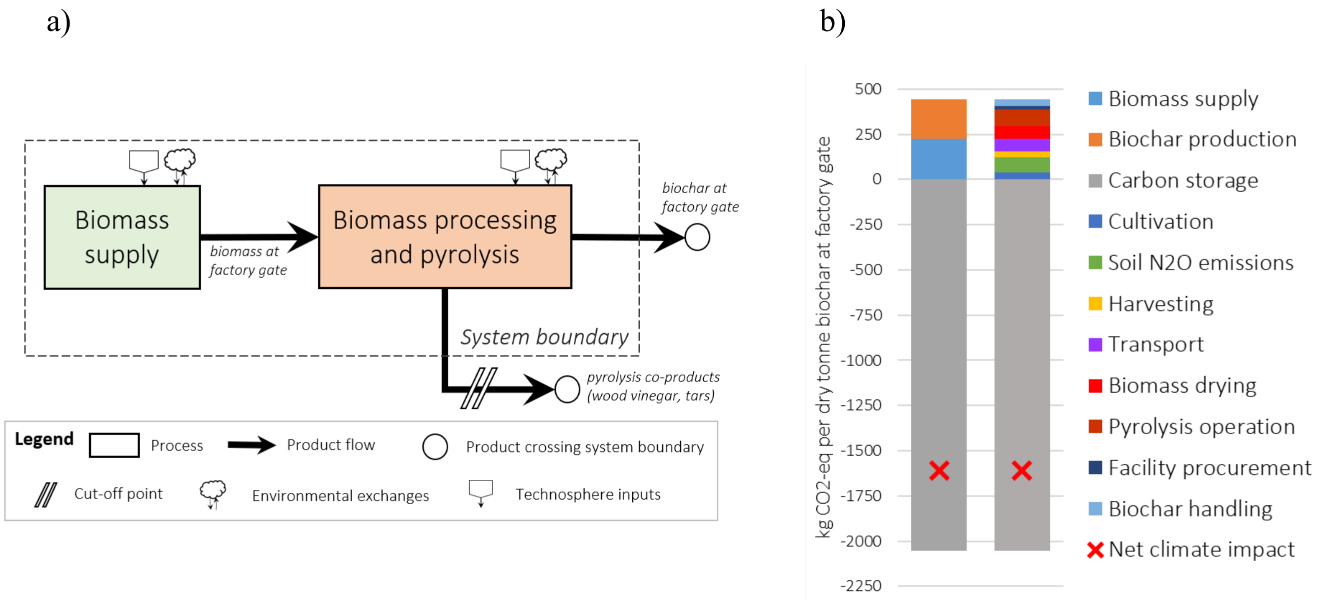


Figure 2. Cradle-to-gate LCA of a biochar supply-chain (a) and its climate change footprint (b) showing contribution of various life cycle stages at different levels of detail, more aggregated in the left bar and more detailed in the right bar.

An interpretation of the fictional results shown in Figure 2b would be that biomass cultivation and the biochar production equally contribute to the emissions of this supply-chain, totalling about 500 kg CO_2-eq per tonne of biochar. This amount can be set in perspective with the biochar carbon storage value, which is about 5 times larger than the supply-chain emissions. When looking at the detailed contribution analysis, it appears that major sources of emissions are soil emissions during biomass cultivation due to fertilizer use, but also biomass drying and operation of the pyrolysis reactor. Other transport and handling steps as well as facility procurement add up to a non-negligible contribution. These results can be used to understand how to reduce the impact from the biochar-supply chain and can be used to benchmark different supply-chains, provided that calculations have been performed in the same way.

Note that this is only one example of a fictional supply-chain, and that emissions from the system can vary greatly depending on energy sources and agricultural practices. For Swedish biochar LCA case studies, see Azzi (2021).

2.1.2 Type 2: LCA for determination of the climate change impact of a biochar system

The goal here is to determine the net climate change mitigation effect of deploying a biochar system relative to one or several alternative references in a given context. The biochar system is multifunctional: biomass is used, energy services are delivered, and a useful biochar product is made (Figure 3a). For these functions, a reference system is also defined and the outcome of the LCA can be visualized with bar charts as in Figure 3b (fictional example). The reference system is in this case comprised of alternative uses of biomass when not used to produce biochar, alternative energy supply when not provided from pyrolysis and an alternative to biochar use.

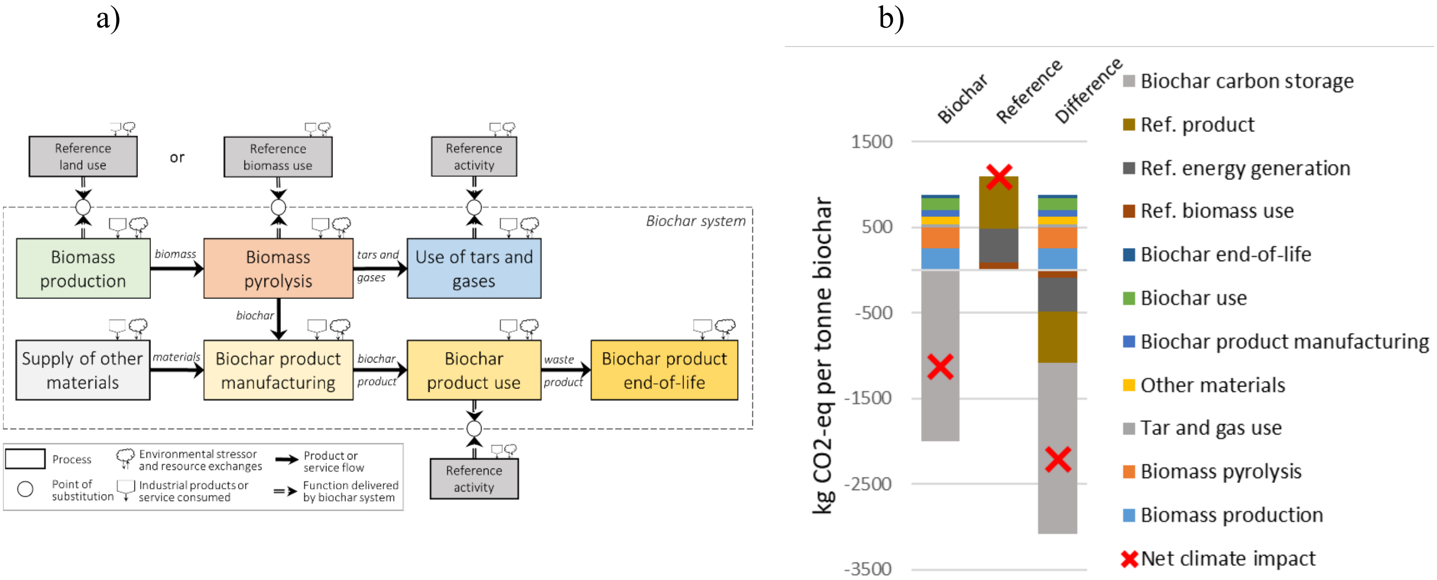


Figure 3. Cradle-to-grave LCA of a biochar system with a reference (Ref.) alternative system (a) and the climate change impact of the biochar system, the reference system, and the difference between them (b) showing contribution of various life cycle stages.

An interpretation of the fictional results shown in Figure 3b would be that biochar provides climate change mitigation in comparison with the reference. The net mitigation effect is of -2.3 tonne CO_2-eq per tonne biochar. Positive mitigation effects are mainly arising from carbon storage in biochar and avoided emissions when the biochar system is implemented instead of the reference system. The outcome of this mitigation effect is dependent on the choice of reference system and background context. In some contexts, biochar systems albeit storing carbon dioxide may not necessarily mitigate climate change (Woolf et al. 2010).

2.1.3 Remarks on biochar carbon storage value in LCA studies

- In both examples above, as in most published biochar studies, the climate metric used is the static Global Warming Potential (GWP) in a 100-year time perspective. When expressing the carbon storage value of biochar, a time perspective must be chosen as the time after which a certain amount of carbon remains stored. Commonly used is 100 years, in alignment with but not to be confounded with the 100 year GWP, however alternative time perspectives can be explored.
- Technically, LCA studies do not demonstrate what the carbon storage value is, but rather assume it based on the best available knowledge from other scientific domains, namely soil and carbon cycle sciences. In practice, most LCA studies have assumed that carbon storage value is high, usually above 80% of the initial carbon content.

- The biochar carbon storage value in a 100-year perspective is often the largest contribution to the climate change mitigation effect of biochar systems (Tisserant and Cherubini, 2019; Matuštík et al., 2020; Terlouw et al., 2021; Azzi et al., 2021).
- There are a few LCA studies that have used other approaches to model the climate effect of biochar carbon storage, e.g. using dynamic carbon models (Ericsson et al., 2017; Thers et al., 2019).
- With life cycle thinking in mind, it becomes apparent that the amount of stored carbon in biochar and the climate change mitigation effect of the biochar system are not the same quantities. Storing carbon is a physical flow resulting from an activity, but it is only one process in the biochar life cycle.

2.2 National greenhouse gas inventories

National greenhouse gas (GHG) inventories are comprehensive reports of all greenhouse gas emissions by sources and removals by sinks within the geographical boundaries of a nation during one year. The inventories are compiled and reported according to guidelines decided on by the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris agreement. Currently, the IPCC Guidelines for National Greenhouse Gas Inventories (2006) shall be used, and the 2019 Refinement is voluntary if the methodology is expected to give a more accurate estimation. The inventories are reported to the UNFCCC as part of the international cooperation to limit climate change. Emissions are reported in sectors such as energy, industry, and transport.

Since the 2019 Refinement to the IPCC guidelines, there is an appendix for estimating biochar carbon storage using the 100-year time perspective in the volume on Agriculture, Forestry, and other Land use (AFOLU). It is voluntary for countries to report biochar carbon storage.

National GHG inventories do not have a life cycle perspective, but an annualised sectorial approach. Different parts of the life cycle of a biochar system would be accounted in different sectors. For instance, biochar transport emissions would be in the transport sector and production of a pyrolysis reactor would be in the industry sector. Emissions from biochar production is reported in the energy sector (IPCC, 2019), while carbon removals with biochar storage can be reported in the AFOLU sector among other carbon removals.

When reporting biochar durability in a national GHG inventory, it is the national total biochar storage that is of interest. It is not a problem to have a combination of some estimates that are too high and others that are too low, as the purpose is to have a representative estimate of the average. When summed up on a country level, this gives a good estimation of the total carbon storage of all biochar in the country.

2.3 Carbon trading and issuing of carbon credits

A carbon credit is a tradable financial instrument that is issued by a carbon crediting programme and that traditionally represents an additional, verified GHG mitigation outcome of one metric tonne of carbon dioxide equivalents. Carbon credits are uniquely serialised, issued, tracked, and retired or cancelled by means of an electronic carbon registry operated by an administrative body such as a carbon crediting programme. The quantification of the mitigation outcome underlying a carbon credit is usually project-specific, often using standardized methodologies, calculating the project emissions of project activities relative to estimated baseline emissions. Carbon credits are traded, and buyers can use them to make offsetting claims, e.g. that the purchased carbon credits will compensate for (or "counterbalance") all or part of the buyer's carbon footprint. For reasons related to environmental integrity of carbon markets, the estimations of the climate change mitigation outcome (= baseline emissions - project emissions) shall be conservative.

Biochar Carbon Removal (BCR) is a new project category in the carbon markets. There are a few carbon crediting programmes that have standards for biochar (e.g. Verra VCS, Puro.earth, EBC C-sink). They use different approaches to estimating biochar durability and there is not yet any established practice or consensus. The Supervisory Body of the Paris Agreement Article 6.4 Mechanism has initiated work to develop recommendations for activities involving removals, including, inter alia, appropriate monitoring, reporting, accounting for removals and crediting periods, and addressing reversals. In accordance with carbon credit principles, estimates of durability of biochar carbon storage should:

- represent a specific biochar project or activity
- be conservative (avoid overestimation and safeguard environmental integrity)
- use a time horizon specified for the traded product and relevant for the production system tied to the offset claim[5].

The most common offset claims regard compensation for carbon dioxide emissions from fossil fuels. For offsetting carbon dioxide from fossil fuels, permanent land use change, or other emission intensive activities, a time horizon of much more than 100 years is needed for the carbon removal (Archer et al 2009). For comparing other greenhouse gases to carbon dioxide, the global warming potential in a 100-year perspective (GWP100) is the most established metric. However, it is not the only metric and it is being discussed how to consider the climate impacts of different greenhouse gases in a fair way (Allen et al 2022). This is not a purely scientific question but also a question of purpose and values.

[5] This report does not provide guidance on how to make claims of carbon removal from biochar for offsetting greenhouse gas emissions. Although biochar is a viable method of climate mitigation, we see several problems with use of biochar credits, or any other carbon credits, for offset claims, but that is beyond the scope of this report.

The voluntary carbon market is very dynamic. The growing interest in carbon dioxide removal has led to the establishment of new actors focusing on carbon removals only (Arcusa and Sprenkle-Hyppolite, 2022). They challenge some of the established principles in the voluntary carbon market that originate from the Kyoto Protocol, including accounting principles. The Paris Agreement has also introduced new market-based cooperative approaches for compliance markets. In addition, the structure of the Paris Agreement has changed some of the basis for carbon markets, including for voluntary carbon markets, and details are still being negotiated (Carbon Brief, 2019, 2022). The European Union has launched a proposal for regulation (including a certification framework) of carbon removals, which is currently under negotiation (European Commission, 2022).

2.4 Organizational greenhouse gas accounting

The expectations on organizational disclosure on sustainability metrics, in particular climate impact, are increasing. Both legislators and stakeholders expect declarations on current status, ambition level and transparency concerning climate mitigation targets and the progress towards targets. Organizations in the agriculture and forestry sectors along with, e.g., energy and waste sectors, together with actors in their value chain, may have biochar as a component of their climate strategy and the accounting system must therefore support calculations for removals.

2.4.1 The GHG Protocol and the Land sector and removals guidance

The greenhouse gas protocol (GHG Protocol) is the world's most widely used standard for GHG emission accounting and reporting on a corporate and organizational level. It was initially developed in the late 1990s by the World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The GHG Protocol provides a standardized framework and guidance for how to account and report GHG emissions in the operation and value chain of actors within the private and public sector.

Carbon removals have previously not been included in reporting or covered by the GHG Protocol. This is about to change with the development of a new guide for land-related emissions, along with all carbon removals. The land sector and removals guidance (LSRG) (GHG Protocol, 2023) covers how companies account for GHG emissions and removals from the following activities:

- Land management and land use change
- Carbon removals and storage in land and geologic carbon pools
- Carbon stored in biogenic products and products derived from technological carbon removals

The LSRG guidance underwent pilot testing and review during the autumn of 2022. Feedback from the pilot testing is now under review, and the finalized guide will be published in late 2023. With the launch of the LSRG, reporting of all land-related emissions is mandatory. In alignment with the GHG Protocol corporate standard, land-related emissions can be calculated using secondary data and global emission factors. Reporting carbon removals is, however, optional according to the LSRG guide. If carbon removals are to be included in carbon accounting, data quality requirements are much higher in comparison to activities that are mandatory to report. In addition to using either national or more specific methods and data, reporting entities must also fulfil the following requirements:

- Ongoing storage monitoring
- Traceability from biomass harvest to storage
- Use of primary data
- Reporting of uncertainty range
- Reversals accounting when stored carbon is lost as emissions

Biochar could, in the latest draft of the guidance, be interpreted either as a product carbon pool or, after application, as part of a soil organic carbon pool. This has implications for both how the carbon removal is to be reported and how the requirement on ongoing storage monitoring is to be fulfilled. More uniform guidelines for how biochar or similar carbon removals are to be handled within reporting is likely to either be included in the final version of the guidance, or to be developed as an industry standard outside of the guidance itself. Regardless of the outcome of this however, the estimation of durability will be essential for including biochar as a carbon removal within organizational greenhouse gas accounting.

2.4.2 Science based targets initiative

Science based target initiative (SBTI, 2021) is a target-setting framework that drives ambitious corporate climate actions. SBTi has, based on the scientific need of climate action, developed principles for greenhouse gas mitigation targets for the corporate sector that are in line with a 1.5-degree development. The framework includes sector-specific guidance for several different sectors and offers both near term and long term target formulations. In the Forest land and agricultural guidance (FLAG, SBTi, 2023), the production and storage of biochar is explicitly mentioned as a possible mitigation action that could contribute to fulfilling of targets within a company's own operations. For companies outside of the FLAG sector with no ability to produce or store biochar themselves, biochar is still relevant, along with other carbon removals, when setting and reaching a net zero target which requires mitigation efforts outside of the company's own value chain. For reaching net zero, emissions must be reduced in line with the 1.5-degree target and remaining emissions must be offset by carbon removals.

3 Estimation of biochar persistence

Estimation of biochar persistence, but also the persistence of fire-derived chars and charcoal, has been investigated by multiple research groups using different approaches, including:

i) Approaches built on biochar decomposition experiments

ii) Approaches built on relative thermo-chemical resistance tests and molecular structure analyses

iii) Approaches built on global carbon budgets

iv) Approaches built on analysis of archaeological remains of charcoal

The focus of this chapter is the approaches that are built on biochar decomposition experiments (i), which has been the main modelling paradigm to date, and the one put forward in multiple reviews as well as the IPCC's latest revision of greenhouse gas inventory reporting (IPCC 2019). Sections 3.1 and 3.2 provides scientific background knowledge and explain how the modelling is done. The other approaches are briefly described in section 3.3. This intention of this chapter is to provide rather detailed information. The reader more interested in the conclusions and recommendations can go directly to chapter 4.

3.1 Substitution

The chemical composition of biochar is critical for determining its persistence and thereby the durability of carbon storage. It is well known to be determined by pyrolysis conditions and feedstock. In general, increasing pyrolysis intensity (temperature and duration) results in increased degree of aromatisation and aromatic condensation, which makes biochars more resistant to degradation (Howell et al., 2022; Leng and Huang, 2018; Ippolito et al., 2020). During pyrolysis, the chemistry of the feedstock is altered in several ways; many compounds such as carbohydrates, lipids, proteins etc. are volatilized or form bio-oils/tars, resulting in a significant decrease in the biochar yield (weight loss) as the temperature rises, especially at pyrolysis temperatures between 200 and 500 °C (Weber and Quicker, 2018; Howell et al., 2022). As temperature increases, more stable polymers such as cellulose and lignin are gradually transformed into more condensed polyaromatic structures and oxygen containing functional groups such as carboxylic acids, phenols, carbonyls etc. are gradually lost, making the biochar less reactive (Leng and Huang, 2018). This is reflected in decreasing O/C and H/C-ratios with increasing temperature and weight loss (Weber and Quicker, 2018; Howell et al., 2022). At low to intermediate pyrolysis intensity (HTT:s around 350-550 °C) the transformation processes may still be incomplete and as a result, the chemical structure of the resulting biochars can be quite complex. At these formation temperatures, aromatic structures will be less condensed (fewer rings), partially untransformed biopolymers may still be present within the biochar structure, and more easily degradable aliphatic compounds may be deposited on the surface of the biochar. However, as pyrolysis intensity increases further (HTT around 600-1000°C) remaining non-aromatic compounds are more or less completely volatilized and lost, and the aromatic structure becomes gradually more condensed (Mcbeath et al., 2011; Wiedemeier et al., 2015). Biochars may also contain different amounts of inorganic compounds and salts. This inorganic fraction is usually measured as the ash content and is important for some of the properties of biochar, such as regulating its pH-value.

When biochar is added to soil, several processes will occur (Joseph et al., 2021). The dissolution of salts is quick and results in the release of a rapid pulse of carbon (from carbonates) within the first few days or weeks, which is a chemical reaction not involving microbes. Lower molecular weight water soluble organic compounds can also be released into the soil solution (dissolved organic carbon, DOC) and are quickly mineralized by microorganisms (days-months). Aliphatic compounds and organic compounds of intermediate bioavailability are mineralized by soil microorganisms at a slower rate, but still within a period of a few months to a few years. The polycyclic aromatic structures are significantly more resistant to decomposition, particularly if they are very condensed.

Since the decomposition of organic matter, and thus biochar in soils is primarily a microbially mediated process (Zimmerman, 2010), the rate at which the different carbon fractions are decomposed is dependent on the general microbial activity of the soil, which depends on factors such as temperature, moisture content, soil organic matter quality and availability (Ameloot et al., 2013).

Biochar is altered in several ways over time which affects its biodegradability in soil. The process of ageing results in oxidation of the biochar surfaces and in the introduction of more functional groups, which increases its reactivity (Sorrenti et al., 2016). On the other hand, biochar can also become coated by minerals and organic matter, and be incorporated into soil aggregates over time, which may help to stabilize it. Physical fractionation of biochar occurs due to tilling, bioturbation by worms and other soil fauna, or frost-thaw cycles and this exposes new surfaces for microbial attack and may release more biodegradable organic compounds that were initially trapped within the biochar matrix. However, it can also make biochar more susceptible to downward transport into the subsoil where microbial activity is lower. Such vertical movement can be significant in certain soils and climatic conditions (Haefele et al., 2011; Singh et al., 2015). Furthermore, the low density of biochar particles makes them sensitive to transport by surface runoff during intense rain events (Kätterer et al., 2019).

Finally, introduced biochar carbon and soil organic matter already present can affect each other mutually (Fang et al., 2019). On one hand, addition of biochar to soil usually leads to a negative priming, i.e. slower decomposition of soil organic matter (Ding et al., 2018). On the other hand, addition of plant litter or other organic inputs like manure to a soil containing biochar can also increase biochar decomposition rates for a short period of time, associated with the higher microbial activity in the soil following the amendment of fresh material (Zimmerman and Ouyang, 2019). Biochar, moving downwards in the soil profile, can possibly affect decomposition of soil organic matter in the subsoil (Naisse et al., 2015). The magnitude and direction of these priming effects vary with time, but also depend on the type of soil, biochar, and management strategy. There is also a potential dynamic effect; biochar may lead to increased plant productivity causing increased addition of organic matter from plants to soil.

Overall, biochar and soil organic matter interactions in relation to soil carbon stocks can be summarized as in Figure 4.

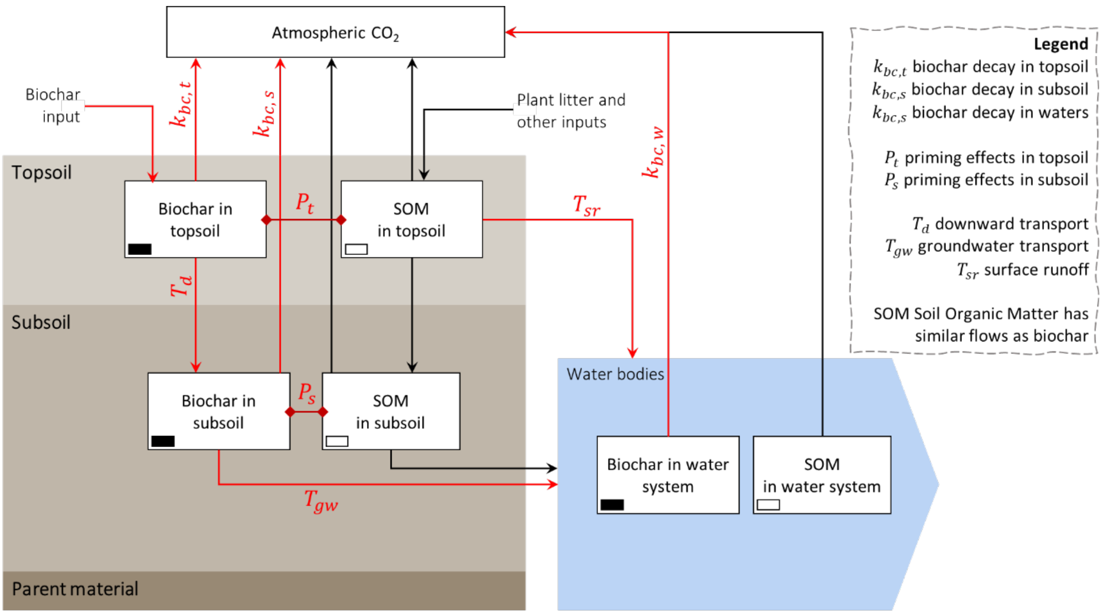


Figure 4. Overview of decomposition, transport and interaction between biochar and soil organic matter (SOM) in a soil profile, with a topsoil and subsoil, and receiving water bodies. Biochar amended to topsoil is subject to decomposition and transport processes and can induce priming effects with soil organic matter. Likewise, soil organic matter and plant litter inputs are subject to decomposition and transport and can induce priming effects on biochar. Most research on biochar persistence has focused on biochar decomposition ($k_{bc,t}$) and priming effects with soil organic matter (P_t) in topsoil.

3.2 Persistence estimates based on biochar decomposition experiments

This modelling approach relies on several steps (Figure 5). First, biochar decomposition experiments are set up, in which biochar properties and decomposition rates are measured over time for a set of given conditions. Second, data from multiple experiments are compiled in a dataset. Third, the dataset is analysed to draw conclusions regarding decomposition characteristics of different biochars under different conditions, and durability models are built. Finally, for specific applications, additional adjustments can be made to the model to accommodate alignment with the goal of the application (e.g. need for conservative estimates in carbon trading, need for representative averages in national inventories).

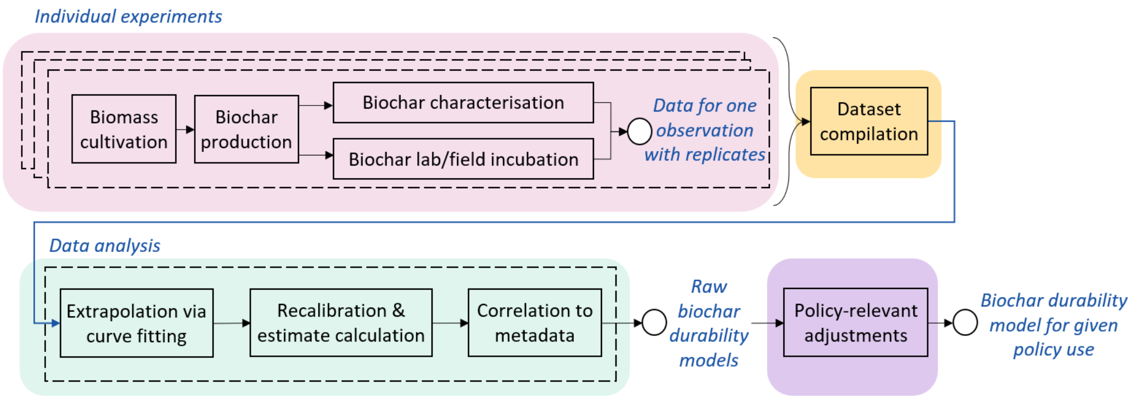


Figure 5. From measuring a flux of carbon dioxide emission to calculating correlations between estimated persistence and experimental variables: individual experiments, database compilation, and data analysis.

3.2.1 Experiments for measuring biochar decay rates in topsoil

Biochar decomposition rates can be evaluated using various methods, including by measuring soil respiration in the presence and absence of biochar, by utilizing isotopically labelled biochar, and by observing changes in organic carbon content over time in biochar-amended soil. In laboratory incubations, biochar is usually mixed with a soil sample and incubated in the dark at a constant temperature and a moisture level optimized for microbial activity (Ameloot et al., 2013). A control soil without biochar is also included. Incubation is performed in a closed system where all CO_2 emitted from the soil can be captured. Often, CO_2 is trapped in a hydroxide solution and the amount of CO_2 can be determined by either titration or by measuring the conductivity. Plotting the emitted CO_2-C over time and fitting a curve to it (see section 3.2.2) gives an overall decay rate for soil organic matter plus biochar. The decay rate of biochar can be calculated by subtracting the CO_2 emissions from the unamended control soil. However, this method does not account for so called priming effects, where biochar affects the decomposition of the natural soil organic matter (Rasul et al., 2022). By using a biochar that is labelled or naturally enriched with carbon isotopes 14C or 13C, CO_2 released through the degradation of the biochar can be distinguished from that stemming from the natural organic matter, and any priming effects can be elucidated (Chalk and Smith, 2022).

A complementary approach is to measure the total carbon content of the soil samples at the at different time points during the incubation. This approach may be further refined by analyzing the contents of specific carbon fractions over time, which may help to establish diverging decay rates for carbon pools of different durabilities.

In addition to the quantitative approaches described above, more qualitative approaches, where the chemical composition, surface chemistry and physical structure of the biochar is studied over time are common and can help to elucidate mechanisms and give insights into how degradation proceeds, and how biochar is transformed in the soil.

Laboratory incubations have several limitations; studies are usually relatively short, which means that they may not deplete the more easily degradable carbon fractions from the biochar within the time frame of the experiment – this may lead to underestimation of durability depending on how decay rates measured within the experiment are extrapolated into the future. Under field conditions, the soil is subjected to animal perturbations, intermittent drying-wetting, freeze-thawing and additions of plant litter and root exudates etc. that may contribute to physical fractionation and stimulation of microbial activity. During laboratory incubations such sources of microbial stimulation are absent and microbial activity and biomass tends to decay exponentially with time as sources of easily degradable carbon are depleted – this may lead to an overestimation of durability (Kirschbaum, 2004).

Field studies are more realistic when it comes to the conditions encountered by the biochar but tend to be associated with higher uncertainty and variability. Unlike in incubation studies, CO_2 emissions can be measured in situ using portable gas analyzers equipped with a soil CO_2 flux chamber or by taking gas samples from static boxes. Alternatively, litter bags can be employed to measure the biochar durability under field conditions (Ngo et al., 2016). However, it is impossible to monitor all emitted CO_2 using such gas-analyzer or litter bag techniques. In addition, biochar might be transported into deeper soil layers or washed away during intense rainfall events (Haefele et al., 2011; Singh et al., 2015; Lutfalla et al., 2017).

3.2.2 Curve fitting of decay time series and extrapolations

Data measured during incubation experiments, whether in field or in laboratory conditions (section 3.2.1), must be processed and analysed. An often-reported result is the amount of carbon lost at the end of the incubation period, expressed as % of initial carbon present. Another type of analysis is the extrapolation of measured time series. Extrapolation is enabled by curve fitting and is used to determine characteristic decay rates, with various modelling choices. Such modelling is associated with the calculation of mean residence time (MRT, i.e. time after which 66% of initial carbon is released), half-lives ($t_{1/2}$, i.e. time after which 50% of initial carbon is released), fraction remaining after 100-years (BC100, i.e. amount of carbon remaining after 100 years) and similar metrics. These terms are not specific to biochar carbon persistence studies, but derive from kinetic studies of soil organic matter.

3.2.2.1 How is curve fitting done and what does it yield?

Curve fitting is a process to adjust a mathematical function with a limited number of parameters to a series of data points. In organic matter and biochar decomposition studies, curve fitting can be applied to several measured variables, e.g. decay rates, total carbon remaining, or cumulative carbon lost as a function of time. These variables can be expressed in absolute units (e.g. mg C lost per day) or in relative units (e.g. % of initial C lost per day). The fitted variables and time can also be modified to make fitting easier, e.g. via logarithmic transformation, normalization, or temperature scaling (degree-days) (Weihermüller et al., 2018; Leng et al., 2019a).

The choice of a mathematical function depends on the shape of the data and the understanding of the processes studied. In organic matter and biochar decomposition studies, the functions used for fitting carbon remaining over time are usually exponential models: single, double, triple and power models have been used (Zimmerman 2010; Weihermüller et al., 2018). Exponential models and power models have different assumptions on what observed characteristics are extrapolated in the future.

Curve fitting is an optimisation problem: the optimal solution, if it exists and is found, minimizes the error between the data and the model function. Curve fitting of linear and single-exponential functions has a unique solution and algorithms always converge. However, curve-fitting of non-linear problems do not necessarily have a unique solution and algorithms are not guaranteed to converge towards to global optimum. Hence, when performing curve-fitting for instance with double exponential functions, it is critical to disclose what algorithm, initial conditions, and fitting constraints were used and how the quality of the selected fit was assessed. This has usually been inadequately reported in biochar incubation studies (Weihermüller et al., 2018) and hinders reproducibility.

Curve fitted models provide the metrics mentioned above (MRT, $t_{1/2}$, BC100), as well as additional information on analysed data, e.g. numerical model parameters and their associated uncertainties, or residual distributions. This information can be useful when analysing the quality of the data used for building the models.

3.2.3 Correlating biochar decomposition metrics to biochar and environmental properties

Data collected from multiple incubation studies and their analysis (3.2.1 and 3.2.2) can be compiled in a dataset of observations. The dataset contains: i) time series of measured decay rates, ii) calculated parameters derived from curve fitting of decay rates, iii) measured variables that describe the experiment, such as biomass properties, pyrolysis conditions, biochar properties, and incubation conditions, and possibly iv) combinations or recalculations of these variables (e.g. H/Corg ratio is calculated from H and organic C content; dry ash free carbon content is calculated from carbon content and ash content; decay rates can be recalibrated for temperature differences). The dataset can be analysed for correlation between the variables (also known as metadata), and in particular correlation with decay metrics from curve fitting (Figure 5). Note that a correlation does not necessarily imply a causation relationship. Search for correlations in the dataset must be followed by an interpretation and a confrontation to theory, in order to interpret and validate the models.

3.2.3.1 The search for correlation: how and what?

Searching for correlations in a dataset can be done in multiple ways. As a first step, it is common to perform an exploratory analysis e.g. by visualizing scatter plots of all pairs of numerical variables, calculating linear and non-linear correlation matrices, or performing principal component analyses. Such exploratory analysis can provide an overview of pair-wise relationships in the dataset. Special strategies can also be applied to visualise correlation with non-numeric variables (e.g. categorical variables like type of feedstock). In a second step, specific regressions between selected variables can be calculated and assessed. Another way of identifying correlations, commonly used for training machine-learning models, is to systematically test all combinations of variables and model parameters, i.e. not only pair-wise but also multivariate.

Search for correlations is sometimes qualified as descriptive or predictive. Descriptive analysis refers to situations where the whole dataset is used to identify a correlation. Conversely, predictive analysis refers to situations where only part of the dataset is used to train a model whose performance is then assessed on the remaining unseen part of the dataset. In previous assessments of biochar incubation data (see 3.2.4), all analyses have been descriptive, due to the limited size of the dataset.

Different types of correlations or regressions can be searched for. Correlations can be found between one or multiple input and output variables and the nature of the relationship can be linear or non-linear. In previous assessments of biochar incubation data (see 3.2.4), most suggested regressions have been linear, single-target, single-variable, e.g. linear relationship between BC100 and H/Corg ratio. No non-linear and multivariate regressions have been suggested so far, mainly because of the absence of a comprehensive dataset.

3.2.3.2 Correlations presented in previous assessments

Previous assessments of biochar incubation data include the work of Spokas (2010), Zimmerman (2010), Harvey et al. (2012), Singh et al. (2012), Budai et al. (2013) for the International Biochar Initiative, Lehmann (2019) for the IPCC 2019 Inventory guidelines, Lehmann et al. (2021), Woolf et al. (2021) and Rodrigues et al. (2023). Each of these have put forward at least one relationship between an estimate of biochar persistence and one variable describing the biochar, most often using a linear relationship (Table 1). Wang et al (2016) is a widely cited paper that provides some numbers on biochar persistence, but it is not based on correlations between input variables and target values, and we do not recommend it to be used for estimations of biochar persistence.

Table 1. Compilation of regressions between biochar persistence estimate and variable published in previous assessments.

Reference	**Number of observations**	**Target variable**	**Input variable**	**Relationship**	**R^2**	**Remarks**
Spokas 2010	34	Half-life	O/C	Log-linear	NA	
Zimmerman 2010	25	BC_{100}	Volatile matter (%)	Linear	0.35	In supporting material
Harvey et al. 2012	25	BC_{1yr}	Recalcitrance index[a], R_{50}	Exponential	NA	Based on data from Zimmerman 2010
Singh et al. 2012	10	MRT MRT BC_{loss} BC_{loss}	Non-aromatic carbon (%) Aromatic condensation Non-aromatic carbon (%) Aromatic condensation	Power Power Power Power	0.94 0.95 0.91 0.86	Limited to 10 observations. Introduces new biochar characterisation method to measure aromaticity.
Budai et al. 2013	31	BC_{100}	H/C_{org}	Linear	0.50	Not peer-reviewed
Lehmann 2019	59	BC_{100} BC_{100}	Pyrolysis temperature H/C_{org}	Linear Linear	0.09	In IPCC 2019 Inventory guidelines appendix; with few erroneous data points. Soil temperature recalibration.
Liu et al. 2020	5	BC_{100}	Chemical Oxidation Test	Linear	0.99	Limited to 5 observations. Makes the link between and incubation studies chemical oxidation method, earlier presented in Cross and Sohi (2013).

Lehmann et al. 2021	85	BC_{100} BC_{100} BC_{100}	Pyrolysis temperature H/C_{org} O/C_{org}	Linear Linear Linear	0.28 0.33 0.11	Soil temperature recalibration.
Woolf et al. 2021	85	BC_{100} BC_{100}	Pyrolysis temperature H/C_{org}	Linear Linear	0.13 0.33	Soil temperature recalibration. Same data as Lehmann 2021.
Rodrigues et al. 2023	77	BC_{100}	H/C_{org}	Power	0.35	Soil temperature recalibration. Similar data as Woolf 2021, with some new data and different data exclusion criteria.

[a] The recalcitrance index was defined as the ratio of two temperatures: the temperature at which 50% of the carbon content of a biochar sample is oxidised during thermogravimetric analysis, over the same temperature for graphite.

We consider the correlations provided in Woolf et al. (2021) as better than previous models, because:

- It builds on the largest dataset, so far established, with 85 observations of at least 1-year incubation duration.
- The dataset corrected multiple reporting errors that were present in previous datasets, including the IPCC 2019 dataset.
- It reports the primary output from curve fitting (decay rates and pool sizes), an important step of the modelling.
- It proposes a dependency of biochar persistence on one environmental factor, namely soil temperature.

The publication by Rodrigues et al (2023) provides one advantage over the Woolf model: it provides more conservative data for very low H/C-ratios. It also uses data from one more recently published experiment and also considers different data selection criteria.

Some of the authors of this report have done additional modelling, available as a pre-print (Azzi et al 2023). That modelling is the basis for the model that we recommend in Chapter 4 and includes:

- Careful selection of which incubation data to include and exclude, based on assessment of experimental conditions and outliers.
- The same extrapolation methods (i.e. curve fitting) are applied to the whole dataset.
- Similar to Rodrigues et al (2023), a power model is applied, which gives conservative estimates at low H/C ratio.
- All modelling using this approach suffers from some limitations:
- The soil temperature correction is associated with high uncertainties, especially at lower soil temperatures.

- Too few data points available in the range of low H/Corg ratios (below 0.2)
- The linear correlations are rather weak ($r2 \leq 0.33$ for BC100 and H/Corg)
- Biochar is assumed to remain in the active soil layer
- No use of any margin of safety or other adjustments for potential intended applications such as policy and decision making.

3.2.4 Limitations of laboratory incubations with respect to in-field durability estimation

Most biochar incubation experiments have been performed in laboratory conditions, i.e., at constant soil temperature, in the dark, at optimal moisture content for microbial activity, and without crop cultivation. This raises the question of how to translate durability estimates to in-field conditions. Differences between laboratory and in-field conditions include the following aspects (Kuzyakov et al., 2014):

- In the field, the biologically active time is less than in laboratory conditions (due to both moisture and temperature variations), which can make biochar decay slower in field than in laboratory.
- In the field, freezing-thawing cycles as well as drying-wetting cycles can disperse and alter the structure of biochar, possibly making biochar decay faster in the field than in a laboratory.
- In the field, the presence of fresh carbon input, living roots, and root exudates, which stimulate microbial activity, can make biochar decay faster in the field than in a laboratory.
- In the field, the presence of processes leading to formation of aggregates between soil particles and biochar (bioturbation, rain, soil operations) can increase the protection of biochar particles, and possibly making biochar decay slower in the field than in a laboratory.
- In the laboratory, the absence of regular carbon and nutrient inputs can lead to a decrease in the amount of microbial biomass, thereby potentially leading to slower biochar decay in the laboratory than in the field.
- It should be noted that arguments go in both directions, faster and slower decay in field compared to laboratory, but that the magnitude of these effects have not been studied in detail.

In addition to these remarks, it can be noted that:

- Laboratory incubations do not take into account possible movements of biochar in the environment, and thereby implicitly assume that biochar remains in the soil layer where it is amended.

- Some have suggested that at higher rates of biochar in soil, the microbial community could shift towards preferential uses of biochar carbon over soil organic matter, but this remains unverified.

3.3 Brief overview of other approaches

Several other modelling approaches of biochar durability have been put forward and some are gaining new attention in 2023[6].

3.3.1 Accelerated thermo-chemical degradation

Rather than analysing the degradation of biochar in soils, several studies have developed metrics to describe the thermo-chemical resistance to degradation of a biochar sample relative to another substance, like coal, graphite, or fire-derived charcoal. Chemical oxidation using hydrogen peroxide was suggested by Cross and Sohi (2013), and further studied by Liu et al. (2020). Decomposition measured in thermogravimetric analyses, relative to graphite, has also been presented as a durability metric (Harvey et al., 2012). More recently, other thermochemical degradation procedures have been suggested to attempt discerning the different chemical fractions of carbon present in a biochar sample, namely hydrogen pyrolysis (Ascough et al., 2009; McBeath et al., 2015; Howell et al., 2022) and extended slow heating® (Petersen et al. 2023).

3.3.2 Analysis of chemical structure

Other studies suggest the use of advanced characterisation techniques to elucidate the chemical structure of biochars and heterogeneity within a biochar sample. The focus is on different ways of describing the degree of aromaticity of biochars because aromaticity is thought to explain the resistance of biochar to microbial and other oxidative processes. Techniques to characterise aromaticity include: i) portion of non-aromatic carbon and degree of aromatic condensation, measured by nuclear magnetic resonance (NMR) (Singh et al., 2012., Budai, 2017), ii) molecular markers of benzene poly-carboxylic acids (BPCA) (Glaser et al., 1998; Glaser et al., 2021), iii) hydrogen pyrolysis (Ascough et al., 2009; McBeath et al., 2015; Howell et al., 2022), iv) extended slow heating® (Petersen et al., 2023), v) optical analyses (Petersen et al., 2023; Mastalerz et al., 2023).

Petersen et al (2023) compared the random reflectance of biochar to geological forms of organic carbon and concluded that biochars produced at 700°C and 900°C had a large proportion of material with reflectance properties and morphotypes

[6] e.g. Session conference session at EGU 2023: Dynamics and functions of SOM pools under new and traditional soil amendments, with a special focus on pyrolytic carbon. https://meetingorganizer.copernicus.org/EGU23/session/44947

equivalent to inertinite[7], the most aromatised form of organic matter in geological formations (see more in next section). This differed from biochars produced at 500°C.

For a further review of biochar characterisation methods used as proxy for durability and persistence, see Söderqvist (2019) and Leng et al. (2019b).

3.3.3 Analysis of archaeological charcoal and biomass remains

Archaeological charcoal remains as well as biomass remains can be analysed for determination of their age and chemical characteristics (Ascough et al. 2020). In essence, these analyses demonstrate that very old charcoal and biomass can be preserved for millennia, provided the right environmental conditions. The analysis of the chemical structure present is also informative on the possible processes at work over long-time scales (Ascough et al. 2018).

3.3.4 Global pyrogenic carbon cycle modelling

Pyrogenic carbon (PyC), mainly derived from forest fires throughout the history of the planet, has long been an object of study to understand the planetary carbon cycle (Bird et al., 2015; Abiven and Santín, 2019; Bowring et al., 2022). An important aspect of PyC studies for estimation of persistence is the movement of PyC via runoff, erosion and downward transport in soil profiles (Haefele et al., 2011; Lutfalla et al., 2017), ultimately leading to PyC accumulating in sediments and oceans (Abney and Berhe, 2018). In recent years, with biochar use in soils gaining importance, the link between biochar persistence studies and global pyrogenic carbon cycle studies has been made.

3.3.5 Dynamic soil carbon modelling

Dynamic soil carbon modelling is an extensive field of research, with a long tradition. A few attempts have been made to include biochar carbon dynamics in such models, e.g. Pulcher et al. (2022), but this was limited to one specific type of biochar and excluding biochar carbon transport.

3.3.6 Remark on notions of time

All modelling approaches described above used notions of time to describe durability of biochar carbon storage. However, it must be noted that notions like age, transit time, or mean residence time have different meaning in incubation studies, soil carbon modelling, and global carbon cycle modelling (Sierra et al.,

[7] Inertinite is a form of oxidized organic matter or fossilized charcoal, found within sedimentary rocks but also in most types of coal (maceral). Presence of inertinite in geological record can be an indication of wildfire taking place at the same time as sedimentary rocks formed, but also the indication of fungal decomposition of organic matter during sedimentary rock formation.

2017 ; Sierra et al., 2018). Until now, these terms have been used in biochar persistence research without enough attention to the difference in meaning.

3.3.7 Notes on a recent publication

The research findings by Petersen et al (2023) have received wide attention in biochar business in 2023. We therefore provide some comments specifically on the research article Petersen et al., 2023. Overall, we believe that the manuscript presents solid experimental work of importance for progress in understanding of biochar durability. However, in the discussion section there are some claims that are unsubstantiated or unclear, leaving some of the interpretation of the work questionable.

The research brings novelty:

- By comparing biochar to geological organic matter (macerals) more knowledge can be gained about the properties of biochar.
- By analysing many points in one sample, the heterogeneity of biochar in a biochar sample can be determined.

The finding that some biochars are very similar to inertinite (in terms of reflectance properties and morphotypes) is an indication that large proportions of many biochars may be very persistent in soil.

The research confirms previous knowledge about biochar persistence:

- Higher temperature pyrolysis results in more persistent biochar.
- Biochars classified as highly persistent have low H/C ratio while less persistent biochars have higher H/C ratio.

There are claims in the discussion in the paper that are not well substantiated:

- It is claimed that inertinite and biochars with similar composition are inert in soil environments. The claim that the mere existence of inertinite in geological formations that are millions of years old is proof that biochars will not degrade is not correct. Soils and other biologically active environments at the Earth´s surface are very different from deep geological layers.
- The references to biochar research are not the most recent and relevant for the discussion.
- There are problems with the terminology.
- This is the first paper on biochar published by these authors and it is published in Coal Geology. Several terms are unfamiliar to biochar researchers or defined differently.

- The terminology regarding terms such as “inert” and “labile” is not used consistently, sometimes it refers to definitions from geology which are related to persistence at high temperature in environments without oxygen, and sometimes referring to conditions relevant for biochar in soil.

Research priorities based on the work of Petersen et al (2023), in order to increase the understanding of biochar durability:

- Analysis of the random reflectance of biochars that have been used in incubation experiments, to the extent that these biochars can be made available. This will give new information about these biochars, which will guide the interpretation of performed incubation studies.
- Laboratory incubation of inertinite samples in soils, to test the claims that inertinite is inert also in biologically active environments.

4 Estimation of biochar durability and use for accounting purposes: towards a recommendation

This chapter presents our conclusions and recommendations for estimation of biochar durability and its use for accounting purposes. This chapter builds upon the previous chapters, namely Chapter 2 on greenhouse gas accounting and management systems and Chapter 3 on the science of biochar durability estimation. These supporting chapters will be cross-referenced here.

4.1 From an observed correlation to a policy-relevant model

In Chapter 3, we described the scientific state of the art in estimation of biochar durability. However, when moving from scientific descriptions to policy-relevant recommendations, it is important to consider the purpose of the recommendations. For instance, when dealing with project-level accounting for issuance of carbon credits, the following two conditions generally apply:

i) Project-specific parameters shall be known, e.g. properties of the biomass feedstock, the biochar production process, the biochar quality and the biochar use.
ii) Estimates are expected to be conservative, i.e. to not overestimate the carbon storage value.

Attempts to estimate biochar persistence and its carbon storage value should also recognise these facts (some of which were described in Chapter 3):

i) not all biochars are equal,
ii) multiple environmental processes affect biochar,
iii) the relative importance of these processes may vary with time,
iv) biochar decomposition has been mainly studied in topsoil,
v) biochar is known to physically move in the landscape and the soil profile
vi) biochar persistence is associated with inherent uncertainties, largely due to general uncertainty of the future.

Biochar durability models that have been used in practice usually estimated the fraction of biochar remaining at a specified time horizon (commonly 100 years, see section 4.5) and soil temperature as a function of either pyrolysis temperature or the molar H/Corg ratio of the biochar. Among these two correlations, we consider the use of molar H/Corg ratio as preferred for project-level use cases (i.e. in LCA, carbon credits, organisational accounting) because it is an easier and more reliable measurement than pyrolysis temperature, provided that laboratory analyses are accessible.

4.2 Recommended biochar durability model

To date, we recommend estimating biochar durability with the model shown in Figure 6 and extensively described elsewhere (Azzi et al., 2023). The model is also made available in an Excel file[8]. This model is built on data from incubation studies, a new harmonized data analysis process, careful selection of experiments, extrapolation using multi-pool exponential models, and a non-linear power relationship between H/C and BC100. The model is similar in nature to previously published models (Woolf et al. 2021, Rodrigues et al. 2023) but with different data processing and selection.

The model is presented here for a time horizon of 100 years, at two soil temperature: 20°C temperature at which most incubation studies have been performed, and 7°C representative of average Swedish soil conditions. Other soil temperatures and time horizons are available elsewhere (Azzi et al., 2023).

[8] https://biochar.systems/stability/guidelines

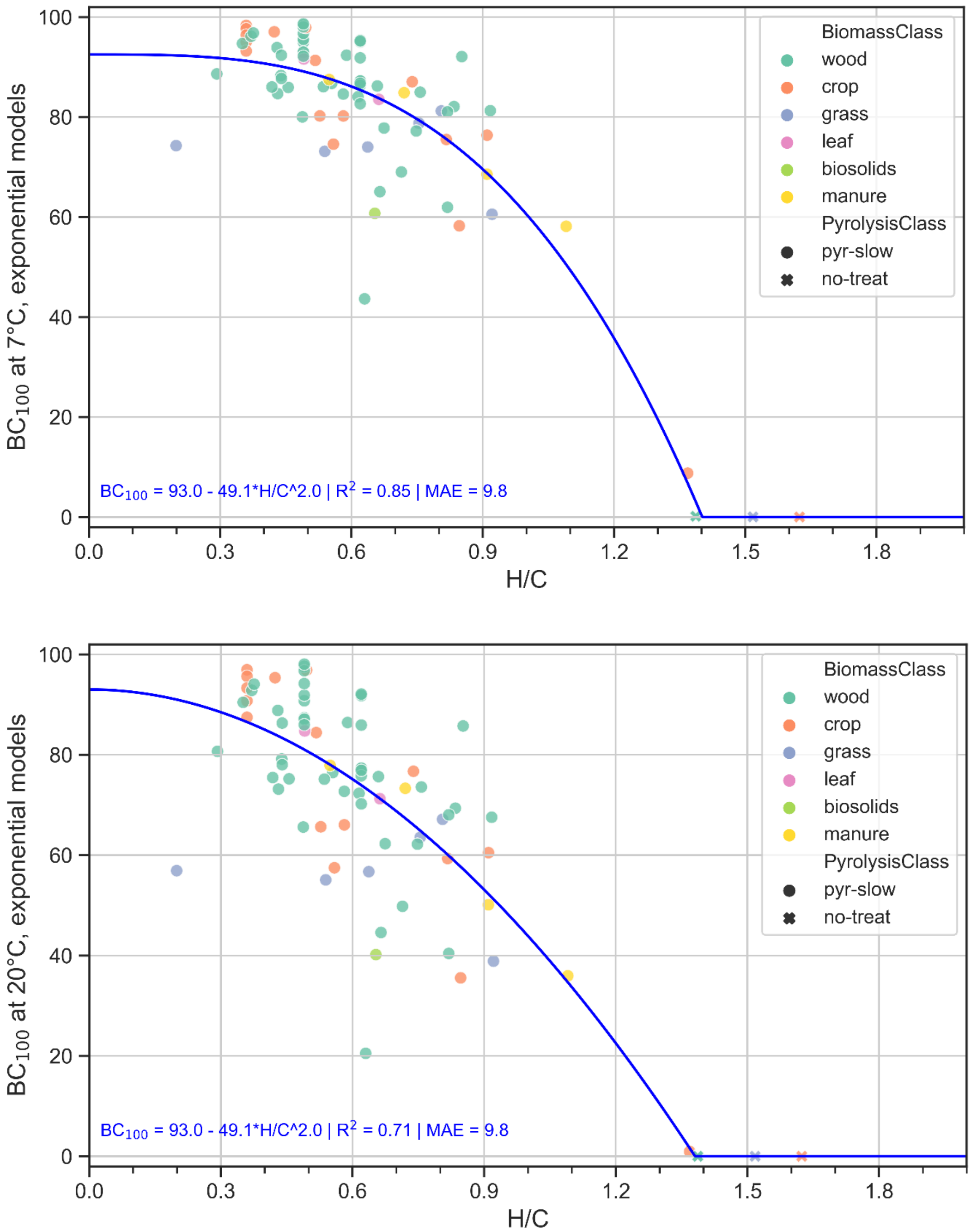


Figure 6. Fraction of biochar carbon remaining in soil after 100 years (BC100) as a function of biochar molar hydrogen to carbon ratio (H/C) at a mean annual soil temperature of 7°C (top; representative of Swedish soil conditions) and 20°C (bottom; temperature at which most incubation studies have been performed). Colours refer to different types of biomass used as feedstock for biochar production, circles are biochars from slow pyrolysis and crosses are non-treated biomass. Figures are adapted from the data analyses performed as part of this project (Azzi et al. 2023) and available online[9].

There is a need for a safety margin on top of the modelled correlation, in order to provide a conservative value rather than an average value. We are not able to

[9] https://github.com/SLU-biochar/biocharStability

give any general advice on a safety margin, as that will depend on the conditions of the specific use case.

This model can be used to determine the amount of carbon dioxide stored in biochar when used in soil applications, provided that the following data is available:

1. Reliable measurement of the dry mass of biochar produced.
2. Laboratory measurements of hydrogen content and organic carbon content.
3. The soil temperature representing the annual average in the region where biochar is used.
4. A time horizon in line with the accounting tool or standard used (in most cases, 100 years).

For items 1 and 2 to give reliable numbers, biochar projects need a protocol for representative biochar sampling and laboratory testing, adapted to the variability of the biochar production process (e.g. changes in biomass type, change in pyrolysis conditions). Inaccurate measurements of those parameters can lead to large inaccuracies in estimating in the amount of carbon dioxide stored in biochar. These topics were not tackled in this report and are known to often be associated with challenges in practice. Dry mass determination of a produced biochar remains challenging because of moisture varying with weather. This is not specific to biochar production, but also applies for instance to the charcoal industry (FAO, 1985). The (organic) carbon content and hydrogen content of a biochar sample can be accurately determined via laboratory analysis, but sampling and analysis protocols must be conceived so that samples are representative of the actual production, taking into account variability and seasonality. For item 3, global datasets of soil temperature can be used such as the one from Lembrechts et al. (2021), and in particular the data layer SBIO1 Annual Mean Temperature in 5-15cm soil layer.

Durability estimation methods that are based on other principles than extrapolations from incubations, which suggest higher or longer durability (see section 3.3), are not recommended at this stage. Likewise, other extrapolation techniques of incubation data (e.g. using infinite pool models) are not recommended at this stage. They are too uncertain and do not fulfil the criterion to be conservative estimates of biochar durability for project-level accounting.

This said, we expect knowledge to improve rapidly in the next two years thanks to on-going research in various research groups.

4.3 Biochar transport from topsoil

These models rely on a major assumption: the biochar placed in a soil layer is assumed to remain in that soil layer. However, multiple in-field biochar studies have observed that biochar is mobile in soil environments (see Section 3.1) and can move laterally via runoff and erosion, as well as vertically via leaching downward in the soil profile, ultimately reaching the water system (sediments, rivers, oceans). These processes are important, but their magnitude may vary considerably with biochar particle size and application method, soil type, topography, and rainfall or irrigation regime.

To date, there is no established model to quantify, at the project- or field-level, biochar transport in the landscape (horizontal and vertical). Isolated studies have investigated biochar movements and a few planetary carbon cycle studies have attempted to determine the global pyrogenic carbon stock and its average residence time (see Section 3.3).

Hence, if biochar translocation is large, this has several implications for biochar persistence and its estimation:

- The persistence and carbon storage value of biochars may be larger than estimated in incubation studies, as the little evidence available suggests that biochar decomposition in deep soil layer and water systems is likely smaller than in the active upper soil layers.
- The differences in susceptibility to decomposition between biochars of different degrees of carbonisation (e.g. as indicated by H/C ratio) observed in topsoil may be of less importance in deeper soil layers and water systems.
- Ultimately, as for archaeological remains of charcoal and other biomass (see Section 3.3), the persistence of biochar is a function of the environment in which it is stored.
- Monitoring of biochar carbon stocks in the soil where it was applied (e.g. via core sampling and analysis of molecular marker, see Section 3.3) may not be a valid way to estimate biochar decomposition, unless there is adequate accounting of biochar movements.

Possible longer durability due to biochar translocation to water systems is not a license, nor a reason, for dispersing large amounts of biochar directly in oceans, water systems, and other deep compartments, for the sole sake of carbon removal, without appropriate risk assessments and adequate systemic thinking on the best use of biomass resources.

4.4 Non-agricultural biochar use

The research on biochar durability has focused on agricultural soil environments. However, biochar is increasingly being used in other applications, including e.g. urban constructed soils, concrete and other construction materials, filter materials, or plastic materials. Some even suggest biochar disposal in underground mines.

With respect to durability, several distinctions can be made between these applications.

- Short-lived products, with possible incineration at end-of-life: in some biochar applications like filter or plastic materials, there is a risk that the material is burnt at its end-of-life, which can be relatively soon after production (i.e. within decades). In this case, no carbon storage value should be accounted for.
- Long-lived products, with no/little risk of incineration at end-of-life: in other applications, like construction materials and concrete, the expected life span is long enough for a carbon storage value to be estimated. As of today, no studies exist on the persistence of biochar in construction materials. In voluntary carbon markets, the practice has been to assume that durability estimates derived for soil applications can be used as a good enough and conservative proxy also for construction materials.

4.5 Time horizon

Most estimations of biochar durability have used a 100-year time horizon for biochar persistence, with BC100 as a commonly used metric. This metric highlights how much carbon is estimated to be lost within the first 100 years. This does not imply that after 100 years all the carbon is lost. Moreover, this metric does not provide any estimate of the climate effect of temporary carbon storage within the first 100 years.

The BC100 metric remains valid, but other time horizons, shorter and longer, are increasingly being used and discussed. Models for biochar durability should provide results for a range of time horizons, but also adequately explain the validity of the time extrapolation made. Accounting systems should select the time horizon deliberately, in line with their goals. The topic of time horizons for carbon storage is complex and we are unable to give more guidance here.

This said, we believe that current biochar durability models that are derived from incubation experiments are not suited for extrapolation on longer than centennial timescales because they do not capture all the relevant processes at longer time scales. Other theories and models are needed for longer time scales.

4.6 Ways forward

Understanding and modelling of biochar persistence and its carbon storage value are still very active research fields with multiple ways forward, which we summarize below.

4.6.1 Incubations studies and modelling based on these:

- Soil temperature and moisture effects: incubations have not been performed at soil temperatures below 10°C, which are relevant in cold climates. There is ongoing research in our project and in Denmark on this topic. Likewise, effects of varying moisture in soil on biochar decomposition rates soil have not been studied.
- Biochar with very high degree of aromatic condensation: too few incubations have been performed with biochars having a very high degree of aromatic condensation (e.g. H/C ratio below 0.2). Likewise, it would be relevant to incubate organic carbon residues such as inertinite, residues from hydrogen pyrolysis, or residues from extended slow heating.
- Advanced characterization of biochar samples: to the extent that previously incubated biochars can be made available, an effort should be made to characterize those biochar samples with methods such as random reflectance, hydrogen pyrolysis. This will give new information about these biochars, which will guide the interpretation of performed incubation studies.
- Field studies and longer experiments: there are only a handful of incubation studies performed under field conditions, and studies are usually in the range of 1 to 2 years. With more field experiments, understanding of differences between field and laboratory conditions can be improved.
- Data analysis, compilation, sharing: biochar incubation data has so far not been available to the research community, hindering the additivity and reproducibility of research. Our dataset, now publicly available[10] (Azzi et al., 2023) bridges this gap and opens the way for the broader biochar community to analyse and make use of the data.
- Assumptions, limitations, and implications of models derived from incubation data: previously published models of durability do not clarify their assumptions and the implications of these assumptions on model outputs (e.g. movement of biochar is not included in durability model, resulting in a more conservative model; rationale for exclusion of certain observations; extrapolation technique).

4.6.2 Movement of biochar in the landscape and in the soil profile

From global to project-specific models: models quantifying the flows and stocks of pyrogenic carbon exist at a global scale and some of these models are being refined. However, there are no available models to quantify biochar movements in a specific

[10] https://github.com/SLU-biochar/biocharStability

soil profile that would capture effects of weather and biochar properties and which could be used for project-specific modelling.

4.6.3 Fundamental knowledge

Mechanisms of degradation, protection, transport of biochar: there is a need for improved fundamental knowledge on the processes that affect different fractions of biochar in soils with respect to degradation, protection, and transport.

4.6.4 Non-soil applications of biochar

Biochar durability has primarily been studied in soils, but no detailed studies have been performed on non-soil applications, whether it is short-lived (e.g. consumable plastics) of long-lived products (e.g. concrete, asphalt), or other environments (e.g. mines, landfills, water, sediments).

4.6.5 Comparison, integration, and reconciliation of modelling approaches

There is a need for researchers from different fields to share data, confront and combine theories, and different arguments, possibly leading to a unified understanding of biochar durability.

5 Concluding note

At the start of the project, we hoped that our analysis of incubation data would lead to an improved model of biochar carbon storage durability and solid guidelines, but during writing of the report we have wondered whether we would be able to provide any quantitative recommendation at all. There are two reasons for this.

First, the dataset from incubation experiments is too limited. Data analysis and modelling in our research project (Azzi et al., 2023) has improved the understanding and lead to our recommended model, but it has also shown that it is not possible to develop a solid model based on the existing data. Consequently, we have focused this report on describing the state of the art, the limitations of current models and our thoughts on ongoing and needed research.

Second, we think that the ongoing research, policy processes and industry activities in Europe and globally, will lead to changes in biochar durability estimation in the next few years. It is not clear how and where this will lead. All we can say is that it is not yet time to make any definitive statements on how to estimate biochar durability in soils. Due to the importance and urgency of developing carbon removal methods using biochar however, we attempt in this report to provide applicable recommendations based on the current best available knowledge. Until further developments are made within the research field, these recommendations represent a method that is deemed reliable for the purpose of most use cases.

During the time of writing this report, we also initiated a dialogue with many researchers working on biochar persistence in soil. This resulted in a brief statement published online (Azzi and Sundberg, 2023), and will hopefully lead to new research and industry collaborations. Looking forward, our research project will produce experimental results from laboratory incubations at different temperatures (5-20°C) providing a contribution on one of the knowledge gaps that we have identified. We have also established field trials at SLU, which may give some clues to the fate of biochar in agricultural soils in Sweden. We also look forward to following the international research publications in this field in the coming years.

Finally, we plan to come back to the topic of guidelines for biochar durability and revise this report at the end of our project, in 2025.

6 References

Abiven, S., & Santín, C. (2019). Editorial: From Fires to Oceans: Dynamics of Fire-Derived Organic Matter in Terrestrial and Aquatic Ecosystems. Frontiers in Earth Science, 7, 31. https://doi.org/10.3389/feart.2019.00031

Abney, R. B., & Berhe, A. A. (2018). Pyrogenic Carbon Erosion: Implications for Stock and Persistence of Pyrogenic Carbon in Soil. Frontiers in Earth Science, 6. https://doi.org/10.3389/feart.2018.00026

Allen, M.R., Peters, G.P., Shine, K.P., Azar, C., Balcombe, P., Boucher, O., Cain, M., Ciais, P., Collins, W., Forster, P.M., Frame, D.J., Friedlingstein, P., Fyson, C., Gasser, T., Hare, B., Jenkins, S., Hamburg, S.P., Johansson, D.J.A., Lynch, J., Macey, A., Morfeldt, J., Nauels, A., Ocko, I., Oppenheimer, M., Pacala, S.W., Pierrehumbert, R., Rogelj, J., Schaeffer, M., Schleussner, C.F., Shindell, D., Skeie, R.B., Smith, S.M., Tanaka, K. (2022). Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. npj Climate and Atmospheric Science 5, 5. https://doi.org/10.1038/s41612-021-00226-2

Ameloot, N., Graber, E. R., Verheijen, F. G., & De Neve, S. (2013). Interactions between biochar stability and soil organisms: review and research needs. European Journal of Soil Science, 64(4), 379-390. https://bsssjournals.onlinelibrary.wiley.com/doi/full/10.1111/ejss.12064

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., Tokos, K. (2009). Atmospheric Lifetime of Fossil Fuel Carbon Dioxide. Annu. Rev. Earth Planet. Sci. 37, 117–134.h https://doi.org/10.1146/annurev.earth.031208.100206

Arcusa, S., Sprenkle-Hyppolite, S. (2022). Snapshot of the Carbon Dioxide Removal certification and standards ecosystem (2021–2022). Climate Policy 22, 1319–1332. https://doi.org/10.1080/14693062.2022.2094308

Ascough, P. L., Bird, M. I., Brock, F., Higham, T. F. G., Meredith, W., Snape, C. E., & Vane, C. H. (2009). Hydropyrolysis as a new tool for radiocarbon pre-treatment and the quantification of black carbon. Quaternary Geochronology, 4(2), 140–147. https://doi.org/10.1016/j.quageo.2008.11.001

Ascough, P. L., Bird, M.,. I., Meredith, W., Snape, C., Large, D., Tilston, E., Apperley, D., Bernabé, A., & Shen, L. (2018). Dynamics of charcoal alteration in a tropical biome: A biochar based study. Frontiers in Earth Science, 6, 61

Ascough, P. L., Brock, F., Collinson, M. E., Painter, J. D., Lane, D. W., & Bird, M. I. (2020). Chemical Characteristics of Macroscopic Pyrogenic Carbon Following Millennial-Scale Environmental Exposure. Frontiers in Environmental Science, 7. https://doi.org/10.3389/fenvs.2019.00203

Azzi, E. S. (2021). Biochar systems across scales in Sweden: An industrial ecology perspective. PhD Thesis, KTH Royal Institute of Technology, Stockholm, Sweden. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-303912

Azzi, E. S., Karltun, E., & Sundberg, C. (2021). Assessing the diverse environmental effects of biochar systems: An evaluation framework. Journal of Environmental Management, 286, 112154. https://doi.org/10.1016/j.jenvman.2021.112154

Azzi, E. S., Li, H., Cederlund, H., Karltun, E. &Sundberg, C. (2023, preprint submitted to Geoderma) Modelling Biochar Long-Term Carbon Storage in Soil with Harmonized Analysis of Incubation Data. Available at SSRN: http://dx.doi.org/10.2139/ssrn.4601106

Azzi and Sundberg. (2023). On the durability of biochar carbon storage - A clarification statement from researchers. https://biochar.systems/durability-statement/

Bird, M. I., Wynn, J. G., Saiz, G., Wurster, C. M., & McBeath, A. (2015). The Pyrogenic Carbon Cycle. Annual Review of Earth and Planetary Sciences, 43(1), 273–298. https://doi.org/10.1146/annurev-earth-060614-105038

Bowring, S. P. K., Jones, M. W., Ciais, P., Guenet, B., & Abiven, S. (2022). Pyrogenic carbon decomposition critical to resolving fire's role in the Earth system. Nature Geoscience, 15(2), 135–142. https://doi.org/10.1038/s41561-021-00892-0

Budai, A. (2017). Biochar stability as influenced by production conditions.

Budai, A., Zimmerman, A. R., Cowie, A. L., Webber. J. B. W., Singh, B. P., Glaser, B., Masiello, C. A., Andersson, D., Shields, F., Lehmann, J., & Camps Arbestain, M. (2013).Biochar Carbon Stability Test Method: An assessment of methods to determine biochar carbon stability. International Biochar Initiative, pp. 1–10.

Carbon Brief. (2019). In-depth Q&A: How 'Article 6' carbon markets could 'make or break' the Paris Agreement https://www.carbonbrief.org/in-depth-q-and-a-how-article-6-carbon-markets-could-make-or-break-the-paris-agreement/

Carbon Brief. (2022). Key Outcomes of agreed at the UN Climate Talks in Sharm-el-Sheikh. https://www.carbonbrief.org/cop27-key-outcomes-agreed-at-the-un-climate-talks-in-sharm-el-sheikh/

Celander F. and Söderqvist H. (2021). Miljönyttomodell – Kartläggning av systemeffekter av biokol i lantbruket. https://hushallningssallskapet.se/?projekten=kolsanksratter-med-biokol

Chalk, P., & Smith, C. J. (2022). 13C methodologies for quantifying biochar stability in soil: A critique. European Journal of Soil Science, 73(3), e13245.

Cross, A., & Sohi, S. P. (2013). A method for screening the relative long-term stability of biochar. GCB Bioenergy, 5(2), 215–220 https://doi.org/10.1111/gcbb.12035

Ding, F., van Zwieten, L., Zhang, W., Weng, Z. (Han), Shi, S., Wang, J., & Meng, J. (2018). A meta-analysis and critical evaluation of influencing factors on soil carbon priming following biochar amendment. Journal of Soils and Sediments, 18(4), 1507–1517. https://doi.org/10.1007/s11368-017-1899-6

Ericsson, N., Sundberg, C., Nordberg, Å., Ahlgren, S., & Hansson, P. A. (2017). Time-dependent climate impact and energy efficiency of combined heat and power production from short-rotation coppice willow using pyrolysis or direct combustion. GCB Bioenergy, 9(5), 876–890. https://doi.org/10.1111/gcbb.12415

European Commission. (2022). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a Union certification framework for carbon removals. COM/2022/672 final, EUR-Lex Document 52022PC0672.

Fang, Y., Singh, B. P., Nazaries, L., Keith, A., Tavakkoli, E., Wilson, N., & Singh, B. (2019). Interactive carbon priming, microbial response and biochar persistence in a Vertisol with varied inputs of biochar and labile organic matter. European Journal of Soil Science, 70(5), 960–974. https://doi.org/10.1111/EJSS.12808

FAO. (1985). Industrial charcoal making. https://www.fao.org/3/x5555e/x5555e03.htm

Glaser, B., Guenther, M., Maennicke, H., & Bromm, T. (2021). Microwave-assisted combustion to produce benzene polycarboxylic acids as molecular markers for biochar identification and quantification. Biochar, 3(4), 407–418. https://doi.org/10.1007/s42773-021-00124-z

Glaser, B., Haumaier, L., Guggenberger, G. and Zech, W. (1998) Black Carbon in Soils: The Use of Benzenecarboxylic Acids as Specific Markers. Organic Geochemistry, 29, 811-819. https://doi.org/10.1016/S0146-6380(98)00194-6

GHG Protocol. (2023). Land Sector and Removals Guidance. Greenhouse Gas Protocol , https://ghgprotocol.org/land-sector-and-removals-guidance

Haefele, S.M., Konboon, Y., Wongboon, W., Amarente, S., Maarifat, A.A., Pfeiffer, E.M., Knoblauch, C. (2011). Effects and fate of biochar from rice residues in rice-based systems. Field Crop Research, 121, 430–440. https://doi.org/10.1016/j.fcr.2011.01.014

Harvey, O. R., Kuo, L.-J., Zimmerman, A. R., Louchouarn, P., Amonette, J. E., & Herbert, B. E. (2012). An Index-Based Approach to Assessing Recalcitrance and Soil Carbon Sequestration Potential of Engineered Black Carbons (Biochars). Environmental Science & Technology, 46(3), 1415–1421. https://doi.org/10.1021/es2040398

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

IPCC, 2006. (2006) IPCC Guidelines for National Greenhouse Gas Inventories.

IPCC, 2019. (2019) Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Cayuela, M. L., Sigua, G., Novak, J., Spokas, K., & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. Biochar, 2(4), 421–438. https://doi.org/10.1007/s42773-020-00067-x

Joseph, S., Cowie, A.L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M.L., Graber, E.R., Ippolito, J.A., Kuzyakov, Y., Luo, Y., Ok, Y.S., Palansooriya, K.N., Shepherd, J., Stephens, S., Weng, Z.H., Lehmann, J. (2021). How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. GCB Bioenergy 13, 1731–1764. https://doi.org/10.1111/gcbb.12885

Kätterer, T., Roobroeck, D., Andrén, O., Kimutai, G., Karltun, E., Kirchmann, H., Nyberg, G., Vanlauwe, B., Nowina, K.R. de. (2019). Biochar addition persistently increased soil fertility and yields in maize-soybean rotation over 10 years in sub-humid regions of Kenya. Field Crop Research, 235, 18–26. https://doi.org/10.1016/j.fcr.2019.02.015

Kirschbaum, M.U.F. (2004). Soil respiration under prolonged soil warming: are rate reductions caused by acclimation or substrate loss? Global Change Biology 10, 1870-1877. https://onlinelibrary.wiley.com/doi/full/10.1111/j.1365-2486.2004.00852.x?utm_sq=h3ahgyak9p

Kuzyakov, Y., Bogomolova, I., & Glaser, B. (2014). Biochar stability in soil: Decomposition during eight years and transformation as assessed by compound-specific 14C analysis. Soil Biology and Biochemistry, 70, 229–236. https://doi.org/10.1016/J.SOILBIO.2013.12.021

Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela, M. L., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in climate change mitigation. Nature Geoscience, 14(12), 883–892. https://doi.org/10.1038/s41561-021-00852-8

Lembrechts, J. J., van den Hoogen, J., Aalto, J., Ashcroft, M. B., De Frenne, P., Kemppinen, J., Kopecký, M., Luoto, M., Maclean, I. M. D., Crowther, T. W., Bailey, J. J., Haesen, S., Klinges, D. H., Niittynen, P., Scheffers, B. R., Van Meerbeek, K., Aartsma, P., Abdalaze, O., Abedi, M., … Lenoir, J. (2021). Global maps of soil temperature. Global Change Biology, 28, 3110–3144. https://doi.org/10.1111/gcb.16060
Leng, L., Huang, H. (2018). An overview of the effect of pyrolysis process parameters on biochar stability. Bioresource Technology, 270, 627–642. https://doi.org/10.1016/j.biortech.2018.09.030
Leng, L., Huang, H., Li, H., Li, J., & Zhou, W. (2019b). Biochar stability assessment methods: A review. Science of The Total Environment, 647, 210–222. https://doi.org/10.1016/j.scitotenv.2018.07.402
Leng, L., Xu, X., Wei, L., Fan, L., Huang, H., Li, J., Lu, Q., Li, J., & Zhou, W. (2019a). Biochar stability assessment by incubation and modelling: Methods, drawbacks and recommendations. Science of the Total Environment, 664, 11–23. https://doi.org/10.1016/j.scitotenv.2019.01.298
Liu, B., Liu, Q., Wang, X., Bei, Q., Zhang, Y., Lin, Z., Liu, G., Zhu, J., Hu, T., Jin, H., Wang, H., Sun, X., Lin, X., & Xie, Z. (2020). A fast chemical oxidation method for predicting the long-term mineralization of biochar in soils. Science of The Total Environment, 718, 137390. https://doi.org/10.1016/J.SCITOTENV.2020.137390
Lutfalla, S., Abiven, S., Barré, P., Wiedemeier, D.B., Christensen, B.T., Houot, S., Kätterer, T., Macdonald, A.J., Van Oort, F., Chenu, C. (2017). Pyrogenic carbon lacks long-term persistence in temperate arable soils. Front. Earth Sci. 5, 1–10. https://doi.org/10.3389/feart.2017.00096
Mastalerz, M., Drobniak, A., Briggs, D., Bradburn, J. (2023). Variations in microscopic properties of biomass char: Implications for biochar characterization. Int. J. Coal Geol. 271, 104235. https://doi.org/10.1016/j.coal.2023.104235
Matuštík, J., Hnátková, T., & Kočí, V. (2020). Life cycle assessment of biochar-to-soil systems: A review. Journal of Cleaner Production, 259, 120998. https://doi.org/10.1016/J.JCLEPRO.2020.120998
McBeath, A. V., Smernik, R. J., Schneider, M. P. W., Schmidth, M. W. I. & Plant, E. L. (2011). Determination of the aromaticity and the degree of aromatic condensation of a thermosequence of wood charcoal using NMR. Organic Geochemistry, 42, 1194-1202. https://doi.org/10.1016/j.orggeochem.2011.08.008
McBeath, A. v, Wurster, C. M., & Bird, M. I. (2015). Influence of feedstock properties and pyrolysis conditions on biochar carbon stability as determined by hydrogen pyrolysis. Biomass and Bioenergy, 73, 155–173. https://doi.org/10.1016/j.biombioe.2014.12.022
Naisse, C., Girardin, C., Davasse, B., Chabbi, A., & Rumpel, C. (2015). Effect of biochar addition on C mineralisation and soil organic matter priming in two subsoil horizons. Journal of Soils and Sediments, 15(4), 825–832.
Ngo, P. T., Rumpel, C., Janeau, J. L., Dang, D. K., Doan, T. T., & Jouquet, P. (2016). Mixing of biochar with organic amendments reduces carbon removal after field exposure under tropical conditions. Ecological Engineering, 91, 378-380. https://www.sciencedirect.com/science/article/pii/S0925857416300118
Petersen, H.I., Lassen, L., Rudra, A., Nguyen, L.X., Do, P.T.M., Sanei, H., (2023). Carbon stability and morphotype composition of biochars from feedstocks in the Mekong Delta, Vietnam. International Journal of Coal Geology 271, 104233. https://doi.org/10.1016/j.coal.2023.104233
Pulcher, R., Balugani, E., Ventura, M., Greggio, N., & Marazza, D. (2022). Inclusion of biochar in a C dynamics model based on observations from an 8-year field experiment. SOIL, 8(1), 199–211. https://doi.org/10.5194/soil-8-199-2022
Rasul, M., Cho, J., Shin, H.-S., Hur, J. (2022). Biochar-induced priming effects in soil via modifying the status of soil organic matter and microflora: A review. Science of the Total Environment 805, 150304. https://doi.org/10.1016/j.scitotenv.2021.150304
Rodrigues, L., Budai, A., Elsgaard, L., Hardy, B., Keel, S.G., Mondini, C., Plaza, C., Leifeld, J. (2023). The importance of biochar quality and pyrolysis yield for soil carbon sequestration in practice. European J Soil Science 74, e13396. https://doi.org/10.1111/ejss.13396
Science Based Targets 2021. SBTI CORPORATE NET-ZERO STANDARD, VERSION 1.0. https://sciencebasedtargets.org/resources/files/Net-Zero-Standard.pdf
Science Based Targets 2023. Forests, Land and Agriculture (FLAG). https://sciencebasedtargets.org/sectors/forest-land-and-agriculture
Sierra, C. A., Hoyt, A. M., He, Y., & Trumbore, S. E. (2018). Soil Organic Matter Persistence as a Stochastic Process: Age and Transit Time Distributions of Carbon in Soils. Global Biogeochemical Cycles, 32(10), 1574–1588. https://doi.org/10.1029/2018GB005950
Sierra, C. A., Müller, M., Metzler, H., Manzoni, S., & Trumbore, S. E. (2017). The muddle of ages, turnover, transit, and residence times in the carbon cycle. Global Change Biology, 23(5), 1763–1773. https://doi.org/10.1111/gcb.13556
Singh, B. P., Cowie, A. L., & Smernik, R. J. (2012). Biochar Carbon Stability in a Clayey Soil As a Function of Feedstock and Pyrolysis Temperature. Environmental Science & Technology, 46(21), 11770–11778. https://doi.org/10.1021/es302545b
Singh, B.P., Fang, Y., Boersma, M., Collins, D., Van Zwieten, L., Macdonald, L.M. (2015). In situ persistence and migration of biochar carbon and its impact on native carbon emission in contrasting soils under managed temperate pastures. PLoS One 10, e0141560. https://doi.org/10.1371/journal.pone.0141560

Spokas, K.A. (2010). Review of the stability of biochar in soils: predictability of O:C molar ratios. Carbon Management 1, 289–303. https://doi.org/10.4155/cmt.10.32
Söderqvist, H. (2019). Framework for assessing the stability of different biochar products and uses. Master thesis. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-254674
Sorrenti, G., Masiello, C.A., Dugan, B., Toselli, M. (2016). Biochar physico-chemical properties as affected by environmental exposure. Science of the Total Environment 563, 237–246. https://doi.org/10.1016/j.scitotenv.2016.03.245
Terlouw, T., Bauer, C., Rosa, L., & Mazzotti, M. (2021). Life cycle assessment of carbon dioxide removal technologies: a critical review. Energy & Environmental Science, 14(4), 1701–1721. https://doi.org/10.1039/D0EE03757E
Thers, H., Djomo, S. S. N., Elsgaard, L., Knudsen, M. T., Total, M. K.-S. of T. (2019), undefined, & Knudsen, M. T. (2019). Biochar potentially mitigates greenhouse gas emissions from cultivation of oilseed rape for biodiesel. Science of the Total Environment, 671, 180–188. https://doi.org/10.1016/j.scitotenv.2019.03.257
Tisserant, A., & Cherubini, F. (2019). Potentials, Limitations, Co-Benefits, and Trade-Offs of Biochar Applications to Soils for Climate Change Mitigation. Land, 8(12). https://doi.org/10.3390/land8120179
Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: Meta-analysis of decomposition and priming effects. GCB Bioenergy, 8(3), 512–523. https://doi.org/10.1111/gcbb.12266
Weber, K., & Quicker, P. (2018). Properties of biochar. Fuel, 217, 240-261. https://doi.org/10.1016/j.fuel.2017.12.054
Weihermüller, L., Neuser, A., Herbst, M., & Vereecken, H. (2018). Problems associated to kinetic fitting of incubation data. Soil Biology and Biochemistry, 120, 260–271. https://doi.org/10.1016/j.soilbio.2018.01.017
Wiedemeier, D. B., Abiven, S., Hochaday, W. C., Keiluweit, M., Kleber, M., Masiello, C. A., McBeath, A. V., Nico, P. S., Pyle, L. A., Schneider, M. P. W., Smernik, R. J., Wiesenberg, G. L. B., & Schmidt, M. W. I.. (2015). Aromaticity and degree of aromatic condensation of char. Organic Geochemistry, 78, 135-143. https://doi.org/10.1016/j.orggeochem.2014.10.002
Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., Joseph, S. (2010). Sustainable biochar to mitigate global climate change - Supplemental Information. Nat. Commun. 1, 56. https://doi.org/10.1038/ncomms1053
Woolf, D., Lehmann, J., Ogle, S., Kishimoto-Mo, A. W., McConkey, B., & Baldock, J. (2021). Greenhouse Gas Inventory Model for Biochar Additions to Soil. Environmental Science & Technology. https://doi.org/10.1021/acs.est.1c02425
Zimmerman, A. R. (2010). Abiotic and Microbial Oxidation of Laboratory-Produced Black Carbon (Biochar). Environmental Science & Technology, 44(4), 1295–1301. https://doi.org/10.1021/es903140c
Zimmerman, A. R., & Ouyang, L. (2019). Priming of pyrogenic C (biochar) mineralization by dissolved organic matter and vice versa. Soil Biology and Biochemistry, 130. https://doi.org/10.1016/j.soilbio.2018.12.0

7 Author contributions

Elias Azzi, Cecilia Sundberg and Helena Söderqvist planned the scope of the report. Elias Azzi and Cecilia Sundberg have contributed to all chapters. Helena Söderqvist and Tom Källgren have mainly contributed to chapters 1 and 2. Harald Cederlund and Haichao Li have mainly contributed to Chapter 3.

Appendix 1. Excel calculation file for biochar persistence based on new harmonized data analysis (snapshot)

The Excel file is available for download at https://biochar.systems/stability/guidelines. The figure below presents the main calculation sheet of this Excel file. The user shall input 3 parameters in section 1: the organic carbon content of the biochar, the hydrogen content of the biochar, and the annual average soil temperature at site of use of the biochar. Then, intermediary calculations are shown in section 2, and the calculation output is shown in section 3, including: the permanence factor, the amount of carbon dioxide initially stored by a tonne a biochar, and the amount of carbon dioxide remaining in storage after 100 years.

1. Input data

Parameter name	Value	Unit	Comment
Organic carbon content of biochar	70,00%	%, dry mass	As determined by laboratory analysis.
Hydrogen content of biochar	2,00%	%, dry mass	As determined by laboratory analysis.
Annual average soil temperature at site of biochar use	15,6	°C	Value can be in the range 0 to 30°C depending on location. If decimals are entered, the formulas below will round the temperature to the highest degree (e.g. 7.3 is rounded to 8).

2. Intermediary calculations

Parameter name	Value	Unit	Comment
Time horizon of sequestration	100	years	Default value: 100 years. In this calculator, the time horizon is fixed to 100 years.
Hydrogen to organic carbon molar ratio	0,341	mol / mol	Calculated from input data
Power regression parameter M	92,555	%	Pre-calculated in SLU modelling work
Power regression parameter A	44,064	%	Pre-calculated in SLU modelling work
Power regression parameter C	2,248	no unit	Pre-calculated in SLU modelling work
Coefficient of determination (R^2) of power regression	0,749	no unit	Pre-calculated in SLU modelling work

3. Calculation output

Parameter name	Value	Unit	Comment
Persistence factor $F_p^{TH,Ts}$	88,64%	%	At given soil temperature, and time horizon selected
Carbon dioxide initially stored after biochar production	2,57	t CO_2 / t dry biochar	After biochar production
Carbon dioxide remaining in storage after given time horizon	2,28	t CO_2 / t dry biochar	At given soil temperature, after 100 years

Figure A. Snapshot of the calculation file to determine a 100-year biochar persistence factor at a given soil temperature, depending on the H/C_{org} ratio of the biochar, based on new harmonized data analysis of incubation experiments (see Azzi et al. 2023).