

POLICY COMMENTARY **OPEN ACCESS**

Biochar Permanence—A Policy Commentary

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ABSTRACT

1. The application of biochar to soil is a highly durable nature-based carbon dioxide removal (CDR) pathway. It provides certifiable climate-change mitigation, with mean carbon residence times exceeding 1,000 years, and additional co-benefits for soil health and fertility.
2. Biochar persistence in soil depends on both intrinsic material properties and environmental factors. Its longevity is determined not only by the polyaromatic structure of the biochar itself but also by soil mineralogy, biological activity, and climatic conditions.
3. Biochar aging involves both decomposition and stabilization processes. The complementary mechanisms of decomposition and stabilization include interactions of biochar with minerals and native organic matter, as well as aggregations with soil particles that maintain its long-term persistence.
4. Biochars and inertinite-ranked fossil coals cannot be equated. Inertinite has been protected from biotic and abiotic oxidation for millions of years through burial in sediments and inclusion in minerals under high pressure and temperature. Biochar produced today in modern pyrolysis facilities is a fundamentally different material.
5. No carbonaceous material is completely inert. Field and laboratory studies consistently show measurable, though small, mineralization across a wide range of biochar types. Declaring that soil-applied biochar carbon persists at 100% over millennia is inconsistent with current scientific understanding.
6. Analytical proxies indicate relative, but not absolute, biochar persistence.
7. Policy definitions of biochar CDR should reflect climate-relevant timescales. The degree of persistence should be estimated on the order of centuries rather than millennia, supported by registered material properties, traceable application data, conservative modeling, and continued long-term field experiments for model validation.

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1 | Introduction

Pyrogenic Carbon Capture and Storage (PyCCS) represents one of the most promising, ready-to-deploy carbon dioxide removal (CDR) methods available today (Weng and Cowie 2025). The production and application of biochar, the principal product of PyCCS, can be carried out safely at scale; it is both verifiable and certifiable. Its environmental and climate benefits are widely recognized by scientific and market actors, as well as by national and international regulators. Among natural and nature-based solutions, soil-applied biochar exhibits unparalleled carbon persistence while also offering co-benefits such as enhanced soil fertility, nutrient retention, and improved water management (Lehmann et al. 2025, 2024; Schmidt et al. 2021). With a growing number of certification schemes and rigorous life-cycle assessments, biochar has emerged as a trustworthy pathway for durable carbon sequestration that can make a substantial contribution to global climate mitigation efforts (IPCC 2022).

Research shows that most biochar carbon may persist for centuries to millennia when applied to soil (Budai et al. 2013; Lehmann et al. 2024; Woolf et al. 2021). However, not all biochar is equally stable: its long-term persistence depends on its aromatic, polycondensed structure as well as the soil, climate, and bioactivity where it is applied.

2 | The Inertinite Concept

As biochar transitions to large-scale deployment and CDR certification, the authors of the present commentary are increasingly concerned about the emerging proposal to declare most industrially produced biochars as completely persistent for millennia. The suggested approach uses random reflectance (R_o) measurements and defines biochar carbon with $R_o \geq 2\%$ (i.e., Inertinite Benchmark—IBRo2%) as “inertinite,” which is, by analogy to fossil coal ranking, declared as totally persistent for more than 1000 years when applied to soil (Mastalerz et al. 2025; Petersen et al. 2023; Rudra et al. 2024; Sanei et al. 2025, 2024). Without correlating the results of the analytical method to broadly available data from other techniques for biochar characterization and degradation experiments, the inertinite classification is suggested as a universal indicator of non-degradability. While a material analogy to very old fossil coal exists, no direct proof is provided that biochar carbon, defined as inertinite, is impossible to degrade for >1000 years in soil. Moreover, the burden of proof seems to be reversed, leaving biochar scientists challenged to prove that biochar defined as inertinite can indeed be degraded in soil.

The R_o method provides an indirect proxy for carbon aromaticity and the degree of condensation. It correlates with the molar hydrogen to organic carbon (H/C_{org}) ratio, hydrogen pyrolysis (HyPy), solid electric conductivity, and, to some extent, with Raman spectroscopy and pyrolysis-gas chromatography-mass spectrometry (PyGCMS) fingerprints (Hagemann et al. 2025; Sanei et al. 2025). The method is suitable for biochar analysis as it accounts for the inherent micro-scale heterogeneity of pyrogenic carbon samples. It correlates with increasing pyrolysis intensity and, consequently, with carbon aromaticity and the degree of aromatic condensation, which are the primary predictors of biochar carbon persistence (Budai et al. 2016; Hagemann

et al. 2025; Lehmann et al. 2024; Sanei et al. 2024). Given all of this, it provides valuable inspiration as an additional tool for evaluating biochar persistence.

In short, the higher the measured R_o , the greater the aromaticity of a biochar and the greater its potential for long-term carbon sequestration in soil. However, predicting lower or higher relative persistence based on R_o is very different from claiming that all biochar carbon presenting a R_o above a certain threshold (e.g., IBRo2%) is non-degradable. Notwithstanding this disagreement, we acknowledge the value of the IBRo2% threshold, which correlates with the previously introduced molar H/C_{org} threshold of 0.4, for identifying largely—but not entirely—persistent fractions of biochar carbon (Budai et al. 2013; Camps-Arbestain et al. 2015; Schmidt et al. 2022; Woolf et al. 2021), and could serve to define biochar persistence classes.

The initial inertinite concept originates from coal geology, where inertinite is used to describe constituents of fossil coals that originated several million years ago from carbonized wood or plants, for example, wildfire-derived char, that became part of the coal-forming sediment. However, biochar and pyrogenic carbon produced during the last 10–100 years are fundamentally different from charcoal that has aged for millions of years to become coal. While biochar is applied to soil (i.e., the upper 1–2 m of the earth's crust), where most of its carbon would stay for centuries, coal was formed much deeper underground, under moderate pressures and temperatures, with limited oxygen and microbial activity. Also, the definition of inertinite in petrology is detached from any nominal R_o value (or benchmark) since it only considers the relative reflectance of inertinite in comparison to vitrinite in the same rock sample. In that sense, inertinite cannot be defined if there is no vitrinite present in the same material (ICCP 2001, 1963). Petrologists describe fusinite, a maceral within the inertinite group, as the transformation product of what started hundreds of millions of years ago as a wildfire char, but it is not the same material that it was in the beginning. Biochar applied to soil may one day become fusinite and inertinite, but it needs millions of years of aging, which includes degradation processes. Wildfire chars formed at 350°C–500°C (Doerr et al. 2018; Jones et al. 2019; Santin et al. 2017) typically show low reflectance (mean $R_o < 2.0\%$). In contrast, inertinite formed from such materials over millions of years exhibits high R_o values, indicating that the original charcoal was reactive and evolved into anthracite through long-term biochemical and geochemical transformation within the Earth's crust. It took fusinite and inertinite millions of years to become what they are now, but we do not know how much carbon was lost over those multi-million-year time spans. We only know that a significant amount persisted, enough to drive climate change today (Guo and Bustin 1998).

Thus, the coal ranking systems cannot be directly transferred to soil-applied biochar. Moreover, the definition of inertinite (ICCP 2001, 1963) was never intended to classify coals or other materials as inherently resistant to physico-chemical and biological degradation. As the common saying among petrologists goes, “inertinite is not inert”—nor is biochar.

Supplemented by and correlated with chemical, spectroscopic, and isotopic analyses, R_o is a potential method for categorizing

biochars into various persistence classes and refining predictions about the amount of biochar carbon that will remain after decades, centuries, or more. However, laboratory and field trials with complete mass balances of the applied biochar carbon are still needed. Evidence consistently shows that biochar can contain very stable carbon fractions with mean residence times (MRT) in the pedosphere exceeding centuries and even millennia (Lehmann et al. 2024). However, the persistence of biochar in soil not only depends on its chemical structure but also on the matrix and environment to which it is applied. The soil type, the climate (temperature, water, wind, light exposure), the availability of minerals, and the bioactivity of the soil influence the aging of biochar after its application to soil (c.f., detailed references provided in the section below).

3 | The Complexity of Biochar Persistence in Soil

Aging of biochar is not only characterized by slow microbial degradation processes but also by physical and chemical stabilization processes (Lehmann et al. 2024). The formation of mineral-biochar complexes, mineral coating, and the inclusion into clay sheets are mechanisms of long-term physical and chemical protection of PyC (Czimczik and Masiello 2007; Hagemann et al. 2017). Mineral stabilization may allow PyC to be protected for millions of years, even if its molecular structure is less aromatic or if it is already partly degraded (i.e., oxidized biochar is more likely to react with protecting soil minerals and the charge density of aged biochar is much higher than any other organic material in soil). Some degree of degradation (i.e., surface oxidation) is even a prerequisite for long-term mineral stabilization and, thus, persistence in soil (Cheng et al. 2008; Hardy et al. 2017). However, surface oxidation also renders the material more susceptible to microbial enzymes, which cleave the aromatic C–C bonds between these moieties to break up clusters of aromatic rings (Fuchs et al. 2011).

The absence of published degradation experiments with materials identified by Ro as inertinite cannot be taken as proof that inertinite cannot be degraded. No carbonaceous material is immune to degradation, not even pure graphite (Shneour 1966), which is part of the pyrogenic carbon continuum in high-temperature biochar (Fang et al. 2020). The literature on biochar persistence published during the last two decades provides a complex picture involving several mechanisms of both degradation and stabilization of pyrogenic carbon in the environment. In the following section, we summarize observations that suggest the complexity of these degradation and stabilization mechanisms.

4 | Mechanisms and Evidence of Biochar Degradation and Stabilization in Soil

1. Six field experiments using isotopically labeled biochar directly measured CO₂ emissions from biochar decay of 0.8 to 7.0% per year and up to 40% over 8 years (Leuthold et al. 2025; Major et al. 2010; Pulcher et al. 2022; Rasse et al. 2017; Singh et al. 2015; Ventura et al. 2019). Molar H/C ratios ranged from 0.2 to 0.7, with the lowest presenting the lowest degradation rates. The biochars from five

of the six field experiments would certainly have passed beyond IBRo2% and would therefore be classified as inertinite, as their molar H/C_{org} ratios were below 0.4 or their pyrolysis temperatures exceeded 600°C. Decay rates in the presence of plant roots were higher than in their absence (Ventura et al. 2019). A same biochar (H/C = 0.63) showed a threefold higher degradation rate in a biologically active Ferralsol compared to a poorly active Arenosol (Singh et al. 2015), demonstrating the strong influence of the soil system.

2. Microbial diversity may need a ramp-up time to adjust to carbon compounds from biochar amendments that might exceed the duration of most experiments (de la Rosa et al. 2018; Gross, Šolić, et al. 2025). Soil enzyme responses change over time after biochar application (Wang et al. 2017). Even short-term experiments have shown that biochar decomposes faster when added to soil that has been previously exposed to biochar (Budai et al. 2016). Soil microbes that specialize in breaking aromatic bonds have been observed to become more abundant after the addition of biochar (Jin et al. 2024; Liu et al. 2022; Zhang et al. 2018). Inoculation of a sewage sludge biochar made at 600°C with soil-born fungi led to a carbon decay of 12.2% within 120 days, demonstrating how specialized organisms can significantly increase decay rates and that ash-rich biochars might be more prone to degradation (de la Rosa et al. 2018). Ramp-up times for microbial degradation and mineral stabilization challenge the use of exponential decay curves to predict multi-centennial biochar degradation. While longer-term field experiments showed consistent decay over time, they did not necessarily fit exponential decay curves and seemed rather dependent on discrete events such as exposures to specialized microorganisms, temperature, humidity, etc. (Leuthold et al. 2025; Lutfalla et al. 2015; Pulcher et al. 2022). However, multiyear laboratory experiments with isotopic labeled biochar consistently showed that degradation rates decreased exponentially (Dharmakeerthi et al. 2015; Kuzyakov et al. 2014) and biochar in Terra Preta and other ancient soils is still degrading at a slow, continuous pace (Glaser et al. 2001; Kaal and Filley 2016; Liang et al. 2008).
3. Biochar decay rates derived from lab incubations and field trials may differ by more than one order of magnitude (Lyu and Zimmerman 2025). The static and closed conditions of laboratory experiments may restrict interactions with specialized microorganisms and fail to reproduce the complex environmental processes such as water and air flow-through, exposure to ozone and UV radiation, physical weathering through, e.g., freeze–thaw cycles, soil faunal activity including bioturbation, and organic input from plant debris and root exudates. However, when inoculated with specialized microbes such as from wildfire-exposed soils, ancient charcoal production sites, or coal seams, degradation can also be faster and/or higher in the lab than in natural soil. Also, carbon stabilization processes through the interaction with mineral phases are more likely to occur in bioturbated field sites compared to static laboratory setups. Additions of easily mineralizable carbon from plants can not only increase biochar mineralization through co-metabolism but also decrease it through

substrate switching (DeCiucies et al. 2018). It is therefore not a given that field conditions always promote more rapid biochar decay than laboratory incubations.

4. Microbial decomposition of microcrystalline graphite obtained from synthetic CH₄ (99% carbon + silicon as impurity, H/C=0) was shown to occur when added to soils (Shneour 1966). Also, carbon nanotubes (one-dimensional, hollow cylinders of graphene sheets with H/C=0 and vitrinite random reflectance >4%) are widely used in medical drugs for slow-release medication and are degraded by macrophages in the human digestive system within several months (Elgrabli et al. 2017, 2015). Graphene nanosheets are even degraded in the cerebral system when taken up via nasal inhalation (Newman et al. 2020) and graphene quantum dots were enzymatically degraded by human peroxidases (Martín et al. 2019). Also, degradation of multiwall carbon nanotubes (H/C=0) by bacteria and horseradish peroxidase was demonstrated (Flores-Cervantes et al. 2014; Zhang et al. 2013). Degradation rates of those engineered carbons were low, but the fact that degradation occurs demonstrates that 100% persistence of biochars with high Ro (well above the IBRo2%) over 1000 years is not a credible claim.
 5. Biochar is broken down to smaller particles through mechanisms such as water swelling (graphitic sheet expansion), bioturbation, freeze–thaw cycles, tillage, and others (Hardy et al. 2017; Liu et al. 2018; Santín et al. 2016), which not only influence biotic degradability and stabilization (Czimczik and Masiello 2007; Lyu and Zimmerman 2025; Zimmerman 2010) but also aid downward transport of biochar into deeper soil strata or from the soil into aquifers where the carbon preservation conditions differ (Baveye et al. 2019; Belle et al. 2020; Schiedung et al. 2020; Wozniak et al. 2023). Biochar C losses have been shown to be greater in fine versus coarse biochar-amended treatments (Lyu and Zimmerman 2025; Zimmerman 2010). The mobility of biochar particles highlights that not finding biochar carbon where it was applied cannot be equated with degradation and oxidation (Obia et al. 2024; Rumpel 2024). Vertical downward transport to greater soil depths decreases degradation of soil organic carbon (SOC), including biochar particles. Older SOC with a higher fraction of mineral-associated organic matter (MAOM) is usually found in deeper soil layers and is soil class dependent (Balesdent et al. 2018; Soucémariadin et al. 2018).
 6. Abiotic aging of biochar in soil can be driven by photocatalytic reactions, changing the physicochemical properties of biochar, accelerating its oxidation, increasing porosity, and releasing free radicals (Pignatello et al. 2024; Quan et al. 2020; Zhang et al. 2021). Dissolved pyrogenic carbon (PyDOC) leaching from biochar-amended soils is known to be photolabile and was shown to photomineralize by over 40% within one year (Bostick et al. 2020). Electric fields altered the size and surface functional groups of biochar (Yang et al. 2024). **Environmentally persistent free radicals (EPFRs)** in biochar, particularly those produced at high temperatures and with a high Ro, can drive redox reactions in soils, influencing organic matter turnover, nutrient cycling, and contaminant transformation, which indicates that these biochars are reactive and not inert (Ruan et al. 2019). While biochars applied to soil are not exposed to direct solar radiation, the occurrence of photocatalytic and electromagnetic reactions indicates multiple degradation pathways that may need to be considered. Also, these reactions may enhance biochar carbon stabilization by interactions with soil clay and oxide minerals rather than degradation.
 7. Investigations of ancient Terra Preta soils reveal changes in the oxidation state of biochar (Liang et al. 2008), primarily attributed to biologically driven surface oxidation (Abiven et al. 2011), similar to changes observed in composted biochar (Wiedner et al. 2015). Protection of surface oxidized biochar can result from its adsorption onto mineral surfaces (Czimczik and Masiello 2007). Surface coatings and inner-pore mineral interactions can further protect the aromatic biochar structure from degradation, contributing to its long-term persistence (Archanjo et al. 2017; Gross, Tahery, et al. 2025; Hagemann et al. 2017). In high pH soils, CaCO₃ can precipitate in biochar pores and on its surfaces, which not only protects biochar from degradation but also increases mineral carbon sequestration (Wang et al. 2023).
 8. Historical mass balance of pyrogenic carbon derived from wildfires shows MRTs of 1450–14,500 years. The large MRT range is due to uncertainties regarding the global input (i.e., by fire) under the variable climate of the late Pleistocene and Holocene, sediment deposition, and potential input of non-pyrogenic black carbon (Bowring et al. 2020, 2022; Coppola et al. 2014; Coppola and Druffel 2016; Glaser and Knorr 2008; Goranov et al. 2024; Lehmann et al. 2008; Reisser et al. 2016). Although a large part of wildfire char may not be ranked as inertinite (Belcher et al. 2018), Santín et al. (2017) demonstrated that wildfire-derived char has a structure comparable to that of lower-temperature biochars with molar H/C ratios around 0.4, which would fall within the lower Ro range of inertinite (Guo and Bustin 1998). Even if biochar had only a persistence at the lower end of the historical char MRT range (i.e., 1450 years), and considering that most industrial biochars present higher molar H/C ratios and Ro, its persistence is greater than that of any other CDR currently ready to scale. However, global and regional carbon budgets indicate that a substantial fraction of natural pyrogenic organic matter must decompose over millennial timescales; otherwise, the proportion of pyrogenic carbon in soils and sediments would far exceed the currently estimated global PyC stock of 13.7% (Czimczik and Masiello 2007; Goldberg 1984; Reisser et al. 2016).
- Biochar is a valuable and scientifically supported pathway for CDR with very long, climate-relevant carbon residence times when applied to soil. However, all research published until today indicates that both abiotic and biotic pathways can, to some extent, mineralize biochar carbon to CO₂. The degradation is mainly driven by discrete events such as microbial exposure and priming additions of easily mineralizable organic matter (i.e., root exudates or leaf litter), mechanical fragmentation, moisture and temperature fluctuations, and displacement by leaching or erosion. Also, aging of biochar

in soil is characterized by physical and chemical protection of undegraded and partially degraded biochar carbon determined by environmental conditions and the presence of reactive soil minerals through aggregation and organo-mineral and organo-organic interactions. We conclude that there is no such thing as permanent carbon and, therefore, permanent carbon cannot be measured directly or by proxy, but only the relative probability of more or less extended permanence under a given environmental condition.

Oversimplification of such complex dynamics as described above will create misconceptions, biased applications, and ultimately a global risk of discrediting the entire field of biochar science and technology. Field data at the time scale of decades to centuries, which are the real timescales we should be addressing, remain still out of reach since the longest-running field experiments with well-characterized industrial biochar only cover 25 years (Steiner et al. 2007; Yamato et al. 2006). Persistence can, thus, only be addressed through analytical proxies. In the context of mitigating climate change through CDR, medium-term sequestration over decades to centuries, rather than achieving absolute permanence, is particularly relevant for preventing atmospheric CO₂ overshoot and, consequently, critical tipping points in the Earth's climate system.

5 | Recommendations

Given the complexity of quantifying the persistence of biochar, we call for caution in policymaking and standard definitions:

- Based on our current state of knowledge, biochar persistence should be defined over centuries, rather than thousands to millions of years. Climate-relevant durability does not require eternity, but credible and measurable persistence (Leifeld and Keel 2022; Weng and Cowie 2025).
- Proper registration of biochar characterization and applications in soil, including key properties of the applied biochar, ensures that the climate impact of biochar carbon sinks can be corrected once the degradation models are more reliable and precise for longer terms, given that sufficiently high margins of security and conservative assumptions are applied.
- The various mechanisms of biochar degradation and stabilization call for more fundamental carbon research and long-term biochar field experiments to establish realistic permanence factors for biochar carbon, with respect to biochar type, soil class, and climate variables.

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Conflicts of Interest

Schmidt HP, Abiven S, Glaser B, Hagemann N, Kammann C, Leifeld J are authors of the European Biochar Certificate Guidelines. Schmidt HP and Hagemann N are consultants to Carbon Standards International. Several of the authors serve as advisers to national and international

policymakers, as well as to non-governmental organizations. Beyond this professional engagement, the authors declare no conflicts of interest.

Data Availability Statement

There are no data generated for this Policy Commentary. All quoted data are referenced.

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