Evaluating Biochar Crediting Protocols for Durable Carbon Removal

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Acronyms

CDR - Carbon Dioxide Removal

PyOM - Pyrogenic Organic Matter

PyC - Pyrogenic Carbon

SDGs - Sustainable Development Goals

SOM - Soil Organic Matter

SOC - Soil Organic Carbon

VCM - Voluntary Carbon Market

MRT - Mean Residence Time

MRV - Measurement, Reporting & Verification

GHGs- Greenhouse Gases

Abstract

As biochar expands as a source of carbon credits it has become increasingly clear that there are major differences among biochar protocols. This variation can make it challenging for producers to choose protocols and can make it difficult for buyers to understand the comparative value of different certified biochar credits, and in both these cases investor confidence is jeopardized. Here we comparatively review eight voluntary biochar crediting protocols, evaluating their approaches to six parameters: feedstock eligibility, production conditions, application criteria, permanence, reversal risk, and monitoring, reporting, and verification (MRV). We find that all protocols have three common types of requirements: restrictions on eligible biomass feedstocks, controls in thermochemical conversion, and documentation of end uses associated with carbon storage. However, we also find protocols have major differences in how they operationalize permanence and carbon crediting integrity. Some methodologies treat permanence as a material quality and use compositional indicators such as $H:C_{org}$ ratios to define permanence. Others adopt a temporal or end use approach, quantifying the fraction of carbon expected to remain stored over a specific time period given the final use. Also, requirements for lifecycle assessment, chain of custody documentation, and non-soil application vary considerably. Finally, we identify three key scientific and methodological uncertainties that may present future challenges for all biochar protocols: biochar loss during fire, landscape mobility and erosion, and biochar induced priming of native soil-carbon. We conclude that more harmonized, evidence-based approaches to durability, full life-cycle emissions and uncertainty management are needed to improve credibility and support high integrity biochar CDR markets.

1. Introduction

Biochar is a durable, highly porous material with a high carbon content (1). It is produced through the pyrolysis of biomass, a physicochemical conversion carried out at temperatures generally exceeding 350°C under oxygen-limited conditions (2,3). Traditionally used as a soil amendment, biochar has gained sustained scientific and policy attention over the past two decades for a broad range of environmental and agronomic co-benefits which include improved soil health, enhanced water retention, greater nutrient availability, and increased crop yields (4,5). Beyond its agricultural benefits (4), biochar functions as a remediation and adsorbent medium for removing contaminants from water (6) and air (7). Biochar is also critical for climate policy as the conversion of biomass into biochar transforms a rapidly cycling biogenic carbon pool into a persistent form. The fused aromatic ring structures generated during pyrolysis resist a high degree of microbial decomposition, and the resulting material can be considered a long-lived terrestrial carbon sink, with slower decomposition rates than the original feedstock from which it is derived (8,9). Biochar is one of the few carbon dioxide removal (CDR) approaches that is technically mature, deployable, and scalable within the coming decade (10), which underpins biochar's alignment with international climate objectives including the Paris Agreement, the United Nations Sustainable Development Goals (SDGs), and the European Union's Green Deal ambition of climate neutrality by 2050 (8).

Certification frameworks mediate the translation of biochar carbon storage into a tradable climate commodity. Biochar practitioners, including project operators or farmers, can receive payment for production and end use through a growing number of carbon trading schemes. However, payment is almost always contingent on third-party certification using biochar protocols maintained by carbon registries and standard-setting bodies. A diverse ecosystem of biochar protocols has emerged, comprising product quality and carbon-sink standards such as the

European Biochar Certificate (EBC) (11), the World Biochar Certificate (WBC) (12), the Global Biochar C-Sink (GBC) (13), and Global Artisan C-Sink (GAC) (14), all maintained by Carbon Standards International, as well as project crediting methodologies maintained by carbon registries including Verra's VCS (VM0044) (15), Puro Earth (16), Isometric (17), and Climate Action Reserve (18). Each of these protocols imposes its own requirements on feedstock eligibility, production conditions, permanence criteria, reversal risk, and monitoring, reporting, and verification (MRV). Alignment with one of these protocols is a prerequisite for crediting, and investor confidence in the rigor and internal methodology of a protocol directly determine the market value of the carbon credits it certifies.

The European Union has significantly reshaped the certification landscape through the EU Carbon Removal Certification Framework (19). Established by Regulation (EU) 2024/3012, CRCF created an EU-wide certification framework for permanent carbon removals, carbon farming, and carbon storage in products that emphasizes verifiable permanence metrics and robust risk mitigation for soil-based carbon removals (19). Within this framework, biochar carbon removal has been formally identified as one of only three permanent carbon removal activities, alongside direct air capture with carbon storage and biogenic emissions capture with carbon storage. The scientific knowledge and technological readiness level are sufficient for these three carbon removal activities to support the development of robust and transparent certification methodologies (20). This is significant because it signals that biochar carbon removal has crossed a threshold of scientific and engineering readiness that few other removal pathways have reached. Furthermore, biochar removals are credited on the basis of permanence fractions that account for the durable storage of carbon in soils or non-soil media (20), making the permanence aspect of biochar protocols particularly important.

Despite market growth, the biochar protocol landscape remains fragmented. Differences among methodologies reflect gaps in biochar scholarship, and these differences and gaps carry consequences for future credit comparability, market confidence, and the pace of carbon dioxide removal. The primary objective of this study is to evaluate how voluntary carbon registries currently assess biochar and to characterize areas of convergence and divergence across the protocols. In doing so, we also identify the scholarly uncertainties that must be addressed to further strengthen biochar protocols and to support the credible scaling of biochar as a durable carbon removal strategy.

2. Biochar Protocol Analysis

Biochar crediting protocols converge on three core questions: what biomass can be used, how it is converted to biochar, and what end use is eligible for credited storage. In addition, some protocols are beginning to consider full life-cycle emissions, leakage accounting, environmental and social co-benefits, chain-of-custody traceability, digital monitoring, and reversal-risk buffers as integral components of biochar credit integrity rather than as optional add-ons. The shared goals of all protocols are to ensure additionality, avoid leakage, and credit only carbon that can be expected to remain durably sequestered. Here we examined eight voluntary biochar protocols: VCS (VM0044), European Biochar Certificate (EBC), Isometric, World Biochar Certificate (WBC), CSI Global Biochar C Sink (GBC), CSI Global Artisan C Sink (GAC), Puro Earth, and Climate Action Reserve (CAR) in the context of several parameters including feedstock and production conditions, application criteria, permanence criteria, reversal risk, and MRV approaches. *Detailed comparisons of protocols can be found in supplemental Tables 1-3.*

Protocols also consider additionality, leakage, facility configuration, project boundaries, monitoring, and eligible end uses. In particular, several protocols like VCS, CAR, Puro Earth and Isometric use sustainable feedstock eligibility guidelines to show that credited biomass would otherwise follow a low-value baseline fate and that the project does not create displacement effects elsewhere. For example, the CAR protocol distinguishes waste and by-product biomass from purpose-grown biomass, and only accepts purpose-grown biomass under marginal-land, no-tillage, and waste-management safeguards designed to limit leakage (18). In contrast, VCS allows only non-purpose grown biogenic waste biomass that would otherwise decay (15). Across most protocols, these sourcing rules are reinforced by production and MRV criteria that includes EBC's requirement for gas recovery, batch registration and energy efficient production (11) and GBC's requirements for registry based tracking and offsetting of production related emissions (13).

2.1 Feedstock and Production Conditions

All protocols have standardized criteria for biomass selection and for thermochemical production conditions because key biochar properties (like durability and organic carbon content) depend on the feedstock biomass used and the thermal parameters maintained during production (17). Additionally, the concentration of inorganic contaminants (e.g. metals) is directly correlated to the quality of the feedstock and the efficiency of the pyrolysis technology (17). To mitigate ecological risks and manage leakage, methodologies generally categorize the biomass type and mandate the use of residual organic matter or waste streams, limiting or prohibiting biomass cultivated specifically for biochar production (18). Here we outline commonalities and differences in how protocols consider these two interconnected properties.

2.1.1 Feedstock Constraints in Biochar Protocols

Almost all protocols prefer waste, by-product, or residue feedstocks because these materials are commonly diverted from short-lived baseline fates such as decomposition or open combustion. The CAR protocol also allows purpose-grown biomass, but only under strict restrictions that the feedstock must come from marginal land or reclaimed mining sites and must not have come from land used for commodity crops or recent vegetation conversion in the previous three years. Additionally, the feedstock must be paired with a waste-management plan and no-tillage cultivation to be eligible for consideration (18).

Across the protocols feedstock eligibility functions not only as a sustainability checklist but also as an additionality and leakage screen. For instance, VCS is comparatively restrictive because it requires purely biogenic waste biomass that would otherwise decay or be combusted for non-energy purposes (15), while CAR allows waste, by-products, and some purpose-grown biomass, but constrains purpose-grown feedstocks through marginal-land, no-tillage, and land-use safeguards (18). Isometric makes this logic more explicit by separating sustainability, counterfactual storage, and market-leakage tests, while EBC relies on positive feedstock lists by certification class, and Puro Earth excludes higher-risk feedstock categories such as mixed municipal solid waste (11,16,17). Stricter protocols treat feedstock as a counterfactual problem where the issue is not only whether biomass is natural or waste, but whether diverting it to biochar avoids GHG emissions without displacing existing uses or inducing any new land-use pressures.

2.1.2 Production Condition Constraints in Biochar Protocols

Protocols all converge on the need to control thermochemical conversion parameters, but they differ in how technically prescriptive they are. For instance, VCS accepts biochar from thermochemical processes such as pyrolysis, gasification, and biomass boilers, while excluding torrefaction and hydrothermal carbonization (15); CAR is broader in principle, allowing pyrolysis, gasification, and other thermochemical processes if the resulting biochar satisfies durability and compliance requirements (18). Furthermore, EBC and Isometric are more process-control oriented where EBC emphasizes batch registration, $H:C_{org}$ thresholds, recovery or combustion of pyrolysis gases, and energy efficiency(11) while Isometric requires documentation of location, technology, process parameters, biochar characterization, measurement methods, and storage-module compliance (17). Next, GBC and GAC protocols extend their thermochemical conversion into registry and dMRV systems which requires traceability of carbon sinks and, in artisanal systems, digital monitoring and methane compensation (13,14). WBC is less strict as a crediting protocol because it mainly provides product testing and characterization rather than a full project-level conversion and MRV framework (12).

In some cases, production conditions are treated as a quality-control issue because feedstock composition and thermochemical settings influence properties like biochar yield, as well as properties that impact biochar performance, such as pH, surface area, pore structure, and elemental ratios. Amongst these, high pyrolysis temperature is the dominant factor increasing pH, microporosity, and surface area while also decreasing biochar yield, volatile matter, and O/C ratio (21).

Production facility design is often considered in protocols because it determines the technology tier (high or low), which further dictates the emissions controls, monitoring requirements, and carbon accounting rules that govern whether the biochar's carbon removal can be reliably quantified and verified. High-tech modular industrial systems achieve higher efficiency by recovering energy from captured syngas and bio-oil, which helps power their own operations while using sophisticated emission controls. On the other hand, artisanal kilns such as Kon-Tiki or flame-curtain designs are much more accessible technologies, offering lower entry costs but also lower output and reduced energy recovery. The technology tier also shapes how protocols define project boundaries and allocate credits. To illustrate, for low-tech mobile equipment, the project start date is not a fixed point but a dynamic threshold tied to discrete undertakings such as moving from one forest tract to another which enables developers to initiate new project phases as equipment is deployed to fresh feedstock sources. At the high-tech end, protocols must account for co-product systems where biochar is not the only output. For example, the CAR protocol's Adjustment Factor (18) issues credits only for the proportional energy content of biochar relative to co-products such as syngas or electricity, meaning facilities optimized solely for biochar will yield more credits per ton of feedstock than those designed for combined heat-and-biochar. Across all tiers, maintaining a pyrolysis temperature above 500°C is not just a quality preference but a regulatory prerequisite that maximizes organic carbon content while reducing contaminants, directly affecting the number of credits generated and demonstrating that production temperature is as much a financial decision as a technical one.

2.2 Application criteria

Defining the eligible end use criteria is a crucial component of all biochar certifications. End use choices impact a number of parameters key to valuing a biochar credit, including potential reversal risks, as well as ease of MRV. Hence, several protocols such as VCS, CAR and Puro

Earth require biochar to enter an eligible soil or non-soil end use that preserves long-term storage, whereas Isometric allows dedicated soil, built-environment, and low-oxygen burial modules (15–18). GBC and GAC require incorporation into approved C-sink matrices or final sinks that can be traced to verified storage (13,14).

End use criteria vary across the standards where soil application is the most advanced and widely accepted method. However, the main point of divergence is not only soil vs non-soil end use; it is whether permanence is treated as established/conventional at production level or as something that remains contingent on downstream application and the controls that follow it. For example, VCS assigns default decay values to soil application, CAR applies end-use-specific permanence factors, Puro Earth extends a soil-based persistence model across several centuries, and Isometric's soil module combines proof of end use with reversal-risk and fuel-diversion safeguards (15,17,18). Alternatively, non-soil applications such as concrete, asphalt, and other materials are accepted across several protocols, but usually on more conservative terms. To illustrate, VCS excludes applications with major oxidation or excessive carbon loss, Puro Earth treats some cascading or incineration-prone uses as allowed but non-creditable, Isometric's built-environment module discounts uncertainty from fire, abrasion, and end-of-life transitions, and GBC-GAC only certify matrix pathways that prevent recovery for combustion and preserve a monitored final sink (13–17). The general critical takeaway is that the most restrictive protocols do not just list permitted applications; they rank applications by the stored carbon's fate, whereas the less conservative standards remain closer to product quality control than full end-use governance.

Application criteria are interwoven with permanence and reversal risk, because protocols vary on whether they assume permanence or reversal risk are solely determined by production conditions, or instead are contingent on downstream uses. Methodologies VCS, CAR, Puro Earth, Isometric, GBC and GAC belong to the latter group because they do not treat biochar quality alone as sufficient for crediting. By contrast, EBC and WBC are product-quality certification frameworks whose application criteria rest on class-based material eligibility, not on documented end use and the MRV controls post-application. Under the WBC protocol, admissible uses are defined by certification class: WBC-Premium is approved for all known applications, WBC-Agro for soil and agricultural applications, and WBC-Material is restricted to industrial non-soil uses and excluded from agriculture, soil, and consumer products. The stricter crediting protocols do not list permitted applications; they differentiate applications based on the expected fate of the stored carbon, whereas product-quality standards remain concerned with material eligibility for a specific end use.

End-use eligibility is the protocol parameter that distinguishes biochar production alone from biochar uses that remove carbon. In addition, end use eligibility restricts biochar uses beyond those that just preserve carbon; end uses must also be verifiable, traceable, and tracked. In all protocols, eligible biochar must be applied to an end use that results in long-term carbon storage, and many protocols require that the application appears on an approved end-use list or be tracked through chain-of-custody documentation (17,18). Soil applications are commonly eligible, while non-soil uses may also qualify when they are durable and traceable, but energy production is explicitly prohibited in all protocols. Next, VCS, CAR, Puro, Isometric, GBC, and GAC all require biochar to enter a verified storage pathway such as soil, construction materials, low-oxygen burial, or another approved matrix, rather than being produced and held as a commodity. Critical differences emerge between protocols in how much uncertainty is allowed. For example, soil applications are relatively mature because decay factors, $H:C_{org}$, soil temperature, and end-use tracking can be incorporated into quantification, while non-soil applications such as concrete, asphalt, filters, and industrial materials often require conservative assumptions, end-of-life evidence, or explicit exclusion if the carbon may be oxidized(15,16,18). In the strictest protocols credited storage is not defined by the usefulness of biochar, but by proof that the end use preserves carbon and prevents reversal through combustion, degradation, diversion, or uncertain disposal.

2.3 Permanence criteria and life-cycle analysis

Permanence, or durability, in carbon dioxide removal refers to the length of time for which removed CO_2 remains out of the atmosphere (17). Biochar's permanence is the central property that determines whether carbon storage can be treated as a credible removal rather than a temporary delay in emissions (22). Biochar, however, is not a uniform carbon sink. Its stability depends on the chemical structures created during thermochemical conversion, and the most condensed aromatic fractions can persist on millennial timescales (13,23). This long residence time makes biochar a credible long-term CDR pathway, but not all biochar is equally permanent, with pyrolysis conditions playing an important role, as well as end uses. Potential variations in biochar permanence mean that crediting cannot rely on a generic assumption of stability and instead must distinguish between more and less persistent forms of biochar (24).

All biochar protocols therefore require an estimation of permanence, but there is not yet uniformity among protocols in assessing this property. Permanence requirements are present across all eight frameworks, but are embedded heterogeneously and often as a project-crediting variable as seen in VCS, CAR, Isometric, Puro, GBC, and GAC, and more as a material-quality criterion in EBC and IBI. A project-crediting definition of permanence signifies that permanence is treated as a credit-quantification variable i.e, the share of biochar carbon that can be credited over a defined time horizon after accounting for end use, modeled decay or durable fraction, and reversal risk. By contrast, a material-quality criterion represents permanence as an intrinsic property of the biochar itself, evidenced by compositional proxies such as the $H:C_{org}$ and $O:C_{org}$ ratios that indicate the degree of carbonization and expected stability, rather than a rule for setting the quantity of credits issued. One protocol (VCS) takes primarily a project-crediting approach, but blends in aspects of material quality in its permanence definition as well, because permanence is quantified through application-specific 100-year permanence factors while the eligibility of soil applications also depends on laboratory analysis evidence of biochar quality and a $H:C_{org}$ threshold (15).

CAR is an example of a protocol that treats permanence as a project-crediting variable, defining permanence on a 100-year basis and crediting biochar according to the share expected to remain sequestered over that period (18). It uses default end-use permanence factors and requires placement in end uses where long-term storage is reasonably assured. Isometric adopts a more stratified approach by crediting only the highly durable fraction of biochar carbon and offering both 200-year pathway based on H/C_{org} and soil temperature and 1000-year pathway based on random reflectance (R_0) and inertinite comparison (17). Lastly, Puro Earth methodology differs by using a project-specific persistence model that extends durability claims to several centuries and ties those claims to measurable parameters such as H/C_{org} and average soil temperature (16). These differences show that permanence is part of the overall MRV architecture rather than a stand-alone metric where permanence is built into eligibility rules, quantification methods, monitoring requirements, and verification logic (16,17). GBC and GAC distinguish biochar into geologically persistent and semi-persistent pools, assigning the former to storage periods greater than 1000 years and crediting the latter over shorter horizons (13,14).

By contrast, EBC and WBC are closer to material-definition and product-characterization systems. While EBC organizes admissible uses through certification classes and analytical thresholds such as $H/C_{org} < 0.4$ or < 0.7, IBI uses $H:C_{org} \leq 0.7$ to differentiate thermochemically converted biochar from less-converted material and treats this ratio as an indicator of carbon stability (11,12). In addition, a life cycle assessment is methodologically essential in biochar crediting because permanence alone does not establish a valid net-removal claim. A biochar pathway stores durable carbon, but the climate value of that storage still depends on emissions associated with different stages such as feedstock handling, transport, production, and end use (16). Industrial cradle-to-grave evidence shows that even after whole-system accounting, optimized biochar systems can remain strongly net negative, with an olive-pruning case study reporting approximately 2.68 tCO_2e of permanent removal per tonne of biochar produced (25). Moreover, review evidence shows that feedstock type, pyrolysis conditions, and end application materially influence both product distribution and sequestration performance, which makes broader permanence assumptions methodologically weak (26). Thus biochar methodologies are more accurate when they use LCA as the integrated framework along with permanence.

Protocol	Permanence Criteria	LCA Requirement
VCS	H:C	X
EBC	H:C	X
Isometric	Min 200 years	X
ACR	100 year commitment	Does not specify
IBI	Min 100 years	X
GBC	H:C	Does not specify
GAC	Min 100 years	Does not specify
Puro Earth	Min 100 years	X
CAR	100 year commitment	No requirement

Fig 1: Biochar protocols with different permanence criteria influenced by the ratio of hydrogen and organic carbon and the permanence of the organic carbon. Additionally, VCS, EBC, Isometric, IBI and Puro Earth uses mandatory lifecycle analysis to model biochar permanence, while the rest of the protocols does not specify about using LCA in quantifying biochar carbon permanence.

2.4 Reversal Risk

Reversal risk refers to the possibility that previously credited biochar carbon reenters the atmosphere or can no longer be credibly claimed as permanently stored. The protocols generally treat reversal risk or the "loss of sequestered carbon" as events that could occur through oxidation, physical loss, diversion to an ineligible use for crediting, or long-term degradation. Across the protocols, reversal risk is managed through four broad models; end-use eligibility, physical-risk mitigation, chain-of-custody and proof-of-use requirements, and buffer or discount-based risk accounting. VCS, CAR and Puro earth mostly manage reversal risk by restricting crediting to approved end uses which require evidence that biochar reaches a carbon-storing application (15,18). Isometric uses a more formal risk-accounting model, where project-specific reversal risks inform buffer-pool contributions and monitoring requirements (17). GBC and GAC standards emphasize registry-based tracking and final c-sink documentation as the produced biochar remains vulnerable to risks such as combustion, diversion, or recovery until it is incorporated into soil, concrete, asphalt, or another eligible matrix (13,14).

VCS has distinguished the risks into two types; natural and non-natural. For soil applications, VCS identifies fire as the most significant natural reversal pathway because it can immediately oxidize sequestered carbon, while wind and water erosion can move biochar outside the project boundary and beyond the project proponent's control (15). Its main mitigation strategy for natural risks is sub-soil surface application at a depth of 10 cm or more; where surface application is used, VCS requires mixing biochar with substrates such as manure or compost to reduce combustibility and erodibility. For non-soil applications, VCS treats reversal risks as lower where biochar is embedded in long-lived materials such as concrete, asphalt, mineral plaster, gypsum, or clay, because these matrices reduce exposure to combustion, biological decay, and chemical degradation (15). VCS also treats many non-natural risks as relatively limited because the methodology restricts eligibility to waste biomass, reducing feedstock competition in the surrounding communities and associated social resistance. However, it recognizes that project finance, governance, and community acceptance can also affect reversal risk. Finally, VCS's approach is, once these safeguards are applied, reversal risk for verified biochar carbon sequestration is negligible.

The CAR Protocol narrows reversal risk mostly around combustion and verified end use. It states that, beyond gradual long-term degradation, the primary risk of biochar carbon returning to the atmosphere is combustion, and thus combustion for energy production is considered as an ineligible end use (18). The protocol manages this risk by crediting only biochar that has been verified as an eligible reported end use, while any combustion or carbon loss before application is captured through project reporting boundary and quantification requirements. It makes CAR's reversal-risk approach strongly end-use dependent where permanence is not assumed at the production gate but is calculated according to the proportion of biochar carbon expected to remain sequestered over a 100-year period which uses default permanence factors tied to the reported end use (18). CAR illustrates the prescriptive end of a spectrum in how protocols govern reversal risk: rather than assuring against uncertain future reversals through buffer pools, it restricts eligibility beforehand so that identified reversal pathways are ruled out by design. Intermediate uses such as agricultural filtration are treated cautiously because permanence is not reasonably assured until the ultimate end use is demonstrated. Additionally, residual risks are discounted through end-use-specific permanence factors, which credit only the share of carbon expected to remain sequestered over 100 years.

Next, Puro Earth gives an explicit taxonomy of reversal pathways. It defines a reversal as an event that cancels, wholly or partly, the effect of an already issued carbon removal certificate, and states that such events can arise from natural processes, anthropogenic interference, or both (16). The protocol separates expected biochar degradation from reversal risk. Slow decomposition of labile biochar carbon in soil is treated as expected re-emission and included in the calculation, whereas diversion, accidental combustion during storage or transport, uncertain cascading uses, and later excavation or misuse are treated as risks that must be addressed before credit issuance or through end-use specific rules (16). Hence, its management approach is evidentiary, and certificate creation is the first point in the supply chain where biochar end-use ensures durable storage. Moreover, additional rules are required to demonstrate that re-emission and reversal risks have not materialized (16). For instance, Puro Earth recognizes that pure 100% biochar is more vulnerable to diversion than biochar already mixed into a matrix, especially in regions where charcoal use for energy remains common. Thus, signed attestations alone may not be enough if economic incentives exist to divert biochar into fuel markets. Puro treats forest and agricultural fires as another risk component for soil applications but does not consider material if biochar is mixed into soil and eligibility rules requiring mixing are met (16).

Isometric considers reversal risk through a formal risk-scoring and buffer-pool framework. Its Biochar Production and Storage section uses an appendix “Risk of Reversal Questionnaire” to identify pathway-specific risk factors, and the resulting risk score determines the project’s buffer-pool contribution (17). The questionnaire asks several questions such as, whether reversal is directly observable, whether the carbon is organic, whether natural disasters or human-induced events create any material risk, whether there are more than 10 years of monitoring or laboratory data, whether the pathway has a history of reversals, and whether project-specific factors justify a higher risk level (17). The methodology then links risk category to buffer contribution where very low risk corresponds to a 2% buffer, low risk to 5%, medium risk to 7%, and high risk to 10-20% (17). Isometric also treats reversals as difficult to measure and attribute directly to a particular project. So, biochar projects with soil end use are conservatively categorized as very low reversal risk and contribute 2% of issued credits to the buffer pool for residual uncertainty. However, for built-environment storage, Isometric is more cautious as construction materials may pass through demolition, reuse, landfill, exposure to acid rain or acidic groundwater, and possible future recycling cycles over very long timeframes which further makes biochar’s eventual location and exposure conditions uncertain (17).

The GBC and GAC standards manage reversal risk mainly through physical embedding, tracking, registry controls, and restrictions on trade. GBC considers mixing biochar into soil or incorporating it into an alternative long-lasting matrix for end use permanence whereas carbon loss remains possible due to fire, co-firing or usage in steel production. To manage this reversal risk, it requires biochar to be tracked from the production site to the final carbon-sink site and monitored until end use, i,e, it is applied to soil, concrete, asphalt, or another eligible matrix. GBC also defines a carbon-sink matrix as an organic or mineral material in which biochar is mixed at a biochar-to-matrix ratio below 1:1 by volume, specifically to prevent unintended combustion or recovery for fuel use (13). GAC’s approach is similar for low-technology, distributed artisanal production where carbon sinks must be transparently accounted for, controlled, and entered into the Global C-Sink Registry, while the project managers must track and verify biochar application (14). If artisan biochar is sold through a trader, they must be registered and monitored so that the biochar can be tracked to the eventual carbon sink; otherwise, it cannot be certified as a carbon sink (14).

Finally, EBC and WBC are more conservative in terms of reversal-risk systems because they use class standards and not complete project-level crediting methodologies. EBC manages risks through certification classes, traceability, storage rules, labeling, and safety requirements rather than through a formal reversal buffer (11). The protocol also distinguishes end use classes, including industrial uses such as asphalt, concrete, road construction, electronics, sewage drains, and composite materials, while requiring appropriate handling, storage, and labeling precautions (11). WBC defines biochar through certification classes and material requirements (12) with standardized testing and traceability across all application classes, but without a full reversal-risk

MRV approach. Its contribution to reversal-risk management is indirect, but fundamental. The guidelines require indicators of biochar stability which include the $H:C_{org}$ ratio (< 0.7 in general, and < 0.4 for WBC-Premium) (12), and recognize that lower $H:C_{org}$ ratios correspond to greater carbon stability. EBC and WBC do not manage reversal risk in the same way as VCS, CAR, Puro Earth, Isometric, or GBC. Instead, they reduce upstream uncertainty by defining what qualifies as stable, traceable, safely handled biochar before crediting and considering if the resulting carbon storage is eligible, durable, and adequately protected against reversal.

2.5 Measurement, Reporting, and Verification Approaches: Process and Product vs Project Crediting

Biochar MRV is a multilayered framework system that ensures quality control and assurance of the credibility of the carbon credits issued for both the buyers and the regulators in the carbon market. MRV is crucial as it converts laboratory evidence into a traceable market claim that can be used in third-party verification of end use or permanence as well as high quality carbon credit issuance. For project developers and sellers, MRV raises the evidentiary threshold because credit issuance depends on several factors which are more than only production quantity, such as calibrated measurements, batch records, chain-of-custody documentation and proof of end use (15,16,18). Similarly, it reduces information bias for the buyers as the claimed removal can be traced back and verified through third-party review. Where MRV requirements are transparent, biochar removals become more comparable as market assets; and where methodologies remain fragmented, purchase quality becomes harder to judge and market confidence weakens over time (27).

Some standards operate their MRV at the product and process level, whereas others operate at the project crediting level. Product and process MRV focuses on whether biochar is consistently produced, sampled and analyzed before any crediting claim is made. For example, under the WBC standard, the emphasis is on product definition and material requirements across all application classes. Each production batch is registered with a unique ID and QR code that links feedstock, production conditions, and quality data, enabling batch-level traceability (12). The standard further requires sampling by accredited samplers under company-specific sampling plans (12), laboratory analysis of stability and contaminant indicators such as organic carbon content and the molar $H:C_{org}$ ratio (below 0.7, and below 0.4 for WBC-Premium) (12), and annual third-party inspections by an accredited certification body (12). The WBC further extends product-level control to the downstream supply chain, since processing companies and traders of biochar-based products must themselves be certified and label the application class and C-sink status of the biochar contained in their products (12). EBC extends this approach to production control by requiring technical pre-audits of pyrolysis units, endorsed sampling, annual inspections and process conditions that prevent the release of unburned pyrolysis gases (11). In this category, MRV primarily establishes whether the material is a qualifying biochar and whether the production process satisfies recognized quality and environmental control requirements.

Project crediting MRV, on the other hand, embeds these measurements within a broader accounting and verification framework that determines whether a specific biochar project can issue carbon removal credits. For example, VCS and CAR require several checkpoints such as project boundaries, monitoring plans, laboratory methods, and chain-of-custody records that follow the material from feedstock sourcing through production to final application (15,18). Puro earth and Isometric further link additional checkpoints such as batch records, delivery evidence, geotagged application records and third-party audits to the final crediting system. Next, the GBC Standard adds registry-based digital MRV (dMRV), which requires further checkpoints such as sink registration, tracking of packaging units and documentation of the location, persistence class and emissions portfolio associated with each sink. Thus, the analytical distinction is that product and process MRV establishes whether the biochar itself is acceptable, whereas project crediting MRV defines whether a specific project can turn that biochar into a verified and tradable carbon removal claim.

2.6 Protocol Commonalities

Commonalities between protocols are a strength and establish a future baseline for harmonization. For an effective, tradeable market to develop, harmonization of standards, or the degree to which differences in standards can be codified formulaically, is very important.

Across the protocols, the commonality is not a single permanence factor but a shared regulatory structure around three key parameters - feedstock eligibility and production conditions, emissions accounting, and end-use criteria. First, the protocols define what biomass may enter the system and tie feedstock eligibility to sustainability, traceability, or baseline-fate criteria, even if they operationalize those criteria differently. Second, the protocols require biochar to be produced through controlled thermochemical conversion, most commonly pyrolysis and, in some standards, gasification or related systems, with monitoring, testing, or process controls used to verify production conditions and material quality. Third, the protocols connect carbon accounting or certification to downstream use by requiring strict emissions accounting across the value chain and by linking credited or certified biochar to documented end uses, storage environments, or both. Therefore, the common ground is that the protocols govern the same three stages of the biochar pathway; what feedstock is admissible, how biochar is produced, and under what accounting and end-use conditions it can qualify as a durable carbon sink.

2.7 Protocol Differences

Despite foundational similarities in production processes, protocols impose distinct production criteria. For example, VCS is the only protocol that restricts eligibility to new, greenfield production facilities (15), whereas Puro Earth credits both new and retrofitted facilities under separate baseline scenarios (16). In another example, only the EBC protocol requires not more than 365 days between biochar production and application., The Isometric protocol provides credits to only a single entity or owner from biochar production to storage.

Furthermore, while the protocols share similar criteria for emissions accounting based on production, leakage count, GHG impacts, and risks of carbon reversal, the scopes for emissions accounting differ for each of them. For instance, the entire biochar production LCA is performed for the WBC-issued credits (12). In contrast, CO_2 emissions from fossil fuel combustion, electricity consumption, and transportation exceeding 200 km are considered for production-related GHG emissions in VCS, while methane and nitrous oxide emissions are considered selectively (15). While VCS, EBC, isometric, International Biochar Initiative, and Puro Earth protocols have some LCA requirements, GBC, GAC, and CAR do not specify any LCA analysis. Furthermore, the expected permanence, production temperature ranges, and $H:C_{org}$ ratio for biochar carbon stability differ among these nine protocols. For instance, the biochar credited by the Isometric standard has an $H:C_{org}$ ratio of less than 0.5 and an expected permanence of 200-1000 years (17).

3. Discussion: Effects of Emerging Research Uncertainties in Protocols and Market Implications

While there will always be scholarly unknowns surrounding the details of biochar's environmental behavior, there are relatively few unknowns that have immediate implications for biochar market development. To be included in the analysis below, uncertainties needed to either be large enough to plausibly cause significant variation in biochar properties that control carbon stabilization, or large enough to cause significant variation in biochar properties that control co-benefits that add to carbon credit value.

Constraining uncertainties often comes with financial trade-offs, as more accurate measurements often (but not always) requires more time and financial investment on the part of the credit producer, which reduces scenarios where producers can expect to break even financially. Indeed, a recent joint International Biochar Initiative/US Biochar Initiative report assessed that more than half of all biochar producers do not currently engage with any certification entities, which the authors attribute in part to barriers associated with certification (28). Scholarly activity will serve the biochar market best by constraining sources of uncertainty that limit biochar value, and by developing less expensive ways to measure, report, and verify biochar carbon storage. Below we address three uncertainties that we judge as creating significant variation in biochar C stabilization or co-benefits.

3.1 Uncertainties in Biochar Landscape Mobility

Movement of biochar on the landscape after application does not impact overall carbon removal, as physical relocation from erosion does not increase the likelihood of biochar oxidation to CO_2. However, landscape mobilization does have implications for the delivery of biochar co-benefits: for example, if biochar leaves the agronomic landscape and settles into low-lying areas, it will no longer deliver the crop productivity, water retention, and nutrient retention benefits that farmers may be buying biochar to provide. In addition, significant levels of biochar mobility could result in lack of investor confidence in credit quality because it would limit the ability of carbon credit buyers to confirm carbon storage via detection of biochar in the intended location.

There is ample data showing that biochar moves preferentially on the landscape compared to other forms of organic matter, but we lack a coherent, mechanistic model that can predict these effects. One of the earliest studies hinting at biochar mobility reported that biochar disappeared rapidly after application, while simultaneously confirming through isotopic studies that no decomposition had occurred (29). One explanation for this disappearance is loss by physical mobilization rather than by mineralization (30). Multiple studies support this hypothesis. Obia et al. (2017) reported only 45-66% of biochar in a tropical soil was recovered after 1 year (31). Pyle et al. (2017) found that charcoal was the most mobile fraction of organic matter in the three years after a fire (32). Inoue et al. (2017) documented that highly graphitized biochar, which is potentially more chemically stable, disappeared faster than biochar with lower graphitization, suggesting that physical properties are critical controls on biochar movement (33). More recently field studies of natural charcoal make clear its high rates of erosion (34–36), and hypothesize links between this movement, regional hydrology, and charcoal's low density (37).

Even though landscape mobilization is a key mechanism for biochar loss, erosional flux has not been quantified and biochar landscape movement remains poorly understood (38,39). The effect of ecosystem properties (e.g., topography, rainfall) and biochar properties (e.g., size, density) on biochar movement and fate are yet to be elucidated. These studies are sorely needed to help the market understand the scope of this potential challenge.

Although the scholarly literature provides ample evidence of charcoal and biochar erosion, the lack of mobility quantification in biochar field trials has meant that almost all protocols are lacking guidance on how to prevent biochar loss. Verra is the exception to this, requiring tillage to 10 cm (15). No protocols require any basic erosion controls, and the effects of off-the-shelf erosion control products on reduction of biochar mobility remain untested. Fortunately, many mature technologies exist to reduce erosion in agricultural and land management settings (40–42); see also the Erosion Control Toolbox (43). Studies are needed to determine which of these technologies are appropriate for use with biochar in a range of field settings.

3.2 Uncertainty in Loss of Biochar Carbon Due to Fire

One potential area of uncertainty in biochar carbon crediting protocols is the reversal risk of unintentional fire, where biochar in soils could be lost if an amended ecosystem were burned. The scholarly understanding of the risk of reversal from fire for biochar amendment plots (biochar combustion to CO_2) is almost completely unconstrained. We can get a first understanding of this reversal risk by considering the limited literature specifically on soil charcoal lost during fires as well as the overall literature on soil carbon loss during fires. One field study showed low loss rates of charcoal from soil during fires (~6%) (44); however, multiple fires can rapidly deplete soil charcoal carbon content (45). Moreover, the varied heat flux of fires and biochar burial depth fundamentally alter PyOM's resistance to subsequent combustions which eventually results in the loss of carbon (45). For example, the carbon loss due to fire can be ~90% if the heat fluxes are high while the biochar burial depth is shallow i.e, 0 – 5 cm depth (45).

The existing literature on soil charcoal indicates that pyrogenic carbon typically survives individual fires, particularly when buried below the soil surface, and that losses are driven primarily by fire frequency and severity rather than by any single burning event (45,46). However, high-severity fire events can substantially deplete surface PyC stocks, causing abrupt disruptions to long-term carbon storage (45).

Fire plays both a positive and negative role in soil carbon stabilization: fire supports soil carbon formation through the addition of PyOM to surviving carbon pools (47), and burning vegetation can produce durable PyOM that can lock away carbon underground for centuries (48). Furthermore, severe fires promote the formation of highly aromatic and structurally condensed PyC with higher environmental persistence (45). However, frequent and severe fires may simultaneously trigger soil carbon losses through multiple pathways. Literature on soil carbon loss during fires reveal that while the most immediate impacts are often observed at the soil surface through direct combustion, the long-term dynamics are governed by a complex interplay of altered plant inputs, changes in microbial decomposition rate, and the destabilization of deep soil carbon pools (45,49,50).

Fire generally decreases soil carbon stocks globally, with effects that can persist for over half a century (51). However, these losses are not uniform across all environments. For example, savanna and broadleaf forest ecosystems experience substantial C depletion under frequent burning regimes, with frequently burned savanna grassland plots having 21% less soil carbon compared to protected plots (52) , whereas needleleaf forest responses are more variable. Some studies indicate that soil carbon in these forests may actually increase under certain fire frequencies, though intense wildfires can still consume significant portions of the thick organic soil horizons (52). On the other hand, boreal forest regions are highly vulnerable to carbon loss because fires can consume the "legacy carbon" or organic soil that escaped burning in previous fire cycles and has accumulated over millennia (52). In young boreal forests (<60 years old), fires can shift the ecosystem from a net carbon sink to a net carbon source (52).

In summary, fire alters soil organic matter stability by influencing accessibility (e.g., aggregate formation or destruction), interactions with minerals, and the recalcitrance of the organic matter itself (49). In post-fire soil carbon loss, the net effect of fire, whether soil stabilizes or loses carbon overall, depends on several variables like burn severity, fire frequency, fire history, characteristics (aromaticity and level of condensation) of the burning material or previous PyOM, topography and the landscape's response afterward. SOM is stored in different forms, and the stability of the carbon depends strongly on interactions among plant roots, soil microbes, and minerals (46). Here, fires can accelerate the loss of remaining carbon by reducing the abundance of soil fungi and bacteria by 33-47%, which initially slows decomposition but later can be offset by "pyrophilic" microbes that thrive in post-fire conditions (49), leading to faster decomposition.

A better understanding of the potential for biochar loss during fire is needed to understand the scope of the reversal risk. Present knowledge relies heavily on the intrinsic flammability of pure biochar (53), but biochar in a field setting can exist as an organo-mineral complex (9). One simple approach would be to set up biochar amendment plots in sites where controlled burns are already planned, similar to wildfire re-burn experiments (44). This approach may allow the inexpensive generation of basic data on thermodynamic stability of biochar in soil and the risk of biochar reversibility from fire. Another more accurate, but potentially more expensive option would be the design and execution of controlled burns at sites intentionally designed to mimic biochar treatments.

Furthermore, biochar carbon crediting registries such as Verra, Isometric, Puro earth, Climate Action Reserve, classify the term "buffer ecosystem" or "buffer pool", which is a communal insurance reserve of non-tradable credits that protects the credibility and market integrity against unintentional reversals. Thus, reversal risk due to biochar loss from fires can be constrained using two approaches. First, an assessment of the overall fire risk of the ecosystem will help buyers understand whether the region is prone to burning at all. If there is no fire risk or very limited fire risk, a buffer amended ecosystem may not be necessary. Second, if the ecosystem is fire-prone, consideration of a buffer ecosystem may be merited.

3.3 Uncertainties Associated with Biochar Priming-Driven Soil Carbon Shifts

Biochar amendment often induces priming, a complex biogeochemical response where the presence of pyrogenic organic matter significantly changes the decomposition rate of native soil organic carbon (54,55), where "native soil organic carbon" refers to the organic carbon present in the soil prior to biochar amendment. There are two types of priming: a) positive priming, where biochar application accelerates the decomposition of native soil organic carbon stocks, leading to a loss of native soil organic carbon (56), and b) negative priming, where biochar suppresses the decomposition rate of native soil organic carbon, leading to an increase in native soil organic carbon storage (55). Positive priming of native soil organic carbon (carbon loss, a detrimental outcome) after biochar addition is less common and can often be mitigated through appropriate feedstock selection, production conditions, and management practices (9). Negative priming (carbon gain) is more often observed, with biochar sometimes providing an additional bonus soil carbon storage (57). In cases where negative priming has been quantified it can sometimes be quite significant: for example, Blanco-Canqui et al (2019) returned after 6 years to a field site where 7 Mg of biochar/hectare was amended to a soil and found that soil carbon stocks had increased by 14 Mg/hectare (58). In other words, in that specific case the effect of priming was to *double* the total amount of carbon stored.

It is not uncommon for the biochar carbon credit producers to express interest in selling the additional native soil carbon accrued as a result of biochar carbon amendment, especially since a few studies (e.g. (58)) have shown such large priming effects. In theory quantifying and selling this extra non-biochar soil organic carbon should be possible, as it simply requires quantifying soil carbon stocks, but in real-world practice this adds significant challenges to the biochar carbon crediting process as it requires spatially and temporally accurate measurements of soil carbon stocks.

One key market advantage that separates soil biochar carbon credits from bulk soil carbon credits is that the quantification of biochar carbon storage happens at the production stage and usually does not require soil carbon measurements after application. This brings significant MRV cost savings compared to ordinary soil carbon credits, which require repeated, spatially- and depth-resolved soil carbon measurements. There is significant uncertainty associated with accurately estimating total soil carbon stocks at the landscape (59) and some laboratories that measure soil organic carbon are producing data with surprisingly large errors (60). Soil carbon measurement uncertainty is a fundamental limit on the amount of ordinary soil carbon accrual that can be bought and sold on carbon markets (61). Biochar soil carbon amendment bypasses this challenge because the total amount of carbon credited can be calculated immediately, with minor corrections in some protocols for CO_2 released during the production and transport phases (e.g. (11)). Our understanding of the mechanisms controlling biochar-driven priming are not good enough yet to accurately estimate additional native organic carbon accrual without adding additional layers of soil carbon monitoring. There have, however, been significant advances in determining the drivers of biochar priming effects (62–64), some of which have enabled modeling of biochar priming (65).

Though there is uncertainty regarding the magnitude and mechanisms of biochar induced priming effect, the variables associated with priming direction are broadly understood, and this understanding can be used to, at minimum, prevent the loss of native soil carbon from biochar amendment. One first step may be reviewing protocols to ensure this. Further research on the controls for priming may allow for enough generalization of effects that priming can be included in protocols.

3.4 Carbon Market Challenges from Protocol Heterogeneity

Heterogeneity between protocols and emerging protocol uncertainties have direct consequences for biochar market expansion particularly by limiting protocol adoption and increasing price and investment risk. These challenges can be addressed through two pathways: first, by directing scholarly research to addressing protocol uncertainties, and second, by community-driven collaborations to address major protocol differences. Partial models for both of these pathways exist, although no single framework has yet resolved protocol divergence across the market. International CDR governance assessments recommend achieving convergence in MRV through a small number of coordinated entities rather than a proliferation of competing institutions (10).

Carbon markets globally are not growing fast enough to meet the needs for CO_2 removal under any climate scenario (10). The coexistence of many different, potentially conflicting protocols may slow market growth and undermine investor confidence. Evidence from the carbon market literature suggests that when carbon accounting methods differ across actors, results become inconsistent, and trust in market outcomes can erode (66). The urgency of this problem is also reflected in the State of Carbon Dioxide Removal's assessment that CDR governance remains fragmented (10). Without coordinated international institutions, the decentralized activity of national governments and private organizations risks slow technology deployment, poorly aligned incentives, a(67)nd standards that diverge rather than converge (10). Convergence in monitoring, reporting, and verification is more likely to be achieved by a small number of coordinated entities than by a proliferation of competing institutions (10) which implies that the multiplication of protocols is itself part of the problem.

Qualitative research on the VCM documents how protocol disagreement translates into economic risk (66). One risk is termed "double-claiming," which is when market ambiguity allows the same mitigation outcome to be claimed by both a private actor and the host country toward its Nationally Determined Contributions (66), unless accounting rules prevent this overlap. The double claiming problem of the VCM resulted from the divergent positions adopted by certification standards, producing a deadlock in which principal actors moved in opposing directions and project developers and investors were left bearing substantial risk (66). Along with this, there is no unified approach yet established at several standards like Verra and Gold Standard to measure non-permanence risks (67).

The relationship is mutually reinforcing; inconsistent protocols can slow market growth, while demand for credible and comparable credits can increase pressure to harmonize methodologies across the market. For example, case studies in developing countries show that standardized, independently verified carbon credits create the necessary assurance for investors and project developers to transact with confidence that in turn reduce price volatility and thereby strengthen investor confidence (68). The market's demand-side also reinforces the effort to harmonize methodologies across the market.

The European Union provides another example of process standardization. The EU has developed shared regulatory and certification frameworks that can accelerate market expansion (69). Corporate goals to reduce environmental impact rapidly multiplied within regulated and semi-regulated frameworks after 2018, and shared frameworks were introduced, including the Core Carbon Principles of the Integrity Council for the Voluntary Carbon Market (2023), the European Union's Carbon Removal Certification Framework (2024), and the Paris Agreement Crediting Mechanism* Article 6.4 (2026) which has the potential to facilitate market interlinkages, and enable faster project scaling (10). The protocol coverage rose from <50 in 2018 to nearly 70 percent by the end of 2023, and certification has been shown to raise confidence among industrial purchasers and policymakers during this time (69). The EBC also played a key role in the expansion of the European market by supplying a recognized framework for assessing and certifying biochar products, which in turn facilitated trade.

Standardization gaps have direct consequences for biochar market expansion, particularly by limiting protocol adoption and increasing price and investment risk. This is typically addressed by establishing rules. No market is truly "deregulated". Markets either have significant oversight, or they have a rulebook that a regulator enforces. Markets that have historically grown are in the latter space. In the US, there are already regulatory agencies able to handle this, i.e. the

Departments of Agriculture or Commerce. Expansion in this area would require staffing and budget growth; however, rarely does a government step in before the demand exists. This is where the biochar industry can play a formative role by establishing the standards for harmonization, or a formulaic way to value competing standards against each other, the industry can make the transition to a regulated industry much smoother. Community-driven protocols and scholarly research are both necessary and need to be combined with the clear purpose of market development and growth.

3.4.1 Constraints in biochar protocol adoption

Without widely adopted, commonly accepted production standards, biochar products remain difficult to trade because buyers cannot compare them reliably. More than half of all biochar producers operated without any certification or production standard (28) which means that over half of the biochar produced globally cannot be traded on any market (69). Because biochar's properties vary systematically with feedstock and process conditions, the absence of common protocols leaves buyers unable to compare offerings, which can suppress demand and create difficulties with pricing. The lack of standardized quality metrics is therefore one of the principal barriers to the commercialization of biochar as a CDR approach, and the absence of standards constituted the fourth most frequently cited obstacle to the biochar industry's expansion (69).

3.4.2 Price opacity and investment risk

Protocol divergence propagates into biochar carbon credit markets creating price dispersion, increasing buyers' due-diligence burden, and discouraging investment. Carbon removal credits from biochar currently transact across a broad range of roughly USD 90-600, with most prices concentrated between USD 95-145 (70). Buyers respond to the resulting uncertainty by conducting their own secondary due diligence which is an additional transaction cost attributable to inconsistent certification protocols (70). The price-formation issue extends beyond carbon credits to the physical biochar market. No public database of biochar prices exists, and reported prices span over a wide range, from USD 661 to USD 1,764 per tonne (71). This lack of transparent benchmarking is consequential because product price is a key determinant of profitability and, according to Trapero et al., (2025), the most influential variable.

A lack of price transparency discourages market entry, which, in turn, makes the investment needed for scale-up more difficult. This is particularly debilitating for smaller operators facing high approval and compliance costs (72). The resulting combination of uncertain demand, price volatility, and variable product characteristics across production processes remains a fundamental obstacle to industry scale (70,71). This is compounded by protocol fragmentation, which is also unevenly distributed. With only two internationally recognized product certification standards, the International Biochar Initiative and the European Biochar Certificate, smaller operators, particularly in emerging economies, face approval costs that are difficult to absorb (72). Thus, fragmentation not only slows cumulative market growth but promotes opacity, and biases the market growth toward large, well-capitalized producers.

4.0 Conclusion

The eight biochar protocols have a common foundation of feedstock, production and application criteria. However, these protocols differ substantially in how they define permanence, quantify durability, manage reversal risk, and verify storage across the biochar supply chain. These differences limit direct comparison among different credits and may weaken confidence in the consistency of market claims. Industry faces an uphill challenge in establishing harmonized protocols, recognizing that there are goals related to life-cycle emissions accounting, end-use verification, chain-of-custody documentation, and transparent treatment of uncertainty, while retaining flexibility for different production systems and storage pathways. The effects of emerging uncertainties such as fire, erosion, landscape transport, and interactions with native soil carbon remain insufficiently characterized. Harmonization should ensure that differences among protocols are transparent, evidence-based, and understandable to producers, buyers, investors and regulators. Furthermore, establishing this balance would support the responsible expansion of biochar carbon removal technology while also ensuring that increased deployment is matched by credible scientifically backed evidence of durable atmospheric carbon removal.

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Supplemental Table 1: Biochar Feedstock and Production

Protocol	Year	Feedstocks eligibility	Production Criteria	Sourced locally?	Production Scale	Production Process	Pyrolysis temp	Single/ blended batch	Cost
VCS (VM0044 v1. 2)	6/27/2025	Purely biogenic waste biomass, not purpose grown	Production facility must be new. Facility category - high tech or low tech (different criteria for both)	Sustainability criteria yes, within 200km (round trip)	High tech / low tech	Pyrolysis / gasification / boiler	Low to high, 350 °C to >600 °C	Both single and blended, must follow IBI Biochar Testing Guidelines	High tech - costs more, higher quality biochar
European Biochar Certificate	8/14/2025	Biomass only with detailed records kept for minimum 5 years. PEFC or FSC certification required for forest wood. Mixed biomass feedstock allowed within a batch while proportions may not deviate by more than 20%. Feedstocks must be clean from impurities and hazards	Production batch duration - 365 days maximum. QA /QC documentation and batch traceability required.	Sustainable sourcing	Both industrial and small scale production	Pyrolysis temperature fluctuations not exceeding ± 20% of the declared temperature.	Low to high, 350 °C to > 1000 °C	Both, multiple batch production allowed annually if production parameters change	Does not specify
Isometric v 1.2	11/24/2025	Eligibility determined by market leakage impact, counterfactual CO_2 storage, not purpose grown	One owner (production to storage) - project proponent	Local sourcing is encouraged, not mandatory	Does not specify	Pyrolysis - slow and fast	500 °C to 800 °C	Yes, batchwise, extra calculation for blended / storage batch	Does not specify
World Biochar Certificate v1.1 (successor to the retired IBI Biochar Standard)	12/20/2024	WBC positive feedstock list per certification class (premium, agro, material). Feedstocks mix proportions may not change by more than 20%	Batch ID/ QR registration, maximum 1 calendar year, annual inspection	Sourcing locally and sustainably, no SOC depletion	Small, artisanal kiln to Industry scale	Pyrolysis: fast and slow, gasification	350 °C to 1000 °C , mentions higher temperatures yield higher carbon content	Both, feedstock preparation requires homogeneity in size and moisture	Small scale: low, industrial: $220 -$580 per ton
CSI Global Biochar C Sink	3/30/2026	Carbon neutral biomass sourced responsibly, traceability and certification required in forest biomass	Energy and fuel consumption from transportation to packaging considered	Local sourcing	Requires energy use efficiency thresholds (minimum 60%) and carbon efficiency indicators for operational viability and scale-up considerations	Pyrolysis	Does not specify	Both, mixed batch requires new C-sink IDs and tracking. Emissions and carbon efficiency accounting done per batch.	Does not specify
CSI Global Artisan C Sink	6/15/2024	Must originate primarily from the artisan's own farm and waste, using forest biomass prohibited except for TLUD cooking stoves. Food or feedstocks cannot be pyrolyzed unless expired	Manual, using Kon-Tiki pyrolysis kilns. Producers must document biomass sourcing, production, and application. If biochar is sold to traders, these traders must be certified.	Mandates local and sustainably sourced biomass	C sink farmers, cooks, and Artisanal pro (100 m³ - 1500 m³ biochar /year)	Pyrolysis / TLUD micro gasifier stoves	Ranges between 680°C and 750°C in the main pyrolysis zone. H:C ratio < 0.4	Both allowed with continuous gas escape through flame curtain. For artisan pro - new feedstock types require biochar C content and bulk density analysis	€30 (simple soil pits) to €5,000 (metal kilns)
Puro Earth v2	11/27/2025	1. Sustainably sourced biomass or waste biomass. 2. Must adhere to IPCC Appendix 4 and positive feedstock list of EU Biochar Certificate. 3. Use of invasive species allowed under strict conditions.	1. Facility must undergo third party audit. 2. Fossil fuel may be used for ignition but can not be co-fired with biomass in the same reactor. 3. Pyrolysis gases must be combusted or recovered to minimize CH_4 emission. Producer is CO_2 removal supplier	No mention of the production site; Leaving 30% agricultural biomass residue on field to maintain soil health	Does not specify	Pyrolysis / gasification; includes all stages of LCA	No specific temperature but should meet the criteria of H:C < 0.7	Both allowed, sampling and lab analysis must cover all biomass types to calculate C org and stability	Does not specify
Climate Action Reserve	3/19/2024	Waste and byproducts, purpose-grown feed needs additional verification, feedstock sources require traceability	Credit & ownership - project developer. Stacking of parts needs approval	Only requires physical location identification and acquisition date	Does not specify	Pyrolysis / gasification	Not specified; must be monitored, sampling and testing required annually or upon changes exceeding 10% in feedstock mix, 50°C in pyrolysis temperature, or 10% in residence time	Both with sampling and capturing variability through composite samples from multiple subsamples	Does not specify

Supplemental Table 2: Emissions Accounting

Protocol	Year	Emissions Accounting Scope	Production emissions	Leakage Emission Count	Pollutant Emissions count	GHG Impact count	Risk of C reversal
VCS (VM0044 v1.2)	6/27/2025	CO_2 emissions related to fossil fuel combustion, electricity consumption, and transportation over 200 km included. CH_4 and N_2O emissions are included selectively.	Organic C sequestered in biochar minus project emissions. If fossil fuel energy used for further processing, emissions are included.	Arise from transportation of biomass and biochar when distances exceed 200 km. Activity-shift and biomass-diversion leakage set to zero (waste biomass only).	Complies with biochar material standards	Sourcing, production and application	Risk is considered negligible due to requirements of biochar usage only in approved long-lived applications and monitoring of end-use.
European Biochar Certificate	8/14/2025	Monitoring and controlling the emissions from the pyrolysis process including the release of pyrolysis gases to ensure energy and carbon efficiency.	Refers to GHG pollutants released during biochar production, including pyrolysis gas emissions, VOCs, heavy metals, and organic contaminants like PAHs, dioxins, and PCBs.	Fossil fuels are prohibited except preheating. Pyrolysis gases must be combusted or captured. Syngas combustion must comply with national emission limits. Excess heat must be utilized	Requires initial and periodic testing of pollutants. Heavy metals are strictly limited. PAHs, PCBs, PCDD/F are monitored with set limits.	Carbon sink potential is certified based on pyrolysis unit performance and biochar stability. Production emissions are efficient compared to biomass burning or decomposition.	The risk of reversal for carbon is mitigated by ensuring biochar stability through production parameters, quality controls, and certification processes that verify long-term carbon storage
Isometric v 1.2	11/24/2025	Comprehensive emission tracking across all outputs. Provides allocation of emissions when biochar and bio-oil are both used for carbon storage. All non-CO_2 GHGs must be converted to CO_2e using 100-year GWP values from the IPCC Sixth Assessment Report.	All emissions, regardless of the fate of co-products are tracked and converted to CO_2e.	Must be quantified and deducted from CO_2 removals. Reactor design must include sensors to quantify leakage during operations.	Requires accounting for direct emissions from pyrolysis, including pollutants.	Mandates GHG accounting in every stage of LCA	Each project must set aside a certain number of carbon credits into a "Buffer Pool", a reserve of credits to offset potential future reversals.
World Biochar Certificate v1. 1 (successor to the retired IBI Biochar Standard)	12/20/2024	WBC sets production and material requirements; C-sink quantification occurs under the CSI Global Biochar C-Sink standard, which requires EBC or WBC certification and includes the full production lifecycle in LCA. Baseline emissions are set to zero.	All emissions resulting from pyrolysis should be accounted for. Emissions from pyrolysis gases and tars must be combusted or recovered. Emissions related to the end-use of biochar are also accounted for.	A margin of safety (e.g., 20 kg CO_2e per ton of biochar produced) is typically deducted to cover uncertainties and possible leakage.	Requires accounting for all GHG emissions, not just CO_2.	Net CO_2 removed is calculated as carbon stored in biochar minus emissions from biomass sourcing, production, transportation, end-use, and leakage (tCO_2e).	Permanence factors and stability criteria are applied to estimate biochar carbon durability over 100-years. End uses that permit fuel recovery or uncontrolled decomposition are ineligible.
CSI Global Biochar C Sink	3/30/2026	Emissions are categorized into Scope 1, Scope 2, and Scope 3, and accounts for direct and indirect emissions.	All GHG emissions resulted from biomass production up to application must be assessed and registered. Emissions from processing the by-products are included.	Margin of safety accounts for leakage = 20kg CO_2e per ton of dry biochar (~ 0.7% of the c present)	Non-CO_2 GHGs, particularly CH_4 and N_2O are specifically accounted for	To calculate CO_2e, GWP - 100 for CO_2, 25 for CH_4 and 298 for N_2O applied (per IPCC AR4). CH_4 uses C-sink 20 timeframe of the protocol.	Distinguishes between geological C sinks (PAC fraction) and temporary C sinks (SPC fraction). A safety margin and monitoring systems are in place to manage uncertainties and risks of C loss or reversal.
CSI Global Artisan C Sink	6/15/2024	All emissions occurring due to biomass sourcing, biochar production, and application must be accounted for. A margin of security (20 kg CO_2e per ton of biochar dry matter) is applied.	Average CH_4 emissions from Kon-Tiki kilns = 30 kg per ton of dry biochar produced with variations present.	Sustainable biomass sourcing, transport emissions >100 km accounted, exclusion of high-emission pyrolysis methods	Emissions from proper combustion in pyrolysis is generally lower than open burning of crop residues. PAH limits controlled by technology endorsement	CH_4 = main GHG due to high GWP; compensation must be done within 20 years of application	Requires transparent accounting and registration in the Global C-Sink Registry. Provisions to remove C sinks from the registry if applied biochar destroyed or decomposed
Puro Earth v2	11/27/2025	Conducting LCA to cover a cradle-to-grave system boundary. This includes emissions from biomass production and supply, biochar production, biochar distribution, and application.	Includes energy use, emissions from drying, chipping, pyrolysis reactor operation, flue gas treatment, biochar post-processing, handling and use.	Emissions from indirect effects such as land use change, biomass transport, and mobile unit transport are included to capture relevant sources of leakage.	Compliance with local environmental regulations on air, water, and soil contaminating emissions is mandatory. Presence of heavy metals and PAH testing required.	The LCA must include all major GHGs, including CH_4 emissions from pyrolysis gases, which must be controlled or combusted to negligible levels.	Requires proof that the biochar use does not cause CO_2 release to the atmosphere. Biochar must be used in applications preserving C storage and avoiding fuel uses.
Climate Action Reserve	3/19/2024	Defines the GHG Assessment Boundary to include all relevant GHG sources, sinks, and reservoirs (SSRs) associated with the biochar project activities. This includes emissions from feedstock acquisition, biochar production, and biochar application phases.	All actual GHG emissions within the assessment boundary during the reporting period.	Leakage is considered for two scenarios: use of purpose-grown feedstocks (limited to marginal lands to reduce risk) and diversion of biochar from bioenergy processes.	Primarily accounts for GHG emissions; pollutant emissions related to air quality are addressed indirectly through regulatory compliance requirements.	Net carbon removals are calculated as the difference between baseline and project emissions and sequestered carbon, minus leakage emissions.	Only biochar with H:Corg < 0.7 and eligible end uses with known permanence factors is credited. Chain-of-custody tracking ensures eligible post application end uses to maintain permanence.

Supplemental Table 3: Application Criteria

Protocol	Year	End use	Permanence	Co-benefits	Non-soil application	Risk Mitigation Strategies
VCS (VM0044 v1.2)	6/27/2025	Biochar must be utilized within one year of production to ensure minimal decay before application, with permanence calculated over 100 years. No applications on wetlands are permitted. Biochar should be mixed with other medium for soil surface applications.	Permanence is assessed over a 100-year timeline with default decay factors depending on production temperature. The higher the combustion temperature, the more the stability. High temp (>600°C): 0.89, medium temp (450-600°C): 0.80, low temp (350-450°C): 0.65	Soil applications improve soil-water retention and reduce soil erosion, and increase resilience to abiotic stressors. Non-soil applications in concrete or asphalt, can improve material thermal resistance, while contributing to long-term carbon storage.	Eligible only if biochar is produced in high technology production facilities with pollution controls and energy recovery, and with minimum 50% C on a dry weight basis.	Loss or combustion related natural risks are reduced by subsurface (10 cm or more depth) applications; surface application requires mixing with substrates. Non-natural risks are mitigated through approved end-use requirements and end-use monitoring.
European Biochar Certificate	8/14/2025	Several certification classes based on different end-use applications: EBC-FeedPlus, EBC-Feed, EBC-Agro and EBC-AgroOrganic, EBC-Urban, EBC-Consumer Materials and EBC-Basic Materials.	H:Corg < 0.7 (and < 0.4 for EBC-FeedPlus) indicates sufficient carbonization and long-term stability. Water content adjustment (~30%) to prevent dust formation and spontaneous combustion.	Supports soil conditioning, nutrient cycling, manure treatment, and composting. Urban biochar applications helps in soil remediation and environmental toxin adsorption.	Biochar certified as EBC-Consumer Materials and EBC-Basic Materials are intended for non-soil uses such as construction, composites, textiles, and consumer products.	1. Strict control of feedstock quality, pyrolysis conditions, and contaminant limits. 2. Batch sampling and analysis by accredited laboratories. 3. Water content adjustment ~30% to prevent dust formation and spontaneous combustion for biochar.
Isometric v 1.2	11/24/2025	Soil temperature variation is strictly monitored and presently the storage occurs in agricultural soil and low oxygen burial environments. LCA is performed at all stages.	The protocol allows for credit issuance with durability thresholds of 200 or 1,000 years, depending on the biochar characteristics and measurement methods. H: C org < 0.5 indicates stable carbon in biochar.	Environmental remediation, increased soil moisture, overall soil health and crop yield, and decreased reliance on fertilizers	Eligible under the Biochar Storage in the Built Environment module, which discounts uncertainty from fire, abrasion, and end-of-life transitions.	Must conduct a full risk assessment to identify potential reversal mechanisms and implement monitoring plans. Reversals are classified as avoidable or unavoidable, with respective buffer pool requirements.
World Biochar Certificate v1. 1 (successor to the retired IBI Biochar Standard)	12/20/2024	WBC sets material requirements by certification class (Premium, Agro, Material); use as fuel is excluded. C-sink crediting occurs under the CSI Global Biochar C-Sink standard, for which EBC or WBC certification is a prerequisite.	Stability assessed via H:Corg ratio: < 0.4 (WBC-Premium, strict), up to 0.7 (general classes).	Soil health improvements, increased crop yield, drought resilience, energy production through co-product heat recovery.	WBC Material covers non-soil uses such as construction; biochar must be included in material matrices from which the carbon cannot leach, with B2B trade only.	Quality testing, batch registration and traceability, and annual third-party inspection; end uses must be documented and traceable for C-sink certification under the C-Sink standard.
Global Biochar C Sink	3/30/2026	Biochar mixed with soil or another eligible C-sink matrix at a biochar-to-matrix ratio below 1:1 by volume to qualify as a C-sink; animal farming, construction, and composite applications also recognized.	Soil application with H:C < 0.4 and PAC fraction considered stable for >1000 years creating geological C-sink. Certificates for temporary C-sinks should not be used for CO_2 offsetting.	Biochar contributes to soil fertility and organic matter recycling but must preserve soil organic carbon stocks to maintain ecological functions	Biochar in composites, plastics, textiles, and other materials is recognized as temporary C-sinks with limited permanence and requires lifecycle monitoring and registration.	Includes 1. tracking and digital monitoring, 2. Cumulative emissions offsetting before C-sink registration, 3. Approved matrix positive list 4. Certification and auditing, 5. Landowners' consent 6. Diffuse C-sink labeling to avoid double counting
Global Artisan C Sink	6/15/2024	Biochar must be applied to soil or other eligible C-sink matrices. It can also be used in construction materials as additive or substitute. Biochar must not be burned or sold for burning purpose.	Biochar carbon consists of a persistent aromatic carbon (PAC) fraction of ~75% that persists >1000 years, and a semi-persistent carbon (SPC) fraction ~25% with a shorter mean residence time of ~50 years.	Application can improve soil fertility, increase climate resilience, and reduce other GHGs. The co-benefits are not currently accounted for in C-sink certification.	Biochar can be used in non-soil matrices such as construction materials (cement, asphalt, plastics), where carbon is locked as long as materials persist.	1. Training and certification of artisans to ensure low emissions and high biochar quality; 2. Sustainable biomass sourcing; 3. Strict MRV 4. CH_4 emission during pyrolysis must be offset 5. On site inspection and QC.
Puro Earth v2	11/27/2025	Proof that the biochar's end use causes no CO_2 reversal is required, including documentation on the intended application; biochar must be used in applications that preserve carbon storage.	Permanence is calculated > 100-year timeline based on biochar stability. H:C org < 0.2 is considered highly stable and hardly degradable. The permanence factor also depends on soil temperature of the application site. Soil application model is conservatively applied.	Not extensively detailed in the methodology. Co-benefits includes soil health improvement, water retention and wastewater treatment. Environmental impact assessment of the site required.	Non-soil application are allowed in case of C preservation. It may include application as insulation materials, barriers, or additives in wastewater treatment, provided biochar carbon is not oxidized or combusted.	1. Production facilities must undergo audits ensuring sustainability compliance 2. Thorough LCA needed 3. Safe handling of biochar required throughout all the phases 4. Additionality must be demonstrated to ensure removals are a result of carbon finance
Climate Action Reserve (CAR)	3/19/2024	Application must ensure long-term carbon storage. Only end uses mentioned on CAR list with verification eligible.	Permanence defined on a 100-year basis. Carbon stability verified by lab analysis. Permanence factors applied for crediting.	Ancillary GHG and environmental benefits recognized but not credited currently.	1. Eligible if long-term carbon storage is assured. Eligible uses listed in "Eligible Biochar End Uses List." 2. Must meet regulatory and environmental safeguards.	1. Chain of custody tracking is required throughout the production. 2. Sampling frequency linked to production changes 3. Stacking disclosures required 4. Verification includes risk assessments, site visits in every 5 years, and all documentation