



**Clo Carbon
Cymru**

Deep Soil Carbon Sequestration

*An Evidence-Led Methodology for Durable Soil Carbon Storage
in Temperate Agricultural Systems*

Developed By: Clo Carbon Cymru

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Abstract

Agricultural soils are increasingly recognised as a potential sink for atmospheric carbon dioxide; however, long-term experimental evidence demonstrates that soil organic carbon (SOC) accumulation under business-as-usual (BAU) management in temperate regions is inherently constrained.

Long-running field experiments indicate that ambitious targets such as the “4 per 1000” initiative are rarely achievable at scale without exceptional organic inputs or land-use change. In response to these constraints, Clo Carbon Cymru has developed Deep Soil Carbon Sequestration (DSCS) — an evidence-led methodology designed to enhance carbon persistence by deliberately targeting subsoil environments.

DSCS integrates stable carbon forms, principally biochar, with targeted mycorrhizal and melanotic fungal communities, placing them directly into low-oxygen horizons where decomposition is constrained and stabilisation pathways dominate.

By deliberately mimicking the ecological conditions under which the world’s most carbon-rich soils naturally formed, DSCS offers a scientifically defensible, policy-relevant, and carbon-market -compatible pathway to durable soil carbon sequestration.

Organisation Statement: Clo Carbon Cymru

Clo Carbon Cymru is a Wales-based organisation focused on the development and deployment of evidence-led carbon sequestration methodologies within agricultural landscapes. Its work is grounded in soil science, long-term experimental evidence, and conservative carbon-accounting principles. The DSCS methodology described here has been developed in direct response to documented limitations of surface-based soil carbon approaches in temperate systems, with the objective of translating established ecological mechanisms into practical, measurable interventions.

Introduction

Soils contain more carbon than the atmosphere and terrestrial vegetation combined, positioning them as a critical component of global climate mitigation strategies (Lal, 2004). In agricultural systems, however, historic cultivation, drainage, and mechanical disturbance have substantially reduced SOC stocks, particularly in surface horizons. This has driven growing interest in soil carbon sequestration initiatives, including the widely cited “4 per 1000” proposal (Minasny et al., 2017).

While such initiatives have been valuable in elevating soil carbon on scientific and policy agendas, empirical evidence from temperate agriculture consistently demonstrates that SOC gains under BAU management are modest, spatially variable, and difficult to verify at scale (Powlson et al., 2018; Bellamy et al., 2005).

Recognising this discrepancy between aspiration and observation, Clo Carbon Cymru has adopted a deliberately conservative, science-first approach, grounding its methodology in long-term experimental evidence, soil ecological theory, and robust carbon-accounting principles. Rather than seeking incremental surface accumulation, the work focuses on engineering durable carbon sinks by targeting subsoil environments where carbon turnover is inherently slower and persistence mechanisms are well established.

Constraints on Business-As-Usual Soil Carbon Sequestration

SOC as a constrained equilibrium: SOC stocks represent a dynamic balance between carbon inputs from plants and losses through microbial respiration, erosion, and oxidation. In most temperate agricultural systems, this balance approaches equilibrium under established rotations and management regimes, resulting in limited net SOC change over decadal timescales (Bellamy et al., 2005).

Meta-analyses show that practices such as reduced tillage, residue retention, and cover cropping can enhance soil function, but rarely produce sustained, whole-profile SOC increases without continued intervention (Poeplau & Don, 2015). Gains are typically concentrated in surface layers, which are also the most vulnerable to disturbance and climatic variability. These observations underpin the adoption of a conservative BAU sequestration baseline of approximately $1 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$, consistent with UK and European evidence and aligned with precautionary accounting frameworks.

Long-term evidence from Rothamsted and the “4 per 1000” debate: The most comprehensive evaluation of achievable SOC increases in temperate agriculture comes from long-term experiments at Rothamsted Research. Powlson et al. (2018) demonstrated that annual SOC increases equivalent to the “4 per 1000” target were achieved only under specific, non-representative conditions, notably sustained applications of large quantities of farmyard manure.

Even where high rates were observed, scalability was constrained by the availability of organic inputs, economic feasibility, and trade-offs with food production. Moreover, much of the SOC increase occurred in surface horizons, with limited transfer to deeper, more stable pools. From a policy and market perspective, these findings indicate that uniform attainment of ambitious surface-based SOC targets is unlikely under existing farm structures, reinforcing the need for approaches that deliberately target mechanisms of carbon persistence.

Conservative Baselines, Additionality, and Deliberate Intervention

Accurate SOC measurement is inherently challenging. Small annual changes can be obscured by spatial variability, bulk density shifts, and sampling uncertainty (CarbonPlan, 2020). Clo Carbon Cymru therefore adopts conservative baselines to avoid crediting changes that may reflect natural variability rather than intervention-driven sequestration.

Exceeding BAU sequestration rates in a credible manner requires intentional management change that alters one or more fundamental controls on SOC persistence:

- (i) the addition of known quantities of stable carbon;
- (ii) enhanced physical and biochemical protection; and
- (iii) placement of carbon in soil environments with intrinsically slow turnover.

These principles form the scientific and accounting foundation of DSCS.

Deep Soil Carbon Sequestration

Deep Soil Carbon Sequestration is a hypothesis-driven intervention designed to operationalise established mechanisms of soil carbon stabilisation in subsoil environments. DSCS involves the precision placement of stable carbon forms — principally biochar — into horizons typically between 15 and 100 cm, where oxygen availability, microbial activity, and disturbance are substantially reduced.

Crucially, DSCS is explicitly biomimetic. By delivering carbon and biological partners directly into low-oxygen zones, DSCS mimics the conditions under which the world's most carbon-rich soils were originally formed, rather than attempting to force persistence in highly dynamic surface layers.

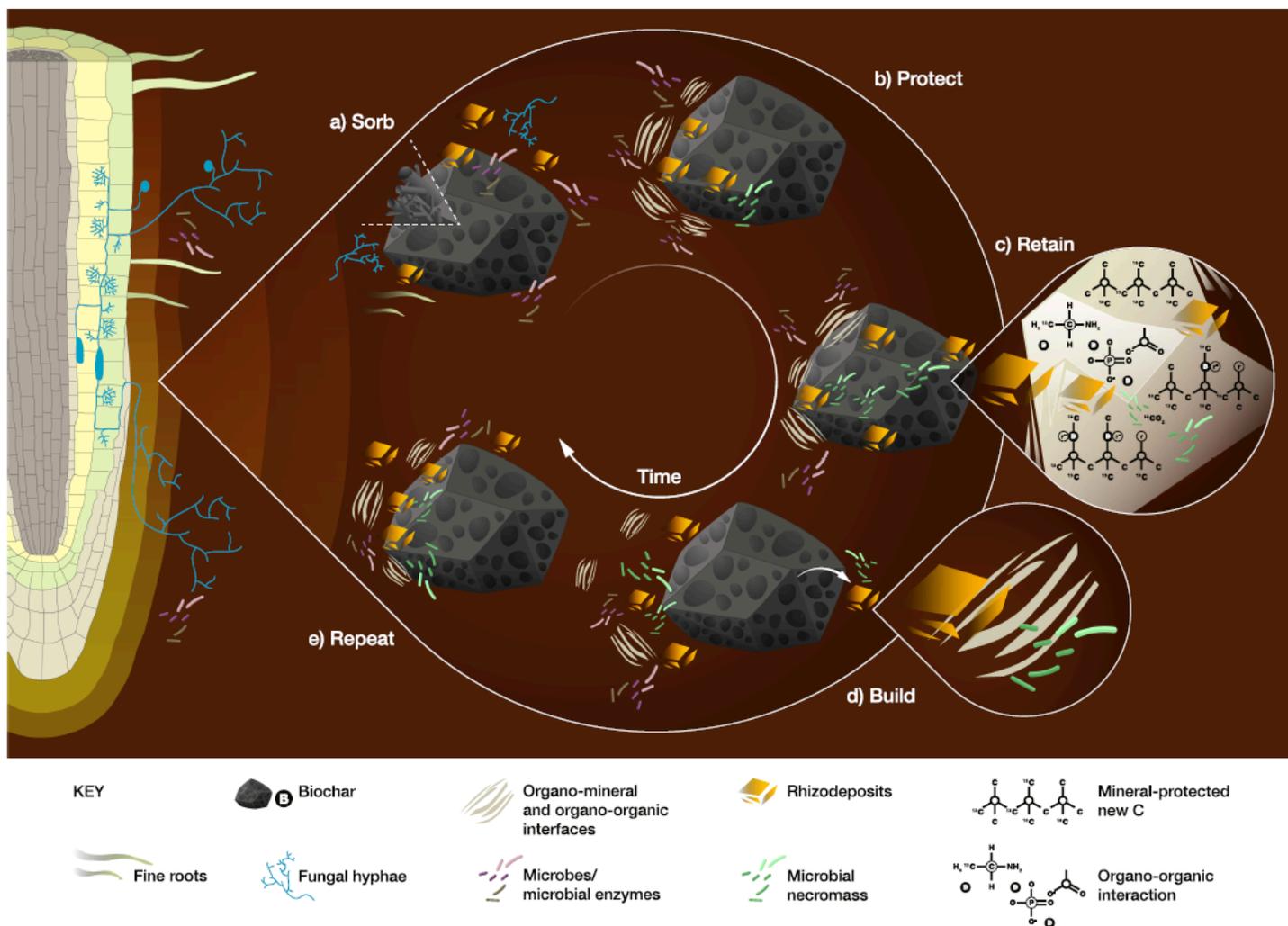


Figure 1 (adapted from Weng et al., 2022) illustrates the microscale processes underpinning this approach, showing how biochar surfaces sorb organic carbon and promote the formation of protected organo-mineral complexes over time.

Fungal Integration as a Core Design Feature

Mycorrhizal fungi and carbon transfer: A defining feature of the DSCS methodology is the intentional integration of mycorrhizal fungi. Mycorrhizal networks act as conduits for plant-derived carbon, transporting it away from the rhizosphere into protected microsites. Recent global estimates suggest that 4–20 % of plant-fixed carbon is allocated to mycorrhizal mycelium (Soudzilovskaia et al., 2023).

Christine Jones has long emphasised that mycorrhizal fungi function as primary agents of soil carbon transfer and aggregation, channelling liquid carbon into stable pools (Jones, 2009). The DSCS methodology translates this ecological insight into practice by co-locating fungal inoculants with biochar at depth, creating conditions conducive to long-term carbon stabilisation.

Fungal necromass and melanin-rich persistence: Contemporary soil science increasingly recognises microbial necromass as a dominant contributor to stable SOC (Liang et al., 2017; Kallenbach et al., 2016). Fungal necromass,

particularly from melanotic fungi, is chemically complex and resistant to decomposition. Melanin-rich residues persist in soil and associate strongly with mineral surfaces, enhancing carbon longevity (Butler et al., 2009; Fernandez & Kennedy, 2016). The deliberate inclusion of melanotic fungi within DSCS reflects a strategy to enhance biochemical recalcitrance alongside physical protection, strengthening carbon permanence.

Biochar–fungal synergies: Biochar provides a porous, chemically stable scaffold that supports fungal colonisation. Experimental studies show that arbuscular mycorrhizal fungi readily colonise biochar particles, enhancing aggregate formation and carbon retention (Hammer et al., 2024). Microspectroscopic evidence demonstrates that fungal activity increases the incorporation of plant-derived carbon into biochar-associated and mineral-bound fractions (Weng et al., 2022). Within DSCS, biochar and fungi function synergistically: biochar provides habitat and sorptive capacity, while fungi actively transport, transform, and stabilise carbon in situ.

Depth-Specific Carbon Permanence and Agronomic Benefits

While most biochar certification standards accept surface application or shallow incorporation as valid carbon sequestration methods, our practice of burying biochar at depths of between 15 and 100cm offers significantly superior carbon permanence. Scientific research demonstrates that deeper soil placement reduces biochar's exposure to the primary degradation mechanisms that occur at the surface: oxygen availability, UV radiation, microbial decomposition, and physical loss through wind and water erosion.

Studies explicitly warn that top-dressing biochar to soil is likely to increase erosion of the biochar particles both by wind (dust) and water, representing a direct loss of sequestered carbon (International Biochar Initiative).

Furthermore, microbial activity — which can gradually decompose even stable biochar — decreases substantially with soil depth. Guidelines from the International Biochar Initiative specifically note that "if biochar were to be applied to soil solely for carbon sequestration purposes, placement deeper in the soil... would be desired since microbial activity that can degrade biochar carbon is reduced deeper in the soil profile."

Research confirms that biochar mineralisation rates decrease significantly with depth, with one study showing reductions of 12.3% at 0-20cm, 8.5% at 20-40cm, and 30.5% at 40-60cm (Kuzyakov, Y., et al, 2014). By deliberately burying biochar deep, we protect it from surface disturbances, prevent physical loss, and create conditions that maximize its millennia-scale carbon storage potential.

Superior Plant Performance Through Root-Zone Placement

Beyond carbon sequestration, deep biochar burial delivers remarkable agronomic benefits that surface application simply cannot match. Groundbreaking research on biochar application depth demonstrates that incorporating biochar at 15-20cm depth produces dramatically better plant growth outcomes than shallow placement. Studies show that biochar applied at 20cm depth increased maize root length by 48.2%, root volume by 42.7%, and root dry biomass by an impressive 56.7% compared to controls — with these benefits substantially exceeding those achieved at 5-10cm depths (Bera, T., et al., 2017).

This depth places biochar precisely within the active root zone where it can most effectively retain water and nutrients for plant uptake throughout the growing season. Deep placement maintains consistent soil moisture across the entire root zone rather than just the surface, with research confirming that "biochar incorporated up to 15-20cm depth maintained more soil moisture in the complete root zone, which increased relative water content in both root and shoot." (Bera, T., et al., 2017).

The mechanisms are clear: biochar at depth creates an ideal rhizosphere environment by improving nutrient availability, enhancing water retention where roots actively forage, and reducing the metabolic cost to plants that would otherwise need to develop extensive deep root systems in search of resources. While surface-applied biochar may wash into the soil profile gradually over years, our deliberate deep burial immediately places this powerful soil amendment exactly where it delivers maximum benefit to plant productivity and resilience.

Implications for Policy, Carbon Markets, and Practice

While aspirational targets such as "4 per 1000" have been valuable in shaping discourse, long-term evidence suggests that policy frameworks must distinguish between incremental soil health gains and durable carbon removal. DSCS aligns with precautionary principles by prioritising permanence, verifiability, and conservative baselines over optimistic projections.

For carbon markets, DSCS addresses common critiques of soil carbon credits by relying on documented carbon inputs placed in low-disturbance environments, reducing exposure to reversal and measurement uncertainty.

Conclusion

Long-term experimental evidence demonstrates that BAU soil management delivers limited SOC gains in temperate agriculture. In response, Clo Carbon Cymru has developed Deep Soil Carbon Sequestration — an evidence-led methodology that deliberately targets the ecological mechanisms responsible for carbon persistence. By integrating stable carbon forms with mycorrhizal and melanotic fungi in low-oxygen subsoil environments, DSCS mimics the processes that formed Earth's most carbon-rich soils. As such, DSCS represents a scientifically credible, policy-relevant, and market-compatible pathway for durable soil carbon sequestration.

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