WHITE PAPER

Rootella Carbon®

Durable Carbon Removal Through Mineral-Associated Soil Carbon

How mycorrhizal inoculation builds mineral-associated organic matter (MAOM), the soil carbon pool that is durable from centuries to millennia, on par with biochar

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Executive summary

Soil carbon credits have traded at a discount to engineered removals for one reason: durability. Carbon added by practice changes such as cover crops and reduced tillage lands mostly in particulate organic matter (POM), the faster-cycling pool of soil organic carbon (SOC), whose gains can reverse when practices lapse. Buyers cannot tell that carbon apart from carbon that will still be in the ground in two centuries, so they price all soil carbon as if it were the former.

This paper sets out why Rootella Carbon® is different. Rootella Carbon is a Verra-registered program that inoculates row crops with concentrated arbuscular mycorrhizal fungi (AMF). The fungi extend the crop's root system by one to two orders of magnitude, receive up to a fifth of the carbon the plant fixes, and deliver it directly to the clay and silt surfaces where it is stabilised as mineral-associated organic matter (MAOM). MAOM is durable from centuries to millennia, and it is the pool that gives soil the same durability class as biochar.

Key findings

Durability. MAOM is durable from centuries to millennia, the same durability class as biochar. It turns over roughly ten times more slowly than particulate organic matter (POM), and radiocarbon dating shows mineral-bound carbon in agricultural soils that is hundreds to thousands of years old, far beyond the 200-year threshold used for durable removal. [12, 13, 14, 26]

Measured sequestration. In the Rootella Carbon program, annual soil organic carbon (SOC) remeasurement against paired control fields shows net sequestration of 2.82 tCO_2e per acre (2023→2024) and 2.39 tCO_2e per acre (2024→2025) after uncertainty deductions under Verra VM0042 v2.0 — four to ten times typical regenerative-practice rates.

Carbon lands in the durable pool. About 90% of the soil carbon in Rootella Carbon enrolled fields is MAOM, and measured gains indicate that new carbon is entering the same pool — more than 60% of it into the durable component. Sections 6 and 10 set out the evidence and its limits.

Headroom. Cropland holds the highest MAOM share of any ecosystem yet is only ~31% saturated with respect to its mineral storage capacity — and its mycorrhizal networks are roughly half as dense as in wild ecosystems [9, 35]. Both the storage capacity and the biological machinery that fills it are under-used, and both are restorable.

The argument, in four steps

1. Mycorrhizae are the key pathway of carbon into soil. Up to a fifth of what the plant fixes flows to the fungi, whose hyphae deliver it directly onto mineral surfaces [5, 7, 29].

2. The effect size is measured. Rootella Carbon fields show 2.82 and 2.39 tCO_2e per acre per year net of paired controls [4]; independently, AMF inoculation raised SOC by +21.5% across 62 published trials [6].

3. The receiving pool is overwhelmingly MAOM. ~85% of cropland SOC and ~90% in Rootella Carbon enrolled fields [10], with roughly two-thirds of that stock in the durable component (Section 6.3).

4. So the tonnes created are mostly durable. Measured gains are consistent with roughly nine of every ten new tonnes entering the mineral-protected pool, more than 60% into its durable component — durable from centuries to millennia, on par with biochar.

Sections 6 and 7 make the durability case in detail, including the distinction between the whole MAOM pool and its persistent fraction, the evidence for each, and the parallel with how biochar registries credit the persistent fraction of biochar. The remaining sections cover mechanism, measurement and program design. Appendices provide definitions, conversions and full references.

1. The durability problem in soil carbon

Soil is the second-largest carbon sink on Earth and the largest on land. Since the spread of agriculture, cultivated soils have released an estimated 400–490 $GtCO_2e$ to the atmosphere, and agricultural soils today hold 25–75% less organic carbon than they did under native vegetation [1, 2]. Estimates of the capacity of agricultural soils to re-sequester carbon range up to 8 $GtCO_2e$ per year [3].

The size of that opportunity has not translated into buyer confidence, because most soil-carbon programs rely on management changes whose gains accrue largely in particulate organic matter. Meta-analyses consistently show that cover crops, no-till and cropping intensification raise particulate carbon two to four times more than mineral-associated carbon [23, 24], and that the two fractions are only weakly coupled: an increase in POM does not imply a proportional gain in MAOM [25]. POM responds fast, but it also reverses fast. The question this paper answers is how to direct new carbon into the pool that lasts, and how to demonstrate that it got there.

2. The Rootella Carbon program

Rootella Carbon is a soil carbon program registered with Verra under VM0042 v2.0, the Methodology for Improved Agricultural Land Management, for 40 years (20 years crediting + 20 years monitoring), covering the United States and Canada [4]. In 2025 Rootella Carbon enrolled approximately 300,000 acres across more than 150 row-crop growers.

2.1 The product

Rootella® is a highly concentrated inoculant of vigorous arbuscular mycorrhizal fungi (AMF) strains, applied to row crops as a soil amendment or seed treatment. Once established, the fungi form mycelial networks (hyphae) that attach to and effectively extend the crop's root system, improving water and nutrient uptake, soil structure and fertility [45, 46], and channelling plant carbon into the mineral soil.

2.2 The measurement design

Rootella Carbon is built on a controlled, measured field design rather than on modelled outcomes:

1. **Treatment.** Growers apply Rootella to enrolled fields each season, with no change in tillage, rotation or other practices required.
2. **Paired controls.** Growers leave comparable fields untreated. Controls are sampled alongside treated fields to isolate the effect of inoculation from weather and management.
3. **Measure and remeasure.** SOC is measured annually across all enrolled fields from a 2023 baseline. Sequestration is estimated as a difference-in-differences: the change between years in treated fields, net of the change in control fields.

In parallel, and outside the crediting program, Groundwork BioAg runs a scientific MAOM fractionation campaign on a subset of the same fields (Section 10) — so that the pool receiving the new carbon is measured, not assumed.

3. From atmosphere to mineral surface: the mycorrhizal pathway

Plants fix atmospheric CO_2 into carbohydrates through photosynthesis. In symbiosis with mycorrhizal fungi, plants transfer a substantial share of those photosynthates, up to 20%, to the fungal partner in exchange for water and nutrients [5, 29]. The hyphae extend the effective root system by a factor of 10 to 100 and, critically for durability, move plant carbon and microbes to mineral microsites that roots never reach [21].

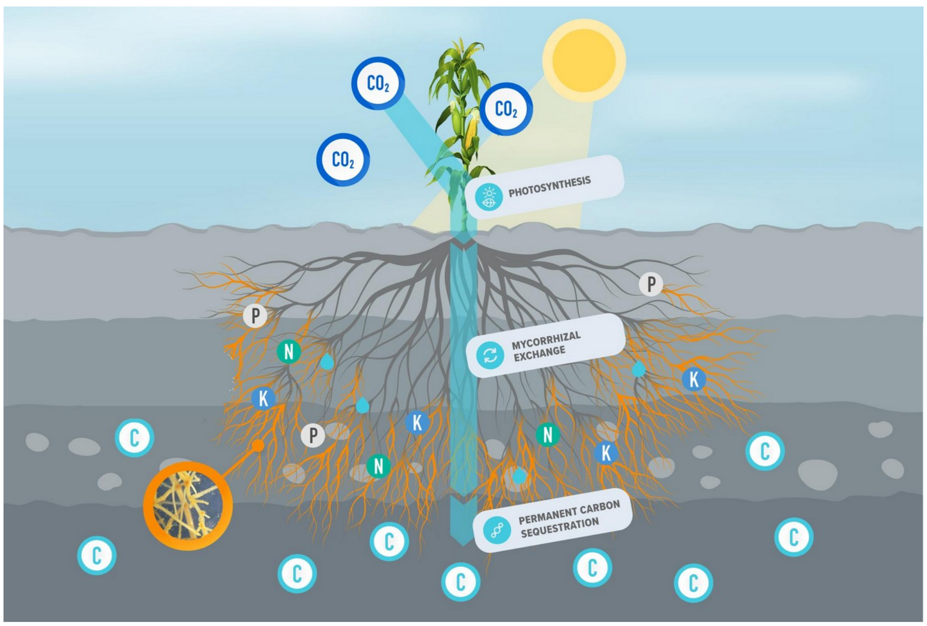

Figure 1. A key pathway of plant carbon into the soil. Photosynthate is allocated to mycorrhizal fungi, whose hyphae transport carbon away from the root zone and into the mineral soil. Illustration: Groundwork BioAg.

At the global scale, Hawkins et al. (2023) estimate that 13.1 $GtCO_2e$ of plant carbon is allocated to mycorrhizal mycelium each year, roughly a third of annual fossil-fuel emissions [5]. The first global maps of these networks, produced by SPUN and AMOLF using machine learning and automated imaging, estimate some 110 quadrillion kilometres of fungal filaments woven through the world's soils [34, 35]. This is carbon flowing through the fungal network rather than net storage; Sections 6 to 9 address how much is retained and in what form.

4. Evidence that mycorrhizae increase soil organic carbon

The most comprehensive synthesis to date is the meta-analysis by Conti et al. (2025), which compiled 62 trials from 19 studies that directly manipulated the mycorrhizal status of crops [6]. Across all trials, mycorrhizal treatment increased SOC by an average of 21.5%. The effect was statistically significant in pot experiments; in field experiments it was positive but more variable, and modulated by soil texture and organic-matter content.

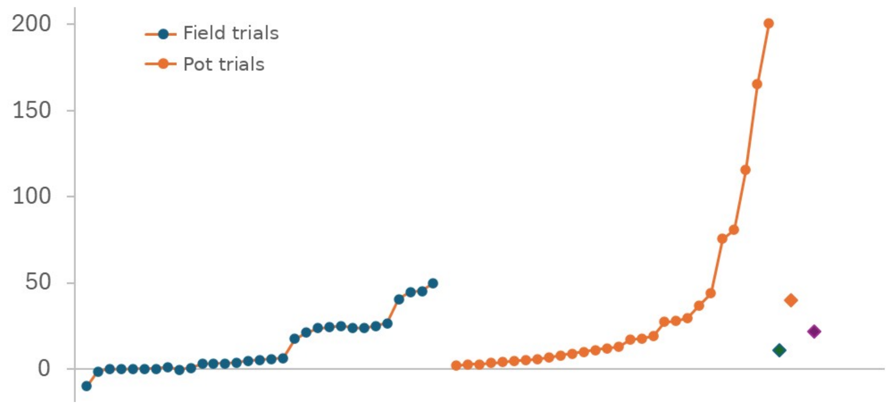

Figure 2. Percentage change in SOC after mycorrhizal treatment in 62 trials. Diamonds show the pooled effect for field trials (green), pot trials (orange) and all trials (purple). Adapted from Conti et al. (2025), Fig. 2 [6].

Field responses are generally positive but more variable than pot trials and depend on soil properties and management conditions [6, 39]. That variability is precisely why Rootella Carbon measures every enrolled field against a paired control rather than relying on a modelled response function.

5. Measured sequestration in enrolled fields

Table 1 summarises the sequestration measured in Rootella Carbon's first two remeasurement cycles. Values are net of control fields and reported after the deduction of measurement uncertainty required by VM0042 v2.0 [4]. Every value is ground-truth soil sampling, measured and remeasured — no modelled estimates.

Period	Design	Net SOC sequestration
2023 → 2024 (Year 1)	Treated vs. paired control, difference-in-differences	2.82 tCO_2e / acre
2024 → 2025 (Year 2)	Treated vs. paired control, difference-in-differences	2.39 tCO_2e / acre

Table 1. Measured soil organic carbon sequestration, Rootella Carbon program, after Verra uncertainty deductions.

Figure 3 places these values in context. Regenerative practices typically deliver 0.25–0.75 tCO_2e per acre per year [31]. Published meta-analyses do not establish a general field-scale AMF sequestration range in these units — responses are site-specific [6, 39] — so Groundwork BioAg maintains its own expected range for AMF inoculation, 1.5–3.5 tCO_2e per acre per year, synthesised from inoculation trials and program measurements [32]. Both measured Rootella Carbon results fall within that expected range, and are four to ten times the practice-change range. Credited volumes rest solely on the measured, project-specific values.

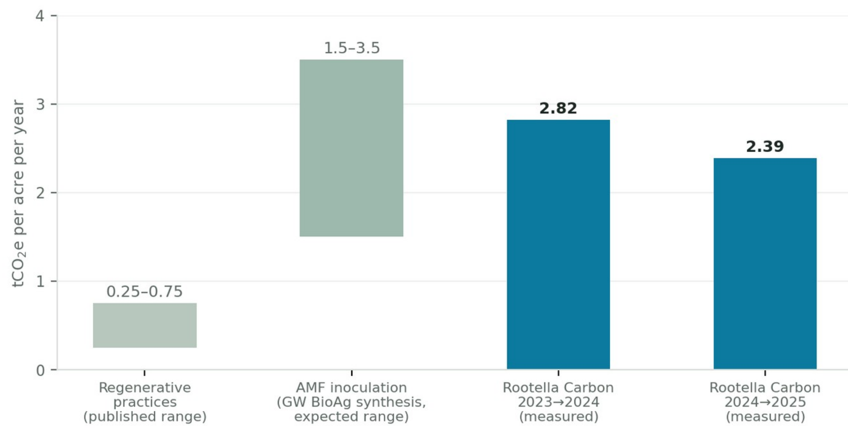

Figure 3. Measured sequestration in Rootella Carbon against the published regenerative-practice range [31] and Groundwork BioAg's expected range for AMF inoculation [32]. Grey bars: ranges; blue bars: project-specific measurements.

6. MAOM: the durable pool

Soil organic carbon is not a single pool. Modern soil science partitions it into two functionally distinct fractions that differ in how they form, where they sit and how long they last [7, 8, 17]:

- **Particulate organic matter (POM)** consists of partially decomposed roots and litter, loosely held within aggregates and accessible to microbial decomposition. Its mean turnover time is about 23 years globally [13], with a slower fraction persisting toward a century.
- **Mineral-associated organic matter (MAOM)** consists of dissolved organic carbon and microbial necromass chemically bound to clay and silt surfaces. Its mean turnover time is about 129 years globally [13], and its persistent fraction, the carbon most strongly bound to minerals, is centuries to millennia old by radiocarbon dating [12, 14].

	MAOM	POM
What it is	Mineral-associated organic matter	Particulate organic matter
How it forms	Dissolved organic carbon and microbial necromass, largely via mycorrhizae and microbes	Decaying roots and litter
Where it is	Bound to clay and silt mineral surfaces	Loosely held in aggregates
Exposure to decomposition	**Protected**	**Accessible**
Size fraction	< 53 µm	> 53 µm
Mean turnover (global)	~129 years [13]	~23 years [13]
Durability	**Centuries to millennia [12, 14]**	Decades, toward a century for the slower fraction
Share of SOC, global	~60–75% [10, 13, 33]	~25–40%
Share of SOC, cropland	~85% [10]	~15% [10]

Table 2. The two main pools of soil organic carbon. Sources: Cotrufo et al. (2019) [7]; Lavallee et al. (2020) [8]; Hansen et al. (2024) [10]; Shi et al. (2020) [12]; Zhou et al. (2024) [13]; Schrumpf et al. (2021) [14].

MAOM is the dominant pool, and its dominance grows as one approaches Rootella Carbon's own fields. Globally, MAOM holds roughly 60–75% of soil organic carbon [10, 13, 33]. In croplands the share rises to about 85%, because decades of disturbance have preferentially stripped out POM [10]. In enrolled fields, the 2025 fractionation campaign measured approximately 90% (Section 10). At every scale, most soil carbon already sits in the durable pool — and most of all in the soils Rootella Carbon works.

6.1 Why MAOM persists

Three mechanisms are repeatedly identified as the drivers of MAOM persistence [7, 17, 18]:

1. **Organo-mineral association.** Organic compounds, usually after microbial processing, bind to reactive mineral surfaces through sorption, cation bridging and chemical bonding. Binding removes them from the reach of decomposers.
2. **Physical protection.** MAOM accumulates in microaggregates and fine pores where the diffusion of enzymes and substrates is constrained. Persistence reflects spatial inaccessibility as much as chemical recalcitrance.
3. **Microbial processing as the gateway.** MAOM forms most efficiently when plant inputs are transformed into small molecules and microbial residues that interact readily with mineral surfaces. Fungal residues are more effective MAOM precursors than plant residues [19].

6.2 Turnover vs. durability, in plain terms

The two headline numbers in this paper — a mean turnover of about 129 years and durability of centuries to millennia — describe different things, and confusing them is the most common mistake made with soil carbon. Turnover is an average speed. Durability is about how long the stabilised carbon stays. Both statements are true at the same time, because MAOM is not one kind of carbon. Throughout this paper, durable from centuries to millennia denotes retention on timescales of roughly 200 to 1,000 years — the medium-durability band of carbon-removal taxonomies, and the band biochar occupies — while radiocarbon ages of mineral-bound carbon in agricultural soils extend well beyond it, to several thousand years [12, 14].

The bathtub and the ice

Turnover answers: how fast does carbon move through the pool on average? Take all the carbon in MAOM and divide it by the flow passing through: about 129 years [13]. It is a single average taken over a very unequal population.

Durability answers: how long does carbon stay once it is stabilised? MAOM holds two kinds of carbon: a weakly held, fast-cycling share that exchanges within years to decades [16], and a strongly mineral-bound share that stays for centuries to millennia [12, 14]. The average sits between the two and describes neither.

The picture to keep in mind: a bathtub with the tap running and the drain open. Turnover is how long the average drop spends in the tub. Now let a thick layer of ice freeze onto the walls: the flowing water still cycles quickly, the ice barely moves at all, and the average time in the tub — somewhere in between — describes neither the water nor the ice. MAOM's persistent fraction is the ice, and the

> mineral bond is what freezes it in place.

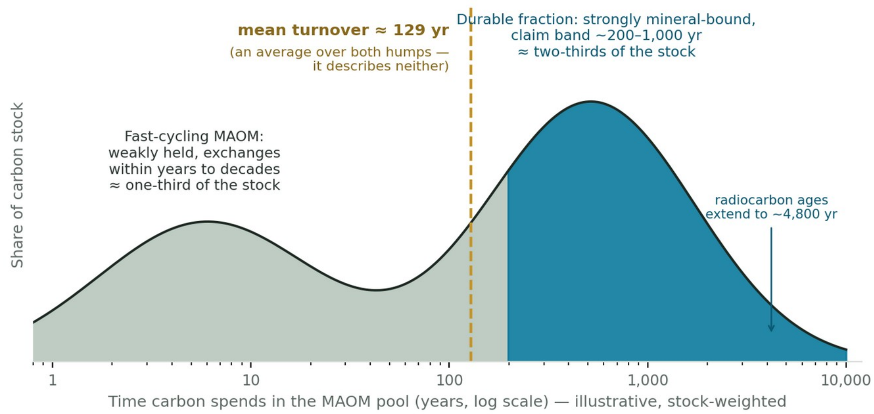

Figure 4. Why one pool carries two numbers. An illustrative, stock-weighted distribution of how long carbon spends in the MAOM pool: a fast-cycling hump (years to decades) and a persistent hump (centuries to millennia). The mean turnover of ~129 years [13] is an average over both and corresponds to neither; consistency with that mean requires the persistent hump to hold roughly two-thirds of the standing stock (Section 6.3). The durability claim is about the blue hump — drawn in the 200–1,000-year claim band, with radiocarbon evidence extending beyond [12, 14].

6.3 How big is the persistent fraction?

Two different questions hide inside this one, and they have answers of very different maturity.

The standing stock. The mean turnover itself constrains how much of today's MAOM can be fast carbon, because turnover is flux-weighted: fast carbon dominates the flow, slow carbon dominates the stock. In a two-component pool whose overall mean turnover is ~129 years [13], a fast component cycling in ~10 years can make up at most roughly 5–10% of the stock, and even a slower fast component (~30–40 years) at most roughly 25–35% — otherwise the pool's mean would collapse toward decades. Under any reasonable assumption, roughly two-thirds or more of the standing MAOM stock sits in the slow, century-plus component. Recent evidence agrees qualitatively: the majority of MAOM is highly persistent, although the relative sizes of its faster- and slower-cycling components remain context-dependent and are not yet directly quantifiable [16]. The radiocarbon record is consistent: a carbon-weighted mean age of ~4,800 years for top-metre soil carbon [12], mineral-bound ages of centuries to millennia even in topsoil [14], and isotope evidence that only about half of topsoil carbon derives from the last ~50 years — with that young half disproportionately POM [36]. In absolute terms, two-thirds of the ~900–975 Pg C of global MAOC (mineral-associated organic carbon — the carbon held in MAOM) [9, 13] is on the order of 600 Pg C, roughly 2,200 $GtCO_2e$, already resident in the centuries-to-millennia component. These shares are derived from the turnover arithmetic and the age record, not taken from a single published estimate, and are labelled accordingly.

Newly added carbon. Two numbers describe the fate of a newly sequestered tonne. Approximately 90% of the existing SOC stock in enrolled fields sits in the operational MAOM fraction (Section 10), and the measured SOC gains are consistent with new carbon entering the two pools in the same proportion — implying that roughly 90% of the increase is associated with MAOM. This is an interpretation of field data rather than a direct flux measurement (controlled-system isotope tracing has measured lower direct-transfer shares, ≤33% [20]). On this interpretation, and applying the persistent-fraction share derived above, more than 60% of newly sequestered carbon is associated with the durable component

— carbon persisting beyond the ~200-year threshold — placing the result within the 60–90% range that biochar registries credit as remaining at 100 years through the H/C-based permanence factor [26, 27]. At the 200-year threshold the qualifying share of the pool exceeds the two-thirds multi-millennial core used above, so 60% is a floor. Transit-time theory cautions that new inputs lean toward the faster component [15]; against that, carbon delivered by fungal hyphae is preferentially stabilised — fungal residues contribute more to MAOM than plant residues [19], and hyphae place carbon directly onto mineral surfaces [20, 21] — so the true durable share of inoculant-driven carbon is likely higher still. Both figures rest on measured stocks, measured SOC change and published turnover values.

6.4 How long: the evidence

With that distinction in place, two independent lines of evidence establish the timescale, and they answer the two different questions.

Turnover of the pool. A global analysis that explicitly separated mineral-associated and particulate carbon in the top metre of soil estimated mean turnover times of ~129 years for MAOC and ~23 years for particulate organic carbon (POC) [13]. MAOM is the slow pool by an order of magnitude, and its mean turnover alone exceeds the 100-year horizon used by most durable-removal standards.

Age of the persistent fraction. Radiocarbon dating shows that mineral-bound carbon in agricultural soils is hundreds to several thousand years old, and that the most strongly bound, least extractable fraction is the oldest [14]. At the global scale, the carbon-weighted mean age of soil carbon in the top metre is ~4,800 years [12]. This is the direct evidence that the persistent fraction of MAOM lasts centuries to millennia.

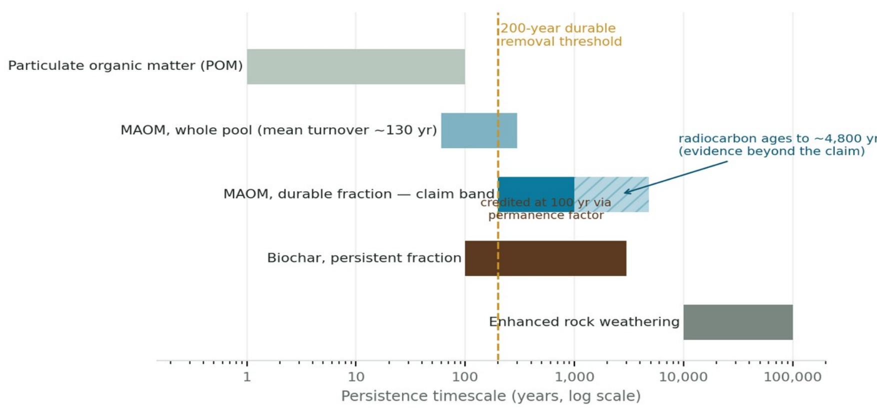

Figure 5. Persistence timescales of soil carbon pools and removal pathways. POM and MAOM whole-pool ranges after Zhou et al. (2024) [13]; biochar persistent fraction from Lehmann et al. (2021) [26]. Dashed line: 200-year durable-removal threshold. MAOM durable fraction is drawn as the 200–1,000-year claim band, with radiocarbon evidence [12, 14] shown beyond it; the POM bar extends toward a century for its slower fraction (derived). See the definition in §6.2.

6.5 Only part of MAOM, and why that is the right claim

MAOM is not chemically uniform. Recent work demonstrates a fast-cycling component of mineral-associated carbon that turns over on short timescales while remaining mineral-bound, alongside the persistent component that carries the long-lived storage signal [16]. Method-comparison studies likewise show that operational fractions contain mixtures of older and younger carbon [14]. The durability claim in this paper is therefore made about the persistent fraction of MAOM, not about every atom in the pool.

Far from weakening the case, this is what makes MAOM comparable to biochar, and it is how biochar is already credited (Section 7). A second distinction matters for the same reason: the age of carbon already in the pool and the expected residence of carbon entering it are different quantities [15]. The radiocarbon ages describe the persistent fraction; the ~129-year mean turnover describes the pool as a whole.

6.6 Durability, permanence and reversal risk

Residence time describes how long carbon stays in a pool under current conditions; permanence describes the likelihood that it remains under future conditions, including changes in management and climate [15]. MAOM scores well on both. On the permanence side, mineral association provides strong protection: particulate carbon is roughly 28% more temperature-sensitive than mineral-associated carbon [40]. Mineral association reduces rather than eliminates vulnerability — warming, moisture and pH shifts, rhizosphere activity and management can destabilise organo-mineral associations [41, 42, 43] — but the most disruptive agent in cropland is tillage, precisely the disturbance absent from the no- and reduced-tillage acres on which Rootella Carbon operates. Where soils have both mineral capacity and stable protection environments, which is the case across the North American row-crop belt (Section 8), the persistent fraction is expected to remain in place on timescales relevant to carbon accounting [9, 10, 18].

7. On par with biochar

Biochar is the reference point for durable nature-based removal, and it is instructive that biochar's durability is established in exactly the way this paper establishes MAOM's. Biochar is not uniformly persistent. It contains a labile fraction that decomposes within years to decades and a persistent, highly aromatic fraction that lasts centuries to millennia [26]. Registries credit the persistent fraction: Puro.earth applies a permanence factor derived from the biochar's hydrogen-to-organic-carbon ratio to estimate the share remaining after 100 years, and credits only that share [27].

	Biochar	Mineral-associated soil carbon (MAOM)
Fast-cycling fraction	Labile, aliphatic carbon; decomposes in years to decades	Weakly bound, exchangeable carbon; turns over in years to decades [16]
Persistent fraction	Condensed aromatic carbon	Carbon strongly bound to clay and silt surfaces and occluded in microaggregates
Persistence of that fraction	Centuries to millennia [26]	Centuries to millennia [12, 14]
What protects it	Chemical recalcitrance	Organo-mineral bonding and physical inaccessibility [17, 18]
Reversal risk	Low; independent of subsequent land management	Low: mineral association strongly protects — particulate carbon is ~28% more temperature-sensitive than mineral-associated carbon [40]. Destabilisation requires disturbance,

	Biochar	Mineral-associated soil carbon (MAOM)
		chiefly tillage — absent from the no/low-till acres Rootella Carbon works [41–43]
Durable share of new carbon	60–90% credited as remaining at 100 years [27]	More than 60% associated with the durable (>200-year) component (interpretation-based; Sections 6.3, 10); likely higher for fungal-delivered carbon [19–21]
How it is credited	Persistent fraction, via permanence factor [27]	Total SOC, measured and remeasured under VM0042 [4]

Table 3. Biochar and MAOM share the same durability structure: a fast fraction and a persistent fraction, with the persistent fraction lasting centuries to millennia.

The persistent fractions of both pathways occupy the same centuries-to-millennia band. The structure is parallel; only the mechanism differs — chemical recalcitrance for biochar, the mineral bond for MAOM. Both clear the 200-year bar. Where MAOM differs is in cost and co-benefits: it is produced by a biological input that also improves yield resilience and fertility [45, 47], on land already in production, with no feedstock, pyrolysis or transport.

The durability statement

MAOM is durable from centuries to millennia, the same durability class as biochar. Its persistence is a property of the mineral bond rather than of the farming practice: mineral association and micro-scale physical protection remove carbon from the reach of decomposers on timescales far beyond the 200-year durable-removal threshold. Rootella Carbon channels new carbon into this pool and measures it directly.

8. Cropland has the greatest headroom for MAOM

Three independent lines of evidence single out cropland as the ecosystem with the greatest potential for durable soil carbon gains.

- **Highest MAOM fraction.** The share of SOC held as MAOM ranges from 30% to 75% across grassland, shrubland, forest, tundra and wetland; in cropland under soybean and corn it is about 85% [10]. Cropland SOC is MAOM-dominated because decades of disturbance have preferentially stripped out POM.
- **Lowest saturation.** Georgiou et al. (2022) modelled the mineralogical capacity of soils to store MAOM. Global MAOC stocks of ~899 Pg C sit against a capacity of ~1,079 Pg C, and cropland is the most undersaturated ecosystem at ~31% of capacity, against ~50% for forest and grassland [9]. Applied to global cropland area, this implies roughly 381 $GtCO_2e$ of unfilled MAOM capacity (Appendix A).
- **Depleted fungal networks.** The first global maps of arbuscular mycorrhizal network density predict that large-scale croplands carry roughly half the network density of wild ecosystems [35].

Cropland is therefore doubly depleted: the mineral capacity to store MAOM is unfilled, and the biological machinery that fills it is diminished. Inoculation restores the machinery precisely where both deficits coincide.

8.1 Mapping capacity across the United States

Figure 6 shows predicted maximum mineral-associated carbon (MAOC max) across the contiguous United States [9, 11]. Capacity is highest in the North Central region, the eastern Great Plains and the Mississippi Alluvial Plain, the heart of the row-crop belt, and lowest in the arid western Great Plains, the forested upper Great Lakes and Atlantic coastal plain, and sandy soils such as the Nebraska sandhills.

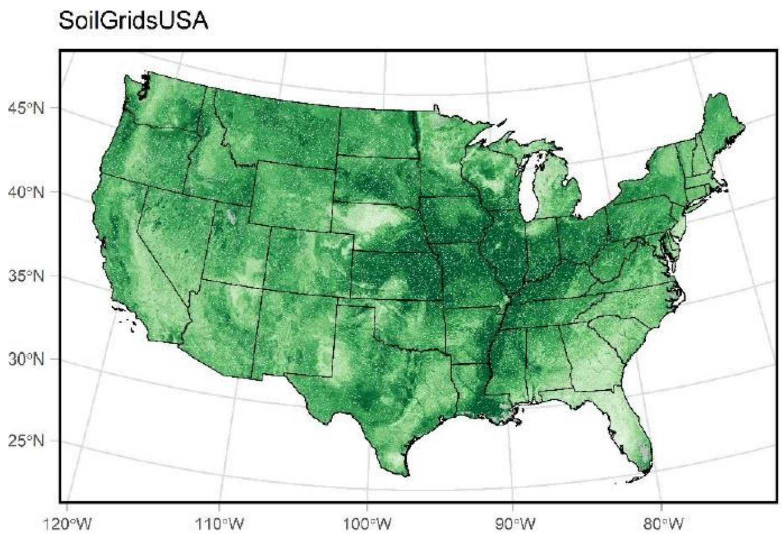

Figure 6. Predicted MAOC max (Mg C ha^{-1}) across the contiguous United States. Source: Spawn-Lee (2023) [11], after Georgiou et al. (2022) [9].

In the high-capacity regions a MAOC max of 75 Mg C per hectare translates to about 110 tCO_2e per acre of storage capacity. If cropland there is ~31% saturated, the remaining headroom is up to ~76 tCO_2e per acre. This is an upper-bound estimate; enrolled fields are assessed against region-specific capacity. Conversions are given in Appendix A. The point for durability is that unfilled mineral capacity is exactly the condition under which new carbon can form the persistent fraction rather than accumulating as POM [9, 25].

9. How mycorrhizae build MAOM

MAOM forms when dissolved organic carbon (DOC) and microbial necromass come into direct contact with exposed mineral surfaces. Both carry functional groups that bind readily to clay particles, forming primary MAOM; additional DOC and necromass then attach as secondary layers [7, 17].

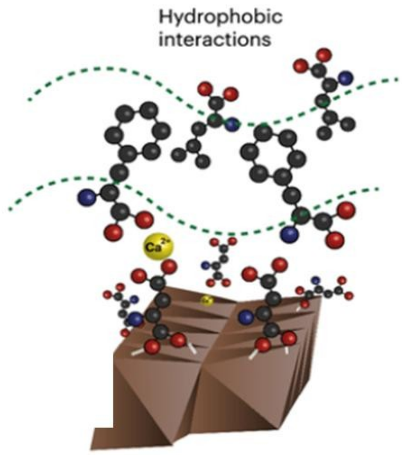

Figure 7. Organic carbon binding to a clay mineral surface through hydrophobic and cation-bridge interactions.

Mycorrhizal fungi are uniquely positioned to drive this process, and recent isotope-tracing work shows it happening directly:

- **Reach.** Hyphae are 1–5 µm in diameter, compared with 500–1,000 µm for fine roots, and traverse 10–100 times the soil volume of the root system. They move carbon and microbes to mineral microsites in the hyphosphere that roots cannot access [21].
- **Direct delivery.** ^{13}C tracing shows arbuscular mycorrhizae convey significant plant carbon to the hyphosphere microbial food web and into mineral-associated organic matter [20].
- **Better precursors.** Stable-isotope studies show fungal residues contribute more to MAOM pools than plant residues do [19]. Hyphal turnover, on timescales of days, is a dominant process for carbon input into soil organic matter [22].
- **Microenvironment.** Glomalin-related proteins and other AMF compounds act as binding agents, supporting aggregate formation and the physical protection of organic matter.

In short, mycorrhizae increase the transfer of plant carbon to the soil, deliver it to the mineral surfaces where it is stabilised, contribute necromass that is itself a superior MAOM precursor, and build the physical structure that protects the result. Each step in the chain, plant allocation → hyphal transport → microbial processing → mineral association, is documented in the recent literature.

10. The MAOM science campaign: measuring the durable pool directly

The Verra-registered Rootella Carbon program credits total SOC; the crediting program does not measure MAOM. To establish where the credited carbon is stored, Groundwork BioAg runs a multi-year scientific MAOM campaign alongside Rootella Carbon, on the same fields but outside the crediting program. POM and MAOM are method-defined operational fractions; Rootella Carbon uses particle-size fractionation at 53 µm, the approach most widely used by external soil-carbon laboratories, and applies it consistently across all samples.

Year	Status	Scope
2025	Complete	1,200 soil samples size-fractionated into POM (> 53 µm) and MAOM (< 53 µm). Rootella-treated fields (1 and 2 years treated) plus untreated controls, spanning a range of total organic carbon, pH, sand content and bulk density.
2026	Planned	3,000 soil samples. First year-over-year comparison (Δ MAOM 2026–2025) against the 2025 baseline; establishes the baseline for 2027 onward; continued sampling of fields treated for 1, 2 and 3 years.

Table 4. The Rootella Carbon MAOM measurement campaign.

10.1 2025 results

The 2025 campaign provides a single time-point snapshot. Three findings stand out:

- MAOM accounts for approximately 90% of total SOC across the sampled fields, consistent with the ~85% literature value for croplands: the dominant pool in these soils is the durable one.
- MAOM% varies across field types mainly through covariates, principally total SOC and pH, so comparisons between field types require covariate adjustment.
- After adjustment, soils treated for one or two years show no statistically significant shift in MAOM % relative to controls.

Read together, the findings point one way: total SOC increased significantly in treated fields, while the cross-sectional results show MAOM holding at approximately 90% of SOC. This is consistent with the interpretation that the SOC increase was distributed between MAOM and POM in roughly the same proportions as the existing stock — implying that about nine-tenths of the sequestration reported in Section 5 is associated with the mineral-protected pool. The 2026 longitudinal remeasurement will test this interpretation using changes in absolute MAOM and POM stocks within the same fields.

10.2 What the 2026 remeasurement will add

A single snapshot cannot resolve whether inoculation channels carbon preferentially into MAOM, or into which sub-fraction of MAOM. Adding roughly 2.5 tCO_2e per acre to a stock of more than 100 tCO_2e per acre shifts MAOM% by only one to two percentage points, below the detection threshold of a cross-sectional comparison. The 2026 remeasurement of the same fields is designed to resolve this with paired, within-field comparisons (Δ MAOM 2026–2025). Taken together with the isotope-tracing evidence that AMF deliver carbon directly into MAOM [20] and that fungal residues are preferentially stabilised [19], the hypothesis under test is that inoculant-driven carbon enters MAOM at or above the baseline proportion.

11. From regenerative agriculture to durable removal

Regenerative practices and mycorrhizal inoculation are not competing approaches but successive layers of the same transition. They differ in the destination of the carbon they add and, consequently, in durability (Table 5).

	Regenerative practices	Mycorrhizal (AMF) inoculation
Practice	Reduced or no tillage, cover crops, perennials in rotation	Rootella® applied to enrolled row-crop fields
Where added carbon goes	Often larger relative increases in POM: cover crops raise particulate organic carbon (POC) ~23% vs MAOC ~5%; no-till ~19% vs ~8% [23, 24]	AMF-mediated pathways may increase the delivery and processing of plant-derived carbon in mineral-associated microsites; fungal residues preferentially form MAOM [19, 20, 21]
Significance of the pool	POM is the small pool: a good indicator of management and fertility	MAOM is the large, dominant pool: changes here matter most for long-term storage
Reversal risk	Susceptible to reversal if practices change	Low: mineral association strongly protects — particulate carbon is ~28% more temperature-sensitive [40]. Destabilisation requires disturbance, chiefly tillage — absent from these acres [41–43]
Durability	Decades, toward a century for the slower fraction	**Centuries to millennia**
Expected rate	0.25–0.75 tCO_2e / ac / yr [31]	**Expected 1.5–3.5 (Groundwork BioAg synthesis [32]); measured 2.82 / 2.39 (project-specific)**

Table 5. Comparison of soil carbon outcomes between practice change and mycorrhizal inoculation.

An evolution of regenerative agriculture. Rootella Carbon is implemented on top of no- and reduced-tillage acres in the US and Canada, mostly in corn and soybean fields, which are depleted of mycorrhizae [35]. Applying Rootella restores the mycorrhizal population. Regenerative practices are the platform: they add carbon inputs and fill the POM pool. On the same acres, Rootella adds the MAOM layer — and the pairing is mechanistically synergistic, not merely additive. Tillage physically disrupts the mycelial networks through which the fungi operate [37, 38]. Low-disturbance fields are therefore precisely the environment in which the introduced mycorrhizal fungal network can establish, persist across seasons and keep delivering carbon to mineral surfaces — and the same low disturbance protects the aggregates and hyphosphere microsites in which MAOM forms and is preserved. Growers who already practise conservation agriculture are not an adjacent audience; they are Rootella Carbon's home ground, and the durable layer is what their platform was missing.

12. Positioning among carbon removal pathways

Carbon dioxide removal methods are commonly classified by storage timescale [28]. Conventional soil-carbon sequestration is placed in the decades-to-centuries band alongside afforestation and wetland restoration, while biochar spans decades to millennia and enhanced rock weathering and geological storage sit at millennia and beyond. Because Rootella Carbon drives carbon into the mineral-associated pool, its removals belong in the same durability band as biochar (Figure 8). Buyer taxonomies draw the same line: Microsoft's carbon-removal criteria class durability as low (under 100 years), medium (100–

1,000 years) and high (beyond 1,000 years). Generic soil carbon is filed as low — 'measured in the span of decades' — while mineral-associated carbon belongs, as biochar does, in the medium band [44].

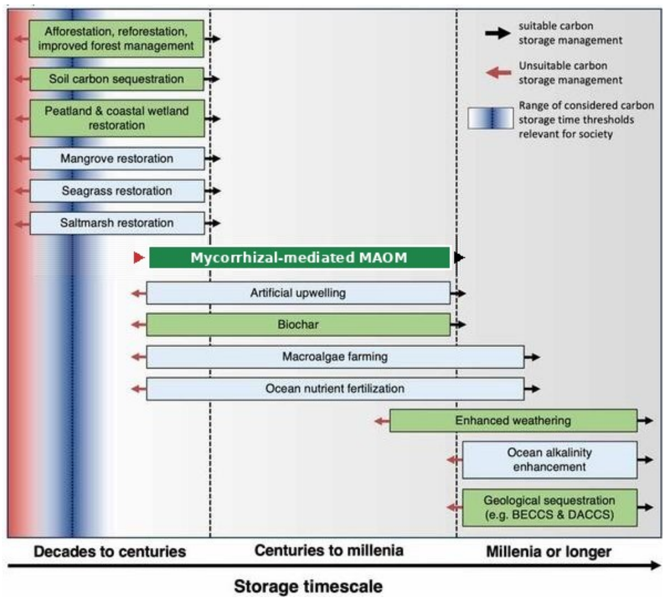

Figure 8. Storage timescales of carbon dioxide removal methods. Adapted from Swoboda & Oschlies (2025) [28]. The green bar is Groundwork BioAg's placement of mycorrhizal-mediated MAOM, spanning the same range as biochar; it is not part of the original figure.

12.1 Defining characteristics

- **Durable.** MAOM is durable from centuries to millennia, the same durability class as biochar.
- **Scalable now.** Approximately 300,000 acres are already enrolled, supporting a capacity of roughly 500,000 VCUs per year from Rootella Carbon as it stands, with no new land, infrastructure or change in farming practice required.
- **Verifiable.** Changes in total SOC are measured against paired controls under Verra VM0042 v2.0 [4], while the parallel MAOM science campaign investigates how newly sequestered carbon is distributed between operational SOC fractions.
- **Cost-effective.** The removal is a by-product of a biological input that also raises yield resilience and fertility, so the cost per tonne is that of a nature-based solution rather than an engineered one.

Rootella Carbon is designed to meet 200-year-plus durability standards and to align with the EU Carbon Removal Certification Framework's carbon-farming provisions [30]; formal assessments are in progress.

13. Conclusion

The case for mycorrhizal-mediated carbon removal rests on six linked propositions, each supported in this paper:

1. MAOM is the durable soil carbon pool: durable from centuries to millennia, on par with biochar, with mean turnover ten times that of POM (Sections 6 and 7).

2. Cropland has the highest MAOM share, the most unfilled mineral capacity, and mycorrhizal networks roughly half as dense as wild ecosystems (Section 8).
3. Mycorrhizal fungi carry plant carbon directly to mineral surfaces, and fungal residues are the preferred MAOM precursor (Sections 3 and 9).
4. Mycorrhizal inoculation delivers high, measured sequestration rates (Section 5).
5. Sequestration is measured, not modelled, under a registered Verra methodology, with a parallel MAOM science campaign investigating the durable share (Sections 2 and 10).
6. Rootella Carbon is operating at scale today (Section 12).

Read together, these propositions are a step-change rather than an increment: mycorrhizae are the key pathway of plant carbon into soil; the tonnes are measured, not modelled; and because ~85–90% of the receiving pool is MAOM, roughly nine of every ten measured tonnes are entering the durable pool. Rate, destination, durability and verification improve simultaneously — a different durability class of soil carbon, delivered at field scale today.

Contact

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Appendix A. Definitions, methods and conversions

A.1 Definitions

Term	Definition
SOC	Soil organic carbon: total organic carbon in bulk soil.
MAOM / MAOC	Mineral-associated organic matter / carbon: the < 53 µm fraction, chemically bound to clay and silt surfaces.
POM / POC	Particulate organic matter / carbon: the > 53 µm fraction of partially decomposed plant material.
Persistent fraction	The component of a carbon pool (MAOM or biochar) that resists decomposition on timescales of centuries to millennia; distinguished from the fast-cycling component of the same pool. Consistency with the ~129-year mean turnover implies it holds roughly two-thirds of the standing MAOM stock (derived; Section 6.3).
Turnover time	Mean time carbon spends in a pool at steady state; ~129 years for MAOC and ~23 years for POC globally [13].
Radiocarbon age	Time since carbon in a pool was fixed from the atmosphere; describes the carbon already present and is generally older than the transit time of new inputs [15].
Durability	Retention of carbon over climate-relevant timescales due to stabilisation mechanisms. In this paper, 'centuries to millennia' denotes ~200–1,000 years (the medium-durability band of buyer taxonomies); radiocarbon evidence extends to several thousand years [12, 14].
Permanence	Forward-looking likelihood that stored carbon remains under future conditions, including changes in management and climate.
MAOC max	Modelled mineralogical capacity for mineral-associated carbon, from soil order and texture [9].
Saturation	Current MAOC as a share of MAOC max.
AMF	Arbuscular mycorrhizal fungi.
Necromass	Dead microbial and fungal biomass; a principal precursor of MAOM.
VCU	Verified Carbon Unit, issued under the Verra Verified Carbon Standard.
CRCF	EU Carbon Removal and Carbon Farming certification framework, Regulation (EU) 2024/3012 [30].

A.2 Measurement design

- Sequestration rate = (Δ SOC in treated fields, year t−1 → t) − (Δ SOC in control fields, year t−1 → t): a difference-in-differences estimate.
- Rates are reported after deduction of measurement uncertainty as required by Verra VM0042 v2.0 [4]; all values derive from ground-truth soil sampling, not models.

- MAOM fractionation: physical particle-size fractionation at 53 µm; 1,200 samples in 2025, 3,000 planned for 2026; comparisons across field types adjusted for SOC and pH. Fraction boundaries are method-defined, so the protocol is held constant across all samples and years.
- Sample sizes, confidence intervals, control-field results and gross (pre-deduction) values are available to prospective partners on request.

A.3 Unit conversions

- Carbon to CO_2 equivalent: multiply Mg C by 44/12 = 3.67.
- Per hectare to per acre: divide by 2.471.
- Worked example (Section 8): 75 Mg C/ha × 3.67 ÷ 2.471 ≈ 110 tCO_2e/ac. At 31% saturation, headroom ≈ 0.69 × 110 ≈ 76 tCO_2e/ac (upper bound).
- Global cropland MAOM headroom (≈ 381 $GtCO_2e$): derived by applying the Georgiou et al. (2022) capacity model [9] to global cropland area. The detailed calculation is available on request.

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