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Hidden Allies Below Our Feet: How Soil Microbes Shape Carbon Farming

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Soils store far more carbon than the atmosphere or vegetation, and carbon farming seeks to rebuild this store on degraded farmland. This article explains why the outcome depends heavily on soil microbes. Bacteria and fungi convert plant inputs into microbial necromass that binds to minerals, mycorrhizal fungi channel plant carbon underground and stabilise soil crumbs, and aggregate formation shields carbon from decomposition. Microbes can also release carbon through respiration and priming, so results vary with soil and climate. Practices that feed and protect the microbial community, including reduced tillage, living cover, organic inputs and balanced fertiliser use, offer the most reliable route to lasting soil carbon. Carbon farming is best viewed as a long-term investment in soil health rather than a quick source of carbon credits.

Keywords: Soil microbiome; carbon farming; soil organic carbon; mycorrhizal fungi; microbial necromass; soil aggregates

Beneath every field lies a vast carbon store. The top metre of the world's soils holds an estimated 1,550 billion tonnes of organic carbon, which is about twice the amount in the atmosphere and nearly three times the amount in living vegetation [1] (Figure 1). Generations of ploughing and land clearing have drained a large share of this reserve; one global estimate puts the historic loss from human land use at roughly 116 billion tonnes of carbon [2]. Carbon farming tries to refill it. Ideas such as the "4 per mille" initiative suggest that even small yearly gains in soil carbon could offset a meaningful part of human emissions, although the realistic potential is still debated [3].

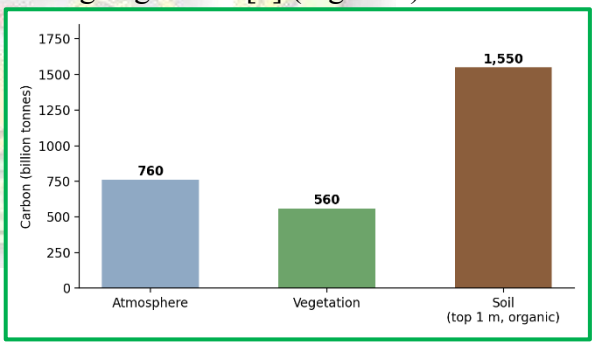


Figure 1. Approximate global carbon pools. Values after Lal (2004) [1]; schematic redrawn by the author.

The microbial engine

Plants pull carbon dioxide from the air, but whether that carbon stays in the ground or drifts back out depends largely on the microbes that process it (Figure 2). Three mechanisms matter most.

1. Turning residues into lasting carbon. Bacteria and fungi feed on roots and plant residues. Some of the carbon they take in is breathed out as CO_2, and some is built into their own bodies. When the cells die, their remains, called necromass, can attach to soil minerals and persist for decades or longer. Research increasingly shows that this "microbial pathway" is a major source of stable soil organic matter rather than a minor by-product [4–6]. A key factor is carbon-use

efficiency, the share of consumed carbon that a microbe converts into biomass rather than respiring. Soils that favour efficient microbes tend to retain more carbon [5].

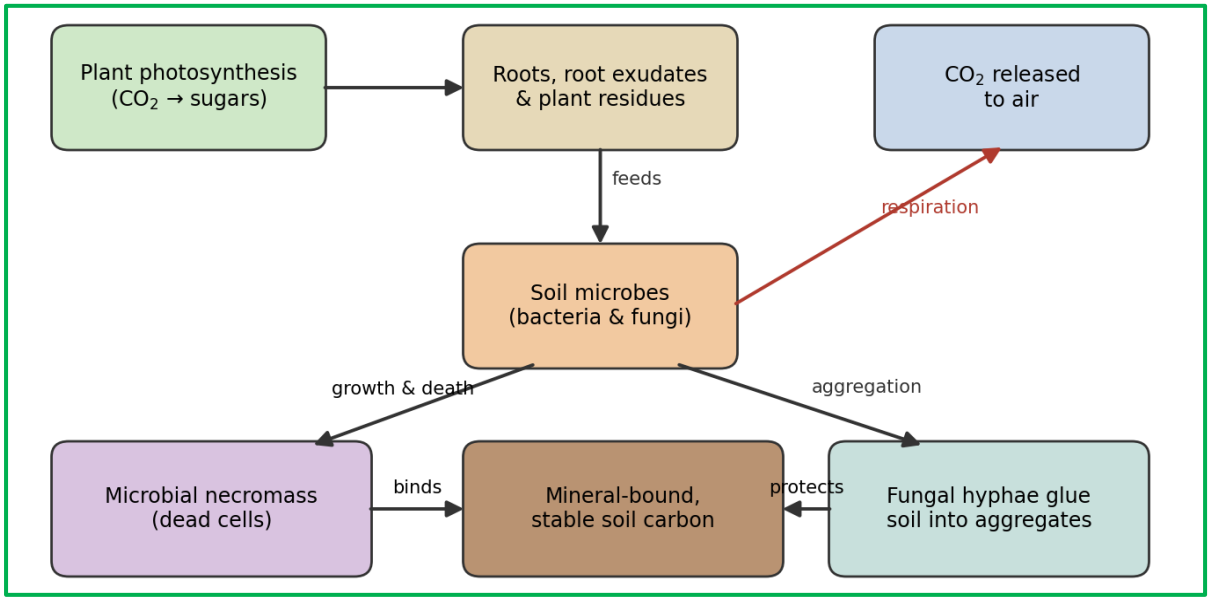


Figure 2. Simplified flow of carbon through the soil microbial community. Conceptual diagram prepared by the author, based on concepts in [4–6, 8, 9].

2. Mycorrhizal fungi as underground carbon pipelines. Most crop plants form partnerships with arbuscular mycorrhizal fungi, swapping sugars for water and nutrients. A recent global synthesis estimated that plants send about 13 billion tonnes of CO_2-equivalent a year to these fungi, an amount comparable to more than a third of annual fossil-fuel emissions [7]. Their fine threads and sticky secretions also bind soil particles together, and field studies have found that soil aggregation and carbon storage track closely with the abundance of these fungi [8, 9].

3. Building structure. Soil aggregates are tiny crumbs that physically shield the carbon inside them from decomposers. Fungal threads, bacterial secretions and root exudates all help form them, while tillage and bare ground break them apart (Figure 3).

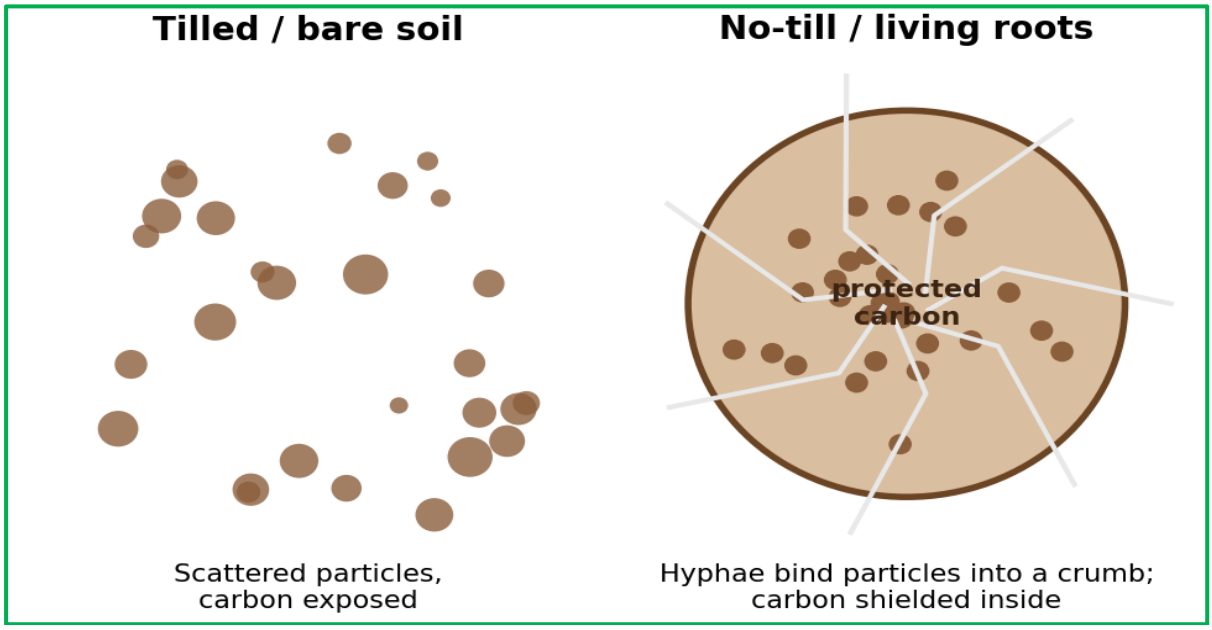


Figure 3. Soil structure under disturbance and under protective management. Schematic by the author, after concepts in [8, 9].

The double-edged side: priming and respiration

Microbes can release carbon as well as store it. Fresh organic inputs may "prime" microbes to break down older soil carbon faster [10], and warming or drought can shift community make-

up and activity, with uncertain effects on the carbon balance [11, 12]. This is why a practice that works well in one soil or climate may disappoint in another.

Working with microbes: what farmers can do

- Minimise disturbance. Reduced or no-till protects fungal networks and aggregates.
- Keep living roots in the soil. Cover crops and diverse rotations feed mycorrhizae and supply a steady carbon source.
- Return organic matter. Residues, compost and manure give microbes the raw material for necromass.
- Avoid excess synthetic fertiliser. Too much can weaken the plant–fungus partnership and alter microbial efficiency.
- Keep the soil covered. Mulch or residue moderates temperature and moisture.

Table 1. Management practices and their microbial rationale

Practice	How it helps microbes	Likely carbon benefit
Reduced or no tillage	Protects fungal networks and soil crumbs	Less physical exposure of carbon
Cover crops, diverse rotations	Keeps living roots feeding microbes year-round	Steady carbon supply to soil
Compost, manure, residues	Supplies food and nutrients to the community	More material for necromass formation
Balanced fertiliser use	Preserves plant-fungus partnership	Supports fungal carbon allocation
Mulch or residue cover	Moderates temperature and moisture	Steadier microbial activity

Honest caveats

Soils can only hold so much carbon before gains level off, and stored carbon can be lost again if good practices are abandoned [1, 3]. Measuring change at farm scale is difficult and costly, and microbial responses vary with soil type and climate [11]. Carbon farming is therefore best seen as a long-term investment in soil health, with better yields, water retention and resilience as co-benefits, rather than a quick route to carbon credits.

Conclusion

The next frontier of climate-smart agriculture may lie less in adding carbon and more in managing the living community that decides its fate. Looking after the soil microbiome is a way of looking after the climate, one handful of soil at a time.

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