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Persistence and Vulnerability of Mineral-Associated Organic Carbon

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As far as carbon is concerned, it is commonly associated with factories, automobiles, and trees. However, one of the biggest sources of carbon is buried beneath our feet. The amount of carbon in the soil is greater than that in the atmosphere and all the plants put together – between 1,500 and 2,400 billion tonnes in the first two meters of soil. This is the main reason soil carbon is now a major theme in climate change studies and policies. Governments, businesses, and farmers are now looking into "carbon farming" and "regenerative agriculture" as methods for taking out CO_2 from the atmosphere and storing them back in the soil. However, Soil carbon does not all go down in the same fashion. Modern science has separated soil carbon into two groups: those that disappear from the soil after a few years, and those that stick around for centuries. The latter group has one form of soil carbon that stands out, and that form is referred to as Mineral-Associated Organic Carbon (MAOC).

Soil Organic Carbon

Soil organic carbon is derived from living organisms. Through photosynthesis, plants absorb carbon dioxide from the atmosphere and convert it into leaves, stems, and roots. This biomass is shed into the soil or dies beneath the soil surface. Roots exudes organic acids and sugars into the soil, which are consumed by soil fauna, fungi, and microorganisms. Through feeding, growth, and death, organic compounds in plant material become soil organic matter.

But most of this carbon will ultimately return to the air as CO2 through respiration. Some will remain. The factor that determines whether or not a particular carbon molecule returns soon to the air or remains for a long time is not just the "durability" of the carbon molecule. It turns out that soil conditions, particularly minerals, play a bigger role than the chemical makeup of the carbon.

Two main pools: POC and MAOC

The soil organic carbon is composed of two major pools:

- **Particulate Organic Carbon (POC):** It is the larger pieces of organic material from plants, including partially decomposed root material and leaf fragments. POC is large-sized, remains plant-like in appearance, and is easily digested by microorganisms. It usually lasts between several years and a couple of decades.
- **Minerals associated with organic carbon (MAOC):** It is the small molecules and remains of microorganisms that adsorb on the surface of small mineral particles, such as clay, fine silt, and iron or aluminum oxide minerals, or are enclosed within small aggregates. The persistence of MAOC can range from decades to centuries, or even longer.

MAOC Forms: Two Pathways

There are two basic methods.

Microbial pathway: The simplest compounds from plant materials that are easy to digest, such as sugars and amino acids from root exudates and freshly fallen litter, are readily absorbed by microbes. Some carbon is utilized for energy production and emitted as CO_2, whereas the remains is transformed into microbial biomass and metabolites. The remains of dead microorganisms with their biomass and metabolites may adhere to mineral particles. This pathway is believed to contribute significantly to MAOC formation, particularly in grassland and agricultural soils.

Direct Sorption Pathway: Organic compounds dissolved during the decomposition of plant matter or released from the roots may be directly absorbed on mineral surfaces as they pass through the soil solution. The importance of this pathway is significant for many forest soils where litter is slow to decompose.

MAOC Is Considered Persistent

The longevity of MAOC is due to many factors that tend to occur simultaneously.

1. **Organic molecules bind to the mineral surface in two ways** via electrostatic forces, via bridges formed by metal ions, for example, calcium, and via reactions with iron and aluminum oxide. Of these bonds, the most powerful are very hard to break.
2. **Protection by physical** means Carbon can be stored within pores and small clusters of mineral particles. Such small pores and clusters are usually too small for bacteria and enzymes to enter the material.
3. **Restricted Access of Enzymes** that Bacteria degrade large organic compounds using enzymes that act outside bacterial cells. If an organic compound binds to a mineral, the enzyme will not be able to bind to it, or, worse, the fragments could bind back to the mineral.
4. **Low energy systems:** Microbial action is reduced by factors such as lack of oxygen, lower temperatures, and limited amounts of fresh carbon, which are prevalent in deeper soil layers.

Radiocarbon dating is consistent with these assumptions. Radiocarbon dating of MAOC in various soils shows age ranges from hundreds to thousands of years, far older than the carbon contained within plant debris and particulate fractions. This is the primary evidence for considering MAOC the “savings account” of the soil.

MAOC is Vulnerable

1. Root exudates and the priming effect

Organic acids and other substances produced by roots are released into the surrounding soil, specifically in a region known as the rhizosphere, which is close to the root system. Oxalic and citric acids are among these acids that may release organic substances attached to minerals via either occupying their bonding sites or dissolution of the minerals. Thus, after being released into the soil environment, carbon becomes available for consumption by microorganisms. Moreover, new carbon provided by plant roots may also affect older carbon through the process known as priming. It has been proven that plants can result in negative impacts on older MAOC content in the soil, in which they are growing.

2. Microbial "mining" for nutrients

In addition to being a source of carbon, soil organic matter is also a source of nitrogen and phosphorus. If these substances are scarce for bacteria in carbon-rich environments, they will start secreting acids and enzymes that will enable them to decompose MAOC to obtain the nutrients tied to it. This process is called nutrient mining and results in carbon leakage into the atmosphere in the form of CO_2.

3. Changes in soil chemistry and moisture

Iron is one of the best carbon protectors; however, it is sensitive to the amount of oxygen present. If the soil becomes waterlogged, such as in case of floods in rice paddies and thawing wetlands, there is no more oxygen. In such cases, some microorganisms use iron

oxides to replace oxygen in order to breathe, and thus, dissolve the mineral and release carbon attached to it. The pH factor may also play an important role. Acidification could make certain connections between the organic material and minerals weaker or even affect the type of minerals, and cycles of drying and rewetting could disrupt the structure of aggregates.

4. Warming

Increase in temperature accelerates the metabolic processes of microorganisms and enzymes. Up until now, it was thought that MAOC was relatively insensitive to such effects. However, more recent research work has shown that some fraction of MAOC, especially the fraction that is loosely held and newly formed, responds to warming. There are other fractions that are much less responsive to increase in temperature. The bottom line is yet to be determined and is probably dependent on the soil and climatic conditions.

5. Land-use change and soil disturbance

Deforestation or the transformation of grasslands into cultivated land is cited as the most well-known reason for soil carbon loss. Plowing leads to the breakdown of soil aggregates, incorporation of oxygen, and exposure of carbon that was shielded from decomposition due to its environment. The decline in organic matter input into soil, bare soil, and soil erosion result in carbon loss. Because the formation of MAOC is very slow but carbon loss is comparatively fast, the equation becomes unbalanced.

6. Rising CO_2 and shifting plant inputs

Higher atmospheric CO_2 can stimulate plant growth and root exudation. This may add more carbon to the soil, but it may also fuel priming and nutrient mining. Whether the net effect on MAOC is positive or negative differs among ecosystems, and scientists are still working to determine when each outcome is likely.

The Key Idea: MAOC Is Not One Uniform Pool

The MAOC is not a single substance. It is a **spectrum** because of:

- **Tightly bound, long-lived MAOC:** Strongly associated with iron and aluminum oxides or sealed in small pores. This portion can last for centuries or longer and is relatively resistant to disturbances.
- **Loosely bound, faster-cycling MAOC:** Weakly attached, often through simple electrostatic forces or located on the outer surfaces of aggregates. This portion can exchange with the soil solution and may turn over within years to decades.

The overall "persistence" of a soil's MAOC is therefore a weighted average of these components. A soil may contain a large stock of MAOC, and yet a considerable fraction could be relatively exposed.

Factors that shape where on the spectrum MAOC falls

Factor	Effect on persistence
Mineral type	Iron and aluminum oxides and poorly crystalline minerals typically bind more strongly than many layered clays.
Mineral surface saturation	When surface is already full, additional carbon sticks more weakly.
Type of organic molecule	Molecules with more reactive chemical groups tend to bind more strongly to the surface.
Soil depth	Deep MAOC is often older, but can be released if roots, water, or disturbance reach it.
Climate and moisture	Warm, wet conditions favor fast microbial activity, and waterlogging can dissolve iron minerals.
Vegetation and management	The type, amount, and timing of carbon inputs influence both formation and loss.

Implications for Climate Policy and Carbon Markets

The vulnerability of MAOC has direct consequences for the value of soil carbon.

Permanence cannot be assumed: Carbon credit schemes often require storage to last for a defined period, commonly decades to a century. If part of the stored carbon is reversible when management or climate changes, then crediting systems must account for the risk of reversal, for example, through buffer pools or periodic monitoring.

Measurement is difficult: Soil carbon varies widely over short distances, and changes take years to detect. Distinguishing POC from MAOC helps because the two pools carry different expectations of permanence, and it may be sensible to value them differently.

Saturation limits matter: Each soil has a finite capacity to hold MAOC and sequestration rates will slow as soils approach their limit. Soils far from their capacity, such as degraded cropland, may offer the greatest gains.

Soil carbon is not a substitute for cutting emissions even under optimistic estimates: Soil carbon gains can offset only a fraction of annual fossil fuel emissions, and they can be reversed. Most scientists view soil carbon as a complement to emission reductions, delivering additional benefits, such as improved soil health, water retention, and fertility.

Practices to protect the MAOC

- **Reduced soil disturbance:** Minimizing tillage helps preserve aggregates that protect carbon.
- **Maintain living roots in the soil:** Cover crops, perennial plants, and diverse rotations maintain a steady supply of carbon that feeds the microbial pathway of MAOC formation.
- **Increased plant diversity:** A mix of species provides varied inputs and supports a more diverse microbial community.
- **Balance nutrients:** Adequate nitrogen and phosphorus can reduce the incentive for microbes to mine existing carbon, although excessive fertilizer application carries its own environmental costs, such as nitrous oxide emissions and water pollution.
- **Manage water carefully:** Avoiding prolonged waterlogging, where possible, helps protect iron-bound carbon.

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