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Introducing the soil mineral carbon pump

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Standfirst Microorganisms and minerals both contribute to organic carbon preservation and accumulation in soil. The soil microbial carbon pump describes the microbial processes, but a separate soil mineral carbon pump needs to be acknowledged and investigated.

[H1] Introduction

Soil impacts climate through the sequestration or release of carbon, which is impacted by soil organic matter formation[1]. The role of microbes in soil organic carbon (OC) production and sequestration is described by the soil microbial carbon pump (MCP) concept[2]. In this model, new organic compounds are produced through microbial anabolism, and are subsequently stabilized on mineral surfaces and within soil structures by the entombing effect. Although mineral-organic carbon associations are traditionally assumed to be protective, emerging evidence suggests these interactions are complicated and include numerous abiotic reactions not considered in the MCP. Here, we propose a distinct soil mineral carbon pump (MnCP) that works in parallel to the MCP.

[H1] The soil mineral carbon pump

The MnCP describes how soil minerals enhance the persistence and accumulation of OC. Soil minerals can transform plant or microorganism-derived labile OC into more stable forms through processes such as adsorption, occlusion, aggregation, redox reactions, and polymerization (Fig. 1). Adsorption, occlusion and aggregation can reduce the availability of OC by lowering its concentration in the dissolved pool, forming organo–minerals that are too large to be ingested by microbes and/or limiting the functioning of hydrolytic enzymes[4]. Clay minerals (kaolinite, montmorillonite) and metal (oxyhydr)oxides (iron oxides, birnessite) can drive polymerization, producing more recalcitrant OC (ref.[3]). Furthermore, redox reactions at mineral surfaces drive OC oxidation to CO_2 and can produce radicalized OC that can be complexed into larger molecules[5].

The MnCP operates in various soil environments, potentially with a key role in OC sequestration in mineral soils. This pump is sustainable and can operate over long periods: there are abundant clays and metal (oxyhydr)oxides in soil to associate with labile OC, protecting it from microbial degradation[4]. Moreover, fluctuating redox conditions in soil can recycle reactive minerals that catalyze polymerization[6], especially in environments like paddy soils and peatlands.

[H1] Relationship to the soil MCP

The initial adsorption of OC with minerals is usually followed by reactions that are distinct from those in the soil MCP; these reactions are included in the soil MnCP, as is mineral-catalyzed abiotic polymerization. However, the MnCP and MCP are not mutually exclusive. As exemplified by the entombing effect in the MCP (ref.[2]), they work synergistically to preserve OC in soil. For example, redox reactions on OC-minerals interfaces can be either abiotic or biotic[7], and the MnCP and MCP can be coupled through mineral–microbe interactions during minerals dissolution and electron transfer. Moreover, the extracellular polymeric substances excreted by microorganisms (as part of the MCP) can strengthen the aggregation of organic matter and minerals via a gluing effect [8] (part of the MnCP) in soil.

[H1] Broader impacts

Minerals can be as important as microorganisms in increasing soil OC persistence and accumulation. The MnCP highlights this role and provides a framework for research into mineral–OC interactions, at fine scales and within the broader soil ecosystem. This work is needed to understand the complexity of soil OC (ref.[9]), and why some OC persists while other OC does not.

Acknowledging the suite of natural reactions that occur through the MnCP will be especially helpful in guiding analytical soil research. For example, the ability of minerals to catalyze polymerization of OC has been mostly found in laboratory settings[3], but its occurrence in the soil and its broader impact on OC structure and persistence are unclear. Polymerization of OC can produce numerous new and larger molecules that are hard to identify analytically. Therefore, emerging new techniques (such as FT–ICR–MS, NEXAFS, and Nano–SIMS) should be used and combined to understand how the MnCP operates under different OC characteristics and mineralogy, and to find fingerprints of polymerized OC that might be used to identify its production and persistence in soils. Experimental work to demonstrate that soil mineral-catalyzed polymerization increases OC stability is also needed.

Interest in enhancing soil carbon sequestration to combat climate change is growing, so it is increasingly important to understand the mechanisms underlying OC preservation. Fostering and strengthening the MnCP in soil could be a part of this effort, analogously to enhanced silicate weathering methods[10], providing another potential tool to stabilize carbon in the soil.

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Competing interests

The authors declare no competing interests.

Fig. 1: The soil mineral and microbial carbon pumps. a| Minerals enhance the persistence and accumulation of organic carbon in soils in the soil mineral carbon pump (MnCP). Organic substrates from plants and microorganisms are stabilized via processes such as adsorption, occlusion, aggregation, redox reaction, and polymerization. **b|** The microbial carbon pump (MCP) is on the right for comparison. Panel b is adapted from ref [2], Springer Nature Ltd.