Chen *et al. Carbon Research* (2024) 3:44
https://doi.org/10.1007/s44246-024-00132-1

Carbon Research

PERSPECTIVE Open Access

Biochar as a green solution to drive the soil carbon pump

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Abstract

Biochar is a nature-based green solution to lift soil carbon storage and mitigate carbon release. Here, we propose a novel concept of biochar carbon pump (BCP) that bridges microbial carbon pump (MCP) and mineral carbon pump (MnCP), facilitating effective carbon sequestration. The BCP functions to promote carbon storage by introducing biochar-derived persistent C into soil, enhancing negative priming effects, altering soil microbial communities, and reinforcing organo-organic and organo-mineral interactions. Recognizing the value of BCP in bridging MCP and MnCP to facilitate diverse natural reactions for soil carbon sequestration is particularly significant in addressing climate change.

Highlights

- A novel concept of biochar carbon pump (BCP) is introduced.
- BCP can boost soil organic carbon storage by bridging MCP and MnCP.
- BCP introduces biochar C and enhances negative priming effects to promote C stock.
- BCP alters microbial function and organo-mineral interaction to enhance MCP and MnCP.

Keywords Biochar, Soil organic carbon, Microbial carbon pump, Mineral carbon pump

Handling Editor: Hailong Wang

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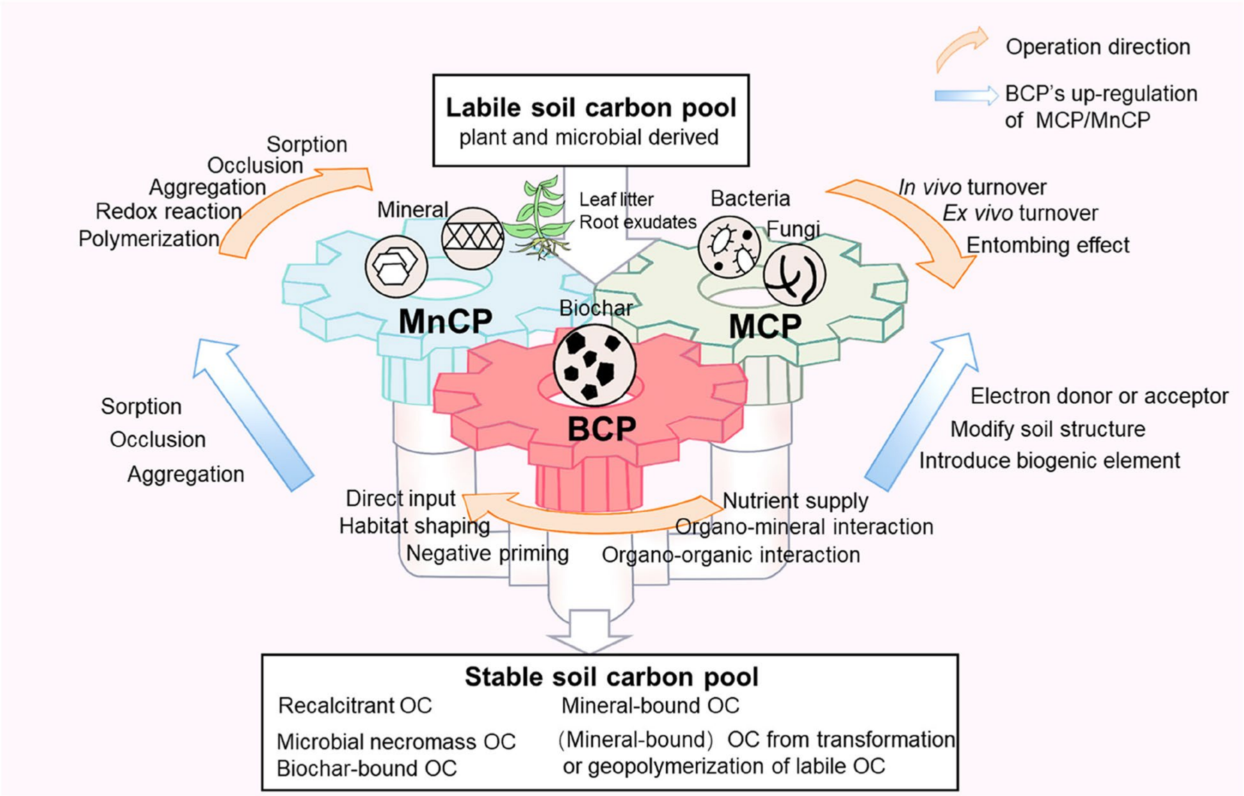
Graphical Abstract



1 Introduction

Soil organic carbon (SOC) plays a pivotal role in mitigating climate change (Bradford et al. 2019). Its storage and stability is contingent upon the effectiveness of microbial and mineral carbon processes, i.e., the operational efficiency of the microbial carbon pump (MCP) and mineral carbon pump (MnCP). The MCP drives soil carbon (C) storage by the microbial transformation of C (derived mainly from plant residues) from labile to persistent forms (Liang et al. 2017); the MnCP drives SOC storage through processes encompassing sorption, occlusion, aggregation, redox reactions, and polymerization (Xiao et al. 2023). Biochar, with its aromatically condensed and long-lasting C composition, aids in SOC stabilization via organo-organic and mineral-organic associations (Lehmann et al. 2021), and the transformation of labile organic carbon (OC) to more persistent forms through in/ex vivo processes and entombing effects (Chen et al. 2023a; Weng et al. 2022). Here, we propose a concept of biochar carbon pump (BCP) that uses biochar to boost SOC storage by stabilizing native and exogenous C, and bridging the MCP and MnCP (Fig. 1).

1.1 Nature-based biochar carbon pump

The BCP leverages biochar as a soil amendment to promote SOC persistence and stabilization of exogenous C in soil. The BCP functions along C processes through four main mechanisms: introducing biochar-derived persistent C into soil, enhancing negative priming effects (inhibit the mineralization of native SOC), altering soil microbial communities and functions, and reinforcing organo-organic and organo-mineral interactions (Weng et al. 2022; Yang et al. 2022). First, biochar can directly contribute to soil stable C pool through importing persistent C to soil. Second, biochar can be engineered to facilitate enhanced negative priming, meaning it helps protect existing SOC from breakdown, while also enhancing microbial catabolic production, and mineral-driven stabilization and polymerization. The BCP-induced negative priming effects, due to substrate switching, dilution, and the adsorption of SOC onto highly porous biochar structures (i.e., organo-organic interactions), act to reduce the bioavailability of native SOC. Third, the BCP introduces biochar-derived biogenic elements (e.g., C, N and P as substrates for microbial growth) and modifications to soil

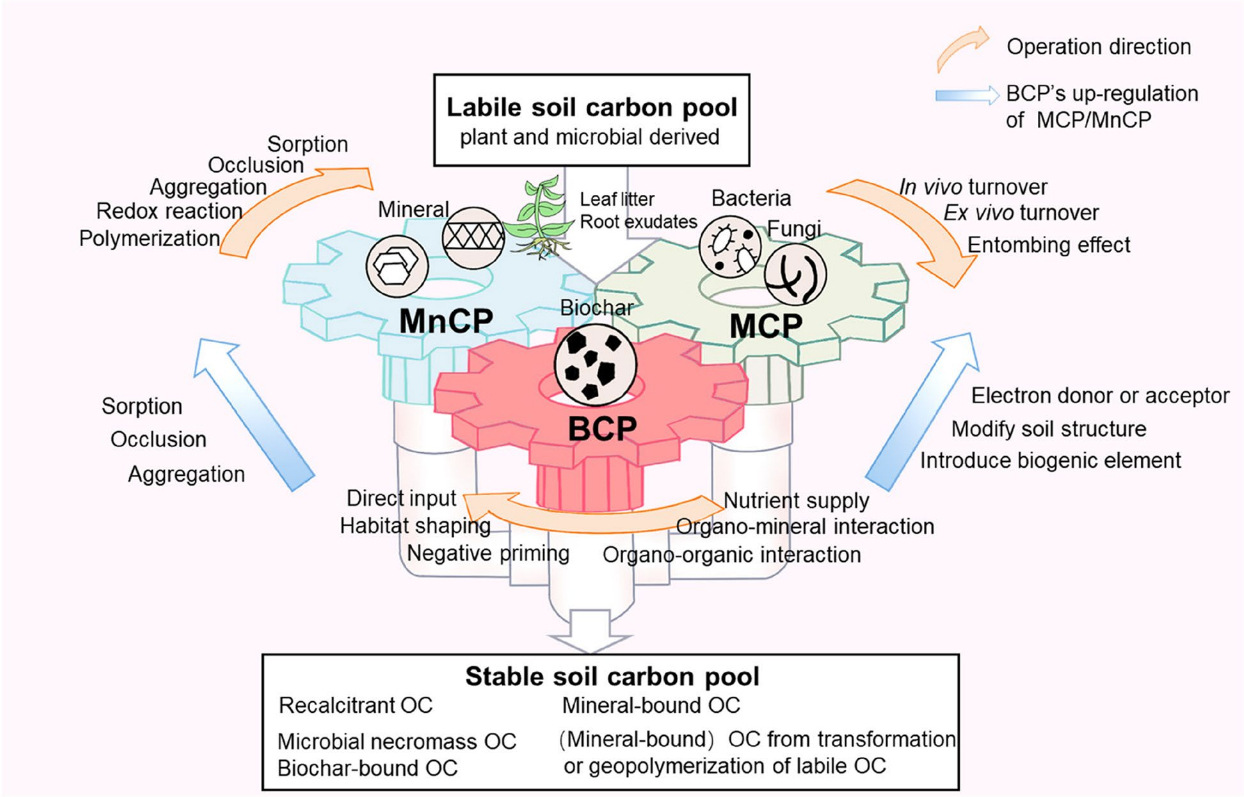


Fig. 1 Conceptual framework illustrating how biochar carbon pump (BCP) boosts the persistence and accumulation of organic carbon in soils through stabilization of native and exogenous carbon, and regulation of the microbial carbon pump (MCP) and mineral carbon pump (MnCP)

structure and alters soil microbial communities and their functions, like promoting the growth of microorganisms involved in the C and N cycle, as well as the growth of fungi in relative to bacteria. These changes play a pivotal role in regulating microbial growth and death pathway, resulting in the increased accumulation and stabilization of microbial necromass C. Ultimately, this has a discernible impact on C metabolism strategies for SOC decomposition. Fourth, the BCP reinforces organo-organic and organo-mineral interactions, reducing the accessibility of OC through sorption, occlusion, and aggregation. On one hand, recalcitrant aromatic components of biochar can form complexes with soil clay minerals, specifically Fe–O-C compounds (Yang et al. 2022). On the other hand, the soluble fraction of biochar can directly interact with soil minerals to generate mineral-associated organic matter via adsorption, Ca^{2+} bridging, ligand exchange, van der Waals interaction (Yang et al. 2021). Additionally, the soluble fraction can be assimilated by microorganisms leading to microbial biomass and necromass formation through in vivo turnover that ultimately associates with soil minerals (Chen et al. 2023a). These interactions lower physical disintegration and abiotic oxidation, forming organo-mineral complexes that are too large for microbial ingestion or obstruct hydrolytic enzymes. The enhanced organo-mineral associations contribute to the further stabilization of newly introduced C (such as plant deposits and microbial necromass) and promote polymerization and formation of more recalcitrant OC. In addition, biochar comprises various components, including mineral phases, amorphous C, graphitic C, functional groups, and redox-active metals. The BCP leverages these components as electron donors or acceptors, thereby facilitating the generation of radicalized OC that can form complexes with larger molecules. The BCP can also use biochar to promote soil aggregation through organo-mineral interactions, culminating in the stabilization and accumulation of plant-derived OC within the mineral-associated fraction and microbial necromass within microaggregates (Weng et al. 2017, 2022).

1.2 The adaptable BCP to control soil MCP and MnCP

The BCP as a green solution can be effective across a wide range of soil environments, being able to control both the MCP and MnCP, resulting in increased SOC. Biochar is projected to elevate the MCP capacity by 10–59% and stabilize an additional soil carbon sink of 1.01 Pg C Pg^{-1} biochar through mineral protection (Chen et al. 2023a, 2024, 2023b; Weng et al. 2022). While biochar C can remain in soil for hundreds to thousands of years, only limited studies on decadal scale impacts on MCP and MnCP exist. However, the BCP shows promise of sustained function. During the initial stages of biochar incorporation into soil, dissolved C and nutrient ions are released from the biochar, stimulating microbial growth. In this scenario, microbial catabolism, rather than anabolism, becomes more pronounced within the MCP, resulting in the often-observed short-term positive priming of native SOC (i.e., accelerate the mineralization of native SOC). As biochar undergoes aging in soil, microbial activities stabilize, lowering respiration and metabolic quotient. This shift towards a more stable microbial community drives the MCP to continuously produce necromass C. Simultaneously, biochar gradually interfaces with soil minerals, promoting the MnCP to stabilize SOC within porous, organo-mineral microaggregates. Factors such as soil clays, Ca^{2+} bridging, and poorly crystalline Fe/Al compounds play dominant roles in this process (Yang et al. 2016). This interaction is further facilitated by the MCP, as the extracellular polymeric substances excreted by microorganisms (part of the MCP) enhance the aggregation of organic matter and minerals, akin to the role of the MnCP, effectively 'gluing' them together within the soil. Ultimately, these processes switch the initially observed positive priming effect into a negative priming effect on native OC. Notably, the operation efficiency of BCP involved in C processes such as microbial carbon transformations and mineral interactions exhibits significant variations depending on soil type, climate conditions, and land management practices. Particularly in mineral-rich soils, biochar exerts a more profound influence on the MnCP by intensifying organo-mineral interactions. The ubiquitous clays and metal (oxyhydr)oxides in the soil tend to associate with both native SOC and biochar-derived organic C, providing protection against microbial degradation. Biochar also has the capacity to alter the redox potential in soil, through electron shuttling, electron buffering or modulating cell distribution and growth (Dong et al. 2023). The resulting fluctuating redox conditions, in conjunction with the prevailing soil conditions, can facilitate the recycling of reactive minerals that catalyze polymerization processes.

1.3 Broader impacts

BCP can bridge the operation of MCP and MnCP, while concurrently importing persistent biochar-derived OC and adsorbing native OC, to enhance soil OC persistence and accumulation. The BCP is crucial in soil C management for both climate change mitigation and adaptation.

The global potential for wood biochar production is estimated to be 0.31–0.59 Pg annually. Acknowledging the array of natural reactions facilitated by the BCP is particularly valuable in guiding research and broad adoption of the technology to meet C drawdown goals. Future research to facilitate broader adoption needs to improve the mechanistic understanding of this nature-based solution across a broader range of soils and environments. For example, it is necessary to elucidate how the interaction between biochar and organo-mineral associations may be impeded by coarse-grained soil texture (Busscher et al. 2011), and how this process influences the effectiveness of soil C pump. Furthermore, long-term field trials need to be conducted to better understand the aging process of biochar, its long-term dynamics of interaction with soil microbes and minerals, and how these processes affect BCP and its up-regulation of MCP and MnCP. To facilitate the broader adoption of this BCP, biochar technologies need to meet the economic and practical expectations of landowners, especially relating to cost, supply and ease of handing and application to soil. On an economically and practically viable basis, it is essential to optimize biochar properties (particle size, porosity, nutrient content, etc.) for specific soil environments and target functions. One strategy to encourage uptake is the utilization of biochar as a platform material to carry nutrients for crop production, enabling lower emissions of soil greenhouse gases such as nitrous oxide, while providing higher nutrient use efficiency through its slow-release properties. Additionally, introducing exogenous minerals before pyrolysis to augment the retention of additional carbon within biochar represents a potential avenue for C sequestration, through chemical bonding, physical encapsulation, and the absorption of CO_2 and CH_4 by structures containing CaO or MgO.

Abbreviations

SOC	Soil organic carbon
MCP	Microbial carbon pump
MnCP	Mineral carbon pump
BCP	Biochar carbon pump
C	Carbon
OC	Organic carbon

Acknowledgements
This work was financially supported by the National Science Foundation for Distinguished Young Scholars (42125703) and National Natural Science Foundation (41977299).

Authors' contributions
All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Yalan Chen. The first draft of the manuscript was written by Yalan Chen, Ke Sun, Jiaqi Ren, Lukas Van Zwieten, Keqing Xiao, Chao Liang, Anqi Zhang, Yang Li, and Hailiang Dong. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and materials
The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

Ke Sun and Lukas Van Zwieten are editorial board members of Carbon Research and were not involved in the editorial review, or the decision to publish, this article. All authors declare that there are no competing interests.

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Received: 12 March 2024 Revised: 22 April 2024 Accepted: 24 April 2024

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