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Understanding and enhancing soil conservation of water and life

Zheng Zhao[1], Cheng Liu[1,2], Ming Yan[1] and Genxing Pan[2,3*]

[1] *Institute of Resource, Ecosystem and Environment of Agriculture, Nanjing Agricultural University, Nanjing 210095, China*
[2] *School of Environment and Natural Resources, Zhejiang University of Science and Technology, Hangzhou 310023, China*
[3] *Soil Health Commission, the International Science Committee on Problems of Environment (SCOPE), 5 rue Auguste Vacquerie, 75116 Paris, France*
* Corresponding author, E-mail: gxpan@njau.edu.cn; pangenxing@aliyun.com

World Soil Day 2023 on December 5th, the 10th celebration of its approval by the 68th UN General Assembly in 2013, aims to raise societal awareness of the importance and relationship between soil and water in achieving resilient agrifood systems and sustainable human well-being (www.un.org/en/observances/world-soil-day). Soil's pivotal role as a key water reservoir and filter in the global water supply, besides C reservoir and biodiversity reservoir, has already been highlighted in the World Soil Resources Reports released by FAO and UNEP in 2015 (Zhang et al., 2016). This call again urges the international academic community to provide novel knowledge on the precious links between soil-water-microbe-plant-human and to develop novel solutions to enhance soil storage and provision of life eligible water sources.

Soil is the soft cover on the earths surface, providing ecosystem services of storage and purification of water for diverse lives besides soil fertility and C sequestration (Fig. 1). Soil health, a cutting-edge global concern for sustainable development (Lehmann et al., 2020), is the consideration of soil capacity to sustain functions across landscape and temporal scales. Through soil structure development, soil provides retention and storage of water, organic carbon and nutrients for plant growth and diverse life conservation (Shen & Pan, 2022). As a particular benefit of this function, soil mediates the quality of aquifers, which have been traditionally used as municipal water sources such as wells in many alluvial plains across the world (Fig. 2). Thus, saving our soil, preventing form land sealing, soil compaction and erosion, is a priority for conserving water and life on earth. With this in mind, nature-based solutions (NbS) should be pursued while water retention, provisioning and global cycling are well understood. Among the well-recognized NbSs, rice terraces in mountain areas in humid zones reflects human intelligence for high efficient water resource conservation and utilization for food production and human wellbeing (Fig. 3). By awarding these terraced sites with Globally Important Agricultural Heritage, FAO raises global concern on exploring ancient lessons for understanding soil's role in, and for developing novel nature based solutions, to conserve water resources for sustainable human life.

Inherently, soil capacity to conserve water depends on its porosity, which is closely associated with soil structure. Driven by soil organic matter accumulation, soil aggregation forces fine mineral particles to form microaggregates and to further build up macro-aggregates with plant roots and/or fungal hyphae (Jastrow, 1996). Thus, soil could be considered as a complexed bio-pore system comprised of large pores in-between peds and macroaggregates, meso-pores within and in-between microaggregates and tiny pores between spacings in mineral matrix (Fig. 4a & b). This unique process creates a complexed pore network in the soil, which is increasingly

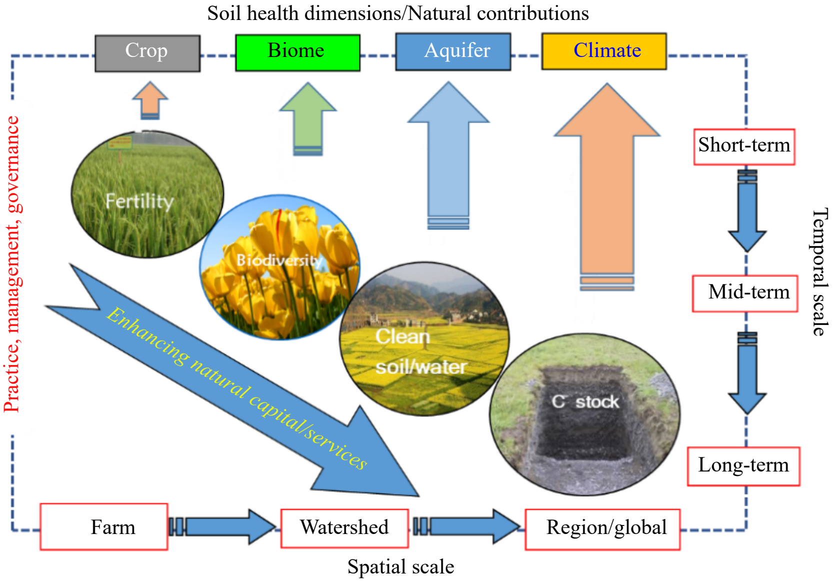

Fig. 1 Soil functions and ecosystem services showing the link between soil fertility, biodiversity, aquifer quality and C storage across spatial and temporal scales.

characterized by micro-CT tomography technology (Fig. 4b & c). The porosity, macro-porosity in particular, and the pore size, shape and the connectivity are strongly relevant to water retention, transport and organic matter as well as to microbial inhabitation (Rabot et al., 2018). Consequently, soil functions of water retention and transport, gas exchange, microfauna activity and nutrient plant uptake are better addressed with pore system perspectives than aggregate system perspectives in recent soil studies (Schlüter et al., 2020). In this context, soil architecture as a complexity of solid particles from fine particle, and microaggregates, to macroaggregates and peds and the soil pore system associated with them in different scales and morphologies, is to be explored for understanding soil functions in its natural state. Consequently, a shifting paradigm in future soil study is in how soil architecture, rather than soil aggregates, control or govern soil functions including water, carbon and biodiversity conservation (Vogel et al., 2021). In other words, the close link between soil mineral and organic matter, between soil aggregation and soil pore system and between water, carbon and biome conservation should be characterized with field-based, non destructive approaches in soil system science in the future.

Fig. 2 A well excavated in the Song dynasty for utilizing underground water in Taizhou, Jiangsu, China. Such wells have been found across the Han to the Qing dynasty as shown in the Ancient Wells Museum of the city (Photo: Ming Yan).

Fig. 3 Rice terraces of Jiabang Village in a high mountain of Guizhou, China. Water resources from vegetated forests are used for rice paddies across the long slopes for grain production (Photo: Ming Yan).

World soil resources have been increasingly threatened with on-going global pressures including climate change, land degradation and environment pollution as well as over intensification of crop production (Smith et al., 2016). As a result, sharp declines in soil organic carbon and in turn, in soil aggregate stability as well as in microbial activities have been widely reported (Smith et al., 2015). Forest and grassland shifted to farmlands caused great reductions of macroaggregate proportion and thus macro-porosity and connectivity by up to 50% (Zhao et al., 2023). The adverse global soil change trends of soil loss of organic carbon, soil erosion, soil compaction, soil salinization, soil acidification and soil pollution, as well as climate change due to the abovementioned pressures, have impacted or threatened global soil water retention capacity. Earth observation and simulation studies revealed an overall decreasing trend for global surface soil moisture content over the last decades, particularly in northern and eastern Asia, Brazil, Mississippi river basin and southern Africa (Pan et al., 2019) as well as the Middle East (Mohseni et al., 2023). These changes have affected food production in agricultural systems as poor food security and hunger are highly coherent to the poor and dry soil regions (www.fao.org/interactive/state-of-food-security-nutrition/2-1-1/en/) and to the SOC poor regions (Global Soil Organic Carbon map (FAO, 2018)) across the world, particularly in southern Africa. However, soil moisture dynamics and the interaction with food production, biodiversity survival and climate change are poorly monitored and characterized in specific agro-systems.

To ensure or enhance food production, regenerating soil water holding capacity is urged with improving land management focusing on replenishing soil organic matter, which is the driver of soil architecture development through soil aggregation. Among the management options, input of organic matter in the form of biochar could induce a rapid increase in soil carbon with benefits of soil moisture and available water enhancement. According to a data synthesis, increase in soil

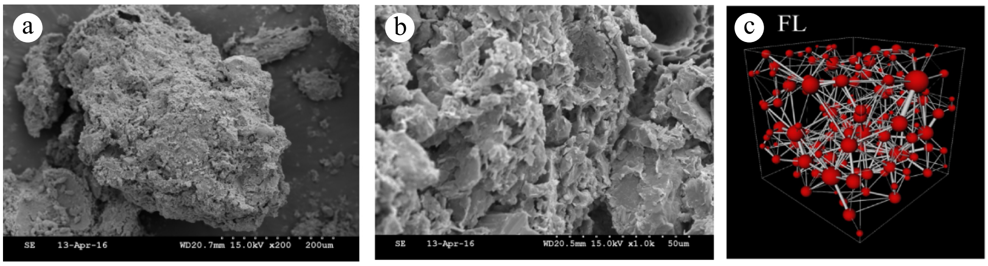

Fig. 4 A macro aggregate of (a) paddy soil and (b) 2-D image of the internal pore system with the modeled pore network based on (c) pore connectivity. Large pores and the connected channels represent pores for water movement while smaller pores are for water retention.

aggregation and soil moisture retention turned one fold higher than increase in crop productivity (Omandi et al., 2016). Biochar, compared to straw and manure amendment, effectively elevated soil (macro-)porosity and pore connectivity while enhanced particulate organic matter accumulated and macro-aggregation in rice paddy (Feng et al., 2022). In Africa, there are significant gaps of soil carbon, soil nutrients and soil moisture along with the large gap of food production (FAO et al., 2023). According to the Africa-Agenda-2063, crop production will be promoted by 6% per annum (Oramah, 2017). To meet the gaps, there will be a great potential of biochar from residue of dry crops, mainly of maize straw, to promote soil water retention and supply so as to help the underdeveloped food production in Africa. The biochar technology developed in China over recent decades (Pan et al., 2015; 2017) could contribute to achieving the African goal to promote food production, *via* China's plant to Assist Agricultural Modernization in Africa (Ministry of Agriculture of China, 2023) released in November 2023. However, applied research on how soil organic matter and biochar mediates soil aggregation, porosity and water dynamics in degraded African soil and the soil-crop system feedback deserve robust field studies across African soil types. Research addressing issues of soil, water and food production are welcome for submission to the Journal of *Soil Science and Environment*.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Pan G, Zhao Z, Liu C; data collection: Yan M, Zhao Z; draft manuscript preparation: Yan M. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

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Conflict of interest

The authors declare that they have no conflict of interest.

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