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PERSPECTIVE

A temporal framework for building up of healthy soils

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Healthy soils are vital for the diverse services provided by ecosystems to human society[1], such as provisioning (food, fiber, timber, and fuel), regulation (climate, disease, and natural hazards), waste treatment, nutrient cycling, and cultural services. Soil has a three phase system and the interactions between soil chemical, biological, and physical attributes determine functions (hydraulic, thermal, and gas fluxes). Intensive agriculture has achieved tremendous successes for increasing crop production to feed the growing population but other soil functions are not fully realized, leading to detrimental impacts on soil properties and environmental quality[2,3]. FAO estimates that nearly one-third of the world's soils are degraded, with an estimation of an irreversible soil degradation of approximately 400 km^2 per day worldwide. Hence, to address the challenge of the rapid growing population and global change, sustainable agriculture requires urgent development for proper management practices to achieve high crop production while increase other soil functions.

Soil health is the capacity of soil to function as a vital living system to sustain biological productivity, maintain environmental quality, and promote plant and animal health[4,5]. Soil is thus viewed as a living organism that functions in a holistic way depending upon its condition or state as compared to a selected reference or benchmark condition. As the term soil health itself encompasses the living and dynamic nature of soil[6], building up healthy soil for sustainable agriculture is time and space dependent which requires the establishment of long-term monitoring program and continuous efforts to ensure the desired functioning of soil. Such efforts are not easily implemented in agroecosystems due to frequent disturbances and shifts of agricultural practices which are driven by the pursuit of high profits by farmers. Hence, analogous to human health, soil health also requires system approaches to achieve not only the short time (visible) benefits and long-term (invisible) benefits which desires the optimization of both dynamic (manageable) and inherent (static) soil properties.

It is widely recognized that current agricultural management practices targeted mainly for crop productivity are not all friendly for soil attributes responsible for other soil functions. Experience based on soil health assessment in intensive crop fields shows that soil nutrients are often in excess, while soil biological and physical attributes are significantly negatively affected[7]. Agricultural practices such as excessive fertilizer and pesticide use, and frequent tillage reduce soil biodiversity result in the disruption of soil functions[8,9]. If soil is viewed as a whole from the perspective of Liebig's Law of the Minimum, the biological properties are underrepresented[10] and the complex interactions between the three soil phases need to be considered (Fig. 1). The gaps lie in the nature of soil communities, as they are extremely abundance and complex, not only at the taxonomic level but also at the phylogenetic and functional levels. As soil organisms are essential in soil processes, such as decomposition of organic materials, nutrient recycling, and the formation and maintenance of soil aggregate[11], they are regarded as the key regulators for soil health. Although it is still debatable whether soil microbial diversity and microbiome complexity are important for plant productivity[12,13], a recent study based on a large-scale field study across contrasting land use types in European revealed that there are positive effects of soil health (e.g., microbial biomass, diversity, and soil nitrogen and carbon content) on primary productivity, particularly for croplands and grasslands[14]. High microbial biomass in croplands has been shown to enhance nutrient use efficiency and nutrient cycling of plants[15]. As soil biodiversity and ecosystem functioning are complex[16], high biodiversity is desired to ensure to attain high soil functions. As such, organic farming has been shown to promote soil biodiversity but often with lower crop yields compared to standard commercial agriculture[17]. Crop diversification at spatial, temporal and genetic levels sustain diverse and active soil microbial communities[18,19], but is constrained by available machinery for management practices in the field. Hence large-scale promotion of soil biodiversity needs systematic design to increase internal regulatory efficiency of soil microorganisms. Deep understanding of the biological component and their network interactions in the soil will facilitate its processes.

Soil organic carbon (SOC) forms the basis of soil health and is another important component contributing to soil health. Improvement of SOC is a complex dynamic process which needs long-term investment. Historically SOM has often been called humus, with plant-derived carbon being considered the major contributor[20]. New mechanistic studies indicate that microbial residues (and exudates) are important for building up SOC[21]. Living microbial biomass making up less than 5% of SOC[22]. Soil microorganisms influence C turnover in multiple ways, not only by releasing C into the atmosphere through breakdown (i.e., catabolism), but they also absorb C, build their own structures, and ultimately die (i.e., anabolism). These processes of constant C turnover via assimilation and biomass construction, and subsequent cell death and metabolic products, can be conceptualized as microbial carbon pump[23]. A recent meta-analysis revealed that microbial necromass can make up more than half of topsoil SOC pool in temperate ecosystems[24]. The question remains how to increase the activity and turnover of soil microbes for carbon sequestration.

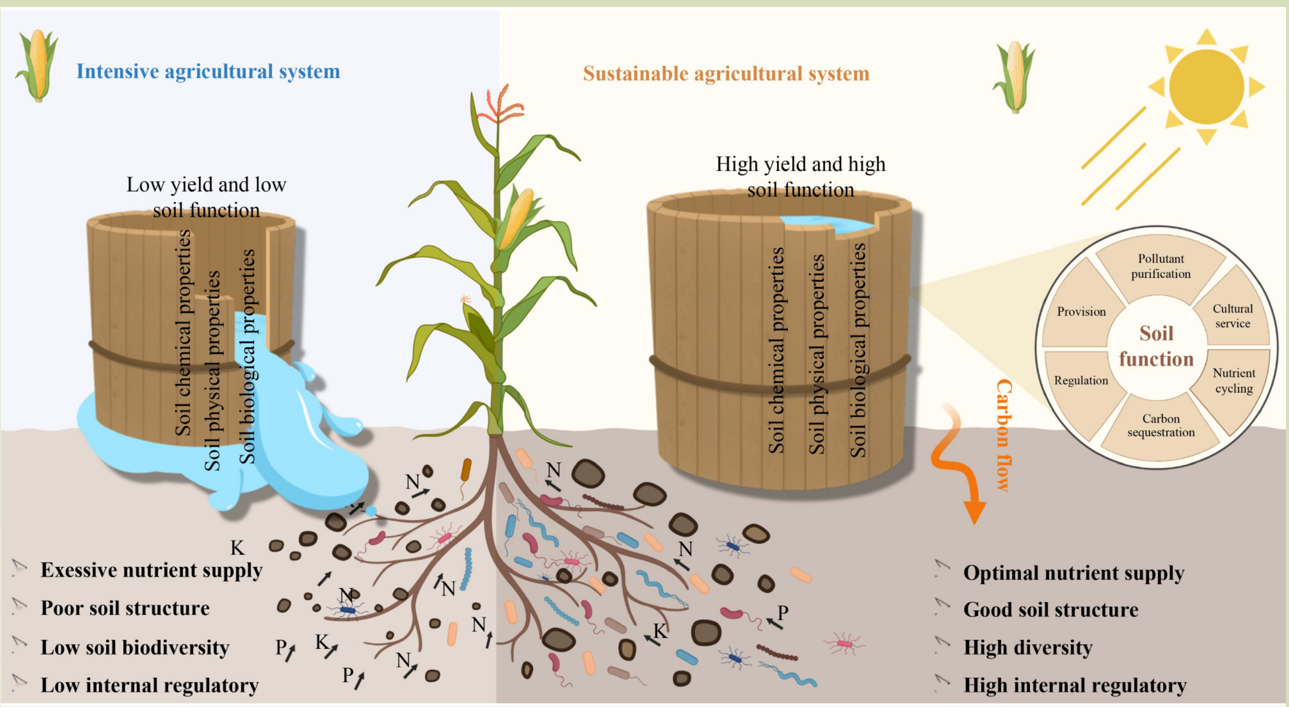

Fig. 1 Illustration of the Law of Minimum, with soil properties as the variables contributing to crop yield and soil function in the intensive vs. sustainable agroecosystems.

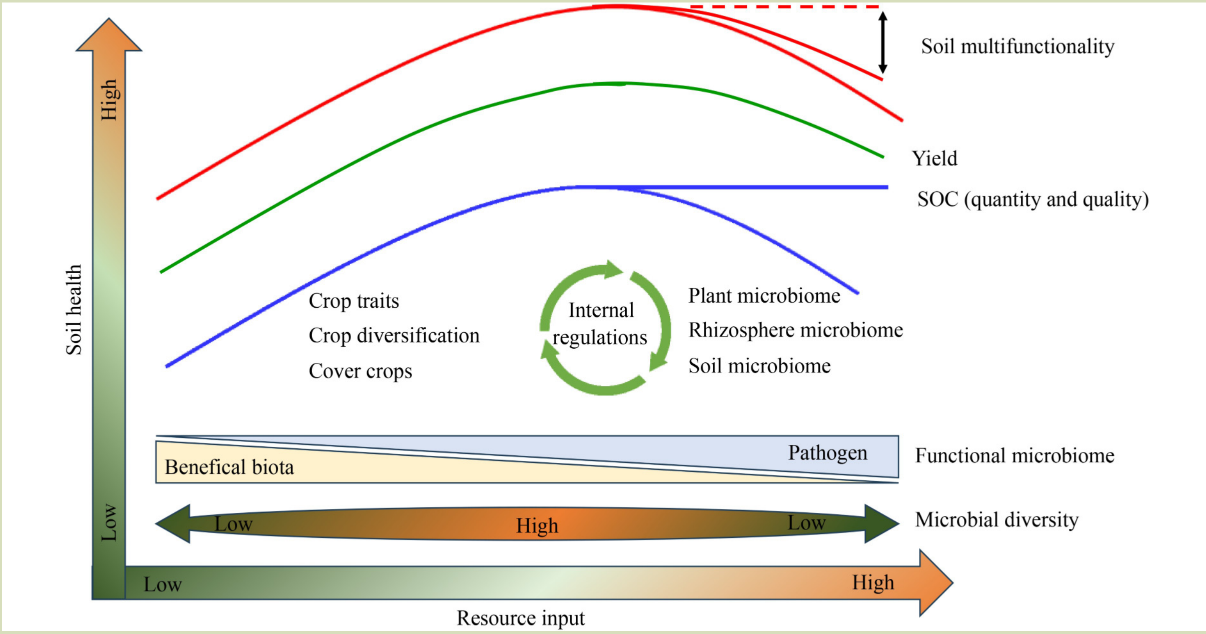

Fig. 2 A schematic of the interaction of soil heath and resource input in agroecosystems.

Manure application is often effective in increasing SOC, but is not often practical and cost-effective due to the decoupling of crop and livestock production[25]. Also, inappropriate manure use can lead to health and environmental problems[26]. Additionally, application of manure is less convenient than mineral fertilizers, and commercial organic fertilizers are often uneconomic for cereal production. Therefore, despite of diverse benefits from manure application, the motivation of farmers to use manure is not strong and may need top-down intervention. In this case, several nationwide policies such as the National Zero-Growth Action Plan, the policy of organic fertilizer replacing mineral fertilizers and straw returning in China encourage the buildup of healthy soils. Intensive overuse of mineral fertilizers has led to soil degradation and also to deterioration of the natural resource[2,3,27]. Currently, China's cropland has an average SOC storage of 36 $t \cdot ha^{-1}$[28], which is far below the global average of 62 $t \cdot ha^{-1}$[29]. Compared to mineral fertilizers, plant available nutrients in manure are relatively low but manure is favorable for soil biological and physical properties[7]. In addition, organic management promotes ecosystem multifunctionality other than providing soil nutrients, especially biodiversity preservation, soil and water quality, and climate mitigation[17]. Therefore, proper manure application is encouraged as an effective management in maintaining soil carbon pool, soil health and achieve sustainable land use.

Simultaneously optimizing all soil functions is not easily achieved and there are often trade-offs between different functions. Hence targeting land management based on a selected set of prioritized soil functions is recommended[30]. Analogous to the relationship between crop yield with soil nutrient supply, here we proposed a schematic of the interaction of soil heath and resource input in agroecosystems (Fig. 2). In low input and vulnerable soil systems, the soil biodiversity-production is established by the coordination of crop management (e.g., crop traits and crop diversification) in addition to the overall increase of soil fertility and SOC (manure application, composts, straw returning, cover crop, etc.) to promote soil biodiversity. With the increase of soil nutrients and SOC to optimal levels, the relative contribution of biological traits is enhanced and soil multifunctionality, including crop production, plateaus. Whereas in the high input systems, the asymmetric of crop yields with soil multifunctionality may be due to the shifts in soil microbiome from beneficial to pathogenic components, and/or to the deterioration of soil properties such as acidification and poor soil structure. Hence, to increase internal regulatory process there is a need for systematic management of soil/plant microbiome (diversity and composition), crop traits (crop diversification), and SOC (quality and quantities), which are highly relevant to resource inputs and other management practices in the context of the climate change. Furthermore, both in-season and long-term management practices in cropping systems need to be considered. With the rapid development of new tools in the omics, the increased understanding of the biological components, and their complex interactions with soil physical and chemical properties, will inform the development of ways to improve the sustainability of agriculture.

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