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The frontier of soil science: Soil health

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Soils provide ecosystem services enabling life on Earth. Soil health is the continued capacity of a soil to function as a vital living ecosystem that sustains biological productivity, maintains environmental quality, and promotes plant and animal health.

The development of theoretical and practical approaches to soil health evaluation and management is urgently needed. In terms of major soil-health scientific goals, current and future soil health research priorities should include detailed elucidation of soil health formation mechanisms and evolution, analysis of the diversity and functional evolution of key soil biological communities, biological multistage network construction and space-time evolution characterization, and establishment of high-throughput monitoring technology and evaluation approaches for soil health, all of which should contribute to the theory and practice of soil health management. In the next 5 to 10 years, we aim to achieve breakthroughs in healthy soil cultivation and provide theories, methods, and technologies for soil resource protection and sustainable utilization.

Soils provide ecosystem services enabling life on Earth. Soil health is the continued capacity of a soil to function as a vital living ecosystem that sustains biological productivity, maintains environmental quality, and promotes plant and animal health. More narrowly, soil health refers to the multilevel biological network formed by soil microorganisms, animals, and plants that drives the metabolism and transformation processes of biogenic elements and hazardous substances. These processes determine the health-service function of the soil–microorganism–animal–plant ecosystem and ultimately affect human health. Along with major issues such as global food security, climate change, and environmental degradation, the maintenance of healthy soil is crucial to life, thus highlighting the importance of soil health research. Soil health is at the frontier of international soil science, a field that includes interdisciplinary research activities, coupled application of multiple technologies and methods, and collaborative development on multi-temporal and spatial scales to confront new challenges. Because soil is a non-renewable, vulnerable resource, soil health and its sustainable management are becoming a major focus of global concern (Shen *et al*., 2020).

Soil health research is currently centered around the establishment of indicator systems and evaluation strategies. Scientifically recognized soil health indicators include soil organic matter content, water permeability, water-holding capacity, aggregate structure, biological activity (including microbial and invertebrate composition and diversity), and resistance stress. With the rapid development of microbial genomics and other molecular techniques, a consensus has arisen as to the role of soil biology in soil health and how biological properties and processes contribute to the sustainability of agriculture and ecosystem services (Zhu *et al*., 2017; Hermans *et al*., 2020; Astudillo-García *et al*., 2019). Meanwhile, two comprehensive evaluation strategies, namely, Comprehensive Assessment of Soil Health (CASH) and The Soil Management Assessment Framework (SMAF), have been developed that integrate multiple soil health indicators from soil physical, chemical, and biological data, with each indicator representing a unique set of important soil functions (Karlen *et al*., 2019; Wu *et al*., 2021). Some limitations still exist in the quantitative evaluation of soil health, however, and large-scale spatial mapping of soil health is difficult; consequently, further development of quantitative expression methods of soil health status based on soil function is still needed.

As we know, a health soil is a “harmonious social system”, which should has good structure, function state, buffering performance and maintain the dynamic balance of soil ecosystem. The health state of soil is mainly manifested in superior physical and chemical properties of soil, rich soil nutrients, active soil organisms, suitable soil moisture and air content, and good ecosystem services. On the contrary, an unhealthy soil is often characterized by some of salinization, acidification, barren, compaction, low nutrient utilization rate, soil pollution, succession cropping obstacle and soil biological function degradation and so on. Therefore, soil health is not all biological issues (Coyne *et al*., 2022), but how to reveal the relationship between biological indicators of soil health and soil function (e.g., production, ecological, and environmental functions) has become an international frontier of soil science research. Significant progress has been made in understanding the relationship between root microbiota and the nitrogen use efficiency of different rice varieties. For example, Zhang *et al*. (2019) found that *indica* and *japonica* rice recruit distinct root microbiota and that *indica*-enriched bacterial taxa are more diverse, with more genera having nitrogen metabolism functions. The mechanisms through which conservation tillage, organic farming, and biochar regulate carbon and nitrogen conversion and influence the structure of microbial networks have also been clarified (Banerjee et al., 2019). A new theoretical framework for soil carbon sequestration mediated by microorganisms has been created (Liang *et al*., 2017; Sokol and Bradford, 2019). Microbial phylogenetic/functional molecular ecological network analyses are continuing to reveal the detailed response mechanism of soil microbial network structure to changes in environmental conditions and the effects of the soil microbiota assembly on nutrient conversion (Crowther *et al*., 2019). The mechanism underlying the influence of climate–soil changes on the microbial network and the succession of key species for nutrient transformation has been studied in depth using transection surveys and soil replacement experiments across climatic zones (Liang *et al*., 2015). Rhizosphere pathogen–bacteria–soil-fauna interactions determine plant-rhizosphere health mechanisms (Xiong *et al.*, 2020; Gu *et al*., 2020). In addition, the soil microbiome, with its stability and efficiency, is clearly a key bioremediation component, and its importance in the field of soil environmental science and technology is now being recognized (Teng & Chen, 2019).

In China, the level of soil health is a limiting factor for ensuring food security, agricultural product quality and safety, environmental integrity, carbon neutrality, and human health. The development of theoretical and practical approaches to soil health evaluation and management is urgently needed. In terms of major soil-health scientific goals, current and future soil health research priorities should include detailed elucidation of soil health formation mechanisms and evolution, analysis of the diversity and functional evolution of key soil biological communities, biological multistage network construction and space-time evolution characterization, and establishment of high-throughput monitoring technology and evaluation approaches for soil health, all of which should contribute to the theory and practice of soil health management. In the next 5 to

10 years, we aim to achieve breakthroughs in healthy soil cultivation and provide theories, methods, and technologies for soil resource protection and sustainable utilization.

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