Soil-Microbe System Functions and Their Regulation Postprint

Authors: Nanjing Institute of Soil Science, Chinese Academy of Sciences

Date: 2017-02-08T00:00:00+00:00

Abstract

Soil is the primary carrier of grain production. Since the 18th National Congress of the Communist Party of China, General Secretary Xi Jinping has, from the perspective of China's overall development, profoundly elaborated on the major theoretical and practical issues of food security, repeatedly emphasizing that "solving the problem of feeding the people has always been the top priority in governance." The strategy of "storing grain in the land and storing grain in technology" has become one of the fourteen major strategies in China's 13th Five-Year Plan and a national priority. General Secretary Xi Jinping pointed out that cultivated land should be protected with the same vigilance as giant pandas. In the explanatory notes for the 13th Five-Year Plan proposals, he further extended the concept of storing grain in the land by proposing the exploration and implementation of a crop rotation and fallow system for cultivated land. Simultaneously, he advocated equipping grain production with technological wings and adhering to an intensive path that relies on technology to increase per-unit yield. Since the 1990s, the yield-increasing potential of traditional soil physical and chemical regulation measures has reached a bottleneck, necessitating the exploration of new growth points for China's food security. For instance, China applies one-third of the world's chemical fertilizers on merely 7% of the global cultivated land area, with nitrogen fertilizer utilization rates averaging below 30%, resulting in annual losses of up to 50 billion yuan. Moreover, the massive input of agricultural chemicals has caused ecological and environmental problems, including accumulation of harmful substances, agricultural non-point source pollution, and greenhouse gas emissions. According to 2010 estimates from the Ministry of Environmental Protection, agricultural sources contributed 57.2% and 67.4% of the nation's total nitrogen and phosphorus emissions, respectively. The morphological transformation of soil nutrient elements depends almost entirely on the soil microbiome. Consequently, unraveling the soil microbiome, developing soil-microbe systems and their functional regulation technologies, and exploring the impacts of modern

agricultural management practices on soil microbial systems and their feedback mechanisms have become critical theoretical and practical challenges for China's "storing grain in the land and storing grain in technology" strategy.

Full Text

Preamble

Strategic Priority Research Programs (Category B) of the Chinese Academy of Sciences
ChinaXiv Partner Journal
Soil-Microbe System Functions and Their Regulation

1. Background and Significance

Soil, often called the Earth's living skin, harbors a staggering diversity of microscopic organisms. Estimates suggest that each gram of soil contains up to tens of billions of microbial cells representing hundreds of thousands of species, yet the functions of approximately 99% of these microorganisms remain unknown. This "dark matter" of soil represents a vast, untapped resource that profoundly limits our ability to harness soil microbial diversity for practical applications. Since the 18th National Congress of the Communist Party of China, President Xi Jinping has repeatedly emphasized that ensuring food security is a paramount governance priority, famously stating that "solving the food problem remains the top priority in state governance." This perspective has shaped national policy, with the "13th Five-Year Plan" establishing "storing grain in the land and storing grain in technology" as one of fourteen core strategies. President Xi has further called for protecting arable land with the same vigilance afforded to giant pandas and proposed exploring crop rotation and fallow systems to maintain soil health while emphasizing that technological innovation must give wings to grain production.

Since the 1990s, conventional soil physical and chemical management practices have reached their yield-enhancement limits, necessitating new approaches to secure China's food supply. Currently, China applies one-third of the world's chemical fertilizers on just 7% of global arable land, yet nitrogen use efficiency averages below 30%, resulting in annual economic losses of approximately 50 billion yuan. This excessive agrochemical input has triggered severe environmental consequences, including pollutant accumulation, agricultural non-point source pollution, and greenhouse gas emissions. According to 2010 Ministry of Environmental Protection estimates, agricultural sources contributed 57.2% of total nitrogen and 67.4% of total phosphorus emissions nationwide. Since soil microorganisms mediate nearly all nutrient transformations, unraveling the soil microbiome and developing soil-microbe system regulation technologies has become a critical theoretical and practical challenge for implementing China's "storing grain in the land and storing grain in technology" strategy.

On May 13, 2016, the White House Office of Science and Technology Policy, in partnership with government agencies and private foundations, launched the National Microbiome Initiative—following the BRAIN Initiative, Precision Medicine Initiative, and Cancer Moonshot as another major national strategic endeavor. This initiative aims to explore microbiome functions across diverse environments, including human, soil, marine, and atmospheric systems, offering novel solutions to 21st-century challenges in agriculture, energy, environment, oceanography, and climate change.

2. Major Progress

Over the past two years, the "Soil-Microbe System Functions and Their Regulation" strategic priority program has made significant advances across three integrated tasks—"Resources," "Functions," and "Regulation"—while simultaneously exploring new technologies and methodologies. As illustrated in Figure 1 [Figure 1: see original paper], this comprehensive effort combining scientific breakthroughs, talent development, and platform construction has yielded substantial progress and generated important international impact.

2.1 Soil Microbiome Resources

The program has completed extensive soil sampling across China's typical farmland, grassland, and forest ecosystems, covering over 8,000 kilometers. First, we evaluated how contemporary environmental and historical factors shape microbial spatial distribution patterns, revealing distinct latitudinal and altitudinal diversity gradients that differ from plant diversity patterns. Under long-term fertilization management, historical factors increasingly dominate farmland soil microbial distributions, with soil pH explaining the greatest proportion of microbial community variation. In alpine regions, organic carbon content better explains microbial distribution patterns across the Tibetan Plateau. Second, we quantified drought impacts on soil microbial communities, demonstrating that aridity index drives bacterial community shifts and fundamentally alters ecosystem nitrogen cycling. Notably, regional nitrogen cycling in northern grasslands exhibits a nonlinear response to aridity, with a critical threshold at $AI = 0.32$. In arid regions ($AI < 0.32$), nitrifier and denitrifier abundances increase with aridity index, while microbial diversity declines sharply under extreme drought conditions.

2.2 Soil Microbiome Functions

First, we discovered that anaerobic ammonium oxidation represents not only an important process in wetland and soil systems but also a major pathway for nitrogen loss in rice paddies. Rhizosphere nitrogen loss has emerged as a critical microdomain for developing high-efficiency nitrogen utilization technologies, and we elucidated the coupling mechanism between anaerobic ammonium oxidation and iron redox processes. Second, regarding microbial mechanisms driving soil carbon transformation, comparative studies of Neolithic ancient paddy soils (6,300 years of cultivation) and modern paddy soils revealed that long-term tillage induces significant shifts in soil microbial community structure. Rice soil microbiomes evolve toward functional homogenization, particularly for ecological functions related to nutrient biogeochemical cycling, which enhances soil activity, accelerates nutrient transformation, and increases rice yields. Furthermore, under high methane concentrations, we found that alternately flooded rice soils can oxidize low-concentration atmospheric methane, with traditional methanotrophs playing crucial roles—providing essential evidence for field observation experiments and accurate estimation of China's greenhouse gas emission inventories.

2.3 Soil Microbiome Regulation

First, we quantified microbial community succession patterns in typical farmland soil carbon and nitrogen transformation, finding that long-term organic fertilizer application promotes nematode-microbe interactions within macroaggregates of red soil, thereby enhancing nitrogen transformation capacity. Second, we screened rice varieties with high nitrogen and phosphorus efficiency, revealing that stomatal regulation can improve carbon assimilation and transpiration pull, elucidating molecular regulation patterns that promote nitrogen and potassium use efficiency. We identified root proton secretion, ABA content, and auxin transport rate as core responses to phosphorus-deficient environments, demonstrating that optimized phosphorus application coupled with water management promotes deeper root growth and improves phosphorus utilization efficiency. Third, we found that no-tillage management in fluvo-aquic soils maintains higher arbuscular mycorrhizal fungal diversity, colonization rates, and maize phosphorus use efficiency. In high-phosphorus soils, inoculation with arbuscular mycorrhizal fungi reduces vegetable phosphorus fertilizer requirements, clarifying how the "high-phosphorus seedling, low-phosphorus planting" strategy significantly improves phosphorus fertilizer efficiency.

2.4 Novel Technologies and Their Applications

First, we achieved, for the first time internationally, nanoliter-level single-cell amplification systems, reducing costs by 100-fold, and constructed the first Raman spectroscopy-based live single-cell screening device. We have filed related patents and secured 4 million yuan in angel investment from CAS Innovation Star for commercialization. Second, we established a spatial database of soil properties integrated with a soil microbiome analysis platform, providing technical support for deep exploration and regulation of soil microbiome resources. Third, we developed stable isotope tracing methods for various microbial biomarkers, including amino sugars (AA), phospholipid fatty acids (PLFA), and nucleic acids (DNA/RNA), along with high-throughput sequencing platforms for microbial biodiversity. These technologies have supported over 100 research groups domestically and internationally. We have organized

12 technical workshops and training sessions, attracting more than 1,000 young researchers from 16 countries/regions, creating an internationally leading soil microbiome research platform that also provides crucial support for microbial function studies in geology, oceanography, and pollution research.

3. Originality

(1) Theoretical Innovation. We pioneered the concept of the soil microbiome as a new scientific paradigm. Oriented toward fundamental human needs—food production, environmental protection, and ecological security—this framework investigates interactions among soil microorganisms, their environment, and other organisms across temporal and spatial scales through in situ observation, laboratory cultivation, and field experiments. The approach integrates metagenomics, transcriptomics, proteomics, and advanced physicochemical and computational analyses.

(2) Methodological Innovation. We developed a full-chain soil biomarker tracing methodology, creating coupled analytical platforms for various microbial indicators including AA, PLFA, and DNA/RNA. This overcomes the inherent limitations of low sensitivity and resolution associated with single biomarker approaches internationally, providing crucial methodological support for systematically studying microbial regulation mechanisms of key nutrient transformations in soil-microbe-plant systems.

(3) Technological Innovation. We developed the world's first live single-cell Raman sorter, which represents the first reported instrument capable of manual and automated cell sorting based on Raman fingerprint spectra. The device enables rapid single-cell Raman spectrum acquisition, reducing collection time to 1–100 milliseconds per cell, and simultaneously performs multiple tasks including rapid cell type and growth status identification based on Raman profiles. The instrument has demonstrated excellent performance in demonstration applications at domestic research institutes, showing enormous potential not only for soil microbiome research but also for bioenergy strain screening, food microbial detection, drug screening, and environmental pollution biomonitoring.

The program has significantly elevated China's international standing in soil microbiology and related fields, with over 200 publications to date. Approximately one-third of these papers have been published in authoritative journals of soil science, microbiology, ecology, agronomy, and global change, including prestigious interdisciplinary journals such as *Nature Communications* and *PNAS*, generating substantial international impact. In 2016, we organized the first Soil Microbiology High-Level Academic Forum with leading international experts. Chinese scientists are now leading the organization of the 2017 Second Global Soil Biodiversity Conference, with renowned scientists including members of the U.S. National Academy of Sciences recognizing Chinese soil microbiome research as an indispensable force that will reshape the international research landscape.

Throughout implementation, the program has collaborated with CAS, the Ministry of Agriculture, Ministry of Environmental Protection, China Association for Science and Technology, and UNEP to host the "Soil and Eco-Environmental Security" High-Level Forum, receiving extensive coverage from mainstream media including CCTV (CCTV-1 Evening News, CCTV-13 News Live), People's Daily Online, Xinhua Net, and Phoenix News. Core team members have chaired China's 30-year soil biology discipline development and planning initiatives, completed strategic reports for the National Natural Science Foundation of China's "30 Years of Soil Biology," and participated in CAS-NSFC soil biology development strategy research, promoting the compilation and publication of *Frontiers in Soil Biology* and *Soil Biology: China's Discipline Development Strategy*.

The program has accelerated talent development in soil science, with team members receiving 12 national-level awards including the National Science Fund for Distinguished Young Scholars. Researcher Yong-Guan Zhu received the TWAS Prize in Agricultural Sciences and was listed among Thomson Reuters' Highly Cited Researchers in 2016, one of only two Chinese scientists in environmental ecology. Researcher Ren-Fang Shen was elected President of the East and Southeast Asia Federation of Soil Science Societies. The core team's work on microbial mechanisms driving soil nitrogen transformation has generated significant international impact. According to a 2015 analysis of Sino-American research frontiers, soil microbiome research represents one of three Chinese research fronts among 11 global frontiers in ecology and environmental sciences.

5. Industrial Promotion Significance

The implementation of the "Soil-Microbe System Functions and Their Regulation" strategic priority program represents a crucial component of China's "13th Five-Year Plan" strategy of "storing grain in the land and storing grain in technology," delivering clear benefits to agriculture and environmental industries. The program has driven the establishment and implementation of two national key R&D programs, with core members leading the "Chemical Fertilizer and Pesticide Reduction and Efficiency Enhancement Technology R&D" pilot special project and participating in the "Grain Production and Efficiency Innovation" key special project, providing essential theoretical and technical support for establishing a sustainable modern agricultural system.

Soil microorganisms constitute Earth's largest gene resource repository, harboring immeasurable quantities of bioactive compounds with broad applications in medicine, animal feed, and agricultural chemicals. Selman Waksman, the first soil microbiologist to receive a Nobel Prize, pioneered microbial cultivation techniques, defined the concept of antibiotics, and discovered streptomycin. Japanese scientist Satoshi Ōmura discovered the active compound ivermectin from soil microorganisms, which has proven enormously effective in treating river blindness and elephantiasis, earning him the 2015 Nobel Prize in Physiology or Medicine. Leading nations, particularly the United States, are actively planning national microbiome initiatives to establish strategic high ground in this interdisciplinary frontier. The "Soil-Microbe System Functions and Their

Regulation" program provides China with pioneering experience for developing cross-disciplinary, cross-sectoral microbiome initiatives that better leverage microbial systems for pollution remediation, human health, and biomanufacturing.

In December 2013, the U.S. government published the book *Microbes Feed the World*, emphasizing that soil microbiome regulation can increase crop yields by 20% while reducing fertilizer and pesticide inputs by 20%, representing a future pathway for environmentally friendly and economically viable green agriculture. The internationally renowned agricultural biotechnology company Monsanto is developing microbiome formulations to transform traditional yield-enhancement models that focus solely on aboveground plant trait improvement, instead harnessing underground microbial functions to enhance soil fertility and productivity. The program's implementation will powerfully advance China's related industries while providing important references for healthcare and industrial production.

Soil microbiomes are critically important for human health, food security, and sustainable ecological and environmental development. The "Soil-Microbe System Functions and Their Regulation" strategic priority program complements major international initiatives while offering distinctive features and advantages, including larger research scales, greater interdisciplinary integration, and cutting-edge positions in technology development and applied research. The program's innovation and publication quality are exceptionally high, positioning it to reshape international research patterns and emerge as a leader in both fundamental soil microbiome research and societal applications.

Expert Evaluations

James M. Tiedje, Member of the U.S. National Academy of Sciences and University Distinguished Professor at Michigan State University, is a pioneer in microbial ecology who revolutionized modern molecular ecological classification strategies and established international standards. With over 500 publications cited more than 70,000 times and an H-index of 134, he has been a major leader in international microbiome research over the past three decades. He notes that soil microbiomes not only provide plants with available nutrients to ensure food security but also serve as regulators of elemental cycles critical for sustainable ecological and environmental development. Unraveling soil microbiomes represents a primary challenge for modern agriculture, environmental sustainability, and international soil science. China's strategic priority program plays a key role in this emerging field by developing novel technologies to reveal unimaginable microbial diversity. Particularly important are the program's numerous large-scale studies that have generated valuable data resources, contributing significantly to understanding microbial regulation of key elemental transformations. The program has achieved outstanding results in soil organic matter and nutrient transformation, with technological innovations showing enormous application potential for improving crop nutrient use efficiency and developing demonstration technologies. The program has already generated substantial international impact through high-level academic symposia with renowned experts and flexible international cooperation models. The new knowledge created will help address not only China's challenges but also enable international colleagues to better manage soils and protect resources, such as reducing overexploitation of non-renewable phosphate rock, decreasing dependence on nitrogen fertilizers, and eliminating negative environmental impacts from improper fertilizer use. These high-level international collaborations will maximize global research benefits and cultivate outstanding young Chinese researchers who will become important drivers and leaders in international soil microbiome research.

Sally E. Smith, Fellow of the Australian Academy of Science and Distinguished Professor at the University of Adelaide, is a world authority on soil fungi and mycorrhizal symbiosis. With over 200 publications and the authoritative textbook *Mycorrhizal Symbiosis* (co-authored with David Read), she emphasizes that China's microbiome initiative positions Chinese researchers at the forefront of the field, with visibility of achievements continuing to strengthen and new knowledge applications holding extremely important economic and social development significance.

Note: Figure translations are in progress. See original paper for figures.