Challenges and Strategic Positioning for Soil Pollution Prevention and Control in China: Postprint

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Abstract

[Purpose/Significance] In response to the severe situation of prominent soil pollution in China in the new century, exploring strategic mechanisms that can effectively improve soil quality, protect the soil environment, and safely utilize land resources holds important practical significance and far-reaching strategic impact for ensuring the quality and safety of agricultural products and public health, achieving sustainable land use, and promoting ecological civilization construction. [Method/Process] This paper systematically analyzes the main problems and challenges faced in the process of soil pollution prevention and control in China, and positions the key initiatives for soil pollution prevention and control from a macro perspective of soil environmental protection and safe land utilization. [Results/Conclusion] The study finds that soil pollution prevention and control efforts in China focus on farmland and industrial land as key remediation targets, and although significant progress has been made in various aspects, the following main problems still exist: (1) For farmland pollution, there are issues such as strong spatial heterogeneity of pollutants, large discrepancies between soil pollution and agricultural product exceedances, inadequate source control of soil pollution, and difficulties in safe utilization of farmland; (2) For industrial contaminated sites, there are problems including an incomplete policy and regulatory system for pollution prevention and control, lagging technical capacity building, one-sided emphasis on engineering remediation, and unsustainable remediation models. To protect national soil ecological security and promote strategic planning for safe land utilization, efforts should be accelerated to improve the top-level design of soil pollution prevention and control, systematically implement source control, precision control, and comprehensive control, adhere to the principles of "sustainable remediation, moderate remediation, and green remediation," strengthen close cooperation among various stakeholders in the industrial chain, develop diversified and stable financing

channels for soil remediation, and establish an early warning mechanism for soil environmental quality.

Full Text

Challenges and Strategic Positioning of Soil Pollution Prevention and Control in China

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Abstract

[**Purpose/Significance**] In response to the increasingly severe soil pollution situation in China in the new century, exploring strategic mechanisms to effectively improve soil quality, protect the soil environment, and ensure safe land utilization holds important practical significance and profound strategic implications for safeguarding agricultural product quality and safety, protecting public health, achieving sustainable land use, and promoting ecological civilization construction.

[**Method/Process**] This paper systematically analyzes the primary problems and challenges in China' s soil pollution prevention and control efforts, and identifies key measures for soil pollution management from a macro perspective of soil environmental protection and land safety utilization.

[**Result/Conclusion**] The study finds that while China' s soil pollution prevention and control efforts have made significant progress in multiple areas by focusing on farmland and industrial land, several major problems persist: (1) For farmland pollution, challenges include strong spatial heterogeneity of pollutants, significant discrepancies between soil pollution and agricultural product contamination, inadequate pollution source control, and difficulties in safe farmland utilization; (2) For contaminated industrial sites, problems include an imperfect policy and regulatory system, lagging technical capacity development, excessive emphasis on engineering remediation, and unsustainable remediation models. To protect national soil ecological security and promote strategic planning for land safety utilization, China should accelerate improvement of top-level design for soil pollution prevention and control, systematically implement source management, precision management, and comprehensive management, adhere to the principles of "sustainable remediation, moderate remediation, and green remediation," strengthen close cooperation among stakeholders in the industry chain, develop diverse and stable financing channels for soil remediation, and establish a soil environmental quality early warning mechanism.

Keywords: Land safety utilization, Risk management, Sustainable remediation, Soil pollution prevention and control, Farmland pollution, Contaminated sites

Soil is a crucial strategic resource for human survival and national stability, fundamentally related to national ecological security and the sustainability of ecological civilization construction [1]. With China' s rapid urbanization, extensive industrialization, and highly intensive agricultural development over the years, soil pollution has become increasingly prominent. According to the "National Soil Pollution Survey Bulletin" jointly released by the Ministry of Environmental Protection and the Ministry of Land and Resources in 2014, the environmental quality of cultivated land and industrial land in China is particularly concerning, with soil sample exceedance rates ranking highest among all land use types [2]. This severe soil environmental situation has already affected ecological environments, crop safety, human health, and sustainable socioeconomic development, prompting the Party Central Committee and the State Council to attach great importance to soil pollution prevention and control. In recent years, governments at all levels have actively implemented measures for soil pollution prevention and control, achieving effective progress in regulation and standard formulation, remediation technology development, and engineering demonstrations. Particularly noteworthy is the "Soil Pollution Prevention and Control Action Plan" (commonly known as the "Soil Ten Articles") issued by the State Council in May 2016, which established the fundamental approach of "prevention first, protection priority, risk management, and safe utilization," and provided systematic strategic deployment for effective soil pollution prevention and control from ten aspects, serving as the action program for current and future soil pollution prevention and control work in China.

Considering food safety issues from farmland pollution and public health risks from contaminated industrial sites, it is certain that the focus of China' s soil pollution prevention and control will concentrate on farmland and industrial land for the current and foreseeable future. However, soil pollution prevention and control efforts remain lagging, with bottleneck problems yet to be effectively resolved.

1 Farmland Soil Pollution Prevention and Control

Farmland soil environmental quality is closely related to agricultural product quality, safety, and human health. Currently, heavy metal pollution in China' s farmland soil is prominent, with pollution rates rising from less than 5% in the late 1980s to nearly 20% at present [3], showing an overall trend of increasing pollution types, expanding polluted areas, intensifying pollution levels, and growing remediation difficulties [4-9]. The contradiction between the management goal of "balancing land use with land conservation and integrating production areas with products" and practical issues such as "spatial heterogeneity of pollutants, differences between soil and agricultural products, pollution source control, and safe farmland utilization" poses significant challenges for farmland soil pollution prevention and control in China.

1.1 Strong Spatial Heterogeneity of Pollutant Distribution

Although the "Soil Ten Articles" established basic tasks for detailed soil pollution surveys, the current status of farmland pollution in China remains unclear, with a lack of comprehensive and specific data on farmland soil pollution and its impacts on agricultural product quality. This is because China has a vast territory with diverse soil types, and significant regional differences exist in both background and current values of soil heavy metals. Combined with complex influences from distance to pollution sources, crop varieties, field management, and climatic conditions, farmland soil heavy metal pollution exhibits substantial spatial variation, with even adjacent plots showing different pollution characteristics. This spatial heterogeneity not only increases the difficulty of farmland soil pollution surveys, making it challenging to accurately determine pollution areas, distribution patterns, and contamination levels, but also hinders large-scale application and promotion of remediation technologies.

1.2 Significant Discrepancy Between Soil Pollution and Agricultural Product Contamination

In reality, soil pollution does not have a direct or inevitable relationship with agricultural product contamination. Although agricultural product safety is affected by soil quality, external factors such as climate environment, atmospheric and water pollution, and heavy metal speciation cannot be ignored. Additionally, due to different migration mechanisms in the soil-crop system, heavy metal accumulation capacity in agricultural products varies significantly among different crops or even among different varieties of the same crop [10-14]. This not only increases the difficulty of soil pollution remediation but also affects the effectiveness and stability of remediation efforts.

1.3 Inadequate Attention to Pollution Source Control

The soil environment is an open and complex system, which determines the extensive nature of soil pollution sources. Pollutants are generated at sources, enter soil through certain pathways, undergo a series of physical and chemical reactions within the soil, and ultimately affect exposed receptors, forming a "source-pathway-receptor" risk mechanism. Controlling and eliminating pollution sources is the fundamental measure for soil pollution prevention and control. However, current prevention and control efforts overemphasize remediation of existing pollution while neglecting pollution source apportionment and source prevention and control, resulting in continuous pollutant input through atmospheric deposition, sewage irrigation, and fertilizer and pesticide application during remediation processes. Moreover, soil pollution sources are highly complex, characterized by scattered distribution, large numbers, and small scales, making decentralized control of each source difficult. Consequently, it is not surprising that soil pollution prevention and control effects have been unsatisfactory.

1.4 Difficulties in Safe Farmland Utilization

With limited per capita farmland in China, conducting farmland soil pollution prevention and control and safe land utilization while strictly safeguarding the 1.8 billion mu (120 million hectares) food security red line, protecting farmers' interests, and ensuring agricultural productivity is extremely challenging. On one hand, soil pollution has complex causes requiring comprehensive treatment combining risk management measures with engineering remediation technologies. However, large-scale, easily promotable, economically effective farmland soil pollution remediation technologies are still lacking. Additionally, farmers' lack of cooperation in implementing risk management measures such as agronomic regulation, alternative planting, and planting structure adjustment further complicates unified management of scattered pollution. On the other hand, most regions have insufficient cultivation of remediation responsibilities and implementation entities, with remediation measures still relying on scattered farmers. Influenced by traditional farming practices and profit risks, farmers show low participation enthusiasm, causing difficulties in land transfer and severely hindering safe land utilization.

2 Contaminated Site Soil Pollution Prevention and Control

With urban layout adjustments and industrial structure upgrades, China has shut down, merged, or transformed numerous industrial enterprises in recent years, leaving behind serious legacy soil contamination problems with prominent environmental safety risks. Analysis of soil remediation practice cases reveals that the key issues in China' s contaminated site management currently lie in the lack of correct risk management concepts and comprehensive consideration of remediation input-output benefits, leading to widespread phenomena of over-remediation, blind remediation, and inefficient remediation [15-20]. Specifically:

2.1 Imperfect Policies and Regulations, Incomplete Standards and Norms

Drawing on successful contaminated site management experiences from developed countries, the key to soil pollution prevention and control lies in effective institutional controls [21], namely a complete supporting policy and regulation system centered on core laws and supplemented by refined technical guidelines and standards to ensure that all stages of soil pollution prevention and control have legal basis and standardized guidance. Currently, specialized soil pollution prevention and control laws have not yet been enacted, soil environmental quality standards for agricultural and construction land have not been implemented, a graded and classified risk management and control system has not been formed, and there is a lack of remediation technology guidelines and operational industry standards for different types of contaminated sites.

2.2 Weak Technical Capacity Foundation, Urgent Need to Improve Market Environment

Since 2011, China's soil pollution prevention and control technology level and independent equipment innovation capability have rapidly improved, with special budgets for soil pollution remediation increasing annually and the soil remediation industry chain continuously optimizing. However, relative to the actual needs of soil pollution prevention and control in China, there remains a lack of professional talent teams, independent equipment research and development and large-scale engineering applications, risk management and sustainable remediation systems, and big data dynamic management for whole-process supervision and monitoring. In terms of the market environment, issues involve funding mechanisms, market incentives, government supervision, corporate ethics, third-party oversight, and disorderly competition.

2.3 Excessive Emphasis on Engineering Remediation, Lack of Risk Management Awareness

The management history of contaminated sites in developed countries, evolving from comprehensive remediation to risk management and then to sustainable remediation, demonstrates that complete and thorough remediation of contaminated sites is neither realistic nor necessary. China is currently in a transition period from comprehensive remediation to risk management but has not yet fully established correct risk management orientation. Soil pollution prevention and control practices still commonly exhibit "over-remediation" targeting absolute safety. This approach is not only costly but also detrimental to optimal allocation of social resources and the multifunctionality and sustainable utilization of land resources, seriously violating the risk-based graded, classified, and zoned management philosophy for soil pollution.

2.4 Prominent Secondary Pollution Issues, Unsustainable Remediation Models

Current contaminated site remediation only considers factors such as reducing pollutants to target concentrations, ease of implementation, and time savings. On one hand, there is a lack of consideration for resource and material consumption during remediation implementation and waste generation, as well as the environmental net benefits throughout the entire lifecycle of remediation material and equipment manufacturing processes. Coupled with non-standard engineering operations and inadequate departmental supervision, secondary pollution from remediation processes easily occurs. On the other hand, front-end project design often neglects ecosystem integrity, isolating contaminated sites from surrounding environments and urban development. There is insufficient understanding of how to balance public social benefits with corporate and government interests, achieve land value appreciation from remediation, and promote coordinated development of surrounding enterprises and regional economies. This narrow remediation concept limits the potential benefits of combined engineering

and non-engineering management measures, creating enormous financial pressure from the substantial funding demands of soil pollution remediation.

3 Countermeasures and Suggestions

Based on the severity of soil pollution in China and the urgency of prevention and control, and building upon analysis of major existing problems, this paper proposes the following soil pollution prevention and control strategies from a macro perspective of soil environmental protection and land safety utilization, in accordance with the strategic deployment in President Xi Jinping' s 19th Party Congress report to accelerate ecological civilization system reform and focusing on the core requirement of "strengthening soil pollution management and remediation."

3.1 Accelerate Improvement of Top-Level Design for Soil Pollution Prevention and Control

Improving top-level design should proceed from two aspects: constructing a policy system and coordinating regional development. First, taking the Soil Pollution Prevention and Control Law as the principled guiding document, China should accelerate formulation of supporting soil pollution prevention and control standards, implementation rules, and technical guidelines for different land uses. From both central and local levels, this would ensure detailed implementation, adaptation to local conditions, and supporting enforcement of the guiding document, systematically and effectively regulating and guiding all stages of soil pollution prevention and control. Currently, this work is advancing in depth, with the Soil Pollution Prevention and Control Law having passed its first review by the National People' s Congress, and other standards such as the "Farmland Soil Environment Management Measures (Trial)" having recently been implemented. Second, China should clarify remediation thinking, coordinate overall design of soil pollution prevention and control projects with local infrastructure projects, land use planning, and regional development layout, and optimize social resource allocation and land use efficiency.

3.2 Advance "Three Types of Governance" Simultaneously

China should simultaneously advance source management, precision management, and comprehensive management in soil pollution prevention and control projects, addressing soil pollution from both "prevention" and "remediation" perspectives. First, the focus of soil pollution prevention and control lies in source prevention, promoting the transformation of soil environment management from end-of-pipe treatment to source prevention. This involves preventing and controlling new pollution generation, promoting clean transformation and pollutant emission reduction in key polluting industries covered by the air, water, and soil pollution prevention and control action plans, and quickly changing the management model of "polluting while treating." Second, soil pollution is

closely related to atmospheric and water pollution while also having obvious regional and local characteristics. While conducting precision management targeting soil pollutants, China should also consider the systematic nature of the ecological environment and overall sustainability of regional development, incorporating atmospheric, water, and other potential influencing factors into the protection action framework.

3.3 Establish Risk-Based "Three Remediation" Concepts

Drawing on the green, intelligent, and sustainable remediation concepts from developed countries, China should establish three principles for contaminated soil remediation: sustainable remediation, moderate remediation, and green remediation. First, the concept of sustainable development should run through the entire process of initial design, implementation, and post-monitoring of remediation projects, comprehensively considering environmental, social, and economic factors. Based on project objectives, costs, and timelines, reasonable remediation technology solutions should be designed using lifecycle assessment and cost-benefit analysis. This would change the traditional "one-size-fits-all" management model and establish a soil sustainable management strategy integrating pollution prevention, risk management, remediation, and land reuse with risk management as the core concept. Second, remediation technology solutions that can effectively control potential risks while improving soil functions should be adopted to reduce or eliminate risks from the perspective of environmental sensitivity. Combined with urban development and spatial planning, moderate remediation should be practiced to reduce the environmental footprint of remediation actions and achieve organic unity of environmental, social, and economic benefits. Third, while protecting human health and environmental safety, environmentally friendly multi-method in-situ combined remediation technologies should be employed to avoid secondary pollution and destruction of soil ecological functions, while also ensuring the long-term effectiveness and sustainability of remediation results.

3.4 Strengthen Broad Cooperation Among Stakeholders in the Industrial Chain

Stakeholder cooperation is essential because soil pollution prevention and control projects and the soil remediation industry involve broad fields, strong professionalism, and obvious regional characteristics, covering multiple links including scientific research and development, engineering construction, project consulting, and departmental supervision. Conducting close domestic and international cooperation as well as enterprise-government cooperation, particularly promoting the connection between scientists and enterprises and governments to drive the transformation and application of scientific and technological achievements, can significantly improve social capital utilization efficiency, balance interests among all parties, and accelerate the healthy and orderly development of the emerging strategic industry of soil remediation and management.

3.5 Broaden Financing Channels and Funding Sources

It is estimated that completing remediation of all risky land will require trillions of yuan in investment, and current central government special funds for soil pollution prevention and control far from meet the enormous market demand. Although the "polluter pays" principle is upheld, practice has proven that various challenges arise in implementation, such as inability to trace responsible parties for historical pollution, responsible parties being unable to afford huge remediation costs, and difficulty in allocating responsibility among multiple polluters. Therefore, it is necessary to strengthen market functions, formulate fund management measures and usage systems, and broaden financing channels and funding sources for soil remediation. Innovative financing mechanisms such as Public-Private Partnership (PPP) models incentivized by the substantial reuse value of remediated land, international funds, high-risk enterprise deposit systems, and environmental taxes should be utilized. A multi-entity, multi-channel, multi-objective investment and financing system based on the principle of "whoever pollutes shall treat, whoever benefits shall pay" should be established as soon as possible to ensure stable, diversified funding sources for remediation and sustainable remediation work.

3.6 Establish a Soil Environmental Quality Early Warning Mechanism

The concealed, lagging, and cumulative characteristics of soil pollution make it difficult to detect contamination promptly. Once soil is polluted, it has large impact scope, long impact duration, serious hazards, difficult remediation, and high treatment costs. Therefore, China must adhere to the principle of "prevention first, protection priority" and establish a soil environmental quality early warning mechanism to accurately predict spatiotemporal trends in soil environmental quality. Based on early warning results, timely measures such as adjusting industrial layout and rationally planning land use should be taken to effectively prevent soil environmental quality deterioration and macro-control strategic implementation of soil environmental risk management at regional spatial scales. Ultimately, this will achieve the unity of five objectives: agricultural product quality and safety, human health, ecological environment protection, land safety utilization, and coordinated socioeconomic development.

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