Promoting Sustainable Development of Regional Farmland Ecosystems through Efficient Soil and Fertilizer Management (Postprint)

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Abstract

The Liaohe Plain constitutes a crucial component of China's temperate farmland ecosystems, and the high yield and high efficiency of agriculture in this region play a vital role in consolidating the "stabilizing grain production and increasing efficiency" function of the Northeast China Granary. However, due to the continuous reduction in cultivated land area and the escalating resource and environmental constraints caused by long-term high-intensity utilization, the sustainable development of the farmland ecosystem in the Liaohe Plain faces severe constraints. The Shenyang Ecological Experimental Station of the Chinese Academy of Sciences, focusing on core issues in regional agricultural production and resource management and based on long-term monitoring and research of farmland ecosystems, has revealed the evolution patterns of comprehensive soil fertility under different nutrient management regimes. Utilizing isotopic tracer technology, the retention, transformation, and regulatory mechanisms of fertilizer nitrogen in farmland ecosystems have been elucidated. Through the establishment of the "carbon-controlled nitrogen, carbon-nitrogen balance" management model for farmland soils, an integrated supporting cultivation technology system for conservation tillage in rain-fed dryland agriculture has been developed. Through the development of environmentally friendly stabilized fertilizers, fertilizer reduction and efficiency enhancement have been achieved, reducing the risk of non-point source pollution. Through the effective integration of research-demonstration-extension, efficient soil and fertilizer management has provided scientific and technological support for regional modern agricultural development and ecological environment construction.

Full Text

Efficient Soil and Fertilizer Management to Promote Sustainable Development of Regional Agroecosystems in the Liaohe Plain

The Liaohe Plain constitutes a vital component of China's temperate agroecosystems and serves as a crucial commercial grain production base. With its strong agricultural capacity, the region plays a strategic role in national food security and economic development. However, rapid economic growth and urban expansion have continuously reduced cultivated land area, while long-term intensive use of existing farmland has caused severe soil degradation, including compaction, salinization, declining organic matter content, and nutrient imbalances. These "thinning, drying, and weakening" soil conditions have significantly compromised the comprehensive productivity of agriculture in the Liaohe Plain.

To address these core challenges in agricultural production and rural economic development, the Institute of Applied Ecology of the Chinese Academy of Sciences established the Shenyang Agroecosystem Experimental Station (hereafter "Shenyang Station") in Sujiatun District, Shenyang, Liaoning Province, in 1987. Building upon the long-term soil fertility research tradition of Rothamsted Experimental Station in the UK [1], Shenyang Station initiated long-term positioning experiments with multiple groups and types to investigate nutrient cycling, budgets, transformation, and migration processes critical to agricultural production in the Liaohe Plain [2]. Research has revealed that aquic brown soils in the region are not phosphorus-deficient and are relatively potassium-rich, with nitrogen representing the primary limiting factor for crop yields. Therefore, phosphorus and potassium application rates should meet crop demands, supplemented with recycled organic manure to achieve a fertilization mode with slight nitrogen-phosphorus-potassium surpluses, thereby building an appropriate soil nutrient pool and maintaining long-term nutrient balance [3].

Revealing Evolution Patterns of Integrated Soil Fertility Under Different Nutrient Management Regimes

Since its establishment, Shenyang Station has deployed a series of long-term nutrient management positioning experiments [Figure 1: see original paper] to examine how different nutrient cycling and management modes affect key fertility indicators—including soil organic matter, total nitrogen, total phosphorus, total potassium, alkali-hydrolyzable nitrogen, available phosphorus, available potassium, and soil pH—and to explore the long-term evolution patterns and driving mechanisms of integrated soil fertility. After more than 20 years of different nutrient management practices [Figure 2: see original paper], integrated soil fertility indices decreased under all chemical fertilizer treatments, with the most significant declines observed in the no-input control and nitrogen-only treatments. Balanced nitrogen-phosphorus-potassium fertilization and organic manure application alleviated this decline, but only the combined application of chemical NPK fertilizers with recycled organic manure maintained or slightly increased integrated fertility. These results demonstrate that traditional nutrient recycling (manure, recycled organic fertilizer) significantly improves soil fertility in dryland farming systems, yet sole application of recycled organic fertilizer cannot achieve high and stable yields.

With the application of chemical nitrogen fertilizers combined with phosphorus and potassium, crop yields increased substantially, confirming that the rapid availability of chemical fertilizers is crucial for maintaining crop production. However, unbalanced chemical nutrient input patterns create "short-board" effects that limit further yield improvements and fail to achieve high-yield, stable production goals. Nutrient recycling plays an important supplementary role to inorganic nutrients, compensating for soil nutrient deficits to some extent, making combined organic-inorganic fertilization more conducive to stable crop yields. Thus, even under modern agricultural management (NPK+M), both chemical and organic fertilizers remain irreplaceable. Combining chemical fertilizers with recycled organic manure supplements nitrogen, phosphorus, potassium, and micronutrients in organic form, improving agricultural waste utilization efficiency while maintaining soil nutrient balance, stabilizing crop yields, and enhancing fertilizer use efficiency.

Establishing Evaluation Methods for Microbial Assimilation of Fertilizer Nitrogen and Clarifying Transformation Mechanisms

Nitrogen use efficiency has long been central to soil fertility management in aquic brown soils. Since the transformation of exogenous inorganic nitrogen to soil organic nitrogen is a microbially-driven biochemical process, strengthening microbial assimilation of fertilizer nitrogen is essential to reduce inorganic nitrogen accumulation in soil and minimize nitrogen loss risks. To overcome methodological bottlenecks in evaluating the continuous transformation characteristics of exogenous nitrogen by microorganisms, Shenyang Station utilized 15N isotope tracing long-term positioning experiments. By exploiting the "memory effect" of stable microbial biomarkers (amino sugars), the station established evaluation methods for the microbial assimilation process of fertilizer nitrogen, enabling quantitative indication of long-term microbial transformation processes and accumulation capacity [4].

When balanced energy sources, carbon sources, and nutrients are added to soil, microbial populations and metabolic activity increase rapidly, accompanied by accumulation of substantial microbial metabolites (such as amino acids) and residues (such as amino sugars). These can provide continuously available nitrogen for crops and microorganisms through depolymerization and mineralization processes, forming an important component of the soil "effective nitrogen transition pool" with high cyclability [5]. Soil microorganisms enhance the "continued burial effect" through the "carbon pump" in their turnover pathways, thereby contributing to soil nutrient assimilation [6]. The depolymerization and mineralization processes of "transitional" nitrogen are regulated by feedback from soil nitrogen levels. The decrease in soil available nitrogen content caused by crop uptake is a necessary condition to initiate the depolymerization process of transitional organic nitrogen, making its mineralization process coincide with crop needs and satisfying nitrogen requirements for both current and subsequent crops. Therefore, through regulation of microbial energy and carbon sources to increase organic matter accumulation and improve organic matter activity, the transformation rate of inorganic nitrogen to "transitional" nitrogen can be enhanced, increasing the capacity of the "transitional" effective nitrogen pool. Through process control of "nitrogen control with carbon to achieve carbon-nitrogen balance," soil nitrogen loss can ultimately be reduced [Figure 3: see original paper]. Ten years of straw cover-15N fertilizer tracing experiments confirmed the regulatory role of the soil "effective nitrogen transition pool" in fertilizer nitrogen transformation and crop utilization. Straw mulching significantly increased fertilizer nitrogen retention in soil by promoting microbial assimilation, and the increased retention of fertilizer nitrogen in the plow layer enhanced nitrogen reuse and reduced leaching risks.

Establishing Comprehensive Conservation Tillage Systems for Rainfed Dryland Agriculture

To address intensifying resource and environmental constraints in the Northeast Plain, Shenyang Station, with its core technology for efficient utilization of agricultural waste, collaborated with the Lishu County Agricultural Technology Extension Station in 2007 to establish the first corn straw mulching cultivation technology demonstration base in Northeast China, covering 15 hectares in Gaojia Village, Lishu County. This initiative promoted the application of corn straw full-cover conservation tillage research results in agricultural production [Figure 4: see original paper]. After ten years of exploration, through technical improvements including standing stubble decomposition, straw row-returning, and timely deep loosening, the station developed no-till straw mulching techniques suitable for local climate and soil conditions. This has fostered a modern agricultural model in Northeast dryland farming areas where the "Lishu Model" and no-till machinery development mutually reinforce each other.

The straw mulching no-till system not only curbs soil degradation but also provides drought resistance, moisture conservation, increased water storage capacity, and reduced wind and water erosion, delivering significant comprehensive ecological benefits. This represents an important development direction for modernized and scaled agriculture in Northeast China. To accelerate research translation and extension, Shenyang Station has worked closely with Lishu County Agricultural Technology Extension Station, the Northeast Black Soil Conservation and Utilization Technology Innovation Alliance, and other organizations to establish and refine a "five-in-one" research and extension mechanism integrating research institutions, universities, technology extension departments, agricultural machinery manufacturers, and agricultural machinery operation organizations (such as cooperatives and service teams). This mechanism has promoted the extension of straw mulching no-till technology across Jilin, Liaoning, Heilongjiang provinces and the Inner Mongolia Autonomous Region, advancing the comprehensive development of new agricultural management entities and modern agricultural machinery research in Northeast China, and laying a solid foundation for farming system reform in the region [Figure 5: see original paper]. By 2017, the promoted area reached 1.5 million mu, generating annual economic benefits of 200 million yuan for farmers. Particularly during the severe spring drought of 2018 in Northeast China, corn straw mulching no-till emerged as a prominent solution for spring sowing in drought and wind-sand areas compared to conventional water-accompanied sowing, becoming a pioneer in green agricultural production methods.

The demonstration and extension work conducted by Shenyang Station has achieved not only excellent economic benefits but also substantial social impact. China Central Television's English channel broadcast the station's research results on "mechanized straw mulching no-till technology" from its research and development base in Lishu County, Jilin Province, on the eve of the 2015 Paris Climate Change Conference . The report suggested that this research provides new ideas and methods for straw utilization, addressing both high-yield and high-efficiency challenges in agricultural production while offering solutions for clean agricultural production and haze prevention in China. On December 19, 2015, CCTV's "Focus Interview" program featured the application of this technology , noting that the research "connects with practical needs" and solves real agricultural problems, accelerating agricultural development and deserving expanded research and demonstration efforts. In 2016, the Ministry of Agriculture's official website published an article stating that "Lishu took the lead in solving the worldwide problem of black soil degradation." Following the Chinese Academy of Sciences' requirements for characteristic research institutes and guided by the principle of serving local needs, Shenyang Station will continue advancing no-till straw mulching technology to provide theoretical and technical support for farming system reform and sustainable black soil utilization in Northeast China.

Developing and Promoting Environmentally Friendly Stabilized Fertilizers for Reduced Application and Pollution Risk

Integrated soil-fertilizer management enhances soil fertility and nutrient supply capacity while using biochemical inhibitors to better align fertilizer nutrient release characteristics with crop demand patterns. As early as 1998, the innovative work "Development and Application of Long-acting Ammonium Bicarbonate" by Zhang Zhiming's team at the Institute of Applied Ecology, Chinese Academy of Sciences, won the second prize of the National Science and Technology Progress Award. In 2008, "Development and Application of Long-acting Slow-release Fertilizers" again received the same national award, demonstrating Shenyang Station's leading position in inhibitor-based novel fertilizer research in China. In recent years, multiple patents have been transferred, generating over 5 million yuan in revenue [Figure 6: see original paper]. The "Chemical Industry Standard of the People's Republic of China: Stabilized Fertilizers" (GB/T35113-2017), led by Shenyang Station in collaboration with Shikefeng Chemical Co., Ltd. and the National Fertilizer Quality Supervision and Inspection Center (Shanghai), was approved by the General Administration of Quality Supervision, Inspection and Quarantine and the Standardization Administration, and implemented on July 1, 2018.

The introduction of biochemical inhibitors into agriculture changes the retention forms and duration of fertilizer nitrogen in the soil-crop system, significantly affecting nitrogen conservation and subsequent supply processes, reducing nutrient losses, and improving utilization efficiency [7,8]. Nitrification inhibitors and urease inhibitors enhance ammonium nitrogen fixation and the transformation of fertilizer nitrogen into organic nitrogen pools [9], while significantly affecting ammonia volatilization, N2O emissions from nitrification-denitrification, NO3− leaching, and comprehensive greenhouse gas emission indices [10], thereby substantially reducing non-point source pollution risks from farmland [11-13]. As a founding unit of the Stabilized Fertilizer Industry-University-Research Alliance, the Institute of Applied Ecology, Chinese Academy of Sciences, and Shenyang Zhongke New Fertilizer Co., Ltd. have strengthened agricultural extension services through Shenyang Station, rapidly translating research achievements into practical productivity for farmers via networked demonstrations. Long-term experiments at Shenyang Station with novel stabilized fertilizers, bio-organic fertilizers, crop-specific fertilizers, and biochar-based fertilizers have shown that in the Liaohe Plain region, modified fertilizers developed and applied locally significantly improve fertilizer use efficiency and yield benefits. Compared with conventional fertilization levels (200-240 kg ha−1), equivalent yields can be obtained with 20%-25% fertilizer reduction, increasing average income by 100-200 yuan per mu [Figure 7: see original paper]. The promoted area across 20 provinces, municipalities, and autonomous regions reached 370 million mu, with an average yield increase of 11.3%, fertilizer reduction of 10%-20%, and generated benefits totaling 15.01 billion yuan.

Deep Analysis of Cadmium Pollution Sources for Source Control and Safe Utilization of Contaminated Land

As a traditional industrial base in China, Shenyang exhibits high heavy metal concentrations in the "three wastes," with severe soil contamination in sewage irrigation areas. Heavy metals persist in soil for extended periods, posing enormous environmental risks. Meanwhile, rapid urbanization has intensified resource and environmental constraints, making safe utilization of contaminated land a core issue in Liaoning Province's "Clean Soil Project." Researcher Guo Shuhai from Shenyang Station established a foundational database for soil cadmium (Cd) contamination in Liaoning Province and developed digital regional prevention and control schemes. In a typical urban-industrial and agricultural pollution overlay area (Xinmintun Station area of Shenyang Station), modern research plots with parcel-based, information-based, and precisely controlled pollutant logistics processes were constructed to provide experimental data and technical support for safe utilization of heavy metal-contaminated agricultural land and agricultural product safety assurance in suburban areas.

Using a soil heavy metal flux estimation model and mean analysis to compare contributions of various elements in input and output pathways, irrigation water was identified as the primary source of cadmium pollution in farmland soil, representing the main cause of contamination in irrigation districts [Figure 8: see original paper]. As corresponding measures are implemented to treat irrigation water, its contribution to district pollution will begin to decline. Atmospheric dry and wet deposition ranks second, accounting for 42.6% of the total. Due to frequent chemical smelting, coal heating, and other activities near irrigation districts, atmospheric deposition is becoming a major pathway for cadmium pollution in farmland. Regarding cadmium output from farmland systems, crop harvest occupies the dominant position, with cadmium removed through aboveground rice plant parts accounting for 89.8% of total output pathways.

Regarding the problem of heavy metal 超标 in agricultural products caused by environmental pollution and resulting food safety risks, Guo Shuhai proposed recommendations for collaborative risk management of heavy metal 超标 in agricultural products. These suggestions address establishing indicator systems for crop heavy metal uptake/accumulation, implementing coordinated risk management, and propose measures including: conducting crop planting suitability assessments and classification based on different soil physicochemical properties and environmental quality, selecting cultivars that can avoid risks, developing categorized and zonal planting plans, demonstrating collaborative management and control technologies in typical areas, and improving agricultural product quality safety assurance systems to effectively advance Liaoning Province's "Clean Soil Project."

Conclusion

Since its establishment in 1987, Shenyang Station has conducted long-term and highly effective scientific research, technology development, and demonstration extension focused on core issues in agricultural production and ecological environment of the Northeast Plain, making important contributions to national food security and regional ecological environment quality improvement. Addressing critical problems of soil degradation and ecological environment deterioration in Northeast China, long-term positioning experiments have revealed evolution patterns of integrated soil fertility in aquic brown soils under different nutrient management regimes. By theoretically constructing the management model of "nitrogen control with carbon to achieve carbon-nitrogen balance," the station established comprehensive conservation tillage systems for rainfed dryland agriculture, promoted rural farming system and supply-side structural reforms, and provided scientific and technological support for regional modern agricultural development and ecological environment construction. Through years of integrated soil-fertilizer management and the development and promotion of stabilized fertilizers, Shenyang Station has curbed soil degradation and made important contributions to achieving fertilizer reduction and efficiency improvement while reducing non-point source pollution risks. In the future, Shenyang Station will fully implement green development concepts, balance rural economic development with ecological environmental protection, and under the guidance of the Chinese Academy of Sciences' "Pioneer Initiative," make greater contributions to sustainable regional agricultural development.

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