

Long-Term Research on Red Soil Degradation and Restoration Promotes the Development of Ecological Circular Agriculture in Southeast Hilly Regions: Postprint

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Abstract

The southeastern red soil hilly region of China confronts degradation problems including erosion, acidification, fertility decline, heavy metal pollution, and seasonal drought, which have resulted in the degradation of red soil ecosystems and decline in land productivity, thereby constraining the sustainable development of regional agriculture. Since its establishment in 1985, the Yingtan Red Soil Ecological Experimental Station has systematically conducted long-term observation and fundamental ecological research on red soil ecosystems, along with applied research and demonstration/extension in red soil degradation and remediation, evolution and improvement of cultivated land productivity, nutrient cycling and efficient utilization in red soils, red soil pollution and control, and red soil ecological agriculture models and regional development strategies. Regarding red soil genesis, studies have discovered that modern desilication and allitization processes continue, with relatively low natural soil acidification rates in small watersheds; in response to accelerated acidification in agricultural utilization of red soils, novel methods for inhibiting proton production and enhancing soil acidification resistance capacity have been developed, new aluminum-tolerant plant resources in red soil regions have been identified, and the molecular biological mechanisms of plant aluminum tolerance have been revealed. Multi-scale monitoring methods for soil erosion in red soil regions have been established, distribution maps of soil erodibility factors have been compiled, the evolution of red soil erosion and development mechanisms of benggang (collapsing gullies) have been clarified, and developmental management models for eroded red soils have been constructed. The occurrence patterns of seasonal drought in red soil regions have been determined, the pore formation mechanisms in red soils and hydrological fluxes at different scales have been revealed,

high-precision remote data acquisition systems for farmland moisture have been developed, and efficient water-saving agriculture models for low-hilly red soil regions have been established. Migration prediction models for heavy metals and rare earth elements in soil-crop systems have been developed, safety thresholds for red soils and paddy soils have been proposed, and integrated remediation technology models for heavy metal pollution in red soils have been assembled. The evolution status of land productivity and nutrient balance in southern red soils has been clarified, the driving mechanisms of biological networks for carbon and nitrogen transformation in red soils have been revealed, and biological fertilization technology for macroaggregates in red soils has been proposed. A modern agricultural technology system for cultivated land conservation and sustainable efficiency in Jiangxi Province has been created, and an ecological circular agriculture model of “mountains-rivers-forests-farmlands-lakes-grasslands” for red soil small watersheds has been developed, making significant contributions to cultivated land quality construction, ecological environment protection, and the development of new-generation ecological circular agriculture in red soil regions.

Full Text

Long-term Research on Red Soil Degradation and Remediation Promotes Development of Ecological Recycling Agriculture in the Hilly Regions of Southeast China

Abstract

The hilly red soil region of Southeast China faces severe degradation challenges including erosion, acidification, fertility decline, heavy metal contamination, and seasonal drought, which have caused ecosystem degradation and declining land productivity, thereby constraining sustainable agricultural development. Since its establishment in 1985, the Yingtan Red Soil Ecological Experiment Station has systematically conducted long-term ecosystem monitoring and basic ecological research, along with applied studies and demonstration projects focused on red soil degradation and remediation, farmland productivity evolution and improvement, nutrient cycling and efficient utilization, soil pollution and treatment, and ecological agriculture models and regional development strategies. In terms of pedogenesis, we discovered that modern desilication and allitization processes continue, while natural acidification rates in small watersheds are relatively low. To address accelerated acidification under agricultural use, we developed novel methods to inhibit proton production and enhance soil acid resistance, identified new aluminum-tolerant plant resources, and revealed the molecular biological mechanisms of plant aluminum tolerance. We established multi-scale monitoring methods for soil erosion, compiled soil erodibility factor distribution maps, clarified erosion evolution and slope collapse mechanisms, and developed development-oriented management models for eroded red soils. We identified seasonal drought patterns, revealed pore formation mechanisms and hydrological fluxes at different scales, developed high-precision remote data

collection systems for farmland moisture, and established efficient water-saving agricultural models for low-hilly red soil regions. We developed migration prediction models for heavy metals and rare earth elements in soil-crop systems, proposed safety thresholds for red soils and paddy soils, and integrated remediation technologies for heavy metal pollution. We investigated the evolution of soil fertility and nutrient balance, revealed the driving mechanisms of biological networks in carbon and nitrogen transformation, and proposed biological fertility management principles for large soil aggregates. We created a modern agricultural technology system for farmland conservation and sustainable high efficiency in Jiangxi Province, and developed a small watershed-scale ecological recycling agriculture model integrating “mountains, waters, farmland, forests, lakes, and grasslands,” making important contributions to farmland quality improvement, ecological environmental protection, and the development of a new generation of ecological recycling agriculture in the red soil region.

Keywords: red soil hilly region, farmland degradation, large aggregate fertility management, ecological restoration, soil pollution remediation, ecological recycling agriculture model

1. Introduction

The hilly red soil region of Southeast China (east of Yunnan-Guizhou-Sichuan, south of the Yangtze River) includes Hunan, Jiangxi, Zhejiang, Fujian, Guangxi, Guangdong, Hainan, and parts of Hubei, Jiangsu, and southern Anhui, covering approximately 1.13 million km² (11.8% of China’s total land area). This region is widely distributed with Ferralsols, primarily including red soils (55.8%), lateritic red soils (17.5%), latosols (3.9%), and yellow soils (22.8%). Spanning the mid-subtropical, south-subtropical, and tropical zones, the region is rich in hydrothermal resources (15–28°C, 10°C accumulated temperature 5,000–9,500°C, annual rainfall 1,200–1,500 mm, with high temperature and rainfall occurring in the same season), offering great potential for agricultural production and economic development. It is an important production area for rice, oil crops, economic forests and fruits (citrus), and cash crops (tea). However, due to natural factors and unreasonable human utilization, red soil ecosystems face degradation processes including soil erosion, seasonal drought, acidification, declining fertility and ecological function, and heavy metal pollution, leading to ecosystem degradation and reduced land productivity that constrain sustainable agricultural development in the region.

Since the 1950s, academician Li Qingkui from the Institute of Soil Science, Chinese Academy of Sciences, led the Southern China Comprehensive Scientific Expedition to investigate red and yellow soil resources and rubber plantation suitability, establishing the Ganjiashan Red Soil Experimental Field in Xinjian County, Jiangxi, where he created the “phosphorus-for-nitrogen” technology of direct phosphate rock powder application for low-yield red soil dryland. During the 1960s–70s, based on ammonium bicarbonate granulation methods, organic manure-ammonium nitrogen application methods were established, and

remediation techniques for secondary gleyization in red soil paddy fields were proposed. In the 1980s, the mechanism of “desilication and allitization” in red soils was proposed, along with vegetation restoration techniques for eroded red soils and acid soil improvement technologies. In 1985, the Red Soil Ecological Experiment Station was established in Yujiang County, Yingtan City, Jiangxi (hereinafter referred to as “Yingtan Station”), systematically studying red soil ecosystem evolution and regulation, red soil quality degradation and reconstruction, and sustainable agricultural development strategies and models in red soil regions, earning a series of national and provincial science and technology progress awards.

2. Research Progress on Red Soil Degradation and Remediation

2.1 Red Soil Pedogenesis and Natural Acidification Red soils in South China formed under humid and hot conditions during multiple interglacial periods since the late Tertiary. Through biogeochemical studies of red weathering crusts (red soil layers), we found that the main pedogenic processes are desilication-allitization and biological enrichment. Based on the degree of weathering of primary minerals ($\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio in <1 mm clay particles), the allitization process can be divided into three stages: quasi-Ferralsols (2.2-2.5), Ferralsols (around 2.0), and allitic soils (<1.7). Clay minerals transition from being dominated by kaolinite and hydromica to kaolinite and gibbsite. Studies of a deep red soil profile in Xuancheng, Anhui [Figure 1: see original paper], show that alternating warm-humid/dry-cool climate cycles and vegetation changes since the mid-Pleistocene have affected pedogenic processes and organic matter content. Although desilication-allitization weakened during dry-cool periods of the Quaternary glacial period, the process continues. Under modern climate conditions, silicon and base migration in forest soil latosols and red soils is relatively high (SiO_2 content of 3.0-13.2 mg L^{-1} and CaO content of 1.63-8.38 mg L^{-1} in leachate at 135 cm depth), while iron and aluminum leaching is minimal (Fe_2O_3 and Al_2O_3 contents of 0.18-0.47 and 0.02-0.57 mg L^{-1} , respectively). Biological enrichment is strong, with high base return through litterfall (CaO , MgO , and K_2O reaching 55.3-156.1, 21.5-74.0, and 33.4-55.2 $\text{kg hm}^{-2} \text{a}^{-1}$, respectively) [3].

Acidification caused by base leaching during desilication-allitization is extremely slow, making direct observation of natural acidification rates difficult in the short term. Based on long-term observations in a typical subtropical small watershed, we accurately distinguished the stoichiometric relationship between silicon and base cations in rock, saprolite, soil, and runoff during weathering and acidification processes. We found that mineral weathering and colloidal cation exchange processes consume protons (H^+) in a 46:54 ratio, with the natural soil acidification rate based on cation exchange processes being only half of traditional estimates [4]. During red soil development, mineral weathering causes positively charged iron-aluminum oxides and negatively charged aluminosilicate mineral surfaces to undergo “diffuse layer overlap,” reducing the effective negative charge

on soil surfaces and thereby inhibiting natural soil acidification [5]. These findings on natural acidification support predictions and management of forest soil acidification [Figure 2: see original paper].

2.2 Control of Accelerated Red Soil Acidification Based on regional surveys and long-term experiments, we found that over the past 30 years, increased acid deposition and ammonium nitrogen fertilizer application have accelerated red soil acidification in forest, grassland, and farmland systems. In the subtropical red and yellow soil region (301 sampling points), mean soil pH decreased from 5.37 (4.40–6.60) to 5.14 (food crops, 4.17–6.52) and 5.07 (cash crops, 3.93–6.44).

To inhibit proton production, we developed methods including: co-application of urea, ammonium nitrogen fertilizer, and nitrification inhibitors to suppress acid production from nitrogen fertilizer nitrification in red soil drylands; and using nitrate nitrogen to replace ammonium nitrogen combined with rhizosphere alkalization to control proton sources in facility vegetable fields. To enhance soil acid resistance, we found that short-term application of straw biochar effectively increases red soil acid buffering capacity, while long-term organic manure application enhances soil organic matter to improve acid resistance. Straw biochar, especially from legume crops rich in carbonates and organic anions, consumes protons primarily through carboxyl protonation, contributing 68%–94% at $\text{pH} > 6.2$, with Si precipitation enhancing proton consumption at $\text{pH} < 6$ [6] [Figure 3: see original paper]. Field demonstrations in Jiangxi and Anhui showed that biochar application increased soil pH by 0.4–1.0 units and increased rapeseed yield by over 50% [8,9].

To address aluminum toxicity in acid soils, we identified aluminum-tolerant plant and microbial resources in red soil regions, discovering a new aluminum hyperaccumulator—oil tea (*Camellia oleifera*, with aluminum content up to 13.5 g/kg in old leaves) [10] and aluminum-tolerant plants such as *Lespedeza bicolor* [11] [Figure 4: see original paper]. We isolated a highly aluminum-tolerant microorganism (100 mmol/L Al)—*Rhodotorula taiwanensis* RS1—from acid soils [12]. Mechanistic studies revealed that aluminum transport in oil tea shoots occurs via phloem, *L. bicolor* tolerates aluminum through root exudation of malic and citric acids [11], and *R. taiwanensis* RS1 relies on its less negatively charged cell wall for high aluminum tolerance [13]. We systematically elucidated the mechanism of “ammonium nitrogen alleviating while nitrate nitrogen aggravating plant aluminum toxicity,” revealing for the first time the pattern that “aluminum-tolerant plants prefer ammonium nitrogen while aluminum-sensitive plants prefer nitrate nitrogen,” and established a nitrogen-aluminum coupling model in soil-plant systems [14]. We also found that phosphorus can only alleviate aluminum toxicity in aluminum-tolerant plants [15], providing a theoretical basis for improving red soil productivity.

2.3 Soil Erosion Monitoring and Control We developed rainfall erosivity observation instruments and established a rainfall erosivity model suitable for small scales (field plots) based on relationships between rainfall amount, intensity, and kinetic energy [16]. At the watershed scale, we determined optimal remote sensing image resolution and DEM accuracy for integrated remote sensing and model (CSLE, SWAT) methods, establishing high-precision soil erosion monitoring methods. We clarified the concept and calculation method of small watershed management degree, providing evaluation methods for soil erosion control effectiveness [8]. We optimized the soil erodibility K-value calculation model and compiled a 1:500,000 national K-value distribution map [Figure 5: see original paper], identifying that purple moist immature soils and light-colored moist immature soils have the highest K values in the Southeast red soil region, providing basic data for the first national water census [17].

Regional surveys revealed the evolution of soil erosion in the Southeast hilly red soil region over the past 50 years, with erosion area increasing from 105,000 km² in the early 1950s to 196,000 km² in 2002. Current erosion area is 160,000 km² (12.5% of the region), including 260,000 slope collapse features (with annual erosion modulus up to 5.9×10^4 t km² a⁻¹ in collapse areas) and a control rate below 1%, indicating severe local erosion [18].

Regarding erosion processes and environmental effects, we revealed water and soil loss patterns in Masson pine forests, finding a vegetation canopy threshold effect where pure Masson pine stands with coverage <24% have minimal impact. We clarified sediment and leachate migration patterns in southern Jiangxi rare earth tailings areas, discovering NH₄⁺ migration with runoff sediment and SO₄²⁻ migration with runoff water. At the watershed scale (Lianshui River Basin, 579 km²), we revealed that long-term afforestation (1971–2009) reduced water and sediment yields by increasing transpiration, with afforestation contribution to sediment reduction increasing from 41% to 68% over the past 20 years (1991–2009). Coupled changes in hydrological cycling and erosion ultimately reduced nitrogen and phosphorus export to only 3.38 kg N/ha and 1.16 kg P/ha annually.

Based on slope sediment and runoff formation mechanisms, we established erosion control theory centered on aggregate protection and runoff reduction. For red soil dry slopes with different gradients, we developed an engineering-biological “runoff collection and fertility concentration” system including contour grass hedges, earth ridges, terraces, and cover measures [19]. After 8 years of management, sediment production was completely controlled in vegetation restoration areas, with average carbon sequestration rate of 4.63 t hm⁻² a⁻¹ and significant ecological benefits [20]. For granite red soil erosion types, we determined community indicators for vegetation restoration in degraded Masson pine forests based on community assembly theory, constructing three-dimensional rapid restoration models including: water-conserving grass cover for severe erosion, tree-shrub-grass mixed planting, native plant supplementation, and economic forest-grass cover models. We revealed the development process and formation mechanism of slope collapse in red soil regions, developed rapid control

technology for large-scale collapses using new water-conserving materials, and established a collapse management model integrating “slope treatment, gradient reduction, and slope stabilization” with agricultural-forestry-fruit-animal husbandry economic development [Figure 6: see original paper], which was demonstrated in Jiangxi and Fujian [8].

2.4 Seasonal Drought and Water-Saving Agriculture Through long-term observation and investigation, we clarified the spatiotemporal occurrence patterns of soil-crop drought and climatic drought in red soil hilly regions, finding annual occurrence probabilities of 86% and 60%, respectively, with summer-autumn drought (July-September) being most damaging. Regionally, northern Jiangnan hills experience frequent summer droughts; eastern red soil regions experience autumn droughts, with Jiangxi and Fujian affected in October and Guangdong, Guangxi, and Fujian in November [21].

Low effective water storage capacity is the intrinsic cause of seasonal drought in red soils. Using CT and image analysis, we studied the effects of two ecological niche earthworms on pore structure in red soils and dark loessial soils, finding that earthworm type significantly affects burrow structure. The litter-feeding *Amyntas carnosus* created thicker, better-connected burrows, especially vertically, significantly increasing saturated hydraulic conductivity compared to the soil-feeding *Drawida sinica* [Figure 7: see original paper] [23].

Regarding long-term fertilization effects on soil pores, we used CT technology and soil water retention curves (SWRC) to reveal macropore and pore distribution characteristics, establishing bimodal models (bimodal lognormal model, BLN; double-exponential model, DE model) for fitting water retention curves. We found that fertilization primarily changes structural pores rather than textural pores [22]. Based on long-term experiments, we studied water flow resistance changes in the soil-plant-atmosphere continuum (SPAC), revealing how climate, parent material, land use, and fertilization affect seasonal changes in soil profile water storage capacity. Long-term fertilization significantly increased impacts on deep soil (100 cm) moisture dynamics. Using shallow soil moisture content and temporal stability characteristics, we predicted deep soil moisture dynamics and regional average moisture content, achieving spatial-temporal scaling of point observations [24,25]. At the small watershed scale (Sunjia Watershed), end-member mixing analysis revealed that irrigation water, rainfall, and groundwater contributed 46%, 26%, and 28% of streamflow, respectively [26].

Yingtian Station developed a comprehensive water-fertilizer-soil management drought resistance and water-saving technology system dominated by agronomic measures. Starting with drought-resistant crop selection, we optimized winter cropping patterns. From the perspectives of maintaining soil moisture, promoting root growth, and improving plant drought resistance, we optimized efficient water-saving dryland planting patterns centered on peanuts. We clarified water-fertilizer coupling mechanisms in rice water-saving cultivation and proposed integrated regulation models for efficient water and fertilizer use under water-

saving irrigation [21]. We developed a triple measurement device for paddy water level-surface irrigation depth-leakage and high-precision soil moisture sensors, enabling precise automatic monitoring of water layer depth, soil moisture, and crop growth status in irrigation districts, supporting water-saving technology development. Based on water balance at field, watershed, and irrigation district scales, we optimized water resource allocation schemes, supported by shallow groundwater well irrigation and small watershed hydrological monitoring technologies, facilitating water-saving renovation projects in red soil irrigation districts. Demonstration areas of 10,000 mu were established in Jiangxi, increasing irrigation water use efficiency from 30% to over 70% and crop water use efficiency from 1.3 kg/m³ to 1.7 kg/m³, with yield increases of 18%-32%.

2.5 Heavy Metal Pollution and Remediation Based on systematic studies of heavy metal pollution mechanisms in red soil-plant systems [27], we established heavy metal migration prediction models based on soil properties (pH and organic matter) [28], preliminarily determined soil heavy metal safety thresholds for vegetables, rice, and navel oranges [28-30], and formulated national standards (draft) for soil arsenic, mercury, cadmium, lead, and chromium thresholds in rice and root vegetable production. These draft thresholds are generally higher than GB 15618-1995 Level I standards [Figure 8: see original paper] and correct the issues of overly strict mercury and overly loose lead regulations in GB 15618-1995 Level II standards. The draft standards refine heavy metal safety thresholds based on soil pH and organic matter ranges, improving applicability in actual agricultural production. Based on surveys and positioning experiments, we clarified heavy metal and rare earth element exceedance issues in southern Jiangxi navel oranges, finding that even in rare earth tailing orchards with rare earth element content up to 1,038 mg/kg, navel orange fruit rare earth element content did not exceed standards.

For cadmium-contaminated farmland, we screened regionally suitable low-accumulation rice varieties, clarified the limiting role of rice stem nodes in cadmium transport to grains [31], developed novel composite passivation materials such as nano-hydroxyapatite [Figure 9: see original paper], and proposed simple methods for evaluating passivation material acid stability [32]. We developed key technologies including alkaline material passivation and micronutrient (Fe, Zn, Se) application at tillering stage, reducing brown rice cadmium content by 75% [33]. We integrated a safe rice production technology system combining low-accumulation varieties + passivation materials + micronutrient root control at tillering stage + physiological blocking through flooding at booting stage, as well as planting structure adjustment technologies combining passivation + soil improvement + fruit/fiber/energy crop development. For rare earth tailing areas, we developed T-ditch water-soil conservation vegetation restoration technology, reducing water erosion by 80% and achieving 90% vegetation survival rate, and integrated reclamation and safe production technology models for navel oranges combining T-ditch water storage, year-round biological cover, and soil fertility improvement. These

technologies have been widely applied in Yingtan, Ganzhou, and other areas.

2.6 Soil Fertility and Nutrient Cycling We investigated the evolution of soil fertility and nutrient balance in red soil regions, revealing the microbial mechanisms of organic matter and nutrient transformation. We assessed organic carbon distribution under different fertilization practices, finding that red soil dryland organic matter content decreased during the 20 years since the 1980s, while paddy soil organic matter increased [34]. Due to large-scale straw return technology, soil organic carbon stocks in eastern and central-southern regions increased by 8.33 and 6.67 Mg/ha, respectively, between 1980–2011 [35]. Long-term experiments revealed straw decomposition mechanisms under different climate zones and optimal nitrogen substitution ratios, finding that microbial community composition and straw chemical structure co-evolve, with fungi/bacteria ratios driving increases in straw aromaticity [36,37]. For medium-low yield paddy fields in the mid-subtropical zone, long-term fertility improvement with full straw return significantly increased soil organic carbon (equilibrium value of 19 g/kg), improved soil aggregate structure and microbial activity, and maintained high rice yield while substituting 20%–30% of chemical nitrogen fertilizer [38].

We identified soil nutrient depletion status in Southeast red soil regions and revealed evolution characteristics of farmland nutrient balance and its effects on nutrient pools. Eastern red soil drylands show moderate nitrogen depletion (~63%) and severe available phosphorus depletion (~78%). With regional economic development, farmland nitrogen and phosphorus surpluses and environmental risks continuously increase, with nitrogen surplus following the pattern: eastern region (Jiangsu, Zhejiang, Fujian, Guangdong >170 kg/ha) > central region (Anhui, Jiangxi, Hubei 64–170 kg/ha) > western region (Guangxi <64 kg/ha). Based on revealing the promoting effect of nutrient surplus on soil nutrient pools, we uncovered the mechanisms of soil biological network formation in promoting nutrient transformation during long-term fertility improvement. We revealed that nematode predation on microorganisms in large aggregates promotes carbon sequestration, nitrogen supply, and phosphorus release in red soils. After organic fertilization of dryland red soils, large aggregate formation was promoted. Nematode predation on active microorganisms in large aggregates inhibited soil carbon metabolism (“negative feedback”), enhancing organic matter accumulation capacity. The dominant bacterivorous nematode genus *Protorhabditis* preyed on key microbial network members including *Nitrosospora* cluster 3a, 9, 10 and *Mesorhizobium*, promoting microbial nitrogen and phosphorus metabolism (“positive feedback”) and improving soil nitrogen and phosphorus supply capacity. Based on these results, we proposed the theoretical framework of “large aggregate biological fertility management” for red soils [Figure 10: see original paper] [39,40]. At the regional scale, we revealed climate-driven effects on functional microbial succession in soil nutrient transformation, finding that climate warming accelerates microbial succession rates, increases abundances of core carbon and nitrogen cycling groups, and

promotes soil respiration and nitrification [41]. These results provide theoretical foundations for proposing microbial function regulation measures adapted to climate-soil types.

3. Development of Modern Agricultural Technology Systems and Ecological Models

Since the 1980s, Yingtan Station has conducted integrated research and technology demonstrations on red soil degradation mechanisms and remediation, continuously advancing comprehensive degradation control levels through acidification and erosion control, water conservation and fertility improvement, and establishment of efficient agroforestry systems. We clarified water and soil loss patterns, allowable erosion amounts, and ecological remediation technologies in southern red soil regions, proposed drought-flood disaster prevention strategies utilizing engineering and soil reservoirs, and revealed principles for resisting seasonal drought through slope water collection, water-saving irrigation, and drought-avoidance cultivation. We identified degradation mechanisms of low-yield paddy fields and barren drylands caused by erosion, acidification, and fertility decline, and proposed integrated prevention and control technology systems including rapid greening and water conservation for eroded red soils, fertility restoration and optimized fertilization, long-term acid soil improvement, and seasonal drought prevention combining water storage-conservation-irrigation. We developed high-yield and efficient planting technologies represented by multi-crop intercropping, established agricultural development models based on high-quality grain-feed industries, and proposed agricultural development strategies for southern red soil regions using geographic information systems, driving local agricultural structure adjustment and characteristic agricultural development [42].

Since the 21st century, we have comprehensively improved soil degradation control and farmland quality improvement technologies, establishing red soil acidification and peanut continuous cropping obstacle remediation models, integrating rice straw rapid decomposition and fertility improvement technologies, and developing high-yield designed cultivation models for double-cropping rice based on spectral diagnosis and controlled-release nitrogen management. We created a modern agricultural technology system for farmland conservation and sustainable high efficiency in Jiangxi Province, establishing compound continuous high-yield models, plain high-yield super-high-yield models, mountainous low-yield targeted improvement models, and hilly basin medium-yield light-production models. These were demonstrated across 15.65 million mu in 14 Jiangxi counties, increasing grain production by nearly 1 billion kg and generating cost-benefit improvements of nearly 1.8 billion yuan, providing technical support for Jiangxi' s plan to increase grain production by 10 billion jin [34].

Yingtan Station continuously improved the three-dimensional “forest on top, fruit on slopes, crops in valleys, fish in ponds” model: timber and water conservation forests on hilltops; economic fruits and crops (citrus, persimmon, grapes,

oil tea, peanut, rapeseed) on middle slopes; grain and forage crops (rice, corn, pasture) at the bottom for livestock and biogas production; and fish farming in ponds with constructed wetlands for waste treatment and recycling. Using linear programming, we established optimal nutrient cycling ratios for small watershed three-dimensional cycling models. For medium-scale farms (1,200 pigs/year, producing 48 tons manure and 360 tons wastewater annually), biogas-treated organic waste recycled at a 1:6:1 ratio in orchards, drylands, and paddy fields can meet the nutrient requirements of 100 mu dryland, 50 mu paddy field, and 10 mu citrus orchard, providing solutions for organic waste from intensive livestock operations in Southeast China. Recently, we proposed establishing a small watershed-scale “mountain-water-farmland-forest-lake-grassland” ecological recycling agriculture model [Figure 11: see original paper], integrating water management, soil improvement, and afforestation measures to establish characteristic planting-breeding-industry chains, improving red soil slope productivity and comprehensive agricultural development scale to achieve both economic and ecological benefits.

4. Conclusions and Future Directions

The eastern red soil hilly region of China is both an ecologically fragile area and a major agricultural production zone (rice, rapeseed, citrus) facing enormous resource-environment-population pressures, with large proportions of medium-low yield farmland and severe quality degradation that constrain sustainable agricultural development. Since its establishment in 1985, Yingtan Station has made important contributions to improving red soil productivity and ecological environmental quality, and ensuring national food security through long-term research and demonstration on red soil degradation mechanisms and improvement technologies. By undertaking national and provincial major projects, the station has promoted and led the development of red soil ecology in China.

Currently, Yingtan Station is improving long-term field experimental platforms, modernizing multi-scale observation equipment, integrating new materials, equipment, information technologies, and biotechnology achievements, constructing comprehensive observation systems at small watershed scales such as red soil critical zones, consolidating research team goals aligned with national needs and disciplinary development, cultivating and introducing outstanding talents, and enhancing academic research and technology development capabilities to contribute to a new generation of ecologically efficient agriculture with moderate scale in red soil regions.

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

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