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Pathways to Sustainable Nitrogen Management in China: Targeted Policies, Technological Innovation, and Incentive Alignment

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Targeted Policies, Technological Innovation, and Incentive Alignment

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Executive Summary

China's drive to simultaneously ensure food security, build an ecological civilization, and meet its "dual carbon" targets is reshaping the trajectory of agricultural development, away from resource-intensive growth and toward practices that are efficient, environmentally sound, and low in carbon. Nitrogen fertilizer stands at the crossroads of crop production and environmental sustainability, making it central to this green transition. This report argues that the goal of nitrogen management is not simply to cut inputs, but to raise nitrogen use efficiency and reduce nitrous oxide (N_2O) emissions without compromising crop yields or farmers' incomes.

China has made substantial progress in cutting fertilizer use, yet the next phase of nitrogen management calls for a more comprehensive and integrated approach, one that addresses food security, resource efficiency, farmer livelihoods, environmental protection, and climate goals in a coordinated way. Agricultural fertilizer use has declined steadily since 2015, falling 17.5% from its peak by 2024, with nitrogen accounting for the largest share of that reduction, having dropped roughly 23% from its 2014 high (Figure 1). At the crop level, nitrogen application rates for food crops have broadly stabilized, while more pronounced declines have been recorded in fruit orchards and vegetables. Even so, excessive application persists in parts of major maize-producing regions and among high-input cash crops, while some areas growing rapeseed and comparable crops still require adequate input levels. These reductions have helped reverse the previously upward trend in cropland N_2O emissions. Nationally, N_2O emissions from chemical fertilizer application are estimated to have fallen from 580,000 tonnes in 2015 to 450,000 tonnes in 2024, a decline of 23%.

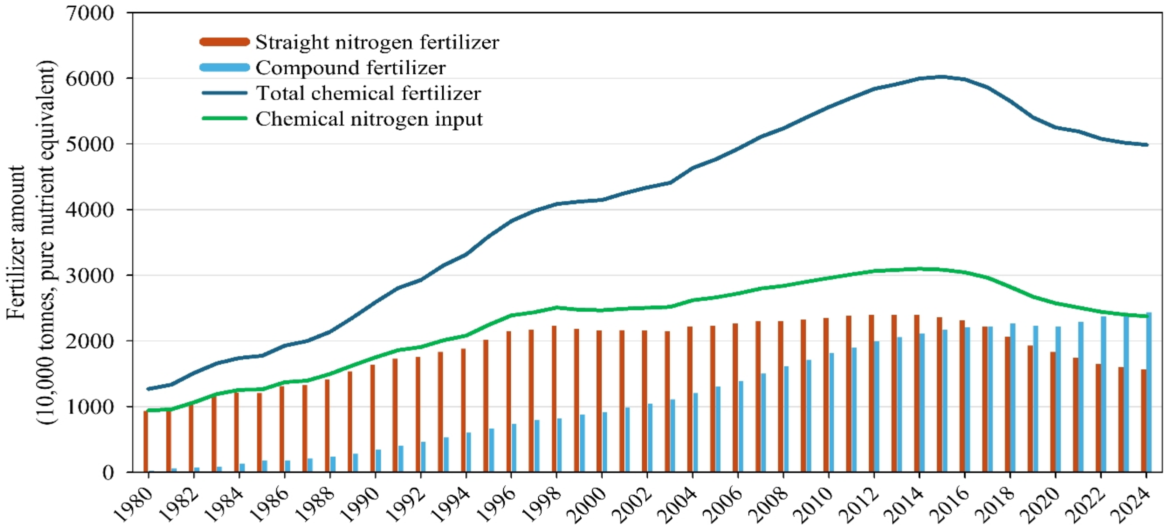

Figure 1. Trends in the Application of Total Chemical Fertilizer, Straight Nitrogen Fertilizer, Compound Fertilizer, and Chemical Nitrogen Input in Chinese Agriculture, 1980–2024

Notes: Data are from the National Bureau of Statistics of China. All series are expressed on a pure nutrient equivalent basis. Chemical nitrogen input = straight nitrogen fertilizer + compound fertilizer × 1/3. In the absence of continuous annual data on the nitrogen, phosphorus, and potassium composition of compound fertilizers, this study assumes a uniform nutrient ratio of 15:15:15 for compound fertilizers, implying that nitrogen accounts for one-third of total compound fertilizer nutrients.

Bringing fertilizer application in line with scientifically established nitrogen quotas offers a concrete and cost-effective pathway to substantial reductions in inputs, emissions, and expenditure. Nitrogen application quotas provide a practical benchmark for pinpointing where and by how much application can be reduced. Modeling based on 2024 crop areas suggests that adjusting per-hectare nitrogen rates to fall within the prescribed quota range for each major crop could reduce chemical nitrogen inputs by approximately 3.2 to 7.3 million tonnes, corresponding to estimated savings of RMB 21.1 to 48.3 billion in fertilizer expenditure. Reduction potential varies substantially by crop; potato, soybean, cotton, and apple show particularly high reduction ratios, pointing to significant room for optimization among certain cash crops and regionally intensive production systems.

A growing toolkit of nitrogen application technologies can meaningfully raise efficiency and lower emissions, but only when matched carefully to local conditions, crop types, and farm realities. Low nitrogen use efficiency and environmental losses often have less to do with total application volumes than with gaps in placement, timing, nutrient form, and how well fertilizer delivery aligns with crop uptake dynamics. Reducing inputs alone is therefore insufficient; raising efficiency requires addressing not just how much is applied, but when, where, in what form, and through what delivery mechanisms. Technologies including mechanized deep placement, fertigation, precision nutrient management, foliar application, slow and controlled-release fertilizers, and bio-regulated approaches each target these gaps through distinct mechanisms, whether by optimizing root-fertilizer proximity, synchronizing water and nitrogen supply, or enabling crop-responsive application. Evidence from large-scale analysis suggests these technologies can support yield gains while holding nitrogen use in check, though outcomes differ substantially by crop and context. Successful promotion therefore requires clear guidance on where each approach applies, what inputs it demands, what returns farmers can expect, and what risks are involved.

Scaling up adoption of these practices hinges less on their technical merits than on whether they deliver clear economic returns under real farming conditions. A 2024 survey found that technology coverage, defined as adoption of at least one type, reached 24%, 60%, and 81% for rice, wheat, and maize respectively, though uptake of specific technologies remains uneven. Insufficient economic incentives stand out as a primary constraint; yield gains and fertilizer savings do not always cover the additional costs of adoption. Cost-benefit analysis suggests that enhanced-efficiency fertilizers and mechanized deep placement tend to generate positive returns, while organic fertilizer substitution offers limited short-term profit improvement for most crops. Beyond economics, field conditions, water access, technical capacity, and the local availability of products, equipment, and services all shape both the feasibility and uptake of these technologies.

Progress on nitrogen productivity and environmental performance will remain uneven and difficult to sustain without a systematic management framework that connects science, technology, policy, and farmer incentives. Because excessive, adequate, and insufficient application coexist across regions, crops, and farm types, a uniform approach is unlikely to prove effective. Targeted reduction, efficiency improvement, and appropriate supplementation each need to be deployed where they are relevant, with interventions differentiated by context to improve overall management effectiveness and lift productivity and returns for farmers. This calls for bringing together new technologies, products, equipment, professional services, and policy incentives within a full-cycle framework spanning scientific assessment, problem identification, goal-setting, differentiated action, outcome verification, and adaptive adjustment (Figure 2). Cost-benefit analysis and environmental performance metrics should inform decisions about which technologies to promote, how subsidies are designed, and how compensation schemes are structured, so that the risks farmers bear in adopting new practices are reduced. Sustained monitoring should feed into regular updates of application standards, technology guidance, and support policies, moving China's agricultural sector toward higher yields and incomes while also improving nitrogen use efficiency and curbing greenhouse gas emissions.

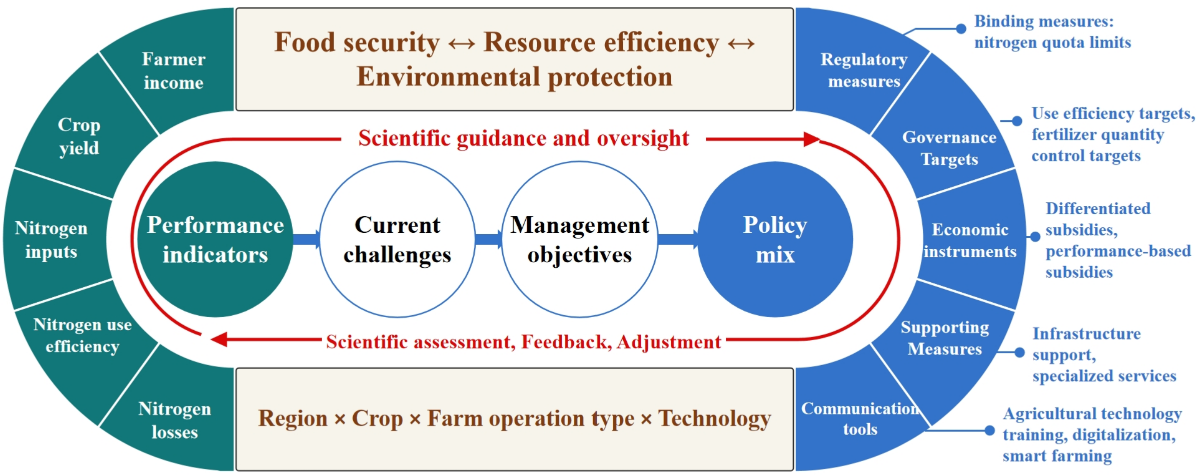

Figure 2. A Systematic Framework for Nitrogen Fertilizer Management under Multiple Coordinated Policy Objectives

Key Findings

I. Policy Objectives Have Shifted from Securing Inputs to Coordinating Multiple Goals

China's nitrogen fertilizer policy has evolved through four successive phases. The first centered on securing input supply to support grain production; the second on promoting rational application and efficiency gains; the third on pursuing fertilizer reduction while advancing green development; and the fourth and most recent on orienting toward low-carbon agriculture and greenhouse gas mitigation. This trajectory reflects a fundamental reorientation in governance logic. Where earlier phases prioritized aggregate supply, current policy is designed around the simultaneous pursuit of production security, resource efficiency, farmer livelihoods, non-point source pollution control, and greenhouse gas mitigation within a single coordinated framework. Achieving that balance requires governance tools capable of operating across production, environmental, and social dimensions at the same time.

II. Aggregate Reductions Are Well Established, yet Structural Variation across Crops and Regions Calls for More Differentiated Management

Total chemical fertilizer and agricultural nitrogen inputs have declined steadily since 2015, and nitrogen management has effectively shifted from aggregate input control to crop- and region-specific optimization. Nitrogen application intensity for food crops has broadly stabilized, though parts of major producing areas retain scope for further efficiency gains. In vegetables and fruit orchards, substantial reductions have been achieved, yet high-input practices remain prevalent in a number of production systems. Meanwhile, certain regions and crops where application falls below established quota minimums require continued attention to maintaining adequate nutrient supply. The overall picture is one of real progress set against persistent variation that undifferentiated targets alone cannot resolve.

III. The Decline in Cropland N_2O Emissions Has Entered a Consolidation Phase, and Sustaining Further Progress Requires More Precisely Targeted Priorities

Between 2015 and 2024, N_2O emissions associated with chemical fertilizer application on farmland fell by 23%, demonstrating that fertilizer reduction efforts have generated tangible climate benefits (Figure 3). Direct emissions remain the dominant source, and high-emission regions as well as nitrogen-intensive crops represent the clearest priorities for continued abatement. Regional emission profiles also diverge in important ways. For cash crops, aggregate input control is the more pressing concern, while for food crops the central challenge lies in advancing yield growth while reducing emissions.

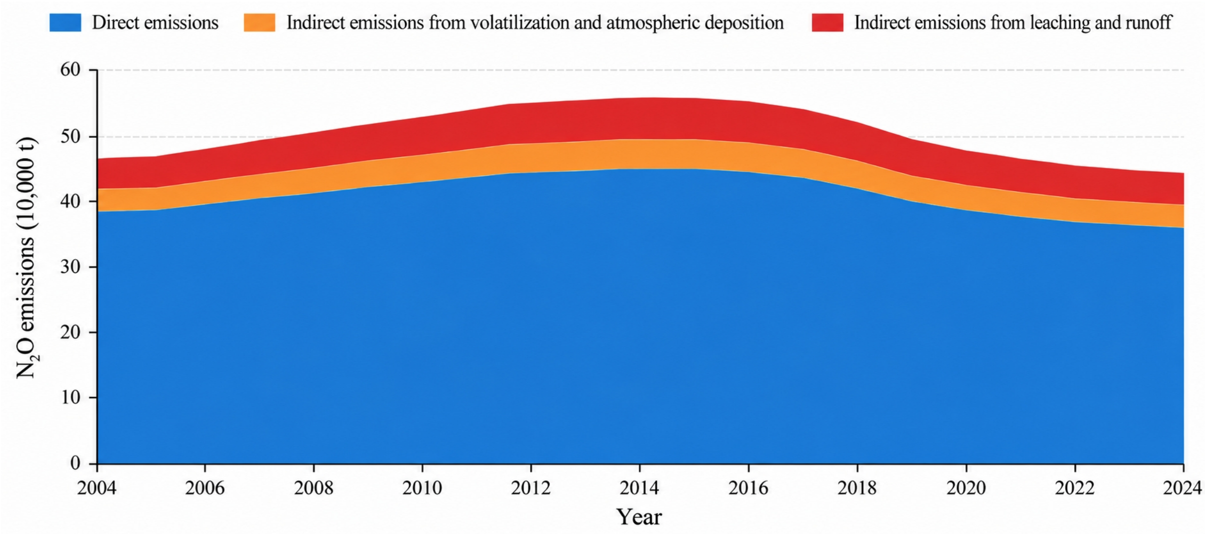

Figure 3. N_2O Emissions from Chemical Fertilizer Application on Cropland in China and Their Composition, 2004–2024

Notes: The baseline inventory covers 31 provincial-level administrative units for the period 2004–2024. Fertilizer application data for 2004–2024 are drawn from the *China Statistical Yearbook*. Nitrogen inputs include the pure nutrient equivalent of straight nitrogen fertilizers and the nitrogen fraction of compound fertilizers, with the nitrogen share of compound fertilizers set uniformly at one-third. The accounting boundary includes direct N_2O emissions from chemical nitrogen fertilizer application on cropland, as well as indirect emissions associated with ammonia volatilization and subsequent atmospheric deposition, and with leaching and runoff. Emissions from manure, crop residues, soil organic matter mineralization, animal excretion, and fertilizer manufacturing are excluded. All results are expressed as N_2O mass rather than CO_2 equivalent. Emission factor parameters are drawn from the *Guidelines for Provincial Greenhouse Gas Inventories (2011 edition)*.

IV. Scientifically Established Nitrogen Quotas Provide a Practical Basis for Quantifying the Potential Gains in Input Reduction, Cost Savings, and Emission Reductions Achievable by Addressing Over-Application

Comparing actual nitrogen application rates against established quota ranges reveals that over-application, adequate application, and under-application coexist across regions and farm types, with the share of farms applying above quota thresholds exceeding that of the other two categories. If 2024 planted areas are held constant, bringing per-hectare nitrogen rates within prescribed quota ranges for ten major crops could reduce chemical nitrogen inputs by approximately 3.2 to 7.3 million tonnes (Figure 4), generating estimated fertilizer cost savings of RMB 21.1 to 48.3 billion. The scope for adjustment varies considerably by crop: potato, soybean, cotton, and apple show the highest per-hectare reduction potential, while the scale of maize, vegetable, rice, and wheat cultivation means that even moderate adjustments in those systems would contribute substantially to national emission outcomes.

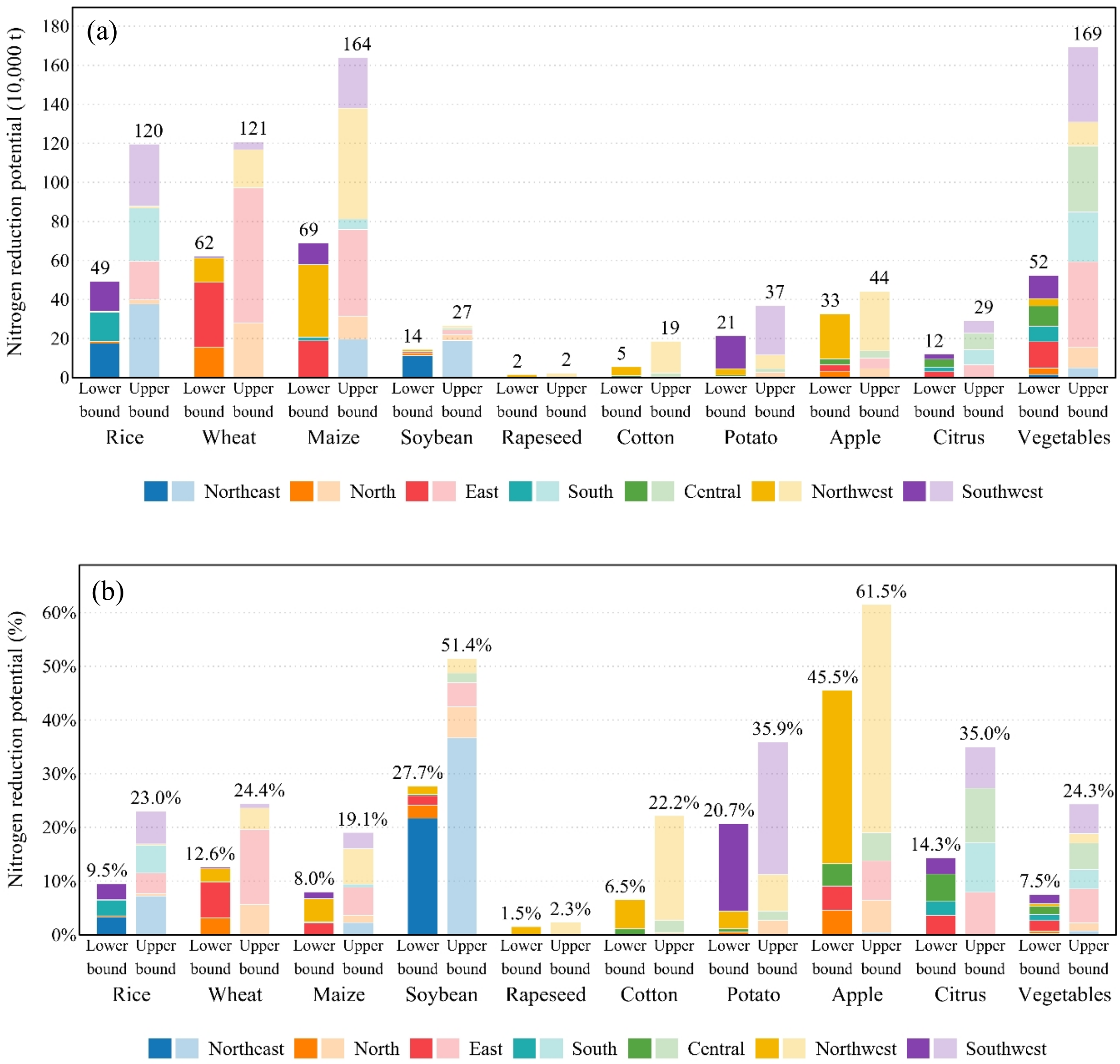

Figure 4. Absolute and Percentage Nitrogen Reduction Potentials for Major Crops

Notes: Panel (a) shows the absolute nitrogen reduction potential for major crops; panel (b) shows the percentage nitrogen reduction potential, with stacked bars representing each region's contribution to the total reduction potential for that crop. The lower bound of the reduction potential is calculated using the upper limit of the nitrogen quota, and the upper bound is calculated using the lower limit of the nitrogen quota. Where actual nitrogen application falls below the applicable quota threshold, reduction potential is set to zero. For vegetables, only national-level quota parameters are available. Estimates were calculated by the research team using data from the *National Compilation of Agricultural Product Cost and Benefit Data*, the National Bureau of Statistics of China, and the National Agro-Tech Extension and Service Center.

V. Technology Combinations That Optimize Nitrogen Application Rate, Timing, Placement, and Form Can Deliver Concurrent Yield Gains and Emission Reductions, Though Performance Is Highly Context-Dependent

Soil testing and formulated fertilization, mechanized deep placement, fertigation, slow and controlled-release fertilizers, precision nutrient management, organic fertilizer substitution, and bio-regulated approaches each improve the alignment between fertilizer supply and crop uptake through distinct mechanisms, whether by refining application volume, placement, timing, nutrient form, or rhizosphere processes. The evidence base supports demonstrable gains in both productivity and emission reduction (Figure 5). Performance nonetheless varies with crop type, soil characteristics, irrigation and drainage infrastructure, and farm management context, which underscores the importance of locally adapted technology integration rather than the generic promotion of individual practices in isolation.

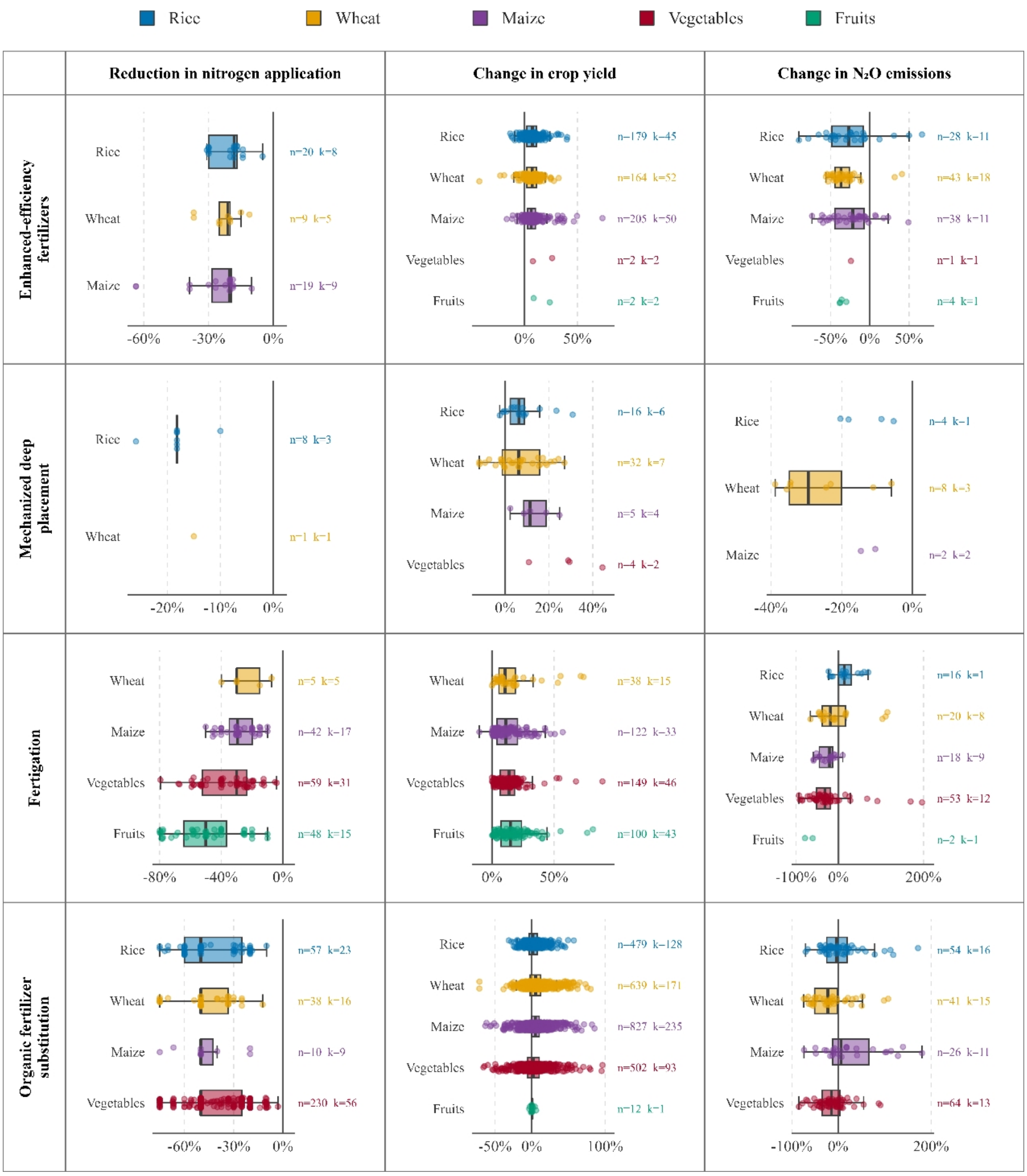

Figure 5. Effects of Nitrogen Management Technologies on Nitrogen Application Rates, Crop Yield per Unit Area, and N_2O Emissions

Notes: All indicators represent the rate of change in the treatment relative to the control; negative values indicate a reduction and positive values indicate an increase. The nitrogen reduction panel retains only comparisons in which chemical nitrogen inputs declined without a corresponding reduction in yield. Each data point represents one treatment–control comparison; n denotes the number of comparisons and k the number of source studies. Box plots are drawn where the number of comparisons is five or more: the box spans the 25th to 75th percentile range, the center line marks the median, and whiskers extend to the furthest observation within 1.5 times the interquartile range from the box edges. Data are drawn from a meta-analysis dataset compiled by the research team.

VI. Farmer Uptake of Nitrogen Management Technologies Is Governed by Economic Returns, Service Accessibility, and Risk-Sharing Arrangements

Enhanced-efficiency fertilizers tend to show favorable short-term economic returns and face relatively low adoption barriers. Mechanized deep placement is viable where machinery and operational services are available, but uptake is limited where local service infrastructure remains underdeveloped. Fertigation entails significant capital investment and ongoing maintenance costs that constrain uptake among smallholders. Organic fertilizer substitution is further complicated by variability in material sourcing, transport distances, and application costs. Going forward, the priority should shift from expanding product and equipment availability toward building complete service chains, reducing the full cost of adoption, and establishing performance-based incentive structures that make the benefits of improved nitrogen management accessible across a broader range of farming operations.

Priority Actions

China's green transition in nitrogen fertilizer management needs to move beyond a framing centered on "reducing fertilizer use" and be reconceived as a strategic agenda for efficient nitrogen resource management. The overarching aim going forward should be to pursue productivity gains, efficiency improvements, and emission reductions in a truly coordinated way, advancing the shift from simply applying less nitrogen toward optimizing its allocation, raising its use efficiency, and minimizing losses across the system. Progress on that front requires alignment across technology development, extension and adoption, economic support, and policy coherence, all within a framework that treats food security and farmer income as essential foundations for agricultural green and low-carbon development.

I. Define Differentiated Nitrogen Application Thresholds and Implement Crop- and Region-Specific Priorities

With established nitrogen quotas as a reference point and calibrated against soil nutrient supply capacity and target yields, management responses should be tailored to three distinct situations. Where application rates are excessive, the priority is reduction; where they are within a reasonable range, the focus should be on raising fertilizer use efficiency; and where current nitrogen inputs fall below adequate levels, the task is to secure appropriate nutrient supply. The greatest potential for total nitrogen reduction lies in maize, vegetables, rice, and wheat given the scale of their cultivation. High-input horticultural systems warrant continued targeted attention. Emission reduction measures should be determined in light of the specific nitrogen loss pathways that characterize each region, rather than being applied uniformly.

II. Optimize Regional Technology Combinations and Establish Clear Application Parameters and Conditions

Regional constraints vary considerably, and technology portfolios should be configured to address the binding limitations specific to each context, bringing together advances in fertilization techniques, fertilizer products, and application equipment in a coordinated way. Multi-site regional trials combined with independent third-party evaluation should be used to establish precise parameters covering application rates, timing, placement, and the appropriate share of organic substitution. The outputs of that process should be organized into county-level inventories specifying the recommended combination of crop, management model, operational parameters, and associated services. Technology integration should aim to simultaneously achieve increased grain yield, improved fertilizer use efficiency, reduced environmental emissions, and higher farmer income.

III. Strengthen Comprehensive Economic Assessment and Reduce the Costs of Technology Adoption

A comprehensive economic assessment should account for yield gains and savings in fertilizer, water, and labor, as well as costs including incremental expenses arising from input price differentials, equipment depreciation, energy, maintenance, and operational expenses. Priority should be given to technology combinations that demonstrate both economic viability and consistent environmental performance. For fertigation, the focus should be on raising infrastructure utilization rates and reducing operating costs. For organic fertilizer substitution, the emphasis should fall on streamlining material sourcing, improving logistics and application infrastructure, and building more organized service delivery models. Where measures with clear environmental benefits generate insufficient short-term private returns, targeted support instruments should be deployed to close that gap.

IV. Develop Differentiated Service Delivery Systems to Support Sustained Technology Uptake

For smallholder farmers, adoption barriers can be reduced through bulk procurement, centralized agronomic diagnosis, shared machinery arrangements, and production management contracting. For larger and more formally organized operations, the priorities are reliable input supply, professional technical personnel, and systematic facility management. Building effective collaboration among agricultural technology extension agencies, input suppliers, and third-party service organizations is essential. The aim should be to establish a functional service chain spanning diagnosis, prescription, fertilizer supply, field operations, record keeping, and outcome evaluation, one that elevates implementation quality rather than simply expanding access to inputs or equipment.

V. Align Cost Support with Performance Incentives to Build Long-Term Institutional Foundations

Support instruments should be calibrated to the specific technical constraints of different adoption pathways, including operational subsidies, shared infrastructure investment, material transport assistance, and capacity building; these should be extended over time to cover maintenance, quality assurance, and continuous service delivery rather than being limited to initial adoption. For measures where environmental benefits are demonstrable but private returns are insufficient to drive uptake, performance-based ecological compensation and emission reduction reward mechanisms tied to monitoring and verification should be explored. The value of N_2O emission reductions should be treated as a complementary incentive, one that works in conjunction with rather than in place of efforts to reduce implementation costs and improve service accessibility.

VI. Strengthen Outcome Verification and Feedback Loops to Enable Adaptive Management

An adaptive management cycle should be institutionalized, following a sequence of scientific assessment, problem identification, target setting, differentiated policy response, outcome verification, and dynamic adjustment. Continuous tracking of nitrogen inputs, yields, farm incomes, use efficiency, and environmental losses across crop and regional contexts provides the empirical foundation for that cycle. A clear analytical distinction should be maintained between trial-scale effects, model-derived potential, and realized field-level outcomes, with that evidence base used to periodically revise nitrogen application standards, approved technology catalogs, and support policies. Strengthening linkages with international nutrient management frameworks and monitoring, reporting, and verification systems would both improve the credibility of domestic assessment and enable China to engage more substantively in global conversations on agricultural emissions.

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