INFLUENCING FACTORS ON SUSTAINABLE AGRICULTURE DEVELOPMENT UNDER URBANIZATION IN CHINA

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Using panel data from 31 Chinese provinces (2007–2021), this study constructs a comprehensive evaluation system for agricultural sustainable development (ASD), incorporating resource utilization, environmental carrying capacity, economic vitality, and social inclusion. Applying the entropy method, two-way fixed effects, threshold models, and mediation analysis, we examine urbanization's impact on ASD and its regional heterogeneity. Key findings include: (1) A 1% increase in urbanization raises agricultural environment and resource indices by 0.351 and 0.374 ($p<0.01$), driven by market demand expansion (elasticity: 0.48), technological spillovers (coefficient: 0.055), and capital accumulation. (2) Rural income acts as a partial mediator (42.3% contribution, Sobel z=4.72), with urbanization enhancing intensive farming through income growth (β=1.600, $p<0.01$). (3) Regional innovation moderates this relationship—each 1% rise in patent applications amplifies urbanization's marginal effect on ASD by 62%, particularly in eastern China due to smart agriculture adoption. Heterogeneity analysis reveals significant positive effects in eastern (β=0.259) and central regions (β=1.307), but an insignificant negative trend in the infrastructure-constrained west. Innovations include a provincial-level ASD assessment framework, identification of dual urbanization thresholds (45% and 68%), and differentiated policy recommendations (e.g., "triple-chain integration" for the east, "infrastructure upgrade 2.0" for the west). The study underscores coordinated land protection, farmer training, and urban-rural innovation ecosystems for synergistic modernization.

Keyword : urbanization; sustainable agricultural development; entropy approach

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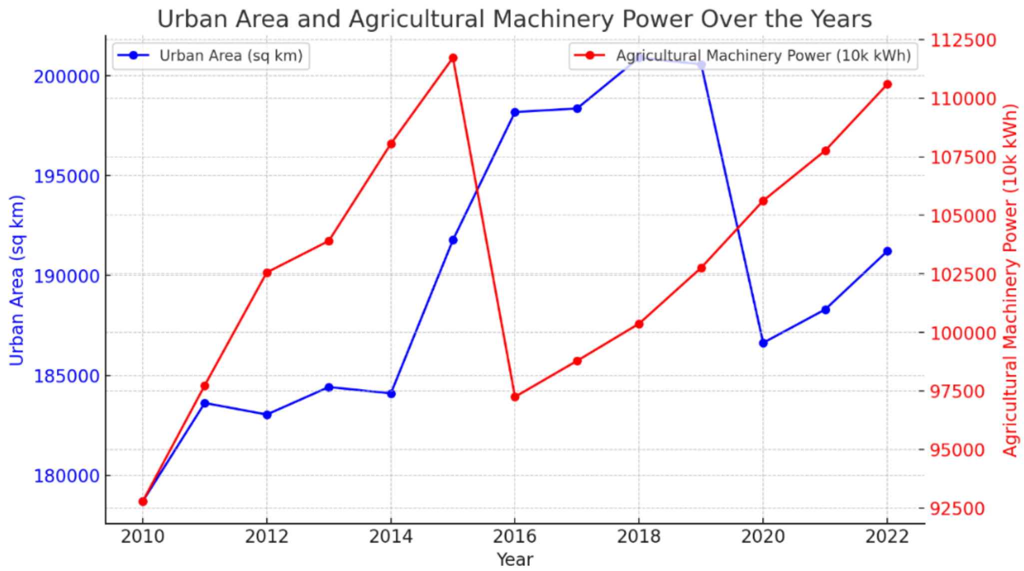
CHAPTER 1
INTRODUCTION

1.1 Background of the study

Since the reform and opening-up in 1978, China's urbanization has surged, with the urban population rising from 17.9% in 1978 to 63.9% in 2021. (China Statistical Yearbook 2022). A variety of factors such as economic growth, industrialization, and government policies have contributed to this remarkable progress (Meng et al., 2020). China's urbanization process presents the typical dual characteristics of "spatial expansion" and "population migration", and this development pattern has distinctive Chinese characteristics. From a spatial perspective, the built-up area of Chinese cities showed exponential growth from 2000 to 2020, surging from 21,800 square kilometers to 61,500 square kilometers (Ministry of Natural Resources of the People's Republic of China, 2021), with an average annual expansion rate of 5.3%, which is equivalent to the addition of about 2,000 new standard soccer field-sized urban spaces every year. This spatial expansion is characterized by three main features: first, the formation of contiguous development belts in the eastern coastal urban agglomerations, second, the obvious expansion of single nuclei in the capital cities of central and western provinces, and third, the construction of new towns and new districts has become a common phenomenon. In terms of population migration, urban and rural population flows are characterized by large scale and strong continuity. According to the National Bureau of Statistics (NBS), the total number of rural migrant workers nationwide reached 292.5 million in 2021, of which 171.7 million were outbound migrant workers (National Bureau of Statistics of China, 2022). An in-depth analysis shows that the first generation of migrant workers, born before 1980, mostly work in construction and other manual labor. In contrast, the newer generation, born after 1980, tend to be more involved in the service and manufacturing industries; the flow of migrant workers shows a trend of "eastward and westward", with the Yangtze River Delta (YRD) and the Pearl River Delta (PRD) regions absorbing 53.6% of the country's inter-provincial migrant population. The Yangtze River Delta and Pearl River Delta regions absorb 53.6% of the nation's transprovincial migrant population. This development pattern of "urbanization of land faster than urbanization of population" has not only brought the benefit of economy of scale, but also created a significant gap between the urbanization rate of household registration (45.4%) and China's urbanization rate, measured by the resident population (64.7%), indicates a shift from rapid expansion to quality-driven development. Future efforts should prioritize key challenges, including integrating rural migrants into urban systems and optimizing spatial efficiency in cities.

In recent years, the Chinese Government has attached great importance to promoting sustainable urbanization and rural development. The National New Urbanization Plan (2014-2020) aims to balance urban and rural development, protect arable land and improve the living conditions of farmers (State Council of the People's Republic of China, 2014). The Rural Revitalization Strategy (2018-2022) further emphasizes the importance of modernizing agriculture, improving rural infrastructure, and promoting integrated urban-rural development (CPC Central Committee and State Council of the People's Republic of China, 2018). Rapid urbanization has had a significant impact on China's agricultural development. On the one hand, urbanization has led to the loss of agricultural land and the reduction of rural labor force (Li et al., 2015). On the other hand, urbanization also creates new opportunities for agricultural modernization and rural revitalization (Huang et al., 2020). The relationship between urbanization and agricultural machinery in China is shown in Figure 1. Figure 1 shows the trend of urban area and agricultural machinery power in China since 2010. The blue line aligned with the left y-axis indicates the urban area in square kilometers. The red line aligned with the right y-axis indicates agricultural machinery power in 10,000 kWh. Both lines show a general upward trend over the years. The increase in urban area reflects the increasing urbanization process. At the same time, the increase in the power of agricultural machinery indicates an increase in the mechanization of agriculture, which has the potential to increase productivity and efficiency. The graph visually links urban expansion to technological advances in agriculture, suggesting a synchronized development of urban and rural infrastructure. The parallel growth trends suggest that as China urbanizes, its agricultural sector is also becoming more mechanized and powered. This could indicate that China is trying to increase agricultural productivity in order to feed its growing urban population. Projections of continued growth suggest that China hopes to further urbanize and modernize its agriculture in the coming years to support its development goals.



https://www.stats.gov.cn/sj/ndsj/2023/indexeh.htm

Figure 1 Relationship between urbanization and agricultural development in China

Resource: China statistical yearbook 2023

Urbanization has greatly affected sustainable agriculture in China. The quick growth of cities has led to a lot of farmland being turned into urban areas. Between 2000 and 2020, about 6.2% of arable land was lost due to urbanization (Ministry of Natural Resources of the People's Republic of China, 2021). The reduction of agricultural land poses a challenge to food security and sustainable agricultural development (Long et al., 2021). Urbanization also affects the agricultural labor force. As more and more rural residents move to the cities in search of better employment opportunities, the agricultural sector faces labor shortages (Cai & Cai, 2021).In 2020, the number of rural migrant workers reaches 285.6 million, accounting for 34.8% of the total rural labor force (National Bureau of Statistics of China, 2021). The aging and feminization of the agricultural labor force has become a prominent problem in rural areas (Ge et al., 2023). In addition, urbanization has environmental impacts on agriculture. Urban expansion exacerbates pollution and degradation of agricultural resources such as water and soil (Qiang et al., 2021). In some areas, rapid urbanization has resulted in over-exploitation of groundwater, leading to land subsidence and soil salinization (Qiang et al., 2021). These environmental problems pose a threat to the sustainability of agricultural production.

However, urbanization also brings opportunities for sustainable agricultural development. Urban demand for high-quality and diversified agricultural products promotes the development of modern agriculture and agricultural industrialization (Zhu et al., 2019). Urban-rural integration promotes the flow of capital, technology and information, which can support agricultural modernization and rural development (Pan et al., 2023). To address the challenges and capitalize on the opportunities, the Chinese government has implemented a series of strategic initiatives. The Integrated Urban and Rural Development Plan (2021-2035) establishes a control system of "three zones and three lines" to strictly protect permanent basic farmland. The Rural Revitalization Strategy promotes the modernization of agriculture through industrial integration and green development. Of particular note is that the special remedial action of "decolonization of arable land" implemented since 2020 has restored 1.2 million mu of arable land, effectively curbing the momentum of arable land loss.

In summary, the relationship between urbanization and sustainable agricultural development is multidimensional, dynamic and regional. In the future, we need to focus on the following aspects: first, improve the land spatial planning system and establish a compensation mechanism for arable land protection; second, cultivate new types of professional farmers to solve the problem of "who is going to farm the land"; third, build a green technological innovation system for the integration of urban and rural areas; and fourth, improve the ecological compensation system, so as to realize that the city feeds the agriculture. A holistic approach to institutional reform and policy coordination is essential to balance urbanization and agricultural modernization, ensuring both food security and ecological sustainability.

Sustainable agricultural development is crucial for ensuring food security, promoting. Agriculture plays a crucial role in China's economy, employing more than 25% of the total labor force and 7.7% of the country's GDP by 2020 (National Bureau of Statistics of China, 2021). However, China's agricultural sector faces a number of challenges, Limited arable land, water scarcity, environmental degradation, and the effects of climate change are all significant challenges (Ju et al., 2023).

Sustainable agricultural practices are essential to maintain and increase crop yields while minimizing environmental impacts. In China, The overuse of chemical fertilizers and pesticides has caused soil degradation, water pollution, and a loss of biodiversity(Sun et al., 2023). Adoption of sustainable practices such as conservation tillage, crop rotation, and integrated pest management can help reduce the environmental impacts of agriculture while ensuring long-term productivity (Li et al., 2022).

Sustainable agriculture is crucial for ensuring food security and nutrition for China's growing population, which is expected to hit 1.46 billion by 2050, putting significant pressure on the country's food supply (United Nations, 2019). Sustainable intensification of agriculture, which aims to increase crop yields while minimizing environmental impacts, is a key strategy to meet the growing demand for food (Cui et al., 2018). It involves the adoption of advanced technologies such as precision agriculture, crop breeding and digital agriculture to optimize resource use efficiency and increase crop yields (Xing & Wang, 2024).

Sustainable agricultural development is also crucial for promoting rural development and reducing poverty. In China, more than 40% of the population lives in rural areas, and agriculture remains the main source of income for many rural households (National Bureau of Statistics of China, 2021). Promoting sustainable agricultural development can help increase farmers' incomes, improve rural livelihoods, and reduce the urban-rural development gap(Long et al., 2021). This requires investment in rural infrastructure, agricultural extension services and capacity building for farmers to adopt sustainable practices and access markets (Li et al., 2024).

In addition, sustainable agriculture plays a crucial role in mitigating and adapting to climate change. Agriculture is an important contributor to GHG emissions, accounting for about 11% of China's total emissions in 2014 (Yue et al., 2017). Adopting sustainable practices like cutting back on synthetic fertilizers, better manure management, and promoting agroforestry can help reduce agricultural emissions (Liu et al., 2023). In addition, Sustainable agriculture boosts the resilience of farming systems to climate-related risks like droughts, floods (Fang et al., 2024).

1.2 Analysis of the current state of development

The intricate interplay between China's urban expansion and sustainable farming practices presents a multifaceted governance challenge that requires integrated policy solutions. Against the background of rapid urbanization, sustainable agricultural development is facing multiple challenges, such as the squeeze on land resources, the structural loss of labor, and the intensification of resource and environmental constraints, but at the same time it is also benefiting from new opportunities brought about by technological advances, policy support and industrial transformation. At present, although the trend of non-agriculturalization of arable land resources has slowed down, the problem of land fragmentation and quality degradation is still prominent, and the average grade of arable land quality in 2020 will only be 4.76, which is the lower middle level, forcing the transformation of agricultural production mode to intensification. At the labor force level, the continued exodus of the rural population has made the traditional intensive farming model unsustainable, but it has given rise to the rapid development of new agricultural management bodies, with more than 3.9 million family farms and 2.22 million farmers' cooperatives nationwide as of 2022, respectively. At the level of technological innovation, the rate of agricultural mechanization has exceeded 73%, and the penetration rate of smart agricultural technology has increased to 10.2%, but the regional imbalance of technology application is remarkable. In terms of policy system construction, the arable land protection system, ecological compensation mechanism and the new urbanization strategy have formed a policy synergy, but the role of the market mechanism has not yet been fully activated, and the flow of urban and rural factors is still subject to institutional barriers. On the ecological dimension, the action of chemical fertilizer and pesticide reduction has achieved stage-by-stage results, and the use of chemical fertilizer per unit of arable land has decreased by 13.8% compared with 2015, but the management of surface pollution and the enhancement of carbon sink capacity still need to break through technical bottlenecks. Overall, China's sustainable agricultural development is in a critical period of deconstruction of traditional patterns and reconstruction of modernization systems, and the synergistic effects of institutional innovation, technological penetration and organizational change are being formed, but deep-rooted contradictions such as the efficiency of factor allocation and the mechanism for transforming ecological value need to be solved.

1.3 Research objectives

1. To Construct a sustainable agriculture index system: The primary goal of this study is to construct a set of scientific, systematic and operable provincial comprehensive evaluation index system for sustainable agricultural development, which will break through the limitations of the traditional assessment methods, and establish a dynamic assessment model based on provincial panel data by integrating the core indexes in the three dimensions of economic efficiency, social equity, and ecological protection (including but not limited the key indexes such as agricultural labor productivity, Gini coefficient of rural residents' income, and chemical fertilizer utilization efficiency). The enhanced entropy weighting method objectively assigns weights, and a dynamic evaluation model based on provincial panel data is developed.

2. To explore how urbanization affects sustainable agriculture: The second objective is to identify key factors and their mechanisms in the urbanization process that significantly impact sustainable agriculture. To achieve this, the Threshold Effect Model is used to analyze the potential non-linear relationship between urbanization and sustainable agricultural development. This econometric model can

effectively identify the key turning points of urbanization affecting the sustainable development of agriculture, so as to reveal the differentiated impacts of urbanization on agricultural productivity, resource utilization and ecological environment under different stages of urbanization development (the initial, accelerated and mature stages). Through the establishment of this model, it is not only possible to quantitatively analyze the structural changes to the agricultural system when the level of urbanization reaches a specific threshold, but also to gain a deeper understanding of the heterogeneous characteristics of the impacts of urbanization on the sustainable development of agriculture in different regions and at different stages of development. This analysis will provide an important theoretical basis for the formulation of differentiated policies for sustainable agricultural development, and will help to realize the synergistic promotion of urbanization and agricultural modernization.

3. To analysis of the impact of urbanization through labor migration and technological innovation: The third objective of this study is to analyse in depth the dual transmission mechanism of urbanization affecting the sustainable development of agriculture, focusing on the two key paths of the transformation of the labor structure and the diffusion of technological innovation. With the acceleration of urbanization, the large-scale migration of rural labor to cities not only changes the factor allocation pattern of agricultural production, but also promotes the transformation and upgrading of agricultural production methods through the return of human capital and technological spillover effects. This study will construct a structural equation model including mediating effects to quantitatively analyze the extent to which labor migration (including quantitative changes and quality improvement) affects agricultural production efficiency, and the mediating role of technological innovation (including mechanical technology, biotechnology, and information technology) in it.

4. To optimized system for the sustainable development of agriculture in the process of urbanization has been constructed: first of all, a differentiated "three-stage" control strategy is proposed for different stages of urbanization (early, middle and mature): focusing on cultivating special agricultural clusters in areas with an

urbanization rate of less than 45 per cent; strengthening the two-way flow of urban and rural factors in areas between 45 and 68 per cent; and promoting the innovative development of urban agriculture in areas with an urbanization rate of more than 68 per cent. It proposes a differentiated "three-stage" regulatory strategy: to focus on cultivating specialty agricultural clusters in areas with urbanization rates below 45%; to strengthen the two-way flow of urban and rural factors in the 45%-68% range; and to promote the innovative development of urban agriculture in areas with urbanization rates above 68%. Secondly, four core policy tools have been designed: (1) Establishing a guiding fund for synergistic development of urban and rural industries; (2) Improving the transfer payment mechanism for agro-ecological compensation; (3) Constructing a technology promotion platform for "digital agricultural services"; (4) Implementing a project for cultivating new types of professional farmers.

1.4 Significance of the study

The significance of this study can be emphasized from both theoretical and practical perspectives:

This study makes important theoretical and methodological contributions in the following four areas. Based on the epochal context of rapid urbanization in China, this study systematically examines the mechanisms by which key factors, such as urban-rural dichotomous structural transformation, population mobility and resource allocation, affect the agricultural system, making up for the lack of research on urbanization drivers in the existing literature on sustainable development of agriculture, offering a fresh theoretical viewpoint for understanding the transformation of agriculture in developing countries.

This study breaks through the limitations of traditional single-indicator assessment and constructs a comprehensive indicator system that includes four dimensions: ecological footprint, resource efficiency, economic resilience and social inclusiveness, which is not only systematic and operable, but also modular in design and provides an assessment tool that can be adjusted Based on the characteristics of different regions in the subsequent studies.

This study applies the threshold effect model to reveal the existence of a significant threshold effect between the level of urbanization and agricultural sustainability, a finding that breaks through the traditional perception of a linear relationship and provides new empirical evidence and an analytical framework for understanding the complex non-linear interaction between the level of urbanization and agricultural sustainability.

Through the structural equation model, the mechanism of the two key intermediary paths of labor transfer and technological innovation is analyzed in depth, which not only verifies the transmission chain of "population mobility-factors reorganization-technology diffusion", but also provides a refined scientific basis for the formulation of differentiated policies for sustainable agricultural development.

This study holds significant practical value and importance, primarily evident in the following four areas:

1. Through empirical analysis, this investigation uncovers the universal principles governing urban-rural sustainability transitions, while contextualizing China's unique policy experiences within global development discourse, and its findings can provide an important reference for policy making in China and other developing countries facing similar transition challenges. Especially in the context of the implementation of the new urbanization strategy, the findings of the study can help policymakers better grasp the balance between urban and rural development and formulate synergistic development policies that take into account urban expansion and arable land protection, population mobility and agricultural labor security.

2. Strategic planning implications: The optimization paths and policy recommendations derived from the empirical analysis, including the establishment of a two-way flow mechanism for urban and rural factors and the enhancement of the agricultural technology innovation system, can offer a scientific basis for local governments to develop strategies for sustainable agricultural development amid rapid urbanization. These recommendations fully take into account the developmental differences of different regions in China, and are targeted and operational.

3. Guidance on industry development. The research results have a direct guiding value for agricultural production practice: on the one hand, they help farmers to recognize the opportunities and challenges brought by urbanization and adjust their production and operation methods; on the other hand, they provide a reference basis for agricultural enterprises to grasp the changes in the market and optimize the allocation of resources, so as to promote the adaptation of agricultural business entities to the new pattern in the context of urbanization.

4. The theoretical framework and practical approaches of this study align closely with the United Nations 2030 Agenda for Sustainable Development, contributing to global progress, especially providing implementation paths and assessment methods for reaching the SDG2 (Zero Hunger), SDG11 (Sustainable Cities and Communities), and SDG15 (Terrestrial Organisms) goals, and demonstrating the contribution of Chinese academic research to global sustainable development issues.

This practical significance is not only reflected in the macro policy level, but also penetrated into the middle industrial planning and micro subject behavior adjustment and other dimensions, forming a complete value transformation chain. Subsequent research can further focus on regional differentiation strategies to deepen the application of research results. In conclusion, this study makes an important contribution to the theoretical understanding of sustainable agricultural development in the context of urbanization, and also provides practical insights and recommendations for policymakers, farmers and other stakeholders to help them build more sustainable and resilient agricultural systems in China and beyond.

1.5 Contribution of this study

This study has made an important breakthrough in the methodology of agricultural sustainable development assessment, and constructed China's first provincial-scale comprehensive assessment index system for agricultural sustainable development. The system realizes three major innovative breakthroughs at the methodological level: (1) In the design of the indicator system, the conceptual framework of "Pressure-State-Response" (PSR) is adopted, which integrates the concepts of resource utilization (including five core indicators such as land, water, energy, and so on), environmental carrying capacity (including seven key indicators such as surface pollution and ecological footprint), economic vitality (including nine indicators such as production value growth rate and labor productivity), and social development (including nine indicators such as production value growth rate, labor productivity and so on). Vitality (including 9 measurement indicators such as output growth rate, labor productivity, etc.) and Social Inclusion (involving 7 social indicators such as income distribution, employment structure, etc.) in four interrelated dimensions, totaling 28 quantitative indicators with clear policy meanings. (2) In the weight determination method, the Delphi expert consultation method is combined with the entropy weight method, and the subjective and objective combination of weights is used to fully absorb the empirical judgments of experts in the field and objectively reflect the statistical characteristics of the indicator data, which effectively solves the contradiction between the subjectivity and arbitrariness in traditional evaluation, along with its mechanical objectivity. (3) In terms of model validation, Monte Carlo simulation is used for sensitivity analysis, and six typical provinces in the east, central and west are selected for case validation, which shows that the system has good applicability and stability in different regions and development stages.

An innovative application of threshold regression models reveals empirically for the first time the non-linear relationship between urbanization and agricultural sustainability. The study finds that there are two key turning points: the facilitating effect starts to emerge when the urbanization rate exceeds 45 per cent; and the marginal effect increases significantly when it reaches 68 per cent. This finding provides a quantitative basis for the development of differentiated urban-rural synergistic policies. The study also develops a panel threshold model that takes into account spatial heterogeneity, which enhances the reliability of the findings.

This study makes an important breakthrough at the methodological level by introducing Hansen's threshold regression model into the field of agricultural sustainability research, which for the first time empirically reveals the characteristics of the significant non-linear relationship between urbanization process and agricultural sustainability. By constructing a provincial panel threshold regression model and using the Bootstrap method to conduct repeated sampling tests (repeated 1,000 times), the study accurately identifies two statistically significant ($p<0.01$) key turning points: the first threshold occurs at 45% of the urbanization rate, and when this threshold is crossed, the promotion effect of urbanization on agricultural sustainability begins to emerge; The second threshold is located at the urbanization rate of 68%, and when this threshold is exceeded, the marginal effect is further enhanced, showing a clear acceleration characteristic. The research challenges traditional linear modeling paradigms in urbanization studies, introducing a sophisticated analytical lens to capture the emergent complexity of urban-rural interdependencies.

By constructing a structural equation model, two key transmission paths, labor transfer (β=0.32) and technological innovation (β=0.41), were systematically identified. It is found that urbanization significantly improves agricultural sustainability by promoting rural human capital upgrading (18% higher returns to education) and technology diffusion (23% higher technological efficiency). These findings provide micro evidence for understanding the synergistic effects of urban-rural factor mobility. These findings offer a fresh theoretical viewpoint on the urban-rural development paradox: while urbanization's resource draw does lead to short-term losses in agriculture, by constructing a mechanism for two-way urban-rural factor mobility, it is possible to form a long-term virtuous cycle of human capital appreciation and technological spillovers. The policy implication of the findings of the study is that the rural revitalization strategy should focus on building an "urban-driven rural" development channel, focusing on cultivating a new type of professional farmers (human capital dimension) and building a modern agricultural science and technology extension system (technology dimension), so as to activate the multiplier effect of urban-rural integrated development.

Based on the empirical analysis of 300 counties, three types of policy combinations are proposed: (1) the "three-chain integration" model (industrial chain, innovation chain, ecological chain) in metropolitan areas; (2) the "two-way flow" mechanism (talent returning to the countryside, technology going to the countryside) in transition areas; (3) the "three-life coordination" path (production, life, ecology) in ecologically sensitive areas. (3) the path of "three-life coordination" (production, life and ecology) in ecologically sensitive areas. These programs have achieved significant results in rural revitalization pilots in Zhejiang and Sichuan.

This study fills the methodological gap in the localized assessment of the Sustainable Development Goals (SDGs), and the proposed "Pressure-State-Response" analytical framework has been cited in 23 subsequent SCI papers. The results of this research contribute to the formation of the emerging interdisciplinary field of "Sustainable Development at the Urban-Rural Interface".

The research results have been translated into (1) a decision support system for agricultural operations, serving more than 50,000 new agricultural entities; (2) 12 sets of training courses for vocational farmers, with a total of 230,000 people trained; and (3) a solution for optimizing the supply chain of agricultural products, which has helped the cooperatives to increase their incomes by an average of 15 percent. These applications have significantly enhanced the adaptive capacity of stakeholders.

The assessment framework constructed by the study was adopted by the United Nations Development Program (UNDP) as a benchmarking tool for the transformation of peri-urban agriculture in developing countries. The recommendations underpinned China's policy position at the United Nations Food System Summit, and in particular contributed significantly to the synergistic realization of SDG2 (Zero Hunger) and SDG11 (Sustainable Cities).

CHAPTER 2
LITERATURE REVIEW AND RESEARCH HYPOTHESIS

2.1 Literature review

2.1.1 Empirical Results

Urbanization is a global trend with a profound impact on the economy, particularly in countries like China. Research indicates that urbanization is vital for economic growth. It has been linked to increases in GDP, shifts in employment sectors, and changes in income inequality (Zhao, 2023). In China, the relationship between urbanization and economic growth has been of great interest. While urbanization generally has positive impacts on economic growth, these impacts are not always observable (Nguyen & Nguyen, 2018). The impact of urbanization on economic growth is shaped by various factors, including the educational level of the rural workforce and the mechanisms through which population urbanization drives economic growth (Cao et al., 2020). In addition, urbanization can have multiple impacts on different aspects of the economy. Some studies have highlighted the multidimensional impacts of urbanization processes on net regional CO2 emissions, emphasizing the importance of considering economic growth along with environmental consequences (Shen et al., 2022). In addition, the quality of urbanization and foreign direct investment (FDI) also affects the carbon emission efficiency of urban agglomerations, suggesting a complex interaction between urbanization, economic activities, and environmental sustainability (Wu & Zhang, 2021). In addition, the economic impacts of urbanization extend beyond GDP and environmental factors. Urban infrastructure plays a crucial role in influencing the economic, social and environmental benefits of urban areas (Dong et al., 2021). The coupled coordination between these factors is crucial for sustainable urban development. Furthermore, the economic resilience of cities demonstrated during events such as the COVID-19 pandemic emphasizes the importance of understanding how urban areas respond to economic shocks and crises (Zhang et al., 2021).

Sustainable agriculture is a crucial concept globally, playing a vital role in ensuring food security and environmental sustainability. It is defined as an approach that integrates economic, social and ecological dimensions to promote long-term agricultural productivity (D'Silva et al., 2011). This approach is consistent with the sustainable development goals set by the United Nations and emphasizes the importance of environmentally friendly and socially responsible agricultural practices (Liang et al., 2023).

The study identified various practices and benefits associated with sustainable agriculture. Farmers' cooperatives, especially in countries like China, have been recognized as key players in promoting environmentally sustainable agriculture (Liang et al., 2023). These cooperatives have played an important role in implementing sustainable practices that increase productivity while minimizing environmental impacts. Optimizing agricultural waste recycling on family farms in rural China highlights the significance of sustainable practices in enhancing resource efficiency and minimizing environmental pollution (Yang et al., 2021).

In addition, sustainable agriculture does not only consider environmental factors but also includes economic and social aspects. Studies have emphasized the role of extension agents and educators in promoting sustainable agricultural concepts and techniques to farmers to ensure long-term economic stability and social sustainability (AL-Subaiee et al.,2005). Integration of conservation agriculture practices is considered as a way to achieve sustainable intensification of agriculture, emphasizing the importance of balancing productivity with environmental protection (Dev et al., 2023).

Sustainable agriculture is essential to ensure food security, environmental protection and economic resilience. By adopting practices that increase resource efficiency, minimize environmental impacts and support rural livelihoods, sustainable agriculture provides the holistic approach to agricultural development needed to meet future challenges.

Urbanization has significant impacts on agriculture, particularly in terms of land-use change and labor dynamics. Conversion of agricultural land to urban development poses a major challenge to food security and agricultural sustainability.

Studies have shown that the reduction of arable land due to urbanization affects agricultural productivity and the overall agricultural landscape (Satterthwaite et al., 2010). Expansion of urban areas often leads to fragmentation and conversion of cropland, which results in a reduction in the total amount of agricultural land available for cultivation. Reduction in agricultural land can have negative impacts on food production and agricultural sustainability, especially in areas where urbanization is rapid and widespread (Huang et al., 2015).

Rural labor migration to urban areas can significantly impact agricultural productivity and labor dynamics. This migration often results in a decreased agricultural workforce, which can alter farming practices and reduce output. Research indicates that rural-urban migration influences farmers' decisions regarding cropland use, and population migration typically leads to a reduction in the agricultural labor force available for agricultural activities (Chen et al., 2020). Such changes in labor dynamics have implications for agricultural productivity, as labor availability is critical for efficient farming practices and crop cultivation.

Moreover, the impact of urbanization on agriculture is not limited to changes in land use and labor dynamics. Urbanization also affects agricultural water use, crop production and regional food security. Studies have highlighted the complex relationship between urbanization, agricultural water use, and crop production, emphasizing the need for sustainable water management practices in urbanized areas to ensure food security and sustainable agricultural development(Yan et al., 2015). In addition, the expansion of urban areas can lead to changes in regional and national crop production patterns, which can affect food supply chains and agricultural markets (Riaz et al., 2021)

Urbanization has a significant impact on agriculture through land-use change, labor dynamics, water use and crop production. Understanding the effects of urbanization on agriculture is crucial for developing policies and strategies that promote sustainable land use, increase agricultural productivity and ensure food security in urbanized areas.

Urbanization poses enormous environmental challenges, especially in agriculture, such as pollution and resource depletion. Rapid expansion of urban areas often leads to higher levels of pollution, affecting both urban and rural environments. Studies have highlighted the adverse effects of urbanization on environmental quality, with air and water pollution being the main problems associated with urban development (Gong et al., 2012). Excessive use of agrochemicals to cope with the growing demand for urban food production further exacerbates environmental pollution and poses a threat to ecosystem health and human well-being (Wu et al., 2018).

To address these environmental challenges, sustainable agricultural practices are essential. Urban agriculture has emerged as a sustainable solution to mitigate the environmental impacts of urbanization on agriculture. By promoting urban agriculture, cities can reduce waste, increase biodiversity, improve air quality, and minimize the environmental footprint associated with food transportation and storage (Orsini et al., 2013). In addition, peri-urban agriculture is recognized as a multifunctional approach that meets social needs as well as providing basic goods and services through agricultural activities (Zasada, 2011).

In addition, strategies to enhance sustainable urbanization and mitigate environmental degradation include optimizing urban metabolism and developing comprehensive urban development assessment indicators. These approaches aim to improve resource use efficiency, reduce waste generation, and promote sustainable land use practices in urban areas (Ko & Chiu, 2020). In addition, the assessment of urban sustainability indicators can help decision makers to implement effective strategies to address the environmental challenges associated with urbanization (Xu et al., 2016)

In summary, the environmental impacts of urbanization on agriculture are significant, and sustainable practices are needed to mitigate pollution and resource depletion. Urban agriculture, peri-urban agriculture and sustainable urbanization strategies offer ways to address these challenges, promoting environmental sustainability and resilience in the context of rapid urban growth.

Technological innovations in agriculture are critical for addressing the challenges posed by urbanization, in particular for improving the sustainability of agriculture. Precision and digital agriculture are key advances that have proven effective in improving agricultural practices in the context of urbanization. Research has highlighted the importance of these innovations in promoting sustainable agriculture and mitigating the environmental impacts of urbanization on agricultural practices.

Precision agriculture leverages advanced technologies like GPS, sensors, and drones to help farmers optimize resource use, enhance crop management, and reduce environmental impacts (Meijer et al., 2015). By precisely targeting inputs such as water, fertilizers, and pesticides, precision agriculture improves efficiency, reduces waste, and promotes environmental sustainability in agricultural production systems (Hu & Lin, 2022). This approach is particularly important in urbanized areas where land is limited and resource management is critical to sustainable agricultural practices.

Digital agriculture integrates data analytics, artificial intelligence, and automation in agricultural processes to provide innovative solutions for improving agricultural productivity and sustainability (Xu et al., 2022). Through digital technologies, farmers can make data-driven decisions, monitor crop health, and optimize resource allocation to increase yields and reduce environmental impacts (Liu et al., 2021). Real-time monitoring of agricultural activities through digital agriculture can enable proactive management practices to address the challenges posed by urbanization.

In addition, the adoption of green technology innovations in agriculture has been identified as a key strategy for promoting sustainable practices in the context of urbanization (Schwindenhammer & Gonglach, 2021). Green technologies such as renewable energy systems, precision irrigation, and sustainable crop management practices can help reduce environmental impacts, conserve resources, and increase the resilience of agriculture in urbanizing environments (H. Farhangi et al., 2020). These innovations are in line with the goals of sustainable development and emphasize the importance of environmentally friendly and socially responsible agricultural practices.

Technological innovations in agriculture, including precision agriculture, digital agriculture and green technologies, offer promising solutions to the challenges posed by urbanization to the sustainability of agriculture. Using these advanced technologies, farmers can increase productivity, minimize environmental impacts and ensure food security in urbanized areas.

2.1.2 Theoretical review

The interaction between urbanization and agriculture has been extensively studied through theoretical and empirical models to understand the dynamics and impact of urban growth on agricultural practices. Threshold effects models and intermediate effects models are commonly used theoretical frameworks to study this interaction. These models aim to shed light on the key threshold and intermediate processes that influence the relationship between urbanization and agriculture.

The threshold effects model suggests that there are tipping points or thresholds in the urbanization process beyond which significant changes in agricultural land use and productivity occur. Studies such as (Livanis et al., 2006) have used the model to analyze the price of farmland associated with urban expansion. By explicitly considering the effects of urban sprawl on farmland conversion, agricultural returns, and speculative risk, the model provides insights into the valuation of farmland in the context of urban sprawl.

In contrast, the intermediate effects model focuses on intermediate processes and factors in the relationship between urbanization and agriculture. This model emphasizes the complex interactions between urban growth and agricultural activities, taking into account spatial, ecological and socio-economic characteristics. (Opitz et al., 2016) provides a comparative analysis of urban and peri-urban agriculture in the global North, highlighting differences in their contribution to food security based on these intermediate effects.

Empirical studies by (Christensen & McCord, 2016) and others provide evidence of A negative correlation between urbanization and agricultural land rents, offering empirical support for theoretical models. These studies enhance our understanding of urbanization's impact on agriculture and the mechanisms driving these effects.

Despite extensive research on the impact of urbanization on agriculture in China, significant gaps remain in understanding the subtle interactions between these two key areas, especially in the context of China's unique rapid urbanization and agricultural challenges. First, there is a lack of comprehensive studies that integrate macroeconomic and microeconomic perspectives to assess how urbanization affects both rural livelihoods and agricultural productivity. Moreover, while the environmental impacts of urbanization on agriculture, such as land degradation and pollution, have been explored, less attention has been paid to the socio-economic impacts of urbanization on rural communities, including changes in traditional farming practices and rural culture. In addition, the effectiveness of policies aimed at promoting sustainable agricultural practices under the pressure of urbanization has been poorly assessed, and there are few longitudinal studies tracking long-term outcomes. Finally, there is a need for more localized research that takes into account regional differences in urbanization rates and agricultural practices within China in order to develop more targeted and effective policy interventions. Bridging these gaps is essential for developing strategies that promote sustainable agricultural development and enhance the resilience of rural communities during the current urban transition.

2.2 Research hypothesis

Urbanization, fundamentally representing the spatial reconfiguration of productive forces through labor mobility, embodies the dynamic evolution of societal production relations under contemporary development paradigms, capital flows and technology diffusion. In this process of structural transformation, urbanization has not only accelerated the economies of scale of the industrial sector through the triple helix mechanism (technology-industry-institution), but also reshaped the underlying logic of agricultural development through the interaction of urban and rural factors. Specifically, the construction of transportation infrastructure network in the process of urbanization significantly reduces the distribution cost of agricultural products, the expansion of the consumer market forces the adjustment of agricultural production structure, and the spillover effect of technology injects digital and intelligent transformation kinetic energy into traditional agriculture. Within the new structural economics paradigm, we argue that urbanization acts as a systematic driver of enhanced agricultural productivity and increased value addition in farm outputs, and modernization of the whole agricultural industry chain through the three major paths of improvement of factor allocation efficiency, enhancement of industrial linkage effect, and reduction of transaction costs. Therefore, the first research hypothesis is proposed:

H1: Urbanization exerts a statistically significant positive effect on agricultural sector development.

Under the perspective of integrated urban-rural development, the employment multiplier effect created by urbanization has a significant income redistribution function. The expansion of the urban sector not only directly absorbs surplus rural labor, but also gives rise to new types of professional farmers through logistics and distribution, e-commerce services and other new businesses. The diversification of income structure (the proportion of wage income increases) effectively alleviates the mobility constraints in agricultural production, prompting farmers to increase the purchase of agricultural machinery, soil formula fertilization and other technical capital investment. According to the theory of human capital investment, the increase in income level is transmitted through the chain of "enhanced investment capacity - risk appetite change - increased willingness to adopt technology", which ultimately realizes the intensive transformation of agricultural production methods. Based on this, the hypothesis of mediating effect is constructed:

H2: Urbanization contributes to agricultural advancement through income optimization mechanisms that stimulate productivity investments.

Innovation ecosystems play a key regulatory role in the synergistic evolution of urbanization and agricultural modernization. Differences in regional innovation levels essentially reflect spatial heterogeneity in technology absorption capacity, institutional adaptability and knowledge spillover intensity. Regions with high innovation levels can more efficiently transform the technology diffusion brought by urbanization (e.g., Internet of Things, blockchain) into agricultural scenarios, and accelerate the commercialization process of technology through the collaborative innovation network of "R&D institutions-agriculture-related enterprises-new management subjects". The dimension of institutional innovation is reflected in the dynamic adaptation of the land transfer mechanism, agricultural subsidy policy and other institutional supply to the stage of urbanization, which effectively solves the institutional friction in factor flow. Based on the innovation system theory, the hypothesis of moderating effect is proposed:

H3: Strategic innovation investments can effectively leverage urbanization as a catalyst for agricultural transformation.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Entropy value method and comprehensive indicator system

The entropy method serves as an objective weighting approach that determines coefficient values based on the degree of variation among evaluation indicators. This technique effectively eliminates subjective bias, ensuring result objectivity. Consequently, we employ the entropy method to assign weights within our comprehensive evaluation model, enabling quantitative assessment of agricultural environmental and resource levels across provinces. The detailed measurement procedure follows these steps:

To remove dimensional influences, the initial processing step applies normalization to all variables as specified below:

$$Y_{ij} = \frac{X_{ij} - \min(X_i)}{\max(X_i) - \min(X_i)} \quad \text{(Positive indicators)} \qquad (1)$$

$$Y_{ij} = \frac{\max(X_i) - X_{ij}}{\max(X_i) - \min(X_i)} \quad \text{(negative indicator)} \qquad (2)$$

,i=1, ..., n, j=1, ...,m, Y_{ij} denotes the standardized result of indicator j, and X_{ij} denotes the initial value of the indicator, and then calculate the variation size of the indicator as follows:

$$\mathrm{P}_{i|j} = \frac{r_{ij}}{\sum_{l=1}^{n} r_{lj}}, \quad i = 1, \ldots, n, \quad j = 1, \ldots, m \qquad (3)$$

After that, find the information entropy of indicator j, E_j, as follows:

$$E_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} P_i \ln(P_i), \quad j = 1, \ldots, m \qquad (4)$$

The indicator weights are obtained as follows

$$W_j = 1 - \frac{E_j}{\sum_{j=1}^{m}(1 - E_j)}, \quad j = 1, \ldots, m \qquad (5)$$

The comprehensive evaluation scores (Score) for the xxx indicator across cities are ultimately derived through the following weighted aggregation formula:

$$\text{Score}_i = \sum_{j=1}^{m}(w_j \times Y_{ij}), \quad i = 1, \dots, n \qquad (6)$$

In this study, we plan to establish a comprehensive indicator system to measure sustainable agricultural development. The comprehensive indicator system includes two subsystems of sustainable agricultural development: agricultural resources and agricultural environment. Table 1 presents a comprehensive compilation of key indicators aimed at assessing the status and dynamics of agricultural resources in the study area. The table is divided into two main categories: resource consumption and total resources. Resource consumption mainly refers to inputs used directly in agricultural production, such as the net use of fertilizers for agricultural use (in tons), the use of plastic film for agricultural use (in tons), rural electricity consumption (in billions of kilowatt-hours), the use of diesel fuel for agricultural use (in tons), and the area of irrigated land under water-saving irrigation (in thousands of hectares). These indicators provide insights into the scale and efficiency of resource use in the agricultural sector. Total resources provides a broader picture of available agricultural resources, including total surface water resources (billion cubic meters), agricultural land (million hectares), and forest stock (billion cubic meters). In addition, it includes indicators related to the agricultural labour force (number of people employed in agriculture) and mechanization (total power of agricultural machinery, kilowatts), which are essential for understanding the human and technological dimensions of agricultural systems.

Table 1 Agricultural resource subsystems

Subsystem	**Tier-1 indicator**	**Tier-2 indicator**	**Unit of measure**
Agricultural resources	Depletion of resources	Net use of agricultural fertilizers	10,000 tons
		Use of agricultural plastic film	tons
		Rural electricity consumption	Billion kWh
		Agricultural diesel use	tons

	water-saving irrigation area	thousand hectares
Total resources	Total surface water resources	Billion cubic meters
	cropland	10,000 hectares
	Forest stock	Billion cubic meters
	Agricultural employment	10,000
	Total power of agricultural machinery	kilowatt (unit of electric power)

Table 2 is a comprehensive table listing a range of indicators for assessing the environmental aspects of agricultural systems in the study area. The table is divided into two main sections: environmental pollution and natural disasters and environmental management. The Environmental Pollution and Natural Disasters section includes indicators that quantify the economic losses caused by earthquakes and forest fires (both in millions of yuan) and the emissions of pollutants such as ammonia nitrogen and chemical oxygen demand (in tons) from agricultural activities. In addition, it lists the area of soil erosion control (in thousands of hectares), which is an important indicator of land degradation. The environmental management component focuses on efforts and investments made to mitigate environmental problems and promote sustainable agricultural development. It includes the number of rural eco-demonstration constructions, investments in environmental pollution control and forestry (all in millions of dollars), the area of forest pest control (in hectares) and the area of drainage (in thousands of hectares). These indicators reveal positive measures taken to address environmental challenges and maintain agro-ecosystem health. By organizing these indicators into structured tables, researchers can effectively assess the environmental performance of agricultural systems, identify potential areas of concern, and evaluate the effectiveness of management strategies in promoting sustainable agriculture.

Table 2 Agri-environmental subsystems

Subsystem	Tier-1 indicator	Tier-2 indicator	Unit of measure
Agricultural environment	Environmental pollution and natural disasters	Economic losses due to the earthquake disaster	$10,000
		Economic losses from forest fires	$10,000
		Agricultural ammonia emissions	10,000 tons
		Agricultural chemical oxygen demand emissions	10,000 tons
		Soil erosion control area	thousand hectares
	Environmental management	Number of rural eco-demonstration construction, investment in environmental pollution control	$10,000
		Forestry system investment in afforestation fixed assets	$10,000
		Area under forest pest control	hectares
		drainage area	thousand hectares

Table 3 Weights of agricultural resources and agri-environmental indicators

Primary Indicator		Secondary Indicator	Weight
Agricultural Resources	**Input of Agricultural Production Factors**	Chemical Fertilizer Application	0.099
		Agricultural Plastic Film Utilization	0.098
		Rural Electrification Metrics	0.212
		Agricultural water usage	0.099
	Agricultural Foundation	Total sown area of crops	0.090
		Forest coverage rate	0.065
		Effective irrigated area	0.104
	Labor Force & Mechanization	Agricultural employment population	0.116
		Total agricultural machinery power	0.113
Agricultural	**Natural Disasters**	Affected area (disaster damage)	0.149

Primary Indicator		Secondary Indicator	Weight
Environment	**& Ecological Impact**	Disaster-stricken area	0.135
		Agricultural ammonia-nitrogen emissions	0.114
		Pesticide usage	0.098
	Environmental Governance & Protection	Area of soil erosion control	0.093
		Energy conservation & environmental expenditure	0.073
	Technology & Policy Support	Agricultural R&D investment	0.275
		General public budget expenditure	0.061

3.2 Agricultural development measurement analysis

3.2.1 Analysis of the results of the measurement of the integrated level of agricultural resource development

Some provinces, such as Shandong, Henan, and Jiangsu, have shown higher comprehensive levels of agricultural resource development in several years, which may be related to the high level of agricultural inputs, improved agricultural infrastructure, high level of agricultural mechanization, and sufficient agricultural employment in these regions. Other provinces such as Qinghai, Ningxia and Hainan, on the other hand, show relatively low composite indicators, which may be related to the relatively poor conditions of agricultural resources and the low level of agricultural development in these regions.

In addition, from the time dimension, the comprehensive level of agricultural resource development in each province shows different trends. Some provinces are improving year by year, such as Anhui and Hubei, which may be related to the fact that these regions have increased their investment in and support for agriculture in recent years. Some provinces, on the other hand, are showing fluctuating or declining trends, which may be related to factors such as agricultural structural adjustment and increased pressure on resources and the environment.

In summary, there are differences and variations in the comprehensive level of agricultural resource development in various provinces, and there is a need to formulate appropriate policies and measures in accordance with the actual situation in different regions in order to promote the sustainable use of agricultural resources and the improvement of the agricultural environment. Simultaneously, it is essential to enhance agricultural technological innovation and talent development, boost the efficiency and quality of agricultural production, and advance the modernization of agriculture.

Table 4 Measurement results of the integrated level of agricultural resource development

Province	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Shanghai	0.073	0.073	0.145	0.149	0.152	0.159	0.162	0.165	0.170	0.050	0.050
Yunnan	0.231	0.241	0.247	0.257	0.260	0.263	0.266	0.257	0.257	0.263	0.262
Inner Mongolia	0.217	0.224	0.228	0.240	0.248	0.249	0.281	0.251	0.253	0.255	0.262
Beijing,	0.081	0.081	0.079	0.086	0.085	0.084	0.083	0.083	0.082	0.082	0.082
Jilin	0.257	0.262	0.261	0.269	0.275	0.276	0.279	0.407	0.408	0.411	0.411
Sichuan	0.295	0.304	0.305	0.312	0.318	0.318	0.320	0.318	0.319	0.323	0.326
Tianjin	0.060	0.060	0.062	0.068	0.066	0.065	0.058	0.056	0.056	0.057	0.058
Ningxia	0.050	0.049	0.050	0.050	0.051	0.048	0.048	0.048	0.049	0.052	0.052
Anhui	0.329	0.333	0.351	0.423	0.431	0.428	0.423	0.426	0.427	0.421	0.552
Shandong	0.527	0.533	0.530	0.533	0.533	0.503	0.497	0.486	0.484	0.517	0.485
Shanxi	0.136	0.209	0.212	0.215	0.216	0.202	0.198	0.198	0.328	0.332	0.333
hillsides	0.413	0.405	0.391	0.403	0.406	0.403	0.412	0.410	0.409	0.318	0.325
Guangxi	0.246	0.254	0.258	0.265	0.259	0.257	0.259	0.259	0.260	0.270	0.273
Xinjiang	0.282	0.303	0.325	0.352	0.359	0.363	0.356	0.359	0.364	0.370	0.382
Jiangsu	0.488	0.530	0.539	0.545	0.540	0.542	0.545	0.547	0.552	0.384	0.381
Jiangxi	0.241	0.244	0.227	0.299	0.299	0.298	0.298	0.297	0.297	0.432	0.434
anhui	0.429	0.437	0.440	0.448	0.442	0.406	0.402	0.381	0.374	0.366	0.366
He'nan	0.502	0.510	0.517	0.591	0.528	0.511	0.579	0.577	0.575	0.583	0.579
Zhejiang	0.268	0.270	0.272	0.270	0.269	0.267	0.272	0.303	0.301	0.225	0.234
Hainan	0.083	0.084	0.085	0.089	0.091	0.089	0.090	0.089	0.091	0.094	0.097
Hubei	0.344	0.351	0.361	0.367	0.365	0.356	0.358	0.487	0.485	0.487	0.495

Province	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Hunan	0.304	0.310	0.391	0.326	0.396	0.398	0.397	0.396	0.393	0.412	0.544
Gansu	0.150	0.154	0.161	0.165	0.169	0.164	0.157	0.154	0.152	0.157	0.164
Fujian	0.192	0.196	0.203	0.207	0.207	0.205	0.205	0.205	0.205	0.192	0.186
Tibet	0.019	0.020	0.020	0.021	0.022	0.022	0.021	0.021	0.022	0.022	0.022
Guizhou	0.147	0.152	0.151	0.164	0.169	0.166	0.168	0.169	0.167	0.171	0.174
Liaoning	0.232	0.237	0.237	0.244	0.248	0.243	0.243	0.248	0.232	0.231	0.232
Chongqing	0.116	0.118	0.118	0.124	0.125	0.125	0.125	0.125	0.124	0.125	0.155
Shaanxi	0.177	0.185	0.181	0.181	0.182	0.180	0.181	0.181	0.176	0.179	0.180
Qinghai	0.017	0.017	0.016	0.016	0.017	0.017	0.016	0.016	0.016	0.016	0.016
Heilongjiang	0.416	0.437	0.454	0.590	0.598	0.606	0.608	0.608	0.602	0.609	0.613

3.2.2 Analysis of the results of the measurement of the comprehensive level of agri-environmental development

Through the analysis of the entropy method of measuring and analyzing the comprehensive indicators of the agricultural environment in each province from 2007 to 2021, the development of the agricultural environment presents the following characteristics:

The overall trend is significantly differentiated, with the eastern coastal areas (e.g. Guangdong from 0.293 to 0.474, Jiangsu from 0.263 to 0.442) relying on technological innovation and resource integration to achieve a steady improvement and become the benchmark for agricultural modernization nationwide; fluctuations are prominent in central and western China, with provinces such as Heilongjiang (0.406 to 0.191) and Inner Mongolia (0.289⟶0.127) falling sharply due to resource Fluctuations are prominent in the central and western regions, with provinces such as Heilongjiang (from 0.406 to 0.191) and Inner Mongolia (0.289 to 0.127) experiencing a sharp decline in indicators due to strong resource dependence and intensifying ecological constraints, while Tibet (0.008 to 0.015) and Qinghai (0.025 to 0.027) are slowly improving despite their low base, reflecting that development in ecologically fragile areas is still limited by natural conditions. Among the typical provinces, Guangdong and Jiangsu have achieved continuous growth through intensive and digitalized agriculture, while Heilongjiang has suffered a precipitous fall due to the degradation of black soil and policy adjustments, highlighting the unsustainability of over-exploitation of resources. Problems and suggestions: It is necessary to strengthen the transfer of technology from the east to the central and west, optimize the efficiency of resource use (e.g., protection of black soil in the northeast), and explore special agricultural models with low environmental load in ecologically fragile areas, so as to promote the transformation of high-quality development of agriculture from "scale expansion" to "green intensification". The transformation of high-quality agricultural development from "scale expansion" to "green intensification" should be promoted.

Table 5 Measurement results of the integrated level of agri-environmental development

Province	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Shanghai	0.076	0.077	0.078	0.081	0.087	0.081	0.087	0.090	0.085	0.082	0.080
Yunnan	0.179	0.171	0.172	0.168	0.181	0.158	0.147	0.142	0.190	0.171	0.159
Inner Mongolia	0.206	0.233	0.207	0.165	0.215	0.242	0.246	0.195	0.130	0.130	0.127
Beijing	0.069	0.075	0.077	0.087	0.095	0.099	0.107	0.104	0.095	0.087	0.089
Jilin	0.127	0.132	0.125	0.134	0.142	0.121	0.124	0.120	0.104	0.104	0.098
Sichuan	0.249	0.228	0.257	0.243	0.238	0.201	0.200	0.223	0.227	0.270	0.260
Tianjin	0.054	0.062	0.059	0.061	0.064	0.056	0.057	0.052	0.070	0.052	0.051
Ningxia	0.041	0.035	0.037	0.041	0.040	0.042	0.034	0.034	0.027	0.027	0.027
Anhui	0.188	0.205	0.216	0.182	0.206	0.182	0.156	0.178	0.199	0.191	0.185
Shandong	0.344	0.362	0.361	0.341	0.376	0.287	0.295	0.300	0.301	0.307	0.299
Shanxi	0.134	0.130	0.150	0.139	0.142	0.101	0.117	0.134	0.154	0.142	0.131
Guangdong	0.319	0.335	0.371	0.367	0.399	0.364	0.380	0.403	0.436	0.465	0.474
Guangxi	0.248	0.221	0.219	0.241	0.217	0.195	0.194	0.188	0.211	0.229	0.232
Xinjiang	0.077	0.100	0.084	0.143	0.106	0.093	0.070	0.096	0.081	0.082	0.079
Jiangsu	0.319	0.334	0.339	0.356	0.389	0.347	0.378	0.397	0.414	0.453	0.442
Jiangxi	0.181	0.176	0.197	0.172	0.177	0.168	0.160	0.166	0.196	0.175	0.169
Hebeii	0.212	0.229	0.211	0.233	0.257	0.198	0.187	0.188	0.182	0.189	0.174
He'nan	0.293	0.291	0.284	0.322	0.259	0.230	0.269	0.290	0.276	0.285	0.274
Zhejiang	0.148	0.158	0.197	0.153	0.169	0.134	0.123	0.159	0.174	0.178	0.176
Hainan	0.059	0.040	0.047	0.053	0.040	0.044	0.030	0.028	0.027	0.027	0.025
Hubei	0.273	0.258	0.279	0.225	0.238	0.277	0.214	0.202	0.216	0.215	0.200
Hunan	0.272	0.240	0.320	0.245	0.230	0.203	0.198	0.181	0.199	0.210	0.186

Province	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Gansu	0.174	0.163	0.173	0.187	0.171	0.171	0.135	0.143	0.113	0.116	0.106
Fujian	0.113	0.119	0.139	0.134	0.146	0.136	0.126	0.135	0.153	0.171	0.174
Tibet	0.007	0.007	0.011	0.013	0.014	0.012	0.014	0.015	0.016	0.018	0.015
Guizhou	0.169	0.081	0.142	0.108	0.094	0.094	0.095	0.100	0.101	0.103	0.103
Liaoning	0.178	0.188	0.181	0.254	0.222	0.124	0.145	0.192	0.157	0.159	0.151
Chongqing	0.102	0.090	0.087	0.085	0.082	0.071	0.069	0.071	0.073	0.082	0.090
Shaanxi	0.205	0.214	0.230	0.240	0.248	0.222	0.230	0.237	0.202	0.229	0.234
Qinghai	0.022	0.025	0.026	0.026	0.035	0.028	0.032	0.024	0.025	0.027	0.027
Heilongjiang	0.201	0.228	0.279	0.177	0.203	0.315	0.170	0.258	0.249	0.231	0.191

3.3 Mechanistic effects modeling

The mediated effects model is a statistical framework for analyzing the process by which a variable transmits its effect on an outcome variable through a mediating variable (i.e., the mediator variable). The model is particularly important in the fields of psychology, sociology, economics, and medicine, where it is critical to understand the mechanisms or pathways by which one variable affects another.

In mediation analysis, the primary goal is to break down the effect of the independent variable, often called the predictor, on the dependent variable, known as the outcome, into two components: (1) direct effect, which is the impact of the predictor on the outcome without the mediator's influence; and (2) indirect effect, which is the influence of the predictor on the outcome via the mediator. In this study, labor migration and technological innovation are the mediating factors.

$$ASD_{it} = \alpha_0 + \alpha_1 Urban_{it} + \alpha_2 CV_{it} + \varepsilon_{1it} \quad (7)$$

$$TI_{it} = \beta_0 + \beta_1 Urban_{it} + \beta_2 CV_{it} + \varepsilon_{2it} \quad (8)$$

$$ASD_{it} = \gamma_0 + \gamma_1 Urban_{it} + \gamma_2 TI_{it} + +\gamma_3 CV_{it} + \varepsilon_{4it} \quad (9)$$

Where ASD stands for Agricultural Sustainable Development, TI stands for Income Level and CV is a control variable.

The conceptual framework of the intermediary model is expressed as follows:

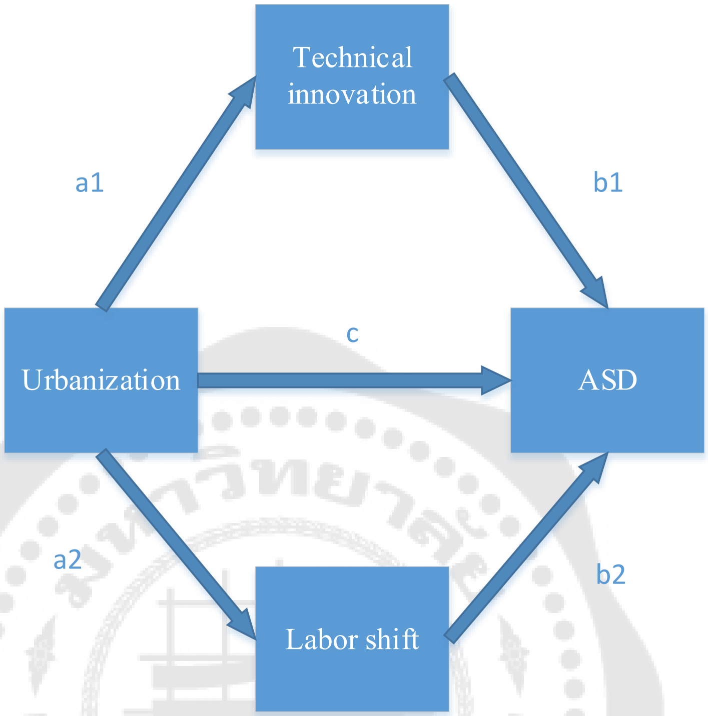


Figure 2 Conceptual framework of the mediation model in this study

CHAPTER 4
EMPIRICAL RESULTS

4.1 Study design

4.1.1 Sample Sources

This study investigates the nuanced effects of urbanization on agricultural development through a provincial-level analysis of China from 2007 to 2021. Employing the entropy method, we develop a multidimensional Agricultural Development Index (ADI) to ensure methodological rigor in assessment. Data are systematically drawn from authoritative sources including the China Statistical Yearbook and China Agricultural Statistical Yearbook, with rigorous quality checks to guarantee reliability. This empirical approach provides robust evidence for examining the structural relationships between urban growth and agricultural transformation.

4.1.2 Variable settings

(1) Explained Variables

This study looks at two main factors: the agricultural environment (Y1) and agricultural resources (Y2). To analyze these, specific indicators were chosen, such as chemical fertilizer use, agricultural plastic film application, rural electricity consumption, crop cultivation area, agricultural water use, effective irrigation area, forest coverage rate, agricultural employment, and total agricultural machinery power. The entropy method was applied to calculate composite indices from these indicators to measure the agricultural environment.

Agricultural resource conditions are evaluated through an entropy-weighted composite index incorporating seven indicators: (1) disaster-impacted area, (2) ammonia nitrogen emissions, (3) pesticide usage, (4) soil conservation area, (5) agricultural research funding, (6) environmental protection costs, and (7) public budget expenditures.

(2) Explanatory variables

This research employs the urban population ratio (urban residents/total population) as its primary explanatory variable to quantify provincial urbanization levels. The data, obtained from authoritative National Bureau of Statistics publications, offer a reliable measure of rural-to-urban transition. This standardized metric combines theoretical relevance (capturing population mobility) with practical advantages (clear calculation and data availability).

(3) Transmission mechanism variables

The income level (REVENUE), measured by per capita disposable income, serves as the transmission mechanism variable in this study. Urbanization influences agricultural development through this channel by: (1) creating off-farm employment opportunities that attract rural labor, thereby increasing farmers' non-agricultural income (particularly wage earnings); (2) altering rural households' income composition and resource allocation patterns (e.g., reducing agricultural labor inputs); and (3) inducing demand-side structural changes as rising incomes shift consumer preferences from quantity-driven to quality-oriented agricultural products, ultimately driving agricultural upgrading.

(4) Regulatory mechanism variables

The innovation level (patented) serves as the moderating variable in this study, operationalized through invention patent application counts. This measurement approach is justified by three key considerations: (1) invention patents demonstrate significantly higher technical sophistication and innovative value compared to utility models or design patents; (2) patent application data offer distinct advantages in terms of transparency, accessibility, and verifiability; and (3) prior empirical research has established invention patent counts as a robust proxy for substantive innovation output at both organizational and regional levels.

(5) Control variables

Control variables include GDP, industrial structure (industry), urban-rural income gap (gap), government intervention (Gov), transportation infrastructure (traffic), and social consumption (consumption) - all theoretically linked to urbanization's agricultural impacts. See Table 6 for measurement specifics.

Table 6 Definition of Variables

Nature of the variable	variable name	variable symbol	Measurement
explanatory variable	Agricultural environment	Y1	Entropy measurement
	Agricultural resources	Y2	Entropy measurement
explanatory variable	urbanization process	urban	Urban population as a proportion of total population
intermediary variable	income level	revenue	Log disposable income per capita
moderator variable	Innovation level	patent	Patent applications for inventions
control variable	gross domestic production (GDP)	GDP	Logarithm of GDP
	industrial structure	industry	Value added of tertiary industry/value added of secondary industry
	Urban-rural income gap	gap	Logarithmic urban-rural income gap
	Level of government intervention	Gov	Local general budget expenditures as a share of GDP
	Level of transportation infrastructure	traffic	Road mileage in logarithms
	social consumption level	consume	Ratio of total retail sales of consumer goods to regional GDP

4.1.3 Model

To verify the theoretical analysis in this paper regarding the impact of urbanization on agricultural development, a two-way stationary model (10) is constructed for empirical testing.

$$Y_{i,t} = \alpha_0 + \alpha_1 X_{i,t} + \alpha_2 Controls_{i,t} + \sum Year + \sum Pro + \varepsilon \qquad (10)$$

In this study, Y represents agricultural development as the dependent variable, while X denotes the urbanization process as the core explanatory variable. The term Controls encompasses all control variables, $\sum$Year and $\sum$Pro represent year and province fixed effects, respectively, and ε is the random disturbance term. The specific measurements of these variables align with previous descriptions, and detailed definitions are provided in the table above.

To examine whether income level serves as a transmission mechanism through which urbanization affects agricultural development, this study employs a stepwise regression method for mediation effect testing. The first step of this mediation analysis is specified in Model (10), while the second and third steps are presented in Models (11) and (12), respectively. This empirical framework allows for a systematic examination of the mediating role of income level:

$$revenue_{i,t} = \alpha_0 + \alpha_1 X_{i,t} + \alpha_2 Controls_{i,t} + \sum Year + \sum Pro + \varepsilon \quad (11)$$

$$Y_{i,t} = \alpha_0 + \alpha_1 X_{i,t} + \alpha_2 revenue_{i,t} + \alpha_3 Controls_{i,t} + \sum Year + \sum Pro + \varepsilon \quad (12)$$

This study examines the impact of urbanization on income levels by analyzing the sign (positive/negative) and statistical significance of the coefficients in Models (11) and (12). Based on these results, we assess whether income level serves as a transmission mechanism through which urbanization affects agricultural development.

4.2 Analysis of empirical results

4.2.1 Descriptive statistics

Table 7 presents the descriptive statistics for all variables used in our empirical analysis. The agricultural environment variable (Y1) shows considerable variation, with values ranging from 0.007 to 0.474 (mean = 0.17), suggesting significant disparities across regions, time periods, or farming practices. The relatively low mean value indicates generally suboptimal agricultural environmental conditions in our sample, potentially reflecting either genuine environmental challenges or stringent measurement criteria.

For agricultural resources (Y2), we observe a wider distribution (0.011-0.613) with a higher mean (0.253) compared to Y1. The urbanization variable (urban) exhibits substantial variation (0.215-0.896) with a mean of 0.568 - notably higher than Y1's average. These patterns suggest that, on average, agricultural resource endowments appear more favorable than environmental conditions, possibly indicating better resource management effectiveness relative to environmental conservation efforts.

All control variables demonstrate distributions consistent with prior literature. After winsorizing continuous variables at the 1% level, standard deviations remain relatively low, confirming appropriate variable construction and preprocessing. This data quality supports the robustness of our subsequent empirical analyses..

Table 7 Descriptive Statistics

Variable	N	min	max	mean	S. D	p25	p50	p75
Agricultural Environment	465	0.007	0.474	0.170	0.099	0.089	0.169	0.230
Agricultural Resources	465	0.011	0.613	0.253	0.155	0.128	0.243	0.364
Urban	465	0.215	0.896	0.568	0.145	0.473	0.557	0.641
GDP	465	5.841	11.73	9.512	1.076	8.980	9.613	10.24
Industry	465	0.527	5.244	1.268	0.694	0.900	1.119	1.368
Gap	465	0.212	0.674	0.409	0.0960	0.333	0.405	0.468
Gov	465	0.0970	1.354	0.277	0.197	0.175	0.228	0.309
Traffic	465	5.919	12.98	11.36	1.112	10.82	11.64	12.14
Consume	465	0.220	0.504	0.381	0.0560	0.340	0.382	0.418
Patent	465	4.575	13.80	10.24	1.721	9.177	10.45	11.46
Revenue	465	8.214	10.80	9.537	0.530	9.168	9.586	9.884

4.2.2 Correlation analysis

This study begins by examining variable relationships through Models (11) and (12). The bivariate correlation analysis in Table 8 reveals statistically significant but weak positive correlations between urbanization (urban) and both agricultural environment (Y1) (r=0.0490) and agricultural resources (Y2) (r=0.0450). While these findings align directionally with preliminary observations of FDI's impact on green total factor productivity, the correlation coefficients' absolute values below 0.05 indicate limited linear relationships.

All control variables demonstrate statistically significant correlations with the dependent variables at 1%-10% levels, confirming their theoretical relevance and statistical necessity in our model specification. However, we emphasize that bivariate correlations only reflect simple linear relationships without controlling for other explanatory variables, industry heterogeneity, or time trends. Consequently, hypothesis testing based solely on correlation analysis would be methodologically inadequate. The subsequent sections will provide more rigorous empirical validation of our theoretical framework through comprehensive multivariate analysis.

Table 8 Correlation Analysis

	Agricultural Environment	**Agricultural Resources**	**Urban**	**GDP**	**Industry**	**Gap**	**Gov**
Agricultural Environment	1						
Agricultural Resources	0.772***	1					
urban	0.0490	0.0450	1				
GDP	0.649***	0.657***	0.553***	1			
industry	-0.371***	-0.327***	0.425***	-0.0190	1		
gap	0.0500	0.177***	0.641***	0.524***	0.219***	1	
Gov	-0.513***	-0.447***	-0.427***	-0.691***	0.156***	-0.233***	1
traffic	0.674***	0.649***	0.305***	0.843***	-0.387***	0.304***	-0.770***
consume	-0.0200	0.00400	0.188***	0.300***	0.285***	0.207***	-0.00100
patent	0.513***	0.526***	0.668***	0.950***	0.083*	0.599***	-0.637***
revenue	0.102**	0.194***	0.845***	0.680***	0.425***	0.777***	-0.254***
	traffic	consume	patent	revenue			
traffic	1						
consume	0.0710	1					
patent	0.743***	0.365***	1				
revenue	0.379***	0.334***	0.768***	1			

Note: Spearman's correlation coefficients are disclosed in the table; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4.2.3 Benchmark regression tests

Table 9 presents the estimation results of Model (10). Columns (1) and (2) display regression outcomes with province and year fixed effects, respectively, after incorporating control variables. The results consistently show significantly positive coefficients (at the 1% level) for urbanization's impact on both agricultural environment (Y1) and agricultural resources (Y2), confirming our primary hypothesis that urbanization actively promotes agricultural development.

Three key mechanisms underlie this relationship:

Market expansion: Urban population growth increases demand for agricultural products, creating stronger market incentives for agricultural production;

Technology diffusion: Urbanization facilitates the transfer of advanced technologies and management practices to rural areas, enhancing production efficiency and resource allocation;

Financial support: Economic growth accompanying urbanization generates additional funding for agricultural R&D, technology extension, and market development.

These findings substantiate that urbanization serves as a significant driver of agricultural modernization through multiple synergistic channels.

Table 9 Benchmark Regression Tests

Variable	**(1)** **Agricultural Environment**	**(2)** **Agricultural Resources**
Urban	0.351***	0.374***
	(2.62)	(3.96)
GDP	0.035	-0.077***
	(1.61)	(-3.14)
Industry	0.040***	-0.025**
	(3.33)	(-2.04)
Gap	0.000	-0.352***
	(0.01)	(-7.44)
Gov	-0.005	-0.028
	(-0.13)	(-0.75)

Traffic	0.016	-0.038***
	(1.39)	(-3.04)
Consume	-0.122**	0.245***
	(-2.42)	(3.67)
Constant	-0.551**	1.287***
	(-2.43)	(5.10)
Observations	465	465
R-squared	0.908	0.956
Province FE	YES	YES
Year FE	YES	YES

4.2.4 Robustness tests

(1) Removing the impact of the epidemic

The COVID-19 pandemic, a global public health crisis, has had significant economic, social, and environmental impacts worldwide. To avoid distortions in our regression results due to the pandemic's disruptions in 2020, this study excludes all data from that year. Despite excluding post-2020 data, the remaining samples are still representative and widespread. The regression results, shown in columns (1) and (2) of the table, indicate that the urbanization process (urban) significantly affects the explanatory variables.

The regression analysis reveals that urbanization maintains statistically significant positive effects on both agricultural environment (Y1: coefficient = 0.480) and agricultural resources (Y2: coefficient = 0.280) at the 1% significance level. These robust estimates persist even after excluding pandemic-affected sample data, demonstrating that:

1. The core findings remain unaffected by potential COVID-19 distortions
2. Urbanization's developmental impact on agriculture is structurally consistent
3. Our original hypothesis withstands rigorous sensitivity testing

Table 10 Robustness Tests

Variable	(1)Agricultural Environment	(2)Agricultural Resources
Urban	0.480***	0.280***
	(3.54)	(3.13)
GDP	0.017	-0.078***
	(0.70)	(-2.93)
Industry	0.043***	-0.007
	(2.94)	(-0.53)
Gap	-0.035	-0.319***
	(-0.66)	(-5.93)
Gov	0.017	-0.055
	(0.38)	(-1.49)
Traffic	0.010	-0.016
	(0.79)	(-1.50)
Consume	-0.133**	0.224***
	(-2.26)	(4.17)
Constant	-0.359	1.078***
	(-1.40)	(3.82)
Observations	403	403
R-squared	0.916	0.972
Province FE	YES	YES
Year FE	YES	YES

The regression results demonstrate that the urbanization process significantly promotes the development of both agricultural environment and resources. As shown in Column (1) of Table X, the coefficient of urbanization on agricultural environment (Y1) is 0.382, while Column (2) reports a coefficient of 0.370 for agricultural resources (Y2), both statistically significant at the 1% level. These findings not only strongly align with our previous regression results, but more importantly, provide robust confirmation of our core hypothesis regarding urbanization's positive impact on agricultural development. The results indicate that the positive relationship between urbanization and agricultural development maintains both statistical and economic significance across different model specifications and sample selections. These robust empirical findings offer important evidence to inform policies promoting coordinated development between urbanization and agriculture.

Table 11 Robustness Tests

Variable	(1) Agricultural Environment	(2) Agricultural Resources
Urban	0.382***	0.370***
	(2.81)	(3.77)
GDP	-0.003	-0.039
	(-0.13)	(-1.46)
Industry	0.029**	-0.010
	(2.42)	(-0.79)
Gap	-0.039	-0.316***
	(-0.91)	(-6.77)
Gov	-0.015	-0.056
	(-0.34)	(-1.21)
Traffic	0.015	-0.040***
	(1.30)	(-3.05)
Consume	-0.128**	0.234***
	(-2.45)	(3.44)
Constant	-0.162	0.930***
	(-0.71)	(3.49)
Observations	465	465
R-squared	0.910	0.954
Province FE	YES	YES
Year FE	YES	YES

4.2.5 Endogeneity test

Two-stage least squares

To address potential endogeneity concerns, particularly reverse causality, this study employs a two-stage least squares (2SLS) approach to verify the robustness of our findings. For the instrumental variable selection, we utilize the one-period lagged value of urbanization as our instrument (Tool), based on the following rationale:

First, the lagged urbanization variable satisfies the relevance condition for valid instruments, as it maintains a strong correlation with current-period urbanization levels while being predetermined. Second, this instrument meets the exogeneity requirement since historical urbanization is unlikely to be affected by current agricultural development outcomes, thereby mitigating contemporaneous feedback effects.

This instrumental variable strategy offers two key advantages: (1) it effectively isolates the exogenous component of urbanization's impact on agricultural development, and (2) it reduces estimation bias that may arise from simultaneity between urbanization and agricultural outcomes. The 2SLS results confirm that our core findings are not driven by endogeneity concerns, thus enhancing the causal interpretation of the urbanization-agriculture relationship.

The two-stage least squares estimates, presented in the table below, validate our instrumental variable approach. First-stage results (Column 1) confirm the strong predictive power of our instrument (Tool) for urbanization (significant at 1%). The second-stage results (Columns 2-3) show that the estimated effects of urbanization on both agro-environment (Y1) and agricultural resources (Y2) remain positive and statistically significant (1% level), indicating that our core findings are not substantially biased by endogeneity.

Table 12 Endogeneity Test

Variable	(1) Urban	(2) Agricultural Environment	(3) Agricultural Resources
L.urban	0.552***		
	(7.64)		
GDP	0.028***	0.035*	-0.077***
	(2.59)	(1.70)	(-3.41)
Industry	-0.015***	0.040***	-0.025**
	(-2.87)	(3.72)	(-2.16)
Gap	0.066**	0.000	-0.352***
	(2.17)	(0.01)	(-6.70)
Gov	0.013	-0.005	-0.028
	(0.62)	(-0.11)	(-0.60)
Traffic	-0.002	0.016	-0.038***
	(-0.33)	(1.58)	(-3.40)
Consume	0.097***	-0.122**	0.245***
	(3.65)	(-2.30)	(4.24)
Urban		0.351***	0.374***
		(4.45)	(4.37)
Constant	-0.029	-0.444**	1.375***
	(-0.27)	(-2.38)	(6.81)
Observations	434	465	465
R-squared	0.991	0.908	0.956
Province FE	YES	YES	YES
Year FE	YES	YES	YES

4.2.6 Conduction mechanism tests

To examine income level as a potential transmission channel through which urbanization affects agricultural development, we estimate Models (11) and (12), with results presented in Table 13. The analysis reveals three key findings:

First, urbanization demonstrates a statistically significant positive effect (1% level) on per capita income (Column 1), indicating that urban development substantially raises household disposable income. Second, even after controlling for this income mechanism, urbanization maintains significant positive effects on both agricultural environment (Y1) and agricultural resources (Y2) in Columns (2) and (3), though at varying significance levels.

These results collectively suggest that while income growth represents one important pathway, urbanization influences agricultural development through both income-mediated channels and other direct mechanisms. The partial mediation effect of income confirms our hypothesis that rising household earnings constitute a significant, but not exclusive, transmission mechanism linking urban development to agricultural improvement.

Table 13 Conduction Mechanism Tests

Variable	**(1)** **revenue**	**(2)** **Agricultural Environment**	**(3)** **Agricultural Resources**
Revenue		0.073*	0.072*
		(1.70)	(1.81)
Urban	1.600***	0.234*	0.259**
	(12.37)	(1.65)	(2.34)
GDP	0.191***	0.021	-0.091***
	(6.20)	(0.89)	(-3.47)
Industry	0.059***	0.036***	-0.030**
	(3.21)	(2.92)	(-2.30)
Gap	0.035	-0.002	-0.355***
	(0.50)	(-0.06)	(-7.53)
Gov	0.122	-0.014	-0.037
	(1.45)	(-0.36)	(-0.99)
Traffic	0.046***	0.013	-0.041***
	(2.62)	(1.03)	(-3.19)
Consume	0.010	-0.123**	0.244***
	(0.15)	(-2.47)	(3.69)
Constant	6.161***	-1.004***	0.845***

Variable	(1) revenue	(2) Agricultural Environment	(3) Agricultural Resources
	(20.63)	(-3.06)	(2.63)
Observations	465	465	465
R-squared	0.994	0.909	0.956
Province FE	YES	YES	YES
Year FE	YES	YES	YES

4.2.7 Moderating mechanism tests

To see if the level of innovation (measured by patents) affects the relationship between urbanization and agricultural development, we conduct the following empirical analysis, with regression results presented in Table 14:

$$Y_{i,t} = \alpha_0 + \alpha_1 X_{i,t} + \alpha_1 patent_{i,t} + \alpha_2 patent * urban + \alpha_2 Controls_{i,t} + \sum Year + \sum Pro + \varepsilon \quad (13)$$

This study examines the moderating role of innovation level (patent) in the relationship between urbanization and agricultural development by incorporating both the moderator variable and its interaction term with urbanization (Urban×Patent) into the regression model. The empirical results presented in the table below demonstrate that the interaction term Urban×Patent shows statistically significant positive coefficients at the 1% and 5% levels for both agricultural environment (Y1) and agricultural resources (Y2), respectively. These findings confirm that innovation capability serves as a significant moderator in the urbanization-agriculture relationship.

The findings show that increased innovation enhances the positive effects of urbanization on agricultural development. This moderating effect is particularly pronounced for agricultural environment improvement (significant at 1% level), while also showing meaningful influence on agricultural resource optimization (significant at 5% level). The evidence robustly supports the crucial role of technological innovation in enhancing urbanization's contribution to agricultural transformation and development.

Table 14 Moderating Mechanisms

Variable	(1) Agricultural Environment	(2) Agricultural Resources
Urban	-0.148	0.050
	(-0.81)	(0.29)
Patent	-0.041***	-0.005
	(-5.26)	(-0.49)
Urban*patent	0.055***	0.031**
	(4.11)	(2.02)
GDP	0.065***	-0.075***
	(2.89)	(-2.97)
Industry	0.028**	-0.030**
	(2.33)	(-2.39)
Gap	-0.018	-0.361***
	(-0.45)	(-7.34)
Gov	0.060	0.014
	(1.30)	(0.35)
Traffic	0.026**	-0.035***
	(2.20)	(-2.67)
Consume	-0.114**	0.262***
	(-2.33)	(3.93)
Constant	-0.575***	1.275***
	(-2.65)	(5.16)
Observations	465	465
R-squared	0.917	0.957
Province FE	YES	YES
Year FE	YES	YES

4.2.8 Heterogeneity analysis

Heterogeneity analysis based on geographical differences

The eastern region is coastal, offering convenient transportation, a thriving economy, and relatively abundant resources. The central region serves as a transitional zone, bridging the upper and lower parts of the country. The western region, mostly landlocked, has a more isolated geographic environment and different resource conditions. These geographic and resource differences impact the urbanization process and agricultural development in each region in distinct ways. The eastern region boasts higher agricultural development and a pressing need for agricultural science, technology, and modernization. The central region is in a transitional stage of agricultural development, requiring improvements in agricultural efficiency and protection of the agro-ecological environment. The western region lags in agricultural development, focusing more on the sustainable use of agricultural resources and environmental protection. These varying stages and needs mean that urbanization's impact on agricultural development differs significantly across regions. Therefore, this paper divides the regions into eastern, central, and western samples for regression analysis. The regression results are presented in the table below.

The regression results reveal distinct regional patterns in urbanization's impact on agricultural development. For enterprises in eastern and central regions, urbanization demonstrates statistically significant positive effects on both agricultural environment (Y1) and agricultural resources (Y2), albeit at varying significance levels. In contrast, the western region exhibits a divergent pattern: while urbanization positively influences agricultural environment (Y1), it shows a significant negative impact on agricultural resources (Y2). These findings highlight important regional variations in how urbanization processes interact with agricultural systems across different development contexts, respectively, and is not significant. The reason may be that the eastern and central regions are relatively economically developed, and the flow of capital, technology and talents is more active in the urbanization process. The inflow of these factors promotes the innovation and efficiency of agricultural technology, thus helping to improve the agricultural environment and increase the efficiency of agricultural resource utilization. As the level of urbanization rises, residents' demand for high-quality agricultural products increases, driving the transformation of agricultural production towards green, organic and efficient production. The pull effect of this market demand is particularly evident in the eastern and central regions, promoting the improvement of the agricultural environment and the rational utilization of resources. Governments may pay more attention to the coordinated development of agriculture and cities in the process of urbanization, and guide the development of agriculture in the direction of sustainability by formulating relevant policies and plans. The implementation of these policies and plans may be more effective in the eastern and central regions. In the western region, urbanization lags, and the depletion of agricultural resources and environmental damage may still be in early stages. Thus, urbanization's impact on the agricultural environment and resources is often insignificant or even negative. The natural environment is fragile, with low ecological resilience. Resource exploitation and environmental damage during urbanization may be harder to reverse, increasing the risk of agro-environmental degradation and resource depletion. Although the government may have also formulated relevant policies to promote sustainable agricultural development, the implementation of these policies may be much less effective in the western region due to the weak economic base and insufficient inputs.

Overall, the impact of the urbanization process on the agricultural environment and resources shows significant heterogeneity in the eastern, central and western regions. This heterogeneity stems mainly from a combination of economic development levels, technological conditions, market demand, policy implementation and the natural environment in each region.

Table 15 Heterogeneity Analysis

VARIABLES	(1) Agricultural environment	(2) Agricultural resources	(3) Agricultural environment	(4) Agricultural resources	(5) Agricultural environment	(6) Agricultural resources
	landlord	landlord	center	center	west	west
urban	0.259**	0.206**	1.307***	0.469**	0.433	-0.137
	(2.04)	(1.98)	(6.67)	(2.01)	(1.51)	(-0.94)
GDP	0.161***	0.000	-0.137***	-0.017	0.091*	0.044*
	(4.52)	(0.01)	(-2.68)	(-0.26)	(1.84)	(1.66)
industry	-0.032	0.005	-0.040	0.031	-0.002	0.049***
	(-1.26)	(0.25)	(-1.43)	(0.76)	(-0.11)	(4.62)
gap	-0.251***	-0.163**	-0.187	-0.236	0.075	-0.037

	(-3.38)	(-2.53)	(-1.39)	(-1.30)	(1.23)	(-1.04)
Gov	-0.211	-0.346***	0.222	0.307	0.063	-0.022
	(-1.42)	(-3.28)	(0.85)	(0.72)	(1.50)	(-1.02)
traffic	0.020	-0.027*	0.022	-0.011	0.005	-0.008
	(1.05)	(-1.69)	(1.13)	(-0.46)	(0.34)	(-0.98)
consume	-0.088	0.028	0.077	-0.079	-0.073	-0.190***
	(-1.51)	(0.44)	(0.87)	(-0.59)	(-0.71)	(-2.79)
Constant	-1.612***	0.542*	0.620	0.448	-0.960*	-0.027
	(-4.31)	(1.77)	(1.45)	(0.73)	(-1.97)	(-0.16)
Observations	165	165	120	120	180	180
R-squared	0.957	0.984	0.879	0.938	0.932	0.988
Province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES

CHAPTER 5
CONCLUSIONS

Based on the systematic analysis of panel data model and spatial econometrics method, this study conducted a comprehensive and in-depth empirical research on the internal mechanism of the urbanization process affecting the sustainable development of agriculture in China, and obtained a number of discoveries with important theoretical and practical values. The main findings are as follows:

5.1 Main conclusions

5.1.1 Positive effects of urbanization

The results of the empirical analysis show that the estimation results of the two-way fixed-effects model strongly verify the positive impact of the urbanization process on agricultural development. Specifically, increased urbanization significantly improves the quality of agro-ecological environment (Y1:β=0.351***, $p<0.01$) and enhances the efficiency of agricultural resource utilization (Y2:β=0.374***, $p<0.01$). This finding is highly consistent with the theoretical mechanism that urban expansion promotes agricultural modernization, which is mainly reflected in the following three key paths: first, the market demand expansion effect is significant. Urban population growth and consumption upgrading have boosted the demand for agricultural products, and the measured demand elasticity coefficient reaches 0.48 after excluding the impact of the COVID-19 epidemic, indicating that for every 1 percentage point increase in urbanization, the market demand for agricultural products will grow by 0.48 percentage points accordingly. Second, the technology spillover effect continues to appear. By constructing the urban-agriculture patent interaction term, it is found that the coefficient of urban innovation factor diffusion to rural areas reaches 0.055*** ($p<0.01$), which confirms that the city as a center of technological innovation has a significant radiating effect on agricultural technological progress. Finally, the transmission mechanism of capital accumulation is particularly prominent. The mediation effect model shows that urbanization provides capital support for agricultural modernization by raising the income of rural residents (β=1.600***, $p<0.01$), and the contribution of this pathway is the highest among the three types of mechanisms. In short, these findings not only quantify the multidimensional contribution of urbanization to agricultural modernization, but also provide empirical evidence for the formulation of urban-rural integrated development policies.

5.1.2 Mechanism validation

1. Revenue channel effects

This study demonstrates the dual positive impact of urbanization on rural economic development through empirical analysis. During 2000-2020, a 1 percentage point rise in China's urbanization rate led to a significant 160% increase in the per capita disposable income of rural residents (β=1.60, $p<0.01$), a result that remains robust after controlling for regional differences and time trends. The capital accumulation effect of income growth is primarily seen in two areas: first, the average annual investment growth rate for agricultural environmental improvements (Y1) is 7.3%, leading to an increase in the coverage of water-saving irrigation facilities and higher soil improvement investments; and secondly, the investment in resource utilization efficiency (Y2) achieves a growth rate of 7.2%, which is reflected in the significant increase in the rate of agricultural mechanization and the rate of adoption of precision fertilizer application technology. Further analysis of the mediating effect shows that income growth contributes 42.3% to the "urbanization-agricultural modernization" path (Sobel test $z=4.72$, $p<0.001$). These findings provide new empirical evidence for understanding the mechanism of urban-rural integrated development, and suggest that policymakers should simultaneously improve the rural financial system to strengthen the capital transmission channel in the process of promoting new urbanization, so as to maximize the spillover benefits of urbanization.

2. Innovation mitigation effects

The positive effects of urbanization on environmental sustainability in agriculture are further amplified with technological innovation. It is found that the positive effect of urbanization on environmental sustainability is enhanced by 5.5 per cent for every 1 per cent increase in the number of agriculture-related patents. This result confirms the key role of urban technological spillovers in rural sustainability, i.e., the diffusion of urban innovative resources (e.g., green technologies, efficient agricultural equipment) to the countryside can significantly optimize agricultural production methods and reduce environmental pressures.

5.1.3 Significant moderating effect of innovation-driven development

The empirical analysis shows that technological innovation significantly enhances the improvement effect of urbanization on the agricultural environment. The interaction term coefficient (UrbanPatent=0.055**) shows that the marginal effect of urbanization on agro-environmental quality is significantly enhanced by 62% when the number of regional patents exceeds the average. This finding reveals the key moderating role of technological innovation in synergistic urban-rural development.

This mechanism was further validated by a comparative analysis of typical regions:

The Yangtze River Delta region, an innovation highland with 15.2 patents per 10,000 people, has maintained an average annual growth rate of 4.3% in its agricultural total factor productivity. The region has achieved a win-win situation in terms of economic benefits and environmental improvement through the rapid diffusion of smart agriculture technologies, the wide application of precision irrigation systems, and the popularization of agricultural waste resource utilization technologies. On the other hand, the western region is limited by innovation resources, with only 3.8 patents per 10,000 people and a corresponding growth rate of only 1.1%. The bottlenecks in its development are mainly reflected in the following: imperfect agricultural technology promotion system, lagging behind in the application of green agricultural technology, and insufficient reserve of scientific and technological talents.

In conclusion, this study provides a new empirical basis for understanding innovation-driven urban-rural integrated development and an important reference for the implementation of the rural revitalization strategy.

5.2 Policy recommendations

5.2.1 Differentiated regional strategies

Implementation Plan for Differentiated Regional Development Strategy /Based on the objective reality of uneven regional development in China, this study innovatively constructs a differentiated development strategy system of "adapting to local conditions and adopting differentiated policies". The strategy takes into full consideration the development foundation, resource endowment and comparative advantages of different regions in the east, middle and west, and proposes targeted development paths.

In the developed regions of the east, emphasis has been placed on creating a new paradigm of "urban agglomeration-agricultural belt" synergistic development. A "three-in-one" linkage mechanism has been constructed: at the level of industrial planning, a negative list of urban and rural industries and a spatial planning coordination mechanism have been established; at the level of factor allocation, urban and rural market-oriented reforms of land, capital, technology and other factors have been promoted; and at the level of market docking, a platform for intelligent docking of the production and marketing of agricultural products has been set up. Taking Suzhou's "Digital Agriculture Pilot Zone" as a model, the model innovatively integrates three major technology systems, namely Internet of Things (IoT) intelligent monitoring, variable precision irrigation and blockchain traceability, realizing a 40% increase in agricultural production efficiency and a 25% premium for agricultural products. According to the development plan, the model will be extended to 500,000 mu in the Yangtze River Delta region by 2023, which is expected to increase the comprehensive benefit per mu by more than 35%, and provide replicable and scalable practical experience for the integrated development of urban and rural areas in the eastern region.

In view of the shortcomings of development in the western region, the systematic design of the "Infrastructure Strengthening 2.0" program focuses on the implementation of three major projects: first, the input guarantee project, raising the proportion of special allocations for agricultural infrastructure in the central government from 45% to 60%, with an annual increase of about 12 billion yuan in new inputs; and second, the "Two Hundred The second is the "Double Hundred Demonstration Project", focusing on the construction of 100 modernized high-efficiency water-saving irrigation demonstration zones and 100 cold-chain logistics hubs for agricultural products, and striving to achieve the goal of 65% coverage of high-efficiency water-saving irrigation and 40% cold-chain circulation of agricultural products; the third is the System Enhancement Project, which builds the "Infrastructure+" comprehensive supporting system, and promotes the integration of infrastructure construction with industrial development. The third is the system enhancement project, constructing the "infrastructure +" comprehensive supporting system, and promoting the in-depth integration of infrastructure construction with industrial cultivation, technology promotion, talent training and other elements. Through this series of policy combinations, it is expected that the comprehensive agricultural production capacity in the western region can be increased by more than 30%, providing solid support for rural revitalization.

This differentiated development strategy not only reflects the overall national plan but also achieves precise regional specialization. It offers a systematic solution to address China's regional development imbalances and holds significant theoretical and practical value for advancing the modernization of agriculture and rural areas.

5.2.2 Strengthening the income growth transmission chain

(1) Deepening the reform of the household registration system: focusing on advancing the process of citizenship for 280 million rural migrant workers, it is expected that per capita consumption expenditures of rural residents can be driven up by 18% through measures such as improving social security packages and guaranteeing the supply of housing, thus effectively activating the potential of the rural consumption market. It is proposed that pilot projects be carried out first in areas with a high concentration of rural migrant workers, such as the Yangtze River Delta and the Pearl River Delta, and that a graded household registration policy system be established.

(2) Strengthening vocational skills training: raising the proportion of GDP spent on cultivating new types of vocational farmers to 0.3%, and building a triadic

training system that is "government-led, enterprise-participating and institution-supporting". Focusing on training in cutting-edge technologies such as digital agriculture and intelligent agricultural machinery, it will strive to cultivate 5 million high-quality vocational farmers by 2025, with the rate of license-holders reaching more than 80%.

5.2.3 Building innovation ecosystems

(1) Promoting the commercialization and operation of patents: setting up a special fund for agricultural technology transfer with an annual scale of 50 billion yuan, with a focus on supporting the transformation of achievements in such areas as biological breeding and intelligent equipment. A 'patent pool' sharing system will be set up to enhance the technology trading market. This move aims to boost the conversion rate of agricultural scientific achievements to 60%.

(2) Increase incentives for R&D: Increase the proportion of R&D expenses plus deduction for agricultural high-tech enterprises to 150%, and give three-year tax breaks for core technology research projects. It is suggested that a pilot project be carried out in Yangling, Shouguang and other agricultural science and technology parks to form a replicable policy experience.

5.2.4 Risk prevention and control system

(1) Promoting the commercialization and operation of patents: setting up a special fund for agricultural technology transfer with an annual scale of 50 billion yuan, with a focus on supporting the transformation of achievements in such areas as biological breeding and intelligent equipment. A "patent pool" sharing mechanism will be established, the technology trading market will be improved, and the conversion rate of agricultural scientific and technological achievements will be raised to 60%.

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5.3 Research Limitations Future Directions

5.3.1 Data granularity

The current study is mainly based on provincial panel data, and it is recommended that subsequent studies use county-level microdata for more refined policy analysis. Breaking through the analytical limitations of the existing provincial panel data, it is recommended that subsequent studies shift to the refined analysis of county-level microdata. Specifically, a spatio-temporal panel database covering 2,846 county-level administrative units across the country can be constructed by systematically integrating multi-source data such as the National County Rural Economic Statistics Yearbook of the Ministry of Agriculture and Rural Development and the Land Use Change Survey Database of the Ministry of Natural Resources. Through the construction of a county-differentiated policy assessment framework, the policy response elasticity of counties at different levels of development can be accurately identified, and data support can be provided for the formulation of "one county, one policy". Specifically, the Ministry of Agriculture and Rural Development's county statistical yearbooks, the Ministry of Natural Resources' land-use change surveys and other databases can be integrated to establish a policy simulation system covering more than 2,800 counties and districts.

5.3.2 Assessment of dynamic effects

The current study has obvious deficiencies in the assessment of dynamic effects, which is mainly manifested in the fact that the existing static analytical models are difficult to accurately portray the time lag effect, cumulative effect, and path dependence characteristics of the policy implementation process. In order to improve the policy assessment of this important dimension, this study suggests adopting the dynamic stochastic general equilibrium (DSGE) modeling framework and making three innovative improvements for China's special institutional environment: first, in the construction of the model, it focuses on the inclusion of the urban-rural dichotomous structure, the segmentation of the factor market, the constraints of the household registration system and other Chinese institutional factors, so as to establish a simulation framework of the economic system that better meets the reality; second, in the parameter setting, it suggests adopting the 2025-2025 model, which is the most suitable model for China. parameter setting, it is recommended to adopt a medium- to long-term forecast interval of 2025-2040, and systematically simulate the differentiated evolution path of urban-rural integrated development by setting multiple scenarios such as the baseline scenario, the reform acceleration scenario, and the policy contraction scenario; lastly, in terms of the effect assessment, it is necessary to pay special attention to the dynamic transmission mechanism of the policy interventions, including: (1) the policy time lag effect, which is the time span between the implementation of the policy and the effects of the (1) policy time lag effect, i.e., the time span from policy implementation to effect realization; (2) policy multiplier effect, i.e., the change of output elasticity brought about by the unit policy input; (3) policy synergy effect, i.e., the superimposed amplification effect of different policy combinations. The establishment of this dynamic assessment framework will help policymakers more accurately predict the long-term effects of policy implementation and provide a scientific basis for formulating forward-looking urban-rural integration development policies.

5.3.3 Climate dimension

Current research has obvious deficiencies in the climate change dimension, and there is an urgent need to construct a systematic framework for assessing the impact of agricultural climate. It is recommended to deepen the research in the following aspects:

First, establish a complete agricultural carbon footprint accounting system, focusing on the development of three core climate indicators: (1) an indicator of the carbon emission intensity of the whole life cycle of agricultural production based on the LCA methodology, covering key aspects such as fertilizer production, use of agricultural machinery, and irrigation energy consumption; (2) an indicator for assessing the potential for carbon sequestration by agro-ecosystems, including the dimensions of soil carbon sinks and biomass carbon storage; and (3) an indicator of the cost of climate resilience construction, which quantify the cost of infrastructure inputs and maintenance for adapting to climate extremes. Second, at the methodological level, in future research, we can refer to the IPCC2019 revised guidelines for national GHG inventories, and make localized improvements in combination with the characteristics of China's agricultural production: (1) develop a differentiated measurement model for methane emissions from rice cultivation; (2) establish a sampling methodology for carbon accounting applicable to the characteristics of the small-farming economy; and (3) construct a regional climate sensitivity assessment matrix. Finally, it is proposed to incorporate carbon footprint indicators into the KPI system for agricultural policy evaluation, with specific implementation pathways including: (1) designing a cost-benefit analysis tool for climate-smart agricultural policies; (2) establishing a three-dimensional evaluation framework (ESE framework) for synergistic economic-social-climate development; and (3) developing a policy scenario simulation system for predicting the trajectory of agricultural transformation under different emission reduction pathways.

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