scientific reports

OPEN

Impact of interprovincial pairing assistance policies on sustainable agricultural development in Xinjiang of China

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While the advancement of sustainable agricultural development aligns with the United Nations Sustainable Development Goals (SDGs), it has witnessed lackluster progress globally in recent decades. This study examines China's pairing assistance policy, executed in Xinjiang since 2010, as a quasi-natural experiment to discern the impacts and underlying mechanisms of the inter-provincial pairing assistance policy on sustainable agricultural development in the beneficiary locale. Employing regression analysis with control methods and a two-way fixed effects model leveraged upon provincial panel data spanning 2007 to 2016, this research reveals that: (1) the inter-provincial pairing assistance policy has markedly enhanced sustainable agricultural development in Xinjiang, demonstrating that a 1% increment in pairing assistance funds correlates with an approximate 0.5% rise in the region's sustainable agricultural development index; (2) the policy primarily bolsters sustainable agricultural development through the meticulous management of agricultural land resources. The insights derived from this investigation elucidate the effectiveness of China's policy framework in fostering synchronized and sustainable regional development and offer a valuable reference point for the augmentation of sustainable agricultural practices worldwide.

Keywords Sustainable agricultural development, China, Policy intervention

Agricultural sustainability is a critical concern for developing regions, where over 3.1 billion people reside in rural areas and rely heavily on agriculture for their livelihoods[1]. For those developing countries, agricultural activities significantly impact poverty reduction, outperforming non-agricultural sectors by a factor of 3.2 in reducing poverty for people of the lowest incomes[2]. However, achieving sustainable development in agriculture faces critical challenges primarily due to a lack of environmental protection awareness, underestimation of environmental costs caused by agricultural activities and insufficient technologies to address agricultural pollution.

Sustainable agriculture has been recognized as a potential solution to address these challenges since it is defined as a "socially just, ecologically sound, and economically viable paradigm of producing the food needed to achieve food security"[3–6]. However, progress toward sustainable agriculture remains unsatisfactory, especially with the onset of the COVID-19 pandemic, leading to a decline in key sustainability indicators[7]. Therefore, identifying effective strategies to promote sustainable development of agriculture in undeveloped areas is of paramount importance.

This study utilizes on Xinjiang, China, as a representative case that shares common characteristics with many developing regions, including economic underdevelopment, ecological vulnerability[8,9], and ethnic diversity[10–12]. Despite government policies like Western Development Strategy, ecological and environmental issues remain a significant challenge in this region, as reflected in several studies. For instance, Ji-yuan et al.[13] highlight the persistent air and water pollution exacerbated by rapid industrialization. Similarly, Jia et al.[14] document the loss of biodiversity due to habitat degradation. Yang et al.[15] provide evidence of soil erosion impacting agricultural productivity. Zhang et al.[16,17] discuss the strain on water resources due to over-extraction and climate change. Lastly, Zheng et al.[18,19] and Zhuo and Deng[20] explore the detrimental effects of urban expansion on local ecosystems. Collectively, these studies underscore the multifaceted environmental challenges that continue to affect the region. To address these disparities, the Chinese government implemented an inter-provincial

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pairing assistance policy that aims to support border regions and underdeveloped areas through coordinated assistance encompassing political, economic, cultural, educational, scientific and healthcare provisions. This pairing assistance policy employs a mechanism of centralized coordination, political mobilization, and multi-level collaboration.

Literature relevant to this study mainly falls into two primary categories: "drivers of sustainable agricultural development" and "pairing assistance policy". The first strand of literature encompasses the determinants of sustainable agricultural development. Within this scope, scholarly efforts have highlighted the European Union's Common Agricultural Policy (CAP) and the main research directions include the equitable distribution of direct payment resources across EU Member States[21], the evaluation of direct transfer schemes on the biodiversity of agricultural landscapes[22], and the CAP's ramifications on the regional sustainability of agrarian pursuits[23]. In contrast, investigations of transfer payment policies and their implications on sustainable agricultural enhancement in underdeveloped regions are less prevalent[24,25]. Some researchers examine the effects of transfer payments within specialized locales or international entities[26–28]. Regarding the pairing assistance policy, most studies have used descriptive analysis to explore its efforts, and empirical evaluations of its multidimensional effects on regions like Xinjiang are infrequent but notable[29–36]. Similar policies have been implemented in other developing regions, such as the agricultural support programs in Sub-Saharan Africa[37] and inter-regional assistance initiatives in South Asia[38], which have shown varied outcomes in promoting sustainable agricultural development. In Sub-Saharan Africa, for instance, regional agricultural assistance programs have been instrumental in addressing food security but have faced challenges in sustainability due to infrastructural and governance issues. Similarly, South Asian countries have implemented inter-regional support initiatives aiming to boost agricultural productivity, yet the ecological impacts of these policies are under-explored. These examples underscore the need for empirical studies assessing the ecological influence of pairing assistance policies on sustainable agriculture in various contexts.

There are, however, some research gaps that need addressing: (1) within the scope of pairing assistance policies, limited research focuses on their ecological influence critical for sustainable development in agricultural sectors of lagging areas; (2) previous literature insufficiently emphasizes the mechanisms driving agricultural sustainability in less developed regions. Additionally, there is a comparative neglect of policies fostering regional coordination, such as pairing assistance, especially relevant in the post-pandemic era's call on integrated development.

This study aims to fill these gaps by exploring the impact of the inter-provincial pairing assistance policy on sustainable agricultural development in Xinjiang by addressing the following research questions: (1) Does the inter-provincial pairing assistance policy impact specific indicators of sustainable agricultural development, such as agricultural productivity, resource efficiency, and environmental health in Xinjiang? (2) What are the mechanisms through which the policy influences sustainable agriculture development? (3) What implications can these findings have for similar developing regions globally?

Using panel data from 18 provinces in China's central and western regions from 2007 to 2016, sustainable agricultural development indicators are constructed, and regression control methods along with two-way fixed-effects models are employed. The findings indicate that the pairing assistance policy has significantly enhanced sustainable agricultural development in Xinjiang. The policy's positive effects are primarily channeled through improved agricultural land governance, particularly in effective irrigation practices.

The possible contributions of this study include: (1) presenting a novel perspective on sustainable development research in China by evaluating regional development policies such as the pairing assistance policy; (2) offering deeper understanding of land governance mechanisms as conduits for sustainable agricultural development, enhancing the effectiveness of development initiatives in underdeveloped regions; and (3) providing empirical evidence on the significant influence of pairing assistance policies on sustainable agricultural development. These findings have implications for shaping future policy frameworks, both within China and globally, particularly in the post-pandemic context where progress toward sustainable agricultural benchmarks has slowed.

The remainder of the study is structured as follows: Section "Research hypotheses and theoretical framework" outlines the theoretical framework and research hypotheses. Section "Data sources, research methodology and description of variables" describes the data sources, variables, and methodology. Section "Empirical analysis" presents the empirical results and robustness checks. Section "Mechanism analysis" analyzes the mechanisms influencing sustainable agriculture. Finally, Section "Discussion" discusses the findings and Section "Conclusions" concludes the study and provides policy recommendations.

Research hypotheses and theoretical framework

Impact of pairing assistance policy on sustainable agricultural development

In the context of China's targeted pairing assistance policy, Xinjiang has been a significant beneficiary of aid from more extensive mainland provinces. Given the crucial role of agriculture in the Xinjiang economy, it has garnered considerable attention within this framework. Despite the absence of studies exploring the explicit impact of pairing assistance on Xinjiang's agricultural sustainability, this research provides an analysis by examining the pertinent aid provided by 19 mainland provinces and cities.

The theoretical foundation for the impact of the pairing assistance policy on sustainable agricultural development is rooted in the concept of resource complementarity and knowledge transfer. The resource-based view of strategic management[39] suggests that competitive advantage arises from the unique combination of valuable, rare, inimitable, and non-substitutable resources. In the context of pairing assistance, mainland provinces with more robust economic statuses, surplus investment capital, and sophisticated agricultural sciences and technology can complement Xinjiang's limited resources.

Furthermore, the knowledge-based view of the firm[40] emphasizes the importance of knowledge as a critical resource for organizational success. The transfer of advanced agricultural practices, technologies, and management techniques from mainland provinces to Xinjiang can be viewed as a form of inter-regional knowledge transfer, potentially accelerating the adoption of sustainable agricultural practices.

Substantial investment has been made in projects and funds geared toward the sustainable agricultural sector, addressing initiatives such as the construction of agricultural greenhouses, enhancements in water conservation and drip irrigation techniques, improvements in crop varieties, and the advancement of agricultural industrialization[31]. These investments align with the principles of sustainable intensification in agriculture[41], which aims to increase agricultural productivity while minimizing environmental impacts.

Based on this theoretical framework, the following hypothesis is proposed:

H1: The targeted and specialized aid from mainland provinces has a significant and positive impact on the sustainable agricultural development in Xinjiang.

Mechanism of fine agricultural land governance

The second aspect of our theoretical framework focuses on the mechanism through which pairing assistance policies influence sustainable agricultural development. It is posited that fine agricultural land governance serves as a critical mediating factor in this relationship.

The theory of adaptive governance[42] provides a foundation for understanding how the diverse and specialized support from mainland provinces can lead to more effective land governance practices. Adaptive governance emphasizes the importance of flexible, collaborative approaches to managing complex social-ecological systems, such as agricultural landscapes.

In the context of pairing assistance, the involvement of multiple provinces and municipalities introduces a wider variety of implementing agents, diversifying and specializing the modes and focal points of support. This diversity aligns with the principles of polycentric governance[43], which suggests that multiple, overlapping decision-making centers can lead to more robust and adaptive governance systems.

The adaptability of such aid is particularly advantageous for agricultural development, which is considerably dependent on local climatic and environmental conditions. This allows mainland provinces to devise bespoke agricultural development strategies attuned to the recipient region's unique circumstances, embodying the concept of context-specific interventions in sustainable development[44].

Furthermore, the theory of institutional capacity building[45] suggests that external support can enhance local institutions' ability to manage resources sustainably. In this case, the pairing assistance policy may contribute to building Xinjiang's capacity for fine agricultural land governance, leading to more sustainable agricultural practices.

Based on this theoretical framework, the following hypothesis is proposed:

H2: The inter-provincial pairing assistance policy promotes the sustainable development of agriculture in the recipient region through the mechanism of fine agricultural land governance.

Data sources, research methodology and description of variables

Data sources

The focus of this study is the most recent iteration of the "Pairing Assistance to Xinjiang" initiative, inaugurated in 2010. This wave of directed support delineates its parameters exclusively to the Xinjiang Uighur Autonomous Region—exempting the provincial capital of Urumqi and the petroleum-rich city of Karamay—thereby establishing a clear perimeter for empirical assessment. Notably, this targeted policy omits other provinces in China's western expanse, which establishes an advantageous precondition for the empirical evaluation of its efficacy and ramifications.

The dataset comprises panel data encompassing 18 provincial-level administrative divisions situated in China's central and western localities, spanning from 2007 through 2016. These divisions are as Anhui, Gansu, Guangxi Zhuang Autonomous Region, Guizhou, Henan, Hubei, Hunan, Jiangxi, Inner Mongolia Autonomous Region, Ningxia Hui Autonomous Region, Qinghai, Shanxi, Shaanxi, Sichuan, Tibet Autonomous Region, Xinjiang Uygur Autonomous Region, Yunnan, and Chongqing.

The rationale behind employing this dataset for empirical inquiry is threefold:

Firstly, the temporal scope of the dataset is significant. Subsequent to the Third National Agricultural Census, the National Bureau of Statistics revised certain statistical indicators pertinent to this investigation for the period spanning 2007 through 2017. Concurrently, after 2016, China initiated a major poverty eradication initiative, expanding interregional pairing assistance schemes. To obviate potential confounding influences upon the empirical analysis and considering data accessibility and integrity, the study period is delimited to the years 2007–2016.

Secondly, inherent disparities in economic development and agricultural progression between regions—especially when comparing eastern territories with central-western counterparts[46]—argue against the inclusion of the eastern province sample for comparative analysis. Additionally, a predominant share of central transfer payments for pairing assistance is derived from the eastern regions' tax contributions; hence, exclusion of the eastern sample is instrumental in attenuating potential endogeneity.

Lastly, the pairing assistance programs were expanded to encompass the Xinjiang Uyghur Autonomous Region (XUAR), excluding urban enclaves such as Urumqi and Karamay since the year 2010. The inaccessibility of municipal-level data germane to sustainable agricultural development metrics necessitates a provincial-level analysis. Given the investigation's focus on sustainable agricultural development indices, the urban locales of Urumqi and the petroleum-rich city of Karamay—with their scant agrarian household presence—were omitted from the provincial data corpus.

In summary, while including data beyond 2016 could enhance the current relevance of our conclusions, limitations arise due to changes in statistical methodologies and data availability post-2016. The National Bureau of Statistics revised key indicators after the Third National Agricultural Census, affecting data consistency.

Additionally, the initiation of China's extensive poverty eradication initiatives in 2016 introduced new variables that could confound our analysis. Therefore, we focus on the 2007–2016 period to ensure data integrity and methodological rigor.

The dataset is obtained from the National Bureau of Statistics of China (NBSC), accessible via their official platform: https://data.stats.gov.cn. This database is augmented by published statistical compendiums including the "China Statistical Yearbook", "China Rural Statistical Yearbook", "Xinjiang Yearbook", among other regional statistical annuals. Necessary normalizations were applied to the raw data. Specifically, figures related to Gross Domestic Product (GDP) were recalibrated using the province-specific annual GDP deflator indices, ensuring an accurate portrayal of economic dimensions in real terms. Parallel adjustments were implemented for other price-sensitive indicators, utilizing the pertinent Consumer Price Index (CPI) to recast the values to reflect constant price levels, thereby mitigating distortions due to inflationary pressures within each province for the year in question.

Research methodology

In assessing policy implications, the Two-Way Fixed Effects (TWFE)-based Difference-in-Differences (DID) approach is frequently endorsed. However, several methodological challenges arise when applying this model to the present inquiry: (1) the dataset may not strictly comply with the requisite assumption of parallel trends; (2) the singular experimental group in this study, Xinjiang, introduces risks of biased coefficient estimation for pivotal explanatory variables owing to potential endogeneity issues; and (3) neither temporal nor locational stochasticity of the pairing assistance policy can be presumed to be wholly evident[47–49].

Therefore, the empirical strategy revolves around estimating the level of sustainable agricultural development in Xinjiang, had the pairing assistance policy not been enacted. The efficacy of this policy intervention is discerned by contrasting the actual level of development post-policy implementation against the estimated counterfactual scenario. The regression control methodology, as expounded by Hsiao et al.[50], presents a more congruent analytical framework for this context. Fundamentally, this approach extrapolates the probable trajectory of sustainable agricultural development in the experimental group, Xinjiang, devoid of the policy's influence, by drawing upon the interprovincial correlational dynamics. This technique has garnered recognition for its efficacy in gauging policy interventions' effects, particularly in instances affecting discrete or limited regional entities[51–57].

The observed panel data is $\{y_{it}\}_{i=1,t=1}^{N,T}$, where y_{it} is the level of agricultural sustainability of province i in period t. The first province (i.e., the experimental group Xinjiang) is assumed to be subjected to a policy shock starting from periods T_0+1, while the time dimension of the panel data $T=T_0+T_1$ (T_0 is the number of periods before the policy shock and T_1 is the number of periods after the policy shock). All other individuals in the sample are not exposed to the policy shock and constitute the control group. Noting that y_{it}^1 is the value of i subjected to the policy intervention in period t, and y_{it}^0 is the value of individual i not subjected to the policy intervention in period t , the treatment effect of the policy intervention on individual i in period t is $\Delta_{it}=y_{it}^1-y_{it}^0$. Since it is impossible for us to observe both y_{it}^1 and y_{it}^0 at the same time, we can write y_{it} as:

$$y_{it}=d_{it}y_{it}^1+(1-d_{it})y_{it}^0 \tag{1}$$

where d_{it} is a dummy variable, $d_{it}=1$ indicates that individual t is affected by the policy in period t, and $d_{it}=0$ indicates that he is not affected by the policy. Suppose y_{it}^0 consists of a FACTOR MODEL:

$$y_{it}^0=a_i+b_i'f_t+u_{it} \quad (i=1,\cdots,N;\ t=1,\cdots,T) \tag{2}$$

where a_i is the individual fixed effect, f_t is the $K\times 1$-dimensional "common factor", b_i is the corresponding $K\times 1$-dimensional factor loading, indicating that the influence of the common factor f_t on individual i can be different, and u_{it} is the idiosyncratic component of individual i. Given the period t, stacking the equations for all individuals are stacked to obtain a more concise matrix expression:

$$y_t^0=a+Bf_t+u_t \tag{3}$$

where, $y_t^0=\left(y_{1t}^0\cdots y_{Nt}^0\right)'$, $a=(a_1\cdots a_N)'$ is the factor loading matrix. Hsiao, Steve Ching and Ki Wan[50] and Li and Bell[58] proved that Eq. (3) can be appropriately transformed under certain regularity conditions to obtain the following Time series regression equation:

$$y_{1t}=\gamma_1+\gamma'\overline{y}^t+\varepsilon_{1t} \tag{4}$$

where, $\overline{y}_t=(y_{2t}\cdots y_{Nt})'$, includes the level of agricultural sustainability for all control group individuals . Using the data before the policy shock, ($t=1,\ldots T_0$) and an os regression of Eq. (4), the resulting equation can be used to predict the counterfactual outcome for Individual 1 after the policy shock:

$$\widehat{y_{1t}^0}=\widehat{\gamma}_1+\hat{\gamma}'\overline{y}^t\ (t=T_0+1,\cdots,T) \tag{5}$$

Before policy implementation, if the OLS regression of Eq. (4) is well fitted (e.g., R^2 is high), there will be more confidence in this model to predict the counterfactual outcome of Individual 1 after policy implementation $\widehat{y_{1t}^0}$

. Obviously, a good fit before policy implementation is an important prerequisite for applying the Regression control method; if the fit is poor, the estimation of the policy effect will be biased. Based on the above counterfactual predictions, an estimate of the treatment effect of the policy intervention can be obtained:

$$\widehat{\Delta_{1t}} = y_{1t}^{1} - \widehat{u_{1t}^{0}} \ \ (t = T_0 + 1, \ldots, T) \tag{6}$$

When estimating Eq. (4) with the pre-policy implementation, it is also necessary to choose the number of control group individuals for this equation. The more control group individuals that are put in, the more explanatory variables there are in Eq. (4), which both improves R^2 and potentially leads to overfit. Therefore, models with too many explanatory variables need to be penalised using an information criterion to select the BEST SUBSET of explanatory variables that will ensure predictive validity of the counterfactual estimates.

Hsiao, Steve Ching and Ki Wan[50] suggested using AIC versus AICC to select the optimal subset, whereas Li and Bell[58] suggested using lasso estimator (Lasso) to screen the control variables before performing OLS regression, this method is known as Post-Lasso OLS. In this study, Post-Lasso OLS is dominated by this method due to its best fitting effect. In this study, the Stata program developed by Yan and Chen[59] was utilized to implement the RCM estimation.

To further ensure the accuracy of the conclusions in this study, the two-way fixed effects model is used as a supplement to the RCM estimation results. Considering the TWFE-based DID and applicable to the objects studied in this study, the TWFE model is constructed as follows:

$$Y_{it} = \beta_0 + \beta_1 \times X_c + \beta \times X_{it} + \gamma_i + \delta_t + \mu_{it} \tag{7}$$

where subscript i denotes province and t denotes year; Y_{it} is the dependent variable, denoting the level of sustainable agricultural development; X_c is the core explanatory variable, i.e., the total amount of funds that Xinjiang receives annually from inter-provincial pairing assistance; and X_{it} is the explanatory variable. γ_i and δ_t denote province fixed effects and time fixed effects, respectively; μ_{it} is the error term, and standard errors are calculated by clustering at the province level. To ensure the accuracy of the results, logarithmised variables for estimation are used in the TWFE model.

The advantage of this is, while avoiding the stringent data requirements of DID, the ability to accurately calculate how the amount of inter-provincial pairing assistance affects sustainable agricultural development in Xinjiang, while avoiding stringent data requirements of DID. At the same time, the results of TWFE can also be compared with the conclusions of RCM to demonstrate the robustness of the conclusions.

Variable description

Measurement of the dependent variable

To rigorously measure sustainable agricultural development, it is imperative to delineate its definition comprehensively. This article recognizes that the extant conceptualizations of sustainable agricultural development as posited in the literature are expansive and multidimensional. Predominant dimensions encompass the economic and ecological, while also enveloping considerations pertinent to social and political aspects. Building upon the foundational works such as[60,61], sustainable agricultural development is depicted as an integrated process directed towards satisfying human requisites for agricultural produce, ameliorating environmental conditions, bolstering social welfare, and stimulating economic advancement.

In the assemblage of measurement indicators, this study embraces a multi-dimensional approach, selecting indicators that encapsulate both economic and ecological aspects. These indicators include, but are not limited to, agricultural output, rural income, the degree of agricultural mechanization, energy inputs in agriculture, and the application rates of pesticides and fertilizers, as per the insights of Gómez-Limón and Sanchez-Fernandez[62], Liu et al.[63], Nambiar et al.[64], and Quintero-Angel and González-Acevedo[65].

To encapsulate the comprehensive panorama of sustainable agricultural development, this study proposes a suite of indicators as Table 1 shows. Each selected indicator reflects a facet of agricultural sustainability affected by the pairing assistance policy. For example, the per capita added value of the primary industry measures economic growth, while agricultural water intensity reflects resource efficiency improvements potentially resulting from technological support provided through the policy. In general, the indicators of sustainable agricultural development, such as value added per capita in the primary sector, rural disposable income, resource efficiency (e.g., water, fertilizer, and pesticide use), and environmental impact, all reflect key aspects of agricultural performance. The pairing assistance policy plays a vital role in improving these indicators by providing financial support, promoting sustainable farming practices, and facilitating access to modern technologies and infrastructure. Through targeted assistance in areas like mechanization, renewable energy adoption, and efficient resource management, the policy helps enhance agricultural productivity, reduce environmental impacts, and improve the livelihoods of rural populations, thereby fostering long-term sustainability in the sector.

Furthermore, these indicators are also specially tailored to Xinjiang's agricultural, environmental and economic context. Value added per capita in primary sector is vital for Xinjiang, where agriculture is a cornerstone of the economy. Per capita disposable income of rural residents is also crucial because of the significant rural poverty and disparities in Xinjiang. Consumption expenditure per rural inhabitant is an important indicator of improving overall well-being for rural residents affected by the pairing assistance in Xinjiang. Gross mechanical power per capita is key to improving efficiency and reducing labor costs in Xinjiang's agricultural sector, especially in remote areas. Agricultural water intensity is crucial because of the Xinjiang's arid climate. Introducing water-efficient technologies, such as drip irrigation and drought-resistant crops, can reduce water intensity and ensure sustainable agricultural practices, addressing water scarcity issues and maintaining crop yields. Intensity of diesel use in agriculture reflects the reliance on diesel-powered machinery in Xinjiang contributes to high costs and environmental harm. Electricity intensity in agriculture is selected because in remote areas of Xinjiang,

Variables	Units	Rationalities
Per capita added value of the primary industry	Billion yuan per 10,000 people	The primary sector encompasses agriculture, forestry, animal husbandry, and fisheries, serving as the most immediate barometer for gauging the expansion of agricultural economic benefits. The per capita value added in the primary sector is adopted as the measurement metric
Per capita disposable income of rural residents	Yuan	The per capita disposable income of rural residents reflects the standard of living among these populations, an outcome that is often influenced by corresponding pairing assistance policy interventions
Per capita consumer spending of rural residents	Yuan	Consumption expenditure per rural inhabitant encompasses the totality of expenses incurred by households in meeting the daily consumption needs of family life. This measure directly mirrors the consumption standards of rural populations, serving as an index of economic change and well-being
Per capita mechanical power	Ten thousand kilowatts per ten thousand people	Agricultural mechanization indirectly influences the ecological environment by amplifying the sown area for food crops and facilitating the reallocation of agricultural labor. Total agricultural machinery power per rural inhabitant is used as a proxy measure for mechanization levels
Agricultural water intensity	Billion square metres per billion yuan	Agriculture consumes a significant portion of China's water resources. The ratio of total agricultural water consumption to the added value of the primary industry is employed to quantify this critical metric for regional resource management
Agricultural Diesel Use Intensity	Ten thousand tonnes per billion yuan	The consumption of diesel in agricultural operations constitutes a significant component of carbon emissions during the agricultural production cycle[66]. The intensity is quantified by diesel utilized per unit of value added in the primary industry
Agricultural electricity intensity	Billion kWh per billion yuan	Electricity consumption in agriculture may contribute to greenhouse gas emissions. Agricultural electricity use per unit of value added to the primary industry is used to evaluate this factor
Fertilizer use intensity	Tonnes per thousand hectares	The application of agricultural fertilisers exerts a significant environmental impact, as demonstrated by Badiani et al.[67]. The adjusted quantity of fertilizer applied per unit area of cultivated cropland is used to assess this impact
Pesticide use intensity	Tonnes per thousand hectares	Pesticide application has the potential to result in the potential for chemical contamination within the biosphere, thereby potentially compromising the ecological integrity of the entire ecosystem[68]. The applied pesticide load per cultivated hectare is used to gauge this impact
Agricultural plastic film usage intensity	Tonnes per thousand hectares	The state of agricultural film recycling in China presents significant challenges[69], as indicated by the intensity of agricultural plastic film utilization per hectare of sown crops

Table 1. Measurement indicators of the dependent variable.

Variable	Obs	Mean	Std.dev.	Weight (%)
Value added per capita in primary sector	180	0.266	0.174	16.44
Per capita disposable income of rural residents	180	0.401	0.253	16.97
Consumption expenditure per rural inhabitant	180	0.375	0.236	16.51
Gross mechanical power per capita	180	0.275	0.18	16.16
Agricultural water intensity	180	0.802	0.236	4.67
Intensity of diesel use in agriculture	180	0.726	0.221	4.96
Electricity intensity in agriculture	180	0.687	0.204	4.83
Intensity of fertiliser use	180	0.625	0.225	6.16
Intensity of pesticide use	180	0.659	0.279	8.97
Intensity of use of agricultural plastic film	180	0.776	0.21	4.32

Table 2. Descriptive statistics of indicators for evaluating sustainable development of agriculture and their weights.

the reliance on electricity for irrigation and processing can increase operational costs. Intensity of fertilizer use reflects the fertilizer use in Xinjiang which may lead to soil degradation and pollution, particularly in water-scarce areas. Intensity of pesticide use reflects the pesticide use in Xinjiang, especially in cotton farming, which may harm the ecosystem and human health. Intensity of use of agricultural plastic film reflects the widespread use of plastic films in Xinjiang's agriculture which may lead to waste and environmental harm.

Given that each indicator possesses its distinct scale, normalization is achieved through utilizing the subsequent normalization equation:

$$\text{Positive indicators}: x_{ij} = \frac{x_{ij} - \min\left(x_{ij}\right)}{\max\left(x_{ij}\right) - \min\left(x_{ij}\right)} \tag{8}$$

$$\text{Negative indicators}: x_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{9}$$

Regarding the normalized values, indicator weights were quantified by applying the entropy weighting technique, with the aim of their collective assessment. The resultant calculations are delineated as Table 2 shows.

Table 2 presents the descriptive results of indicators for evaluating agricultural sustainable development and their weights. The means and standard deviations offer insights into the central tendency and variability of each indicator. For instance, the mean value of 0.266 for "Value added per capita in the primary sector" suggests moderate value addition across regions, with variability indicated by a standard deviation of 0.174. The entropy weights reveal the relative importance of each indicator, with economic indicators such as "Per capita disposable income of rural residents" and "Consumption expenditure per rural inhabitant" having the highest weights at 16.97% and 16.51%, respectively. Environmental impact indicators like "Agricultural water intensity" and "Electricity intensity in agriculture" have lower weights, reflecting their differential impact on the composite evaluation of sustainable agricultural practices.

Independent variables
In the regression control method, the framework does not encompass the notion of "core independent variables". Conversely, within the framework of the Time-Weighted Fixed Effects (TWFE) model, the designated core independent variable is the annual aggregate funding that Xinjiang receives through inter-provincial pairing assistance. This consolidated funding total is compiled from the Xinjiang Statistical Yearbook and the financial disclosures published annually by the Xinjiang Development and Reform Commission. It is noteworthy that pairing assistance initiatives were exclusively operational in Xinjiang commencing from 2010; consequently, for the years 2007–2009, the value attributed to this variable in Xinjiang is consistently zero. For other provinces, this variable retains a perpetual zero value.

Control variables
In order to construct a robust counterfactual scenario, a comprehensive set of control variables is selected based on theoretical considerations and prior empirical evidence. These variables can be categorized into four key aspects: economic indicators, social indicators, environmental indicators and technological ones.

Economic indicators include measures such as proportion of primary sector out and proportion of secondary sector output reflecting the economy's dependence on the agricultural and industrial activities respectively. Additionally, GDP per capita serves as an indicator of the standard of living and overall economic performance[70,71]. Consumer spending effect on economic performance highlights the household consumption's impact on the economy[72]. Furthermore, Economic openness indicates the global market integration[73–75].

Social indicators include urbanization rate reflecting urban development and rural-to-urban migration[76–78], Urban–rural income gap highlighting income inequality and regional economic differences[79–81], educational attainment index indicating education quality and access[82–84], and local health capacity reflecting capacity and accessibility of local healthcare services[83,85,86].

Environmental factors are represented by regional pollution emission intensity measuring the environmental impact of economic activities[87–90]. Finally, technological factors include economic digitalization degree representing the extent of digital technology adoption within the economy.

While the inclusion of these numerous control variables in the TWFE model may introduce multicollinearity, this approach is considered advantageous for the rigorous demands of the RCM. The RCM relies on a well-specified regression equation to generate accurate counterfactual predictions, and the inclusion of a comprehensive set of control variables helps to mitigate omitted bias and improve the overall robustness of the model. Table 3 presents the control variables and their descriptive statistics.

The descriptive statistics of these control variables in Table 3 highlight significant variability across regions. For example, the "proportion of primary sector output" varies from as low as 3.984% to as high as 22.191%, indicating diverse economic structures. Similarly, the "GDP per capita" ranges widely from ¥7,778 to ¥57,195.68, reflecting different levels of economic development. The "economic openness" variable shows substantial deviation, with a mean of 506.478 and a standard deviation of 587.4253, underlining disparities in international trade engagement among regions.

Overall, these control variables provide critical context for understanding the multifaceted dimensions influencing the sustainable development of agriculture. Their inclusion helps to refine the analysis and yields more robust insights into the factors driving sustainability outcomes.

Variables	Measurements and unit	Obs	Mean	Std.dev.	Min	Max
Proportion of primary sector output	Ratio of the added value generated by the primary sector to the regional GDP (%)	180	10.849	3.463	3.984	22.191
Proportion of secondary sector output	Ratio of the secondary sector's value-added to the GDP (%)	180	48.133	7.046	26.887	62.544
GDP per capita	GDP divided by population[70,71] (Yuan per capita)	180	27,332.41	10,909.76	7778	57,195.68
Consumer spending's effect on economic performance	Ratio of total retail sales of consumer goods to the GDP[72] (%)	180	0.417	0.085	0.245	0.705
Economic openness	Ratio of total exports and imports of foreign-invested enterprises to the regional GDP (Thousands of dollars per billion yuan)	180	506.478	587.4253	0.098	3486.108
Urbanization rate	Ratio of the urban population to the total resident population at the year's end (%)	180	0.448	0.088	0.0.215	0.634
Urban–rural income gap	Ratio of the average disposable income of rural households to that of urban households (%)	180	0.338	0.047	0.237	0.438
Educational attainment index	Percentage of individuals aged six years and older with at least tertiary education (%)	180	0.084	0.030	0.012	0.183
Local health capacity	Density of health technicians per 10,000 persons as a tangible measure (Technician per 10,000 individuals)	180	45.189	11.827	21	76
Regional pollution emission Intensity	Ratio of total wastewater discharge to regional GDP (Million tonnes per billion USD)	180	17.299	7.610	6.716	58.415

Table 3. Control variables and their descriptive statistics.

Empirical analysis

Results of measuring sustainable agricultural development

Table 4 delineates the outcomes of an assessment gauging the degree of sustainable agricultural advancement across 18 provinces over the span from 2007 to 2016. The results indicates a positive trend in the sustainable development of agriculture across the evaluated provinces over the period. Notably, each province has exhibited improvement, indicating overall progress in agricultural sustainability.

Moreover, the provinces in the western region demonstrate a marginally lower level of sustainable agricultural development compared to their central counterparts. Within this spectrum, Inner Mongolia exhibits the preeminent position in agricultural sustainability, while Gansu lags at the opposite end of the spectrum. This disparity in ranking can be attributed to the inherent natural resources and distinct agricultural attributes of each region.

Provinces traditionally considered agricultural strongholds in China, such as Henan, Hunan, Hubei, along with Sichuan Province and Chongqing Municipality, register notably high sustainability levels. Conversely, provinces situated in the mountainous southwest, specifically Yunnan, Guizhou, and Guangxi, show comparatively subdued sustainability in agricultural development. These observed trends align with the consensus presented in previous scholarly research on the subject[91–93].

Baseline estimation

RCM model results

As illustrated in Fig. 1, the counterfactual predicted values exhibit remarkable congruence with the actual observed values in Xinjiang prior to the implementation of the policy. The control group possesses a highly precise ability to replicate the level of sustainable agricultural development observed in Xinjiang.

Figure 1 distinctly demonstrates that subsequent to the inception of the counterpart policy in 2010, a progressive divergence emerges between the counterfactual predictions and the empirical data. Notably, while the counterfactual projections remain relatively stable, a pronounced and abrupt surge is observed in the actual values.

TWFE model results

Table 5 delineates the outcomes derived from the TWFE analysis. Model 1 presents regression findings exclusive of annual fixed effects, wherein the policy effect's estimated coefficient is substantial and manifests a robust positive significance. Conversely, Model 2 exhibits regression outcomes devoid of control variables, yet the policy effect's estimated coefficient retains a positive and conspicuously significant magnitude with minimal variation. Model 3 incorporates both provincial and annual fixed effects alongside control variables, yielding an estimated coefficient for the policy effect that sustains its positive orientation and remains highly significant.

The integrated analyses of the RCM and the TWFE models substantiate that the enactment of the inter-provincial pairing assistance policy has effectively augmented the level of sustainable agricultural development in Xinjiang. Specifically, for each 1 percent enhancement in inter-provincial pairing assistance funds, there is an associated increase of 0.4 to 0.6 percent in the sustainable agricultural development indicators within the region. This empirical evidence corroborates Hypothesis H1.

Provinces	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Anhui	0.33	0.35	0.386	0.411	0.451	0.497	0.526	0.575	0.623	0.666
Gansu	0.259	0.272	0.292	0.299	0.296	0.321	0.347	0.376	0.409	0.425
Guangxi	0.323	0.337	0.37	0.389	0.42	0.463	0.493	0.521	0.565	0.583
Guizhou	0.316	0.324	0.347	0.368	0.384	0.415	0.451	0.484	0.516	0.539
Henan	0.351	0.369	0.394	0.412	0.445	0.49	0.526	0.572	0.612	0.631
Hebei	0.302	0.321	0.353	0.386	0.432	0.49	0.541	0.592	0.653	0.694
Hunan	0.355	0.378	0.411	0.428	0.468	0.512	0.551	0.603	0.646	0.691
Jiangxi	0.326	0.345	0.378	0.397	0.445	0.491	0.48	0.525	0.574	0.61
Inner Mongolia	0.479	0.523	0.551	0.59	0.653	0.71	0.767	0.824	0.873	0.902
Ningxia	0.311	0.328	0.361	0.389	0.422	0.462	0.499	0.55	0.594	0.591
Qinghai	0.35	0.359	0.388	0.414	0.448	0.491	0.518	0.559	0.582	0.623
Shanxi	0.29	0.299	0.321	0.342	0.376	0.419	0.444	0.485	0.513	0.494
Shaanxi	0.281	0.304	0.309	0.336	0.365	0.394	0.433	0.479	0.517	0.536
Sichuan	0.352	0.367	0.403	0.415	0.452	0.496	0.539	0.584	0.626	0.665
Tibet	0.341	0.345	0.373	0.381	0.398	0.423	0.452	0.497	0.536	0.572
Xinjiang	0.272	0.279	0.313	0.349	0.387	0.435	0.478	0.501	0.539	0.59
Yunnan	0.31	0.321	0.336	0.349	0.377	0.408	0.433	0.466	0.502	0.535
Chongqing	0.331	0.346	0.37	0.399	0.441	0.482	0.522	0.566	0.615	0.662

Table 4. Results of the measurement of the level of sustainable development of agriculture.

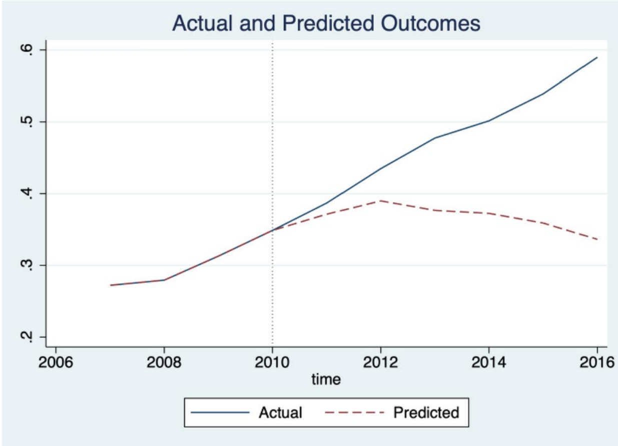


Fig. 1. Observed and counterfactual predictions of the level of sustainable agricultural development in Xinjiang.

	Model 1	Model 2	Model 3
X_c	0.00586*** (10.34)	0.00427*** (8.44)	0.00495*** (11.76)
_cons	−0.24 (−0.2)	−1.03*** (−44.56)	−3.39*** (−3.13)
Control variable	Yes	No	Yes
Time fixed effect	No	Yes	Yes
Provincial fixed effects	Yes	Yes	Yes
R-sq(within)	0.9781	0.9779	0.9874
Number of provinces	18	18	18
N	180	180	180

Table 5. TWFE estimation results. t-statistics in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

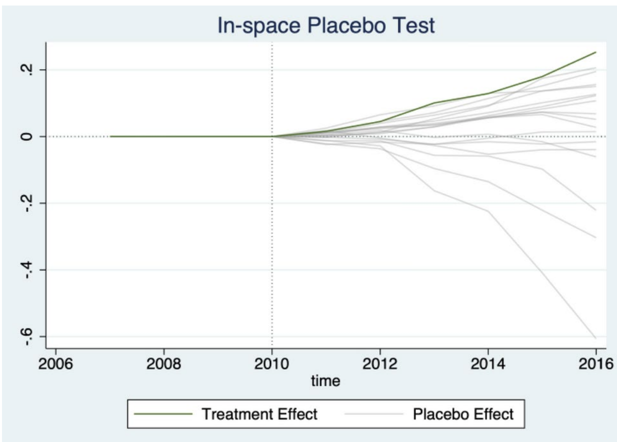


Fig. 2. RCM model placebo test results.

Robustness test

To ensure the robustness of the findings, several tests were conducted.

Placebo test

In the application of the RCM, a placebo test was performed by designating the other 17 provinces as pseudo-treatment units and comparing them with Xinjiang, the actual treatment unit. The results are presented in Fig. 2.

In Fig. 2, the darkened trajectory signifies the patch of the sustainable agricultural development in Xinjiang, the treatment unit, while the lighter trajectories represent the outcomes for the seventeen control group provinces, serving as pseudo-treatment units.

Prior to 2010, both Xinjiang and the control provinces exhibit similar trends in terms of sustainable agricultural development. This parallelism enhances the credibility of the methodological approach. It confirms that any divergence observed post-2010 can be more confidently attributed to the policy intervention rather than pre-existing differences between Xinjiang and the control provinces.

Post-2010, which marks the initiation of the pairing assistance policy, there is a noticeable and significant divergence in the trajectory of Xinjiang's sustainable agricultural development from those of the control provinces. Specifically, the trajectory for Xinjiang rises more steeply compared to the flatter paths of the control provinces. This stark separation between the darkened trajectory of Xinjiang and the lighter trajectories of the control group suggests a considerable positive impact brought forth by the pairing assistance policy.

The results highlight that the pairing assistance policy has had a significant positive effect on sustainable agricultural development in Xinjiang. This divergence provides strong empirical evidence that the policy intervention is successful in its objective to enhance agricultural sustainability in the region. The clear separation of trajectories post-2010 also affirms the methodological robustness of the placebo test. The discernible impact eliminates concerns around random variations or noise in the data, strengthening the argument for the policy's effectiveness.

In the TWFE model, a placebo test was conducted by generating a random error term as a surrogate for the actual pairing assistance funds and performing Monte Carlo simulations 10,000 times.

The distribution of coefficients in Fig. 3 reflects a normal distribution cantered around zero, derived from random sampling. Importantly, the actual estimated effect of the pairing assistance policy is significantly higher than this mean value. This substantial difference suggests that the estimates are unlikely to have occurred by chance. The results affirm the robustness of the methodological approach, indicating that the observed effects are not random variations but are attributable to the policy intervention. The significant deviation of the actual estimate from the simulated mean strengthens the conclusion that the pairing assistance policy has positively influenced sustainable agricultural development.

Alternative dependent variables

To further verify the robustness of the results, the dependent variable was replaced with individual indicators used in constructing the sustainable agricultural development index.

To this end, the substitution of the explanatory variables within the RCM was initially undertaken, followed by the execution of a placebo test to affirm the solidity of the findings. The outcomes of this rigorous assessment are presented subsequently. Figure 4 shows the results.

Based on Fig. 4, it is evident that the pairing assistance policy has a significant impact on several key indicators. Notably, three indicators shows substantial positive growth: per capita value added to the primary sector, rural residents' per capita disposable income, and per capita consumption expenditure of rural inhabitants. These metrics demonstrate a marker increase following the implementation of the pairing assistance policy. In contrast, the pairing assistance policy appears to have limited influence on certain environmental and agricultural indicators. Specifically, gross mechanical power per capita, agricultural water intensity, diesel use intensity in agriculture, and pesticide use intensity show minimal changes after the policy's introduction.

These findings suggests that the pairing assistance policy primarily affects the economic indicators of the agricultural sustainable development, such as per capita value added to the primary sector, rural residents' per capita disposable income, and per capita consumption expenditure of rural inhabitants. To validate the results, the TWFE models were constructed. All TWFE models include control variables, province fixed effects, and year fixed effects. Table 6 presents the results of TWFE models.

From Table 6, notable reductions are observed in electricity intensity in agriculture, fertilizer use intensity, and agricultural plastic film use intensity, further underscoring the effects of the pairing assistance policy. The overall

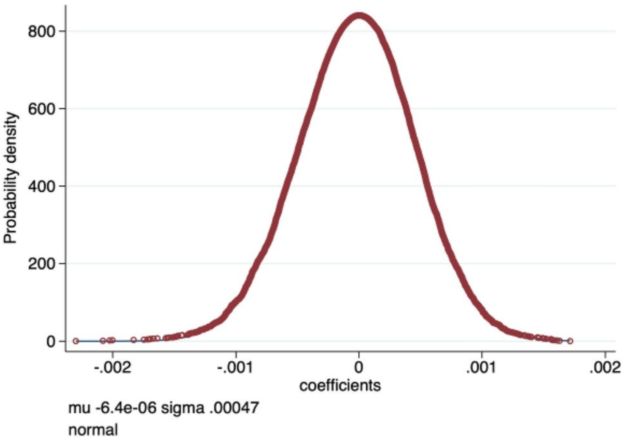
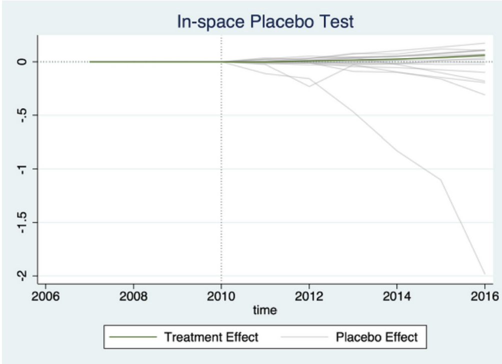
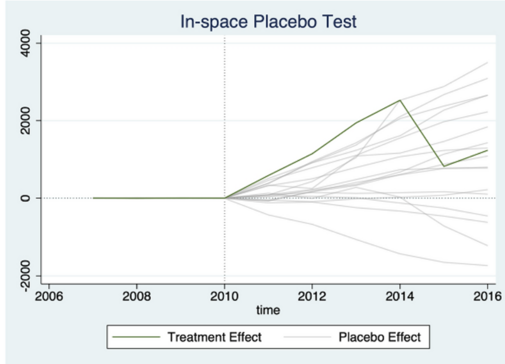


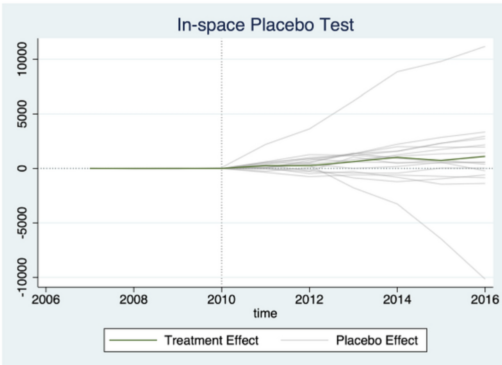
Fig. 3. TWFE model placebo test results.



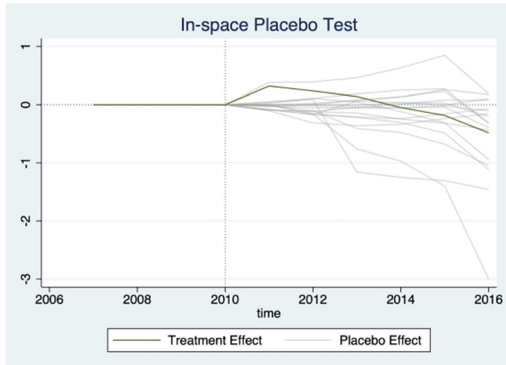
(a) Observed and Counterfactual Projections of Per capita added value of the primary industry in Xinjiang



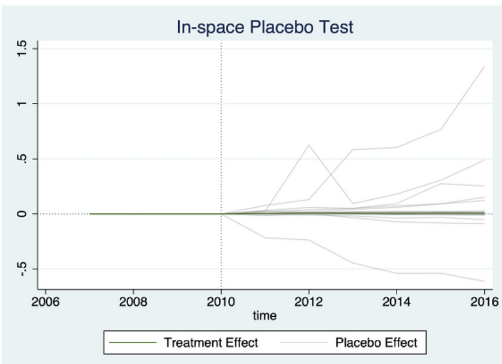
(b) Observed and Counterfactual Projections of Per capita disposable income of rural residents in Xinjiang



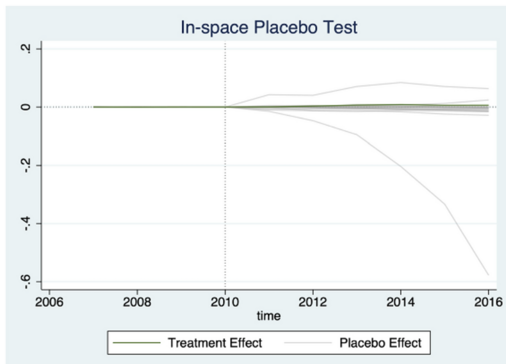
(c) Observed and counterfactual predictions of Per capita consumer spending of rural residents in Xinjiang



(d) Observed and counterfactual predictions of Per capita mechanical power in Xinjiang



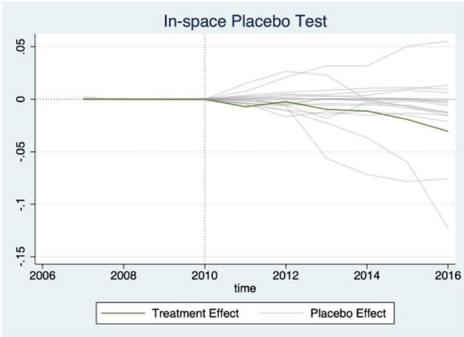
(e) Observed and counterfactual predictions of agricultural water intensity in Xinjiang



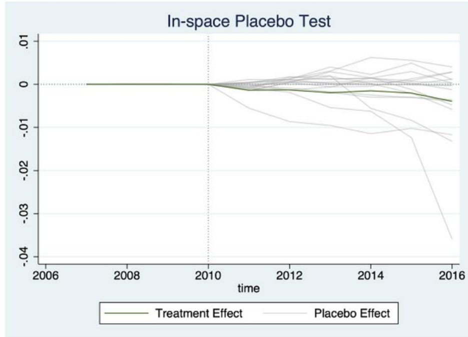
(f) Observed and counterfactual predictions of agricultural Diesel Use Intensity in Xinjiang

Fig. 4. Observed and counterfactual predictions of replaced dependent variables in Xinjiang.

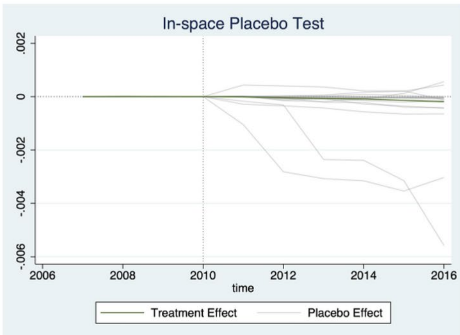
trend indicates that after the implemention of the pairing assitance policy, positive indicators of agricultural sustainable development generally exhibit an upward trajectory, while negative ones predominantly display a downward trend. This pattern indirectly validates the accuracy of the baseline regression outcomes, confirming that the pairing assistance policy has a discernible influence on specific metrics of sustainable agricultural development. Consequently, it incrementally enhances the overall sustainability of the agricultural sector.



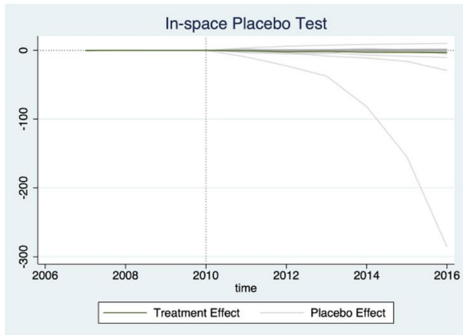
(g) Observed and counterfactual predictions of agricultural electricity intensity in Xinjiang



(h) Observed and counterfactual predictions of fertilizer use intensity in Xinjiang



(i) Observed and counterfactual predictions of pesticide use intensity in Xinjiang



(j) Observed and counterfactual predictions of agricultural plastic film usage intensity in Xinjiang

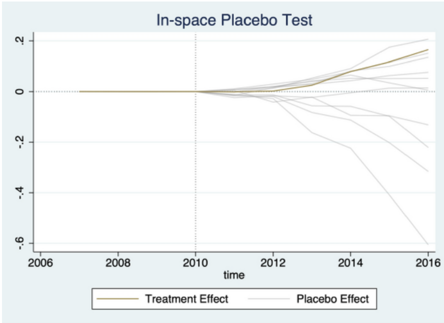
Figure 4. (continued)

Indicator	Coefficient	t-statistics
Per capita added value of the primary industry	0.00272**	(2.56)
Per capita disposable income of rural residents	0.00036	(0.85)
Per capita consumer spending of rural residents	0.00382***	(3.74)
Per capita mechanical power	0.00251	(1.13)
Agricultural water intensity	0.00981***	(10.51)
Agricultural diesel use intensity	− 0.00857**	(− 2.64)
Agricultural electricity intensity	− 0.00441*	(− 1.96)
Fertilizer use intensity	− 0.00275**	(− 2.68)
Pesticide use intensity	− 0.00784***	(− 5.59)
Agricultural plastic film usage intensity	− 0.00566	(− 1.65)

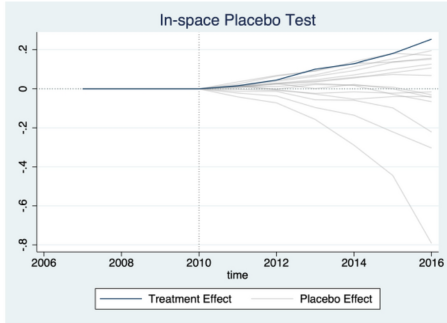
Table 6. TWFE estimates with alternative dependent variable. t-statistics in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Sample exclusion tests
To address potential confounding factors due to other concurrent policy interventions during the 2007–2016 timeframe or unique regional characteristics, robustness checks were performed by excluding certain samples from the analysis. These included excluding central provinces, Qinghai and Tibet (which received other forms of assistance), Chongqing Municipality (due to its unique administrative status), Guizhou Province (which received targeted support in 2013), and data from 2015 and 2016 (when poverty alleviation efforts intensified). The regression control model was re-estimated with the reduced samples, and Fig. 5 and Table 7 demonstrate the results of this refined analysis.

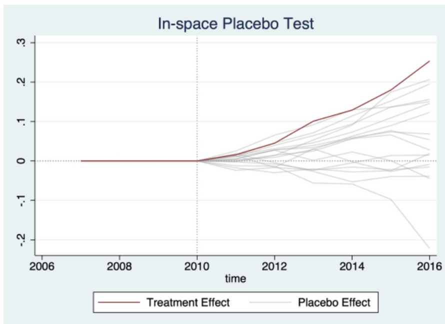
Figure 5 displays the observed versus counterfactual predictions of sustainable agricultural development levels in Xinjiang after removing samples potentially affected by the mentioned external policies. The trends clearly illustrate that even after excluding these samples, the positive impact of the pairing assistance policy on



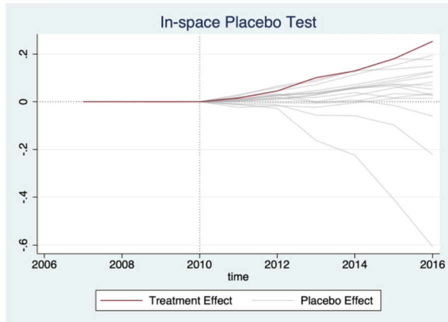
(a) Observed and counterfactual predictions of the level of sustainable agricultural development in Xinjiang after removing the sample from the central provinces



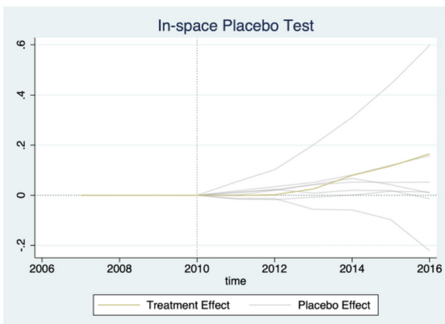
(b) Observed and counterfactual predictions of the level of sustainable agricultural development in Xinjiang after removing the Qinghai and Tibet samples



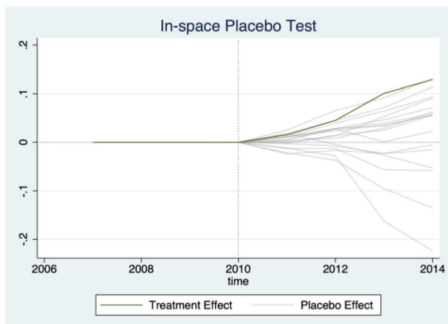
(c) Observed and counterfactual predictions of the level of sustainable agricultural development in Xinjiang after removing the Chongqing sample



(d) Observed and counterfactual predictions of the level of sustainable agricultural development in Xinjiang after removing the sample from Guizhou Province



(e) Observed and counterfactual predictions of the level of sustainable agricultural development in Xinjiang after removing samples from the central provinces, Qinghai, Tibet, Chongqing and Guizhou



(f) Observed and counterfactual predictions of the level of sustainable agricultural development in Xinjiang with 2015 and 2016 data removed

Fig. 5. Observed and counterfactual predictions of the level of sustainable agricultural development in Xinjiang after removing samples.

sustainable agricultural development remains consistent and significant. Each figure examines different aspects, showing upward trends in key sustainable metrics despite the data exclusions. The perturbation incurred by the exclusion of a marginal proportion of the samples from other provinces does not substantively detract from the congruence of the current findings with those of the archetypal analysis.

Table 7 presents the TWFE estimation results after various samples were excluded. Each column shows the regression outcomes after specific samples were removed. It can be concluded that the recalibration of the sample

Exclusion Description	Coefficient	t-statistics
Removal of central provinces	0.00462***	(6.97)
Removal of Qinghai and Tibet	0.00476***	(9.12)
Removal of Chongqing	0.00491***	(12.47)
Removal of Guizhou	0.00497***	(11.49)
Removal of central provinces, Qinghai, Tibet, Chongqing, Guizhou	0.00384***	(5.35)
Removal of 2015 and 2016 data	0.00373***	(7.37)

Table 7. TWFE estimation results after excluding some samples. t-statistics in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

sustains the optimistic narrative: the core explanatory variables retain their positive and significant stance post-adjustment. The metrics offer only a marginal deviation from their original statistics, thereby bolstering the resilience of the preliminary analytical results.

The consistent persistence of these positive trends, even after implementing various methodological adjustments such as replacing dependent variables and excluding confounding samples, strongly supports the hypothesis that the pairing assistance policy has a significant and lasting positive impact on the agricultural sustainability landscape in Xinjiang. This robustness check, evidenced by Figs. 4 and 5 and Tables 6 and 7, reveals that the policy's beneficial effects are not artifacts of data peculiarities or concurrent regional policies but are indeed attributable to the pairing assistance initiative itself.

Figure 4 and Table 6 corroborate this positive trend across different sustainability metrics, portraying a clear divergence between actual developments and counterfactual scenarios where the policy is absent. Specifically, these figures illustrate sustained improvements in key metrics like crop yield efficiency and resource management practices.

Figure 5 and Table 7 further substantiate these findings through statistical rigor. By recalculating the TWFE estimations after sequentially excluding data influenced by other interventions and regions with unique administrative statuses, the table highlights significantly positive coefficients across various adjusted models. These results confirm that the beneficial impact of the pairing assistance policy is resilient to alterations in the sample and withstands the scrutiny of more restrictive analytical conditions, thus reinforcing the credibility and generalizability of our conclusion that the policy has fostered notable advancements in agricultural sustainability within Xinjiang.

While the robustness tests conducted (RCM and TWFE models) offer strong evidence of the pairing assistance policy's impact, certain limitations remain. One such limitation is the potential endogeneity in the models, where unobserved factors may affect both the treatment (policy intervention) and the outcome (sustainable agricultural development). This risk is mitigated to some extent by the use of fixed effects models and rigorous robustness checks, but future studies could benefit from instrumental variable approaches to further address this issue.

Mechanism analysis

Drawing upon the theoretical framework posited, the present study contends that the pairing assistance policy significantly enhances sustainable agricultural practices through the intricate mechanism of meticulous rural land governance. This study upholds the benchmark testing protocol for mechanism analysis, yet with a novel introduction of mediating variables supplanting the explanatory ones.

A pivotal facet of agricultural land governance is its manifestation in the expanse of effectively irrigated land—a concern paramount in the discourse of agricultural development among developing nations. Within the Xinjiang administrative territory, the harsh geographical reality places a premium on efficient water resource management: deserts encompass a third of the land, and the region grapples with meager and sporadically distributed annual rainfall, averaging around 150 mm. A stark disparity is evidenced by the contrast in precipitation between the verdant northern mountains, where annual precipitation reaches a zenith of 500–600 mm, and the arid southern peripheries of Qiamo and Ruoqiang, which are beleaguered by a scant 10 mm. In this milieu, the imperative to augment the efficiency of agricultural water usage and foster an ethos of water-conservative farming practice is brought into sharp relief. Notably, such endeavours are central to the supporting mandate of various regions to bolster Xinjiang's agricultural sector. Instances of this support include Shanghai Municipality's pivotal role in constructing an avant-garde intelligent drip irrigation system in Bachu County of Kashgar; Beijing Municipality's significant investment, totaling 4.06 million, to establish 50 state-of-the-art agricultural facilities in Hetian, wholly financed by the capital's municipal authorities; and Hangzhou Municipality's foray into promulgating high-efficiency water-conservation irrigation projects across Aksu City, with marked success in irrigational outcomes for thousands of hectares. The innovative drip irrigation technology, singularly under the film, has yielded considerable water savings and boosted cotton yields per unit area.

The technologically advanced regions bring to the table a wealth of expertise in the erection of agricultural facilities coupled with a sophisticated technical prowess instrumental for the propagation of water-saving agriculture. The transference of such technologies unequivocally catalyzes the upscaling of land management sophistication in Xinjiang, thereby steering local agricultural sustainability in tandem with regional agronomic exigencies. This empirical evidence substantiates the second hypothesized relationship, denoted as H2, within the framework of this investigation. Figure 6 and Table 8 shows the results.

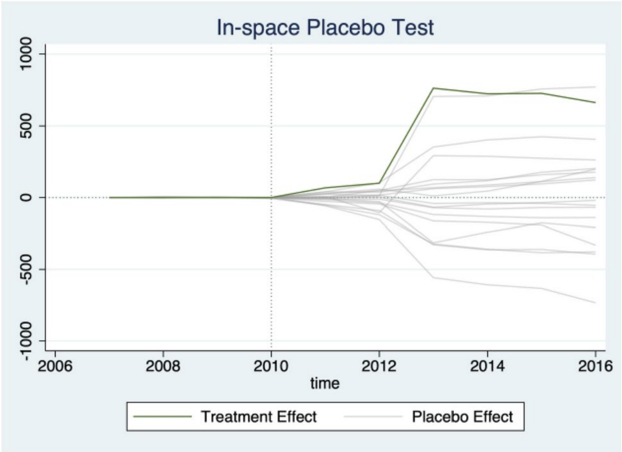


Fig. 6. Observed and counterfactual predictions of Effective irrigated area in Xinjiang.

Implicit variable	Effective irrigated area
X_c	0.00558*** (4.82)
_cons	9.937** (2.73)
Control variable	Yes
Time fixed effect	Yes
Provincial fixed effects	Yes
R-sq(within)	0.4857
Number of provinces	18
N	180

Table 8. TWFE regression results. t-statistics in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Figure 6 showcases the observed and counterfactual predictions of the effectively irrigated area in Xinjiang. The observed data represent the actual outcomes of the pairing assistance policy and associated interventions in water resource management. The counterfactual predictions, on the other hand, illustrate the hypothetical scenario where such interventions did not take place. The significant discrepancy between the observed and counterfactual predictions underscores the positive impact of the policy interventions on the effective irrigation of agricultural land.

Table 8 presents the TWFE results, further substantiating the relationship between the pairing assistance policy and the effective irrigated area. The coefficient of 0.00558, which is statistically significant at the 1% level, indicates a positive and significant effect of the pairing assistance policy on the effectively irrigated area. This suggests that the policy interventions are highly effective in expanding the area of land that benefits from efficient irrigation practices.

Discussion

The empirical analysis in this study demonstrates that the pairing assistance policy has had a significant positive impact on sustainable agricultural development in Xinjiang. The findings from the RCM model indicate that the counterfactual predicted values align closely with the actual observed values prior to the policy implementation, suggesting a robust methodological approach. Post-policy implementation (starting from 2010), there exists a substantial and abrupt divergence where actual values surpass the counterfactual predictions, highlighting the positive effect of the pairing assistance policy.

The TWFE model further supports these findings, showing that the policy effect remained significant under various model specifications. The robustness tests—including the placebo test, replacement of the dependent variable, and exclusion of some samples—reaffirm the stability and reliability of the results. Specifically, for each 1 percent enhancement in inter-provincial pairing assistance funds, there is an associated increase of 0.4 to 0.6 percent in the sustainable agricultural development indicators within Xinjiang.

The mechanism analysis reveals that the policy impacts the region through improvements in effective irrigated area, driven by advanced water-saving technologies and infrastructural investments from more developed regions. This mechanism underscores the importance of technological and administrative interventions in enhancing agricultural sustainability.

These findings align with China's broader agricultural modernization policies such as the Western Development Strategy and the national drive for food security, which emphasize sustainability and technological innovation. The positive impact of the pairing assistance policy in Xinjiang reflects the effectiveness of integrating national priorities with regional development strategies. Considering Xinjiang's unique socio-economic dynamics, including its ethnic diversity and ecological vulnerability, the policy's success underscores the importance of tailored interventions that address local needs while supporting national goals.

These findings contribute to and extend the literature on the effects of regional development policies. Previous studies have documented the benefits of pairing assistance policies in various contexts. For instance, Chai, Zhang, Li, Niu, Zheng, Kong, Yu, Zhao and Xia[91] and Chen, Miao and Zhu[92] observed improvements in general economic indicators, albeit without a specific focus on sustainable development. This study aligns with their observations but specifically highlights the impact on sustainable agricultural practices.

Contrary to certain studies like Shen, Baležentis, Chen and Valdmanis[93], which reported mixed results regarding policy impacts on agricultural practices, our analysis provides clear evidence of positive outcomes. This discrepancy might be attributed to the focus on Xinjiang, a region uniquely suited for examining the interplay between agriculture and sustainability due to its challenging environmental conditions.

This study makes several notable contributions to the field of agricultural and regional development economics. Firstly, it provides the first comprehensive analysis of the pairing assistance policy's impact on sustainable agricultural development specifically in Xinjiang. Secondly, the use of both RCM and TWFE models ensures a robust evaluation of the policy impacts, addressing potential biases commonly faced in policy analysis. Thirdly, by identifying the specific channels—such as technology transfer and infrastructural investments—through which the policy influences agricultural sustainability, we offer valuable insights for designing effective regional policies. Lastly, the study shifts the analytical focus from short-term economic growth to long-term sustainability, a critical dimension often overlooked in policy evaluations.

For policymakers from China and other global contexts, the findings have significant implications: (1) given the positive impact observed, there is a strong case for the continuation and potential expansion of the pairing assistance policy to other regions with similar agricultural challenges; (2) the effectiveness of the policy underscores the need for comprehensive support, encompassing technology transfer, financial investment, and human capital development; (3) the success in Xinjiang suggests that similar policies could be effective in other global regions with challenging environmental and agricultural conditions; (4) policymakers should integrate sustainability metrics into the design and evaluation of regional development policies to ensure long-term beneficial outcomes.

Conclusions

This study has rigorously examined the impact of the pairing assistance policy on sustainable agricultural development in Xinjiang, employing robust empirical methodologies such as the RCM and TWFE models. The findings reveal that the policy has had a substantial positive effect on sustainable agricultural practices in the region.

First, the policy has significantly enhanced sustainable agricultural development indicators in Xinjiang. For each 1% increase in inter-provincial pairing assistance funds, there is an associated 0.4% to 0.6% increase in these indicators. The robustness checks confirm the credibility and reliability of these results.

Second, the mechanism analysis reveals that the policy's positive effects are primarily driven by improvements in effective irrigated areas, through the introduction of advanced water-saving technologies and infrastructural investments. This highlights the importance of technological innovation and targeted investments in promoting sustainable agricultural development.

This study contributes to the literature by providing empirical evidence on the significant influence of pairing assistance policies on sustainable agricultural development in underdeveloped regions. By highlighting the mechanisms through which such policies operate, it offers insights for policymakers aiming to promote sustainability in similar contexts.

The findings carry important implications for policymakers. The observable positive impact advocates for the continuation and potential expansion of the pairing assistance policy to other regions facing similar agricultural and environmental challenges. Additionally, the results emphasize the need for comprehensive support that includes financial investment, technology transfer, and human capital development. Policymakers are also encouraged to incorporate sustainability metrics into future policy designs and evaluations to ensure long-term benefits. Furthermore, policymakers should facilitate technology transfer by establishing dedicated agricultural innovation hubs in Xinjiang that leverage expertise from more developed provinces. These hubs can focus on adapting advanced irrigation technologies to local conditions. Implementing comprehensive water management programs that include training for local farmers on efficient water use practices will also enhance sustainability. Investing in infrastructure for water conservation, such as modern drip irrigation systems, can significantly reduce water wastage in the region. Despite the positive impacts identified, this study acknowledges that the long-term sustainability of the pairing assistance policy may be compromised if it leads to an over-reliance on external aid. This could stifle local innovation and resilience in the agricultural sector. Future research should explore these potential long-term consequences and examine how pairing assistance policies can be gradually phased out while ensuring sustainable local development.

Despite these significant findings, this study has several limitations. The regional specificity of focusing on Xinjiang may limit the broader applicability of the results, suggesting the need for future research to examine similar policies in other contexts. Additionally, the quantitative nature of this study does not capture the nuanced implementation details of the policy, highlighting the potential benefit of qualitative methods. Investigating the long-term effects over a more extended period and exploring interactions between the pairing assistance policy and other regional initiatives could provide a richer understanding in future research. Future research could extend the analysis beyond 2016 to capture the effects of more recent developments. However, the findings within our study period provide valuable insights into the policy's impact during a critical phase of agricultural development in Xinjiang.

In conclusion, this study provides compelling evidence of the positive impacts of the pairing assistance policy on sustainable agricultural development in Xinjiang. By adopting a comprehensive and methodologically rigorous approach, the research offers valuable insights that contribute to the broader discourse on regional development and sustainable agriculture. Our findings not only affirm the efficacy of targeted regional policies but also provide actionable recommendations, paving the way for more effective and sustainable agricultural practices in challenging environments.

Data availability

The raw data supporting the conclusions of this article will be made available by the corresponding author HUANG Juan through the mailbox 2,021,592,118@cupk.edu.cn on request.

Received: 9 November 2024; Accepted: 27 February 2025
Published online: 11 March 2025

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Author contributions
All authors contributed to the study conception and design. Data collection and material preparation were performed by Zhang Shengwu. The first draft of the manuscript was written by Huang Juan. Funding acquisition, Huang Juan. All authors have read and agreed to the published version of the manuscript.

Funding
This research was funded by Joint Foundation of China University of Petroleum-Beijing at Karamay (No. XQZX20230002) and the Xinjiang Tianchi Talent Talent Program.

Declarations

Competing interests
The authors declare no competing interests.

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