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Temporal and Spatial Effects of Heavy Metal-Contaminated Cultivated Land Treatment on Agricultural Development Resilience

Danling Chen [1,2] and Wenbo Hu [1,3,*]

[1] College of Public Administration, Huazhong Agricultural University, Wuhan 430070, China
[2] The Key Laboratory of Natural Resources Monitoring in Tropical and Subtropical Area of South China, Ministry of Natural Resources, Guangzhou 510663, China
[3] College of Engineering, City University of Hong Kong, Hong Kong, China
* Correspondence: wenbo_hu2018@163.com

Abstract: Heavy metal-contaminated cultivated land treatment (HMCLT) plays an essential role in the realization of sustainable utilization of cultivated land resources and sustainable agricultural development. Evaluating this policy's impact on agricultural development resilience (ADR) has great practical significance. This paper reveals the impact HMCLT has on ADR from the perspectives of time and space, utilizing data from Hunan province between 2007 and 2019. The synthetic control method (SCM) and spatial Durbin model (SDM) are employed for investigating the temporal and spatial effects HMCLT has on ADR. The results demonstrate that the HMCLT policy has effectively improved the pilot cities' ADR and can enhance ADR in adjacent areas from a spatial perspective. In addition to HMCLT policy, financial support for agriculture, farmers' per capita disposable income, and rural population density are key factors affecting ADR. However, they all have a crowding-out effect on the ADR in neighboring areas. Due to these circumstances, while the governments make efforts in promoting the policy design and improvement of HMCLT, increasing the disposable income of farmers, narrowing regional differences in government financial support and human capital, and promoting regional interactions are essential to enhance ADR. This study formulates valuable insights for policymakers and researchers in the field of sustainable agricultural development.

Keywords: cultivated land use; agricultural high-quality development; impact mechanism; spatio-temporal effect

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1. Introduction

Agricultural development resilience (ADR) refers to the ability of the agricultural system to maintain its original structure, essential functions, and basic services following the absorption and resolution of external interference [1]. ADR improvement can result in many benefits, such as tackling inevitable shocks, ensuring food security, cultivating the endogenous forces that drive agricultural economic growth, and creating a modernized agricultural system [2,3]. In 2022, the Chinese "Central No.1" document noted the importance of actively responding to a variety of risks and challenges both domestically and abroad, stabilizing the essential agricultural market, maintaining and promoting agricultural production, and enhancing the stable and sustainable development of both the economy and society, thereby affirming the state and position of agriculture and the importance of ADR enhancement. Cultivated land is the fundamental resource of social and economic activities and can be regarded as the agricultural "input-output" system, in addition to playing a crucial role in ADR enhancement. However, as urbanization and industrialization progress rapidly, the ecological costs resulting from population growth and food production will keep increasing significantly. Agriculture faces imminent challenges, including heavy metal-contaminated cultivated land and groundwater over-extraction [4–6]. As reported, more than one-fifth of cultivated land has been polluted by heavy metals in China, resulting in the problems of grain production reduction and food pollutants exceeding limits [7]. This has become an issue of great concern for both central and local governments.

To promote the circulation of cultivated land while also alleviating the negative impact environmental pollution has on regional agricultural production and sustainable agricultural development, China implemented the pilot policy of heavy metal-contaminated cultivated land treatment (HMCLT) in 2014. For example, promoting collaboration to the enhancement of technological innovation and conducting research on the restoration of cultivated land. Meanwhile, much investment has been put into this field. Around 150 billion to 200 billion yuan can be invested annually; moreover, as predicted, the total investment is expected to exceed 5.7 trillion yuan in the long run. In practice, 1.7 million mu (a Chinese unit of area, equal to around 1133 km^2) area of cultivated land in the Changsha-Zhuzhou-Xiangtan urban agglomeration of Hunan province was chosen as the pilot area, which is a significant pilot project in eliminating the heavy metal-contaminated pollution. Numerous measures were taken according to the condition of the heavy metal-contaminated cultivated land. Alternative crop planting or fallow methods were employed for cultivated land with less pollution. Meanwhile, advanced agricultural technologies (e.g., removing chemical materials) were utilized for cultivated land with more pollution to achieve HMCLT. Anticipated outcomes were achieved after the implementation of HMCLT, with the average cadmium reduction rate of the pilot area reaching approximately 60%, as this triggered the additional policy design and practice. In addition, along with the improvement of top-down policy design and bottom-up practice exploration of HMCLT, the implementation of HMCLT has gradually been expanded. Some reports have revealed that the coordination between agricultural production and ecology in the pilot areas has exhibited gradual improvement because of the adoption of this policy. At the same time, agricultural production is becoming increasingly stable because it can cope with the negative impacts of natural disasters and cumulative energy shortages [8]. HMCLT has long been seen as a driving force for green agricultural development that can continuously optimize the agriculture system through resource reallocation and spillover effects, thereby enhancing ADR. In practice, since Hunan province was chosen as the pilot area, the ecological and economic effects of HMCLT have arisen; however, its output growth and structural changes in agriculture have remained rigid, and agricultural production, distribution, and consumption continue to be relatively low. Therefore, further optimizing the policymaking of HMCLT is necessary as a means of enhancing its sustained role in agricultural development.

Relatively few studies have investigated the relationship between heavy metal-contaminated cultivated land management strategies and ADR. Previous literature has mainly focused on the role played by heavy metal-contaminated cultivated land technologies in the sustainable use of cultivated land and ecological restoration, including improving sustainable agricultural development potential through the green chemical material of soil [9], utilizing the biological methods to remove heavy metals in soil [10], and planting wind-proof, sand-fixing, water-conservation plants [11]. With an increasing number of insights into cultivated land loss, degradation, and ecological pollution, numerous scholars have focused on the impact management strategies have on agricultural financing [12], agricultural productivity stability [13], and sustainable agricultural development [14]. Meanwhile, they focused on agricultural production, ecological changes, and the farmers' income after the implementation of HMCLT policies [15–18]. In addition, a small number of scholars have explored the green development effects of HMCLT [19], reflecting the indirect influence HMCLT has on ADR.

These studies provided great practical value for enhancing the effects of HMCLT on ADR. However, they could not reveal the influencing mechanism of the effects HMCLT has on ADR. Previous research has mainly employed qualitative analysis, biochemical experiments, or detection, but ignored the characteristics and effects of HMCLT policy at the macro level. At the same time, heavy metal-contaminated cultivated land has the characteristics of peripheral aggregation, meaning that heavy metal-contaminated cultivated land close to the pilot area may have a higher risk of being polluted [20]. However, a small number of papers have comprehensively studied the spatial effects of HMCLT on ADR, providing tailor-made policy advice for the regional joint prevention and treatment of heavy metal-contaminated cultivated land. Therefore, this paper theoretically reveals the internal mechanism of the effects HMCLT has on ADR. This study uses the HMCLT pilot policy in Hunan province in a quasi-natural experiment. Synthetic control method (SCM) and spatial econometric models are employed for empirically testing and analyzing the temporal and spatial effects HMCLT has on ADR. This paper also makes several contributions, providing tailor-made suggestions for the promotion of HMCLT and the achievement of green and sustainable agricultural development, while providing policy references for HMCLT policy enhancement in similar regions.

2. Analysis of the Spatio-Temporal Mechanism

HMCLT is a complex issue that aims to adjust interactions between ecological environment services and human activities to realize sustainable agricultural production. With the dynamics of HMCLT, a series of policy changes, capital support, and technological innovation took place that can impact ADR. Specifically, HMCLT can positively affect ADR from both temporal and spatial perspectives (Figure 1).

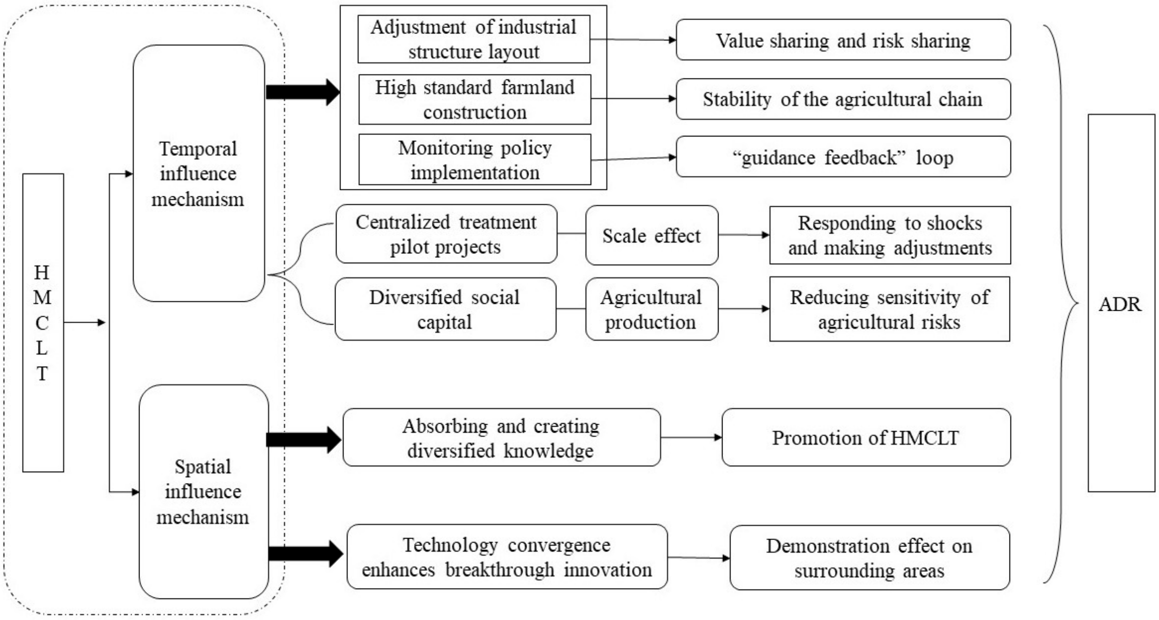

Figure 1. Temporal and spatial influence mechanism of HMCLT on ADR.

2.1. *Temporal Mechanism of HMCLT on ADR*

Firstly, central and local governments and their departments continuously issue policies and regulations as a means of effectively intervening and regulating the scale and impact of HMCLT policy. In the case of adjusting the industrial structure and layout of HMCLT, stakeholders (including governments, enterprises, and farmers) are able to realize the sharing of interests and risks with their involvement in HMCLT [19], thereby helping the farmers recover from the external shock and improve the overall ADR. At the same time, implementing policies, such as the vigorous promotion of high-standard farmland construction and comprehensively transforming agricultural land in key areas, can effectively improve cultivated land quality and productivity in pilot areas, optimize the production, storage, and transportation of agricultural products, and assist the regions in responding to the potential risks in the agricultural production chain [21,22]. In addition, the bottom-up policy supervision provides feedback on farmers' actual expectations and attitudes towards HMCLT from a demand perspective, which contributes to forming a production elasticity "guidance-feedback" loop [23–25]. This serves to balance the relationship between agricultural production and consumption while improving ADR.

Secondly, massive investment in special funds for HMCLT, in addition to exploring and establishing diversified fund-raising channels, provides a solid foundation for ADR enhancement in HMCLT [26]. This massive investment will swiftly promote the HMCLT to become comprehensive and centralized, which forms a scale effect and accumulation effect that can help the agricultural system tackle the changing issues [27,28], thereby affecting ADR. Meanwhile, the farmers can promote the labor resources in agricultural development [22], and higher labor productivity is conducive to ADR enhancement. In addition, diversified social capital into HMCLT can help stabilize and ensure sufficient fund resources, stimulating agricultural production and output, and reducing the sensitivity of agricultural risks [26].

2.2. Spatial Mechanism of HMCLT on ADR

HMCLT is an effective tool for promoting the sustainable utilization of cultivated land resources, in addition to the penetration and sharing of new-generation information technology into agriculture (e.g., the Internet of Things, cloud computing, and big data), which will inevitably result in spatial spillover effects. The effects are mainly manifested in the following aspects. Firstly, the cultivated land system must adapt to the dynamic changes and changing environment, advanced technologies, and novel products that are commonly used for achieving HMCLT. The combination of technologies, knowledge, and information can be regarded as a "technology pool" that can promote the absorption of diversified knowledge in agriculture [29,30]. In this regard, a regional knowledge network of agricultural production can be formed to promote HMCLT and enhance ADR spillover effects. Secondly, the cross-fusion of HMCLT technologies can generate breakthrough innovations, which can change resource allocation and reduce the dependency on agricultural production on labor [19]. At the same time, the effects can have an impact on the surrounding areas while mutually promoting ADR between regions. Finally, the pilot area of HMCLT in a specific region can result in the enhancement of the ADR level of the surrounding regions through information sharing and resource transfer. Ultimately, the endogenous momentum of coordinated ADR promotion can be strengthened from economic, production, and ecological perspectives.

3. Material and Methods

This paper adopts the synthetic control method (SCM) and spatial econometrics model for studying the spatio-temporal effects of ADR affected by HMCLT for the following two considerations. Firstly, as a non-parametric estimation method, SCM can be used for evaluating the treatment effects in comparative studies. The basic principle of the approach is to assign a total weight of 1 to a non-negative weighted synthesis of an optimal control group that is consistent with the trend of treatment group unit changes. On this basis, policy effects can be evaluated by calculating the difference between the treatment group and the synthetic group before and after policy implementation. In comparison to the difference-in-differences (DID) method, this method eliminates endogenous and control group selection bias and can be applied for assessing policy effects in small samples [31]. Therefore, this method performs an HMCLT experiment and constructs a "synthetic group" of a "counterfactual state" using data weighting and linear fitting for other regions. This means that differences in ADR between the implementation (treatment group) and the non-implementation (synthetic group) can be compared as a means of evaluating the net effect of the policy from a temporal dimension. Secondly, based on the theoretical framework of the impact HMCLT has on ADR, the existence of spatial spillover effects of HMCLT can be confirmed. If such effects are neglected, the effects and mechanisms obtained will be biased. Therefore, spatial econometrics models are used for studying the effects of HMCLT on ADR.

3.1. Measurement and Index Selection of ADR

ADR is the ability of the agricultural system to resist external shocks, recover from shocks, and transform to other paths as a means of achieving adaptive development, which is composed of the three interrelated capabilities of resistance, recovery, and regeneration. The pressure-state-response (PSR) model is commonly used for assessing environmental quality [32–36]. Due to its advantages in revealing the interactions of multiple factors, the PSR model is widely used in the field of eco-environmental quality [32], regional ecological change [33], and ecosystem health [34]. With this model, the pressure (P) represents the damage and disturbance of external pressure to the system, the state (S) is the current state of the system under pressure, and the response (R) is the response measures that are taken in situations where the system faces external pressure.

ADR is a complex process that involves the "input-transformation-output" cycle [37,38], where the output is heavily reliant on the adaptation and adjustment of the input. From this perspective, the PSR model is adequately used for mapping the realization of ADR. Therefore, based on existing conclusions regarding the definition and connotation of resilience, together with the PSR model, the comprehensive measurement index system of ADR is constructed from the three dimensions of resistance (P), recovery (S), and regeneration (R). More specifically, resistance is the ability of the agricultural system to reduce external shocks under uncertainty, which has a close relationship with the state of cultivated land, its water conservancy infrastructure conditions, and machinery input density. Therefore, the proportion of the effective irrigation area of cultivated land (the area of effective irrigation/the area of cultivated land), agricultural machinery usage intensity (total power of agricultural machinery/the area of cultivated land), and the proportion of the disaster area of cultivated land to the total area of cultivated land are chosen as indicators for measuring resistance. In addition, recovery is the ability of the agricultural system to recover from the impact of pressure, as reflected in terms of the agricultural economy, society, and stakeholders before and after the external shocks. Therefore, the average agricultural output value (agricultural output value/agricultural population), rural road network accessibility, and the expenditure of farmers are chosen as indicators for measuring recovery. Finally, regeneration emphasizes the agricultural system's self-adjustment and adaptation before and after the external shocks, including remedial measures that the government takes or farmers for repairing and enhancing the agricultural system. Therefore, investment in agricultural infrastructure, the pure amount of agricultural fertilizer application per unit sown area, the amount of agricultural plastic film use per unit sown area, and rural electricity consumption are chosen as regeneration indicators. On this basis, the entropy weight method [39,40] is used for calculating ADR following the standardization of each indicator.

3.2. Research Object and Model Specification

The majority of heavy metal-contaminated cultivated land in China is distributed in 14 provinces (municipalities and autonomous regions), including Hebei, Jiangsu, Guangdong, Shanxi, Hunan, and Henan, which accounts for approximately one-fifth of the total cultivated land area, thus the implementation of HMCLT is of great importance. The Chinese government started piloting and promoting the HMCLT policy in 2014 in several regions. Compared to other pilot areas, Hunan province is an area that is rich in nonferrous metals and non-metallic minerals, and its cultivated land has been contaminated, and it is in a severe condition. However, the planting area and yield of Changsha ranked first in China. As a result, governments and scholars have given extensive attention to the pilot policy of HMCLT. Investigating the effects of HMCLT on ADR in Hunan province is conducive to the promotion of HMCLT and has significant value for sustainable agricultural development in other regions of China and even the world.

The SCM was used in this study for investigating the time effect of HMCLT on ADR in Hunan province. It is assumed that the total sample is the relevant data of $J + 1$ regions in $t \in [1, T]$, and only the first region ($i = 1$) implements the HMCLT policy during the period $t = T_0$, so that the region is the treatment group, and the dependable variable is $\text{Resilience}_{i,t}$.

The remaining J regions are the control city groups without the implementation of the pilot policy. Under the SCM, $\text{Resilience}_{i,t} = \text{Resilience}'_{i,t} + D_{it}\eta_{it}$ (where $\text{Resilience}_{i,t}$ and $\text{Resilience}'_{i,t}$ represent ADR in one city in the treatment group and the control group, D_{it} indicates whether it is a dummy variable of the HMCLT pilot, while η_{it} represents the net effect of the policy). As it is possible to directly observe $\text{Resilience}_{i,t}$, but not $\text{Resilience}'_{i,t}$, in order to obtain the estimated parameter value η_{it}, the "counterfactual" method must be used to construct the variable $\text{Resilience}'_{i,t}$ as follows:

$$\text{Resilience}'_{i,t} = \alpha_i + \delta_t Z_i + \lambda_t \mu_i + \varepsilon_{it} \tag{1}$$

Z_i is the control variable of this paper; δ_t is the estimation coefficient vector; λ_t is the unobservable factor vector; μ_i is the individual fixed effect; and ε is the random error term. This study fitted the characteristics of the cities in the treatment group where no policies have been implemented by weighting the cities in the alternative control group. Therefore, Formula (1) is converted into:

$$\sum_{j=2}^{J+1} v_j w_{it} = \alpha_t + \beta_t \sum_{j=2}^{J+1} v_j Z_j + \lambda_t \sum_{j=2}^{J+1} v_j \mu_i + \sum_{j=2}^{J+1} v_j \varepsilon_{it} \tag{2}$$

$v_j (j = 2, 3, \cdots, J+1)$ can constitute $J + 1$-dimensional multiple vector group $V = (v, \cdots, v_{J+1})$. For those $\forall J$ that meet the conditions of $V_J \geq 0$ and $v_2 + \cdots + v_{J+1} = 1$, it is further assumed that there is a vector group $V^* = \left(v_2^*, \cdots, v_{J+1}^*\right)'$, which meets the conditions of $\sum_{j=2}^{J+1} v_j^* w_{jt} = w_{11}, \cdots, \sum_{j=2}^{J+1} v_j^* w_{jT0} = w_{1T0}$ and $\sum_{j=2}^{J+1} v_j^* Z_j = Z_1$. If $\sum_{i=1}^{T_0} \lambda'_t \lambda_t$ is full rank, it can be concluded that:

$$\text{Resilience}'_{i,t} - \sum_{j=2}^{J+1} v_j^* w_{jt} = \sum_{j=2}^{j+1} v_j^* \sum_{s=1}^{T_0} \lambda_t \left(\sum_{i=1}^{T_0} \lambda'_t \lambda_t \right)^{-1} \lambda'_s \left(\varepsilon_{js} - \varepsilon_{is}\right) - \sum_{j=2}^{J+1} v_j^* \left(\varepsilon_{js} - \varepsilon_{is}\right) \tag{3}$$

According to Abadie et al. [41], $T_0 < t \leq T$, $\sum_{j=2}^{J+1} v_j^* w_{jt}$ is regarded as an unbiased estimation of $\text{Resilience}'_{i,t}$. At this timepoint, the core parameter estimator is obtained via regression analysis using Formula (1) $\eta_{1t} = w_{it} - \sum_{j=2}^{J+1} v_j^* w_{jt}$.

The pilot policy of HMCLT in Hunan province was implemented in 2014, thus 2014 is the time point of policy impact for this study. The three aforementioned cities (i.e., Changsha, Zhuzhou, and Xiangtan) are taken as the treatment group for the empirical study, while the remaining cities in Hunan province (excluding Tujia and Miao Autonomous Prefecture in Xiangxi) are taken as the control group. The research period for this paper is 2007–2019.

In addition, the theoretical analysis framework of this paper indicates an apparent spatial dependence between HMCLT and ADR. Spatial econometric models have been employed in numerous fields, such as eco-environmental quality [42], cultivated land protection policy [43], cultivated land use efficiency [44], and land supply [45], indicating that these spatial models are suitable for this paper. Therefore, the following spatial Durbin model (SDM) is constructed in this paper for investigating the spatial effects of HMCLT on ADR in Hunan province, and the spatial autoregressive model (SAR) results are compared.

$$\text{Resilience}_{it} = c_0 + \rho \sum_{j=1}^{n} W\text{Resilience}_{it} + c_1 Policy_{it} + c_2 Policy_{it} + \kappa_1 X_{it} + \kappa_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{4}$$

$$\text{Resilience}_{it} = h + \rho \sum_{j}^{n} W\text{Resilience}_{it} + h_1 Policy_{it} + \rho \sum_{j}^{n} W Policy_{it} + X_{it}\theta_3 + \varphi_i + p_i + \varsigma_{it} \tag{5}$$

Formula (4) is the SDM model, Formula (5) is the SAR model, i and t represent year and city, and $Policy$ is the core explanatory variable. X_{it} refers to control variables. W is the nested spatial weight matrix, μ_i and φ_i represent the individual effect, λ_t and p represent the time effect, and ε_{it} and ς_{it} represent the random error term.

3.3. Data Sources

The original data used in this paper is obtained from the Hunan Provincial Statistical Yearbook, Hunan Rural Statistical Yearbook, Cities and Prefectures Local Statistical Yearbook in Hunan province, and the national economic and social development statistical bulletin for each city. Missing values for some years or regions are filled using neighboring values or the linear fitting method. However, due to the data unavailability in Xiangxi Tujia and Miao Autonomous Prefecture, this region was not included in this paper. Table 1 provides descriptions of variables and indicators used in this analysis.

Table 1. Summary statistics of the variables.

Variables	Unit	Descriptions
Nature	Hectare	The area of cropland [46,47]
Modernization	%	The ratio of the added value of the service industry to that of agriculture, forestry, animal husbandry, and fishery [48]
Finance	%	The proportion of agricultural and forestry financial expenditure in total financial expenditure [49]
Income	Yuan	Per capita disposable income of farmers [50]
Information	Person	The total workload of all full-time employees and the number of full-time equivalent part-time employees [51]
Labor	Person/km^2	Rural population density [52]
Intensive	_	Location quotient [53]

4. Results

4.1. Temporal Effect of HMCLT on ADR

4.1.1. Descriptive Analysis of ADR

The ADR values of all cities in Hunan province from 2007 to 2019 were calculated based on the entropy weight method. The natural fracture point method was then applied to map the spatial pattern of ADR in Hunan province (Figure 2). From a time dimension, the evolution of ADR in Hunan province is divided into two stages: slow rise (2007–2013) and steady rise (2014–2019), with significant phased characteristics. In 2007, the ADR value in Hunan province was 0.128, and it fluctuated to 0.238 in 2013 before proliferating to 0.520 in 2019. Shaoyang, Yueyang, Yongzhou, and Changde first experienced falling and then rising, the ADR level of Zhangjiajie, Yiyang, Hengyang, and Chenzhou showed a feature of first rising and then fluctuating, while Huaihua demonstrated a downward trend. At the same time, the ADR level of Changsha, Zhuzhou, and Xiangtan fluctuated and rose. From a spatial dimension, the intra-provincial differentiation of ADR in Hunan province exhibited a widening trend, with higher-value cities moving from the initial concentration in Yueyang, Changde, and Yiyang to Changsha-Zhuzhou-Xiangtan, while the range of lower-value cities decreased in circles. The spatial pattern shows “ridge” distribution characteristics along the southwest line, with Changsha-Zhuzhou-Xiangtan urban agglomeration at the core and extending toward the northeast.

4.1.2. Weight Setting of Synthetic Pilot Cities

This study used data from 2007 to 2019 and employed Stata 15 software for fitting and synthesizing virtual control cities in 10 control city groups. Table 2 shows a comparison of dependent variables between pilot cities and synthetic pilot cities and demonstrates that ADR levels in Changsha, Zhuzhou, and Xiangtan were similar prior to HMCLT policy implementation. Regarding the difference in independent variables, the difference between *Informatization* in Changsha and *Nature* in Zhuzhou and Xiangtan was relatively high.

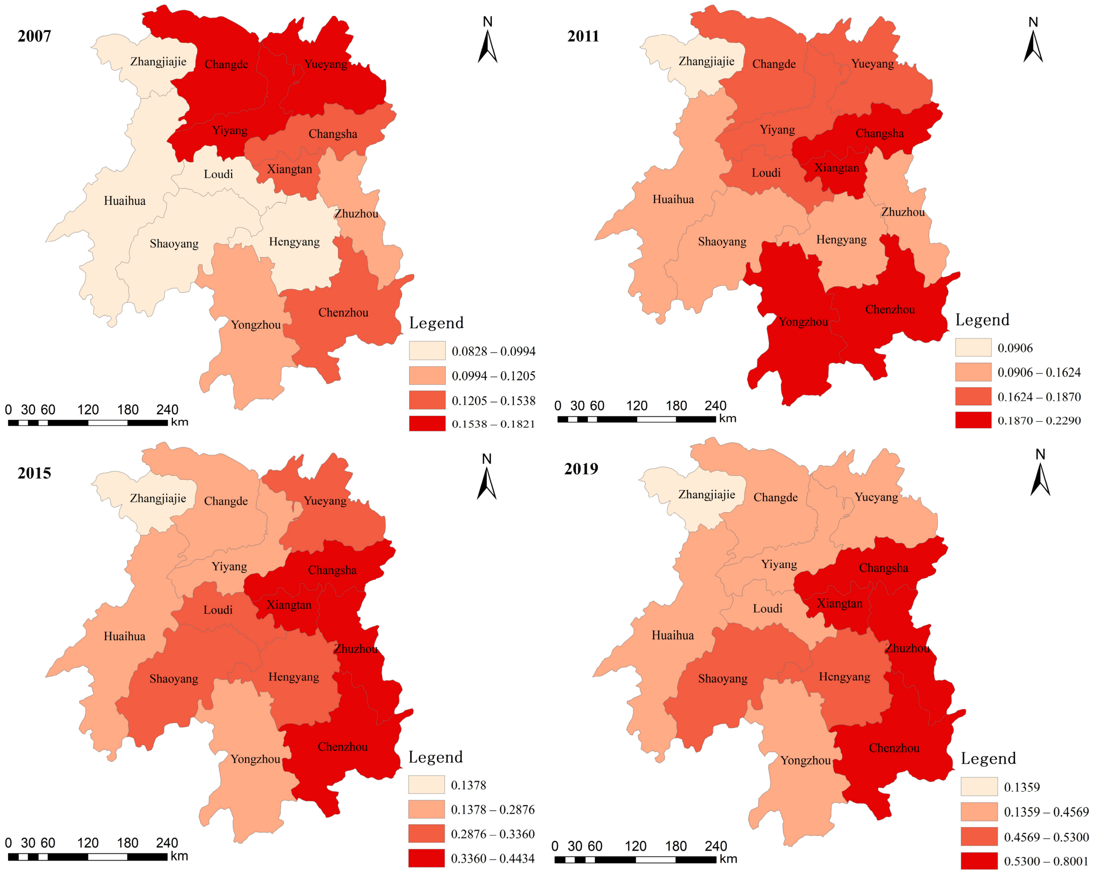

Figure 2. Evolution of ADR in Hunan province from 2007 to 2019.

Table 2. Independent variables of pilot cities and synthetic pilot cities.

Independent Variables		**Changsha**			**Zhuzhou**			**Xiangtan**	
	Synthetic	**Real**	**Difference**	**Synthetic**	**Real**	**Difference**	**Synthetic**	**Real**	**Difference**
Nature	6.772	6.450	0.323	6.759	5.919	0.840	6.643	5.716	0.927
Modernization	0.072	0.023	0.050	0.108	−0.091	0.199	0.184	0.040	0.144
Finance	0.122	0.250	0.128	0.150	0.301	0.151	0.120	0.009	0.111
Income	8.568	9.331	0.763	8.739	8.976	0.237	8.586	9.000	0.414
Information	2.634	5.496	2.861	2.571	2.076	0.495	2.414	2.193	0.221
Labor	7.000	7.256	0.256	7.896	8.148	0.253	7.032	7.776	0.744
Intensive	0.771	0.977	0.206	1.109	1.124	0.015	0.837	1.328	0.491

The weight combinations selected when three HMCLT pilot sites in Changsha, Zhuzhou, and Xiangtan were chosen as the composite areas can be seen in Table 3. Yongzhou is the city that constructed and synthesized Changsha, and its weight is 1. At the same time, cities with positive contributions to Zhuzhou are Hengyang, Yongzhou, Chenzhou, and Changde. Yongzhou and Chenzhou can be forged to synthesize Xiangtan, and the ADR level of these two cities can be summed up by the respective weights of 0.683 and 0.317 for ADR level simulation.

Table 3. Weights of control groups in each synthetic control area.

Region	**Synthetic Area (Weight)**	**RMSPE**
Changsha	Yongzhou (1), Others (0)	0.0285
Zhuzhou	Hengyang (0.467), Yongzhou (0.331), Chenzhou (0.118), Changde (0.084), Others (0)	0.0114
Xiangtan	Yongzhou (0.683), Chenzhou (0.317), Others (0)	0.0211

4.1.3. SCM Results

The evolution of the ADR of pilot cities and their synthetic cities for HMCLT can be seen in Figure 3, which shows that prior to HMCLT policy implementation, the ADR levels of Zhuzhou and Xiangtan were closer to their synthetic ADR level, which indicates that the synthetic pilot can fit the real pilot. It is notable that some differences in ADR exist between Changsha and its synthetic pilot area because Changsha is the economic and political center of the Changsha-Zhuzhou-Tanzhou urban agglomeration. Green agricultural technology, modern agricultural development, and agricultural labor input are at leading levels, thus the independent variables of other cities cannot fit the trends of ADR in Changsha.

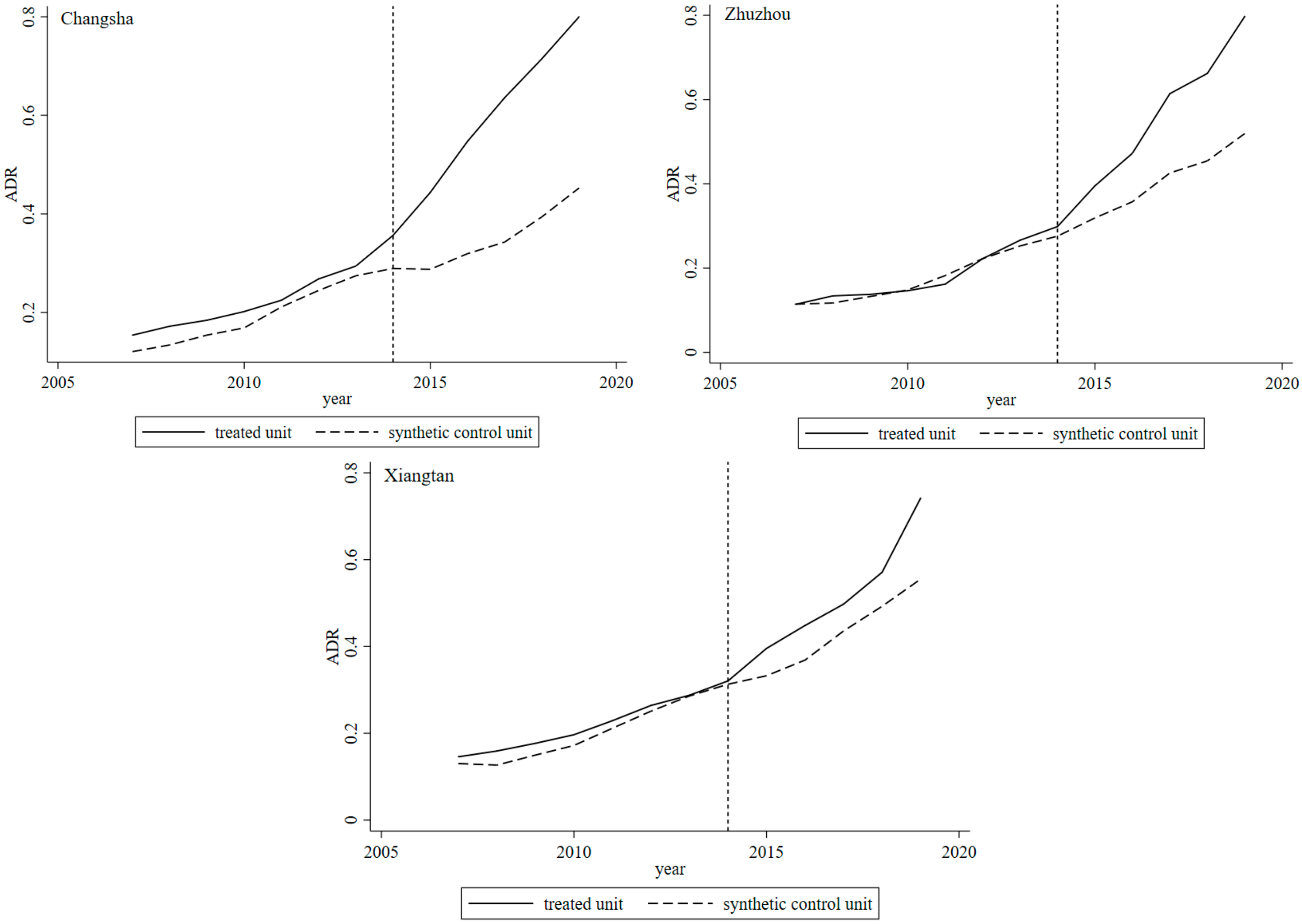

Figure 3. ADR trends in real and synthetic pilot cities.

According to the fitting degree after the implementation of the HMCLT policy, ADR levels in Changsha, Zhuzhou, and Xiangtan improved. Among them, the standards of Changsha improved most significantly, followed by Zhuzhou and Xiangtan. In addition, the impact of the HMCLT pilot policy on ADR was found not to be significant in 2014. One possible reason is that R&D activities can be delayed due to the inducement of the HMCLT policy, thereby inhibiting the policy's effects on ADR that year. The pilot policy of HMCLT should be further explored in this stage. The policy effect will be weakened by the constraints of social capital, the ineffectiveness of management strategies, and the imperfect guidance from the government.

4.2. Spatial Effect of HMCLT on ADR

The effects the pilot policy has on ADR have been investigated. Does the HMCLT policy also lead to ADR improvement in neighboring cities through spillover effects? This section investigates the spatial impact of HMCLT on ADR.

4.2.1. Spatial Correlation Analysis

Before spatial regression, the spatial autocorrelation of ADR was tested using Moran's I index (shown in Table 4). ADR was significant in the research period, with the exception of 2010, which indicates an obvious spatial dependence between ADR in various regions, and the SDM is a reasonable means for analyzing spatial effects.

Table 4. Moran's I test results.

Year	Moran's I	Z	Year	Moran's I	Z
2007	0.017 **	2.120	2014	0.025 ***	2.484
2008	0.004 **	1.910	2015	0.045 ***	2.848
2009	0.000 **	1.855	2016	0.054 ***	3.005
2010	−0.075	1.255	2017	0.054 ***	2.971
2011	−0.021 *	1.398	2018	0.048 ***	2.838
2012	−0.003 **	1.980	2019	0.054 ***	2.977
2013	0.040 ***	2.781			

Note: *, **, and *** represent 10%, 5%, and 1% statistical levels, respectively.

4.2.2. Spatial Effect Estimation Results

In order to avoid the bias and error of the model setting on the model estimation, the maximum likelihood estimation method was used in this study, and the Wald test and LR test were employed to verify the effectiveness of the SDM model. The results found that the Wald test and LR test rejected the original hypothesis at the 5% confidence level, while the results of the Hausman test showed the effectiveness of the fixed effect model. Therefore, the SDM model based on individual fixed effects was chosen for studying the spatial effects of HMCLT on ADR. The results of the SAR model were also provided for comparison. The coefficient of *Policy* was found to be significantly positive at the 1% level in these two models, which indicates that HMCLT can improve ADR, further verifying the results' robustness, as shown in Table 5. The W * Policy coefficient was 0.093 and it was significant, which suggests that HMCLT has spillover effects on ADR in neighboring areas. Under the dual pressure of local government performance improvement and agricultural economic growth, a "bottom-by-bottom competition" phenomenon exists in HMCLT policy, thus the spatial effects of the policy were significantly enhanced. At the same time, to realize high-quality agricultural development, HMCLT can further promote agricultural production development and technological innovation in the pilot areas. Specifically, the ADR in neighboring cities can be affected through economic interaction, industrial cooperation, and technological communication. Therefore, establishing the policy governance system and information-sharing mechanism based on regional cooperation, and realizing the exchange and sharing of agricultural resources between regions are effective means for improving the future policymaking of HMCLT.

4.2.3. Decomposition and Estimation Results of Spatial Effects

Based on the work of LeSage and Pace [54], the spatial effects of HMCLT on ADR were further characterized into direct, indirect, and total effects to avoid estimation result bias. As Table 6 demonstrates, the coefficient of direct effects of HMCLT on ADR is 0.138, which indicates ADR can be significantly improved by the HMCLT policy. The coefficient of indirect effects of HMCLT on ADR is 0.106, which suggests that the HMCLT policy had significant spatial effects on ADR in adjacent areas. This is consistent with the estimated results in Section 4.2. In addition, it should be noted that although HMCLT promotes the formation of an inter-regional governance network, it also produces various transaction costs, thereby weakening the spillover effects HMCLT has on ADR. From the perspective of control variables, the direct and indirect effects of *Finance*, *Income*, and *Labor* were significant at the 5% level, and the direct and indirect effects of Finance and Labor were significantly negative. It can be inferred that the financial support from the local government for agriculture and the scale of human capital in agriculture is currently relatively low, which inhibits ADR improvement in the local region and surrounding areas.

Table 5. The results of the spatial effect of the driving forces on the ADR.

	SDM	**SAR**
Policy	0.137 *** (7.41)	0.151 *** (7.72)
Nature	0.002 (0.02)	−0.084 (1.24)
Modernization	−0.001 (0.22)	−0.002 (0.44)
Finance	−0.402 ** (2.43)	−0.061 (0.38)
Income	0.118 * (1.80)	0.061 ** (2.42)
Information	−0.012 (1.44)	−0.009 (1.06)
Labor	−0.142 *** (3.85)	−0.091 ** (2.53)
Intensive	−0.0001 (0.21)	0.0004 (0.58)
*W * Policy*	0.093 * (1.83)	
*W * Nature*	−0.251 * (1.74)	
*W * Modernization*	0.002 (0.12)	
*W * Finance*	−3.370 *** (3.77)	
*W * Income*	−0.223 *** (2.79)	
*W * Information*	−0.039 ** (2.06)	
*W * Labor*	−0.684 *** (4.73)	
*W * Intensive*	−0.007 ** (2.19)	
ρ	0.027 (0.14)	0.464 *** (5.30)
σ^2	0.002 *** (9.19)	0.003 *** (9.13)
R-squared	0.257	0.423
Log-L	286.095	257.971
N	169	169

Note: *, **, and *** represent 10%, 5%, and 1% statistical levels, respectively. The numbers in the brackets are the standard error of the coefficients. The same is true for the table below.

Table 6. Decomposition results of spatial effects.

	Direct Effects	**Indirect Effects**	**Total Effects**
Policy	0.138 *** (7.17)	0.106 ** (2.21)	0.244 *** (4.99)
Nature	−0.003 (0.03)	−0.250 * (1.78)	−0.252 *** (2.58)
Modernization	−0.0004 (0.11)	0.002 (0.14)	0.002 (0.11)
Finance	−0.427 ** (2.28)	−3.591 *** (2.60)	−4.018 *** (2.68)
Income	0.118 * (1.84)	−0.236 *** (2.70)	−0.118 * (1.81)
Information	−0.011 (1.41)	−0.040* (1.95)	−0.051 ** (2.49)
Labor	−0.144 *** (3.95)	−0.717 *** (6.39)	−0.860 *** (6.98)
Intensive	−0.0002 (0.34)	−0.008 * (1.88)	−0.008 * (1.82)

Note: *, **, and *** represent 10%, 5%, and 1% statistical levels, respectively.

5. Discussion

5.1. Direct Associations

An increasing amount of attention is paid to environmental protection and agricultural production. The central government has made numerous efforts to improve the agricultural environment, especially in the field of heavy metal-contaminated cultivated land. To investigate the effectiveness of the HMCLT policy issued in 2014, SCM was employed to explore this effect, which can provide implications for the central and local governments to take tailor-made actions to address similar issues. The outcomes of this paper demonstrate that the HMCLT can significantly improve ADR in the pilot areas (i.e., Changsha, Zhuzhou, and Xiangtan). Therefore, it can be inferred that the top-down policies are conducive to enhancing ADR to serve agricultural production and protect the environment. Governments need to design additional policies to tackle similar challenges. Moreover, the results of SCM in Changsha show a different trend compared to other cities before the pilot policy. A possible reason for this situation is that the research was conducted in Hunan province, and Changsha maintains a leading and unique role in the research area [55]. The situation in Changsha was hard to synthesize in other Hunan province cities. Therefore, as an increasing number of policies are implemented in different regions, more studies can be conducted to verify the outcomes obtained in this research.

5.2. Spillover Effects

According to the influence mechanism of this paper and Moran' I index, spatial dependence exists in Hunan province's ADR. To explore the spatial effects of the HMCLT policy on ADR, SDM and SAR models were utilized. The results showed that the direct effects and spatial effects of the HMCLT policy on ADR were significant at the 5% level, indicating that the pilot policy cannot only affect its local region but also impact the ADR of its neighboring regions. This contributes to the overall improvement of ADR in all regions. The region's financial expenditure and population density were also significant in the relationship between HMCLT and ADR, but the coefficients were negative. On the one hand, "urban-biased" development causes the proportion of rural and agricultural spending sourced from central finance revenue to decrease. Moreover, there is no strictly spatial match between financial spending and agricultural and rural development needs. On the other hand, a larger number of rural populations commonly make the local government focus on addressing the problem of insufficient agricultural production capacity, and ignore the environmental benefits, thus inhibiting the enhancement of ADR.

In addition, following Liu et al. [56], the policy of HMCLT can be promoted due to its positive and significant effect. However, spatial heterogeneity should be paid special attention to. On the one hand, the market-based mechanism can play a crucial role in improving ADR, leading to competition with governments and weakening the policy effects [56–58]. On the other hand, the economic, environmental, and social conditions can vary significantly in different regions, thus requiring tailor-made actions and policies in various regions [59].

5.3. Theoretical Implications

This paper generated several contributions to the literature on the effects of HMCLT on ADR. Firstly, this paper constructed the ADR index system, enriching the agricultural development literature. This index system can provide references for researchers and policymakers to consider numerous aspects of agriculture to achieve sustainable development. Secondly, this paper integrated the SCM and spatial models into a holistic framework and investigated the HMCLT policy effects on ADR from the time and space perspectives, as this generates fresh insights into enhancing ADR. To our knowledge, this is the first paper to explore the impact of HMCLT policy on ADR, which can extend the boundaries of policy studies and provide implications for the central and local governments.

5.4. Policy Implications

HMCLT has the potential to drive rural revitalization and agricultural high-quality development. Moreover, this policy can result in ADR improvement in terms of economic, social, and ecological aspects through policy support, capital investment, and spillover effects. It is suggested that further strengthening the support of HMCLT on ADR and achieving agricultural modernization and rural revitalization are possible in the following aspects.

On the one hand, considering the practical role HMCLT policy plays in ADR improvement, it is essential to strengthen the policy design and framework from a top-down approach, advance agricultural technologies, and establish a green agricultural system in China. These measures will facilitate the adjustment of the agricultural production supply chain and improve the governance of agricultural ecology, which are conducive to HMCLT achievement. At the same time, strengthening the role of the government and introducing new business entities through the market-based mechanism will ensure policy implementation and its effectiveness.

On the other hand, due to the practical need for strengthening the spillover effects the HMCLT policy has on ADR, focusing on areas with strict resource constraints and heavy ecological pressure, and addressing imminent issues (e.g., water consumption, soil pollution, land degradation, and supply and demand imbalance) are essential. In addition, the priority of the policy implementation areas should be determined based on their situation. In addition, an information-sharing mechanism should also be built to facilitate collaboration among governments to improve ADR. These measures can enable the full utilization of the spillover effects of HMCLT.

6. Conclusions

The literature on agricultural development and sustainability has been extensive. However, the means to realize agricultural development and promote the resilience of agricultural development has been unclear. This paper has investigated the impact HMCLT has on ADR from the dimensions of time and space, using sample data from Hunan province between 2007 and 2019. The SCM and spatial Durbin model were comprehensively employed for studying the spatio-temporal effects of HMCLT on ADR. It was found that the HMCLT policy has effectively improved ADR in the pilot cities, while also enhancing ADR in the neighboring cities. In addition, financial support for agriculture, agricultural disposable income, and rural population density are also essential factors for ADR. However, these factors will have a crowding-out effect on the ADR of neighboring cities. This paper enriches the literature on the agricultural system and agricultural development theoretically and provides important implications for the central and local governments to improve ADR.

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