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Dynamic diffusion of hybrid rice varieties and the effect on rice production: evidence from China

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The widespread adoption of hybrid rice varieties in China is a successful example, showing the role of agricultural technology in terms of food security. However, the dynamic diffusion of hybrid rice varieties and their effect on rice production requires further study. Based on data on hybrid rice adoption at the provincial level from 1984 to 2011, we applied the Ordinary Least Squares (OLS) and Geographically and Temporally Weighted Regression (GTWR) models to investigate the spatial and temporal effects of hybrid rice adoption at national and provincial levels. Overall, the effects of hybrid rice adoption on rice production have decreased over time. However, the results showed possible spillover and crowding effects of hybrid rice adoption across provinces. In particular, the development of hybrid rice varieties in Hunan province has had a significant influence on changes in rice yield and the distribution of rice areas in other regions. This study, therefore, serves as a reference in understanding the dynamic distribution of high-yield rice variety adoption in relation to food security and for designing appropriate agricultural extension strategies. However, further research is needed to identify the determinants affecting changes in rice farming in complex environments and associated ecological systems.

KEYWORDS

spatio-temporal effect, hybrid rice, variety adoption, GTWR model, China

1. Introduction

Food security is one of the Sustainable Development Goals (SDGs) to be achieved by 2030 for the benefit of the global community. It is critical that we satisfy the increasing demands of the growing population created by land and water are becoming more scarce and high crop productivity is required to achieve stable food production under climate change (Atlin et al., 2017). As the progress of the Green Revolution has shown, the development of modern agricultural technologies plays an important role in ensuring sufficient food supplies and contributing to economic growth (Rosegrant and Hazell, 2001; Spielman and Pandya-Lorch, 2009). Agricultural technologies include a variety of technologies such as varieties, agricultural inputs, and management practices, as well as corresponding land preparation practices (Feder et al., 1985; Zheng et al., 2021). Of these, crop variety is prioritized, as farmers' selection of a specific crop variety determines crop productivity and its variability (Spielman and Smale, 2017; Singh et al., 2020). The widespread adoption of modern varieties is the primary factor leading to yield growth. Both national and international research institutions have attempted to promote and facilitate the adoption of improved rice and wheat varieties (Lin, 1992; Fan et al., 2005; Yamano et al., 2016). However, the diffusion of varieties across regions and countries is uneven and unequal (FAO, 2002). Given that the development of plant breeding technology is vital to improving the yield potential of food crops, understanding the diffusion of modern varieties and its effect on food production is imperative for better and more efficient design of technology transfer systems (Qaim, 2020).

Rice is the main staple food for half of the global population and contributes substantially to farm household income and economic growth (Zeigler and Barclay, 2008; Spielman and Pandya-Lorch, 2009). High-yield varieties (HYVs) of rice have helped many developing countries meet the increasing food demand and achieve poverty reduction, and China is a successful example of the extraordinary progress that can be made (Fan et al., 2005; Mishra et al., 2016). Rice varieties include the hybrid bred rice variety and conventionally bred variety. The distribution of semi-dwarf rice varieties with high yield potential and the commercial dissemination of hybrid rice are the two most important achievements in rice research in China (Lin, 1992). Hybrid rice is a first-generation (F_1) crop developed by crossing two distantly related rice varieties, one of which is male (sterile). The range of yield advantage of hybrid rice is over 15–20% higher than that of conventionally bred rice (Ma and Yuan, 2015; Singh et al., 2018). The duration from the initiation of hybrid rice research by Yuan Longping in 1964 to large-scale hybrid seed production in 1975 and subsequent commercial production in 1976 was 10 years (Ma and Yuan, 2015; Singh et al., 2015). The rice cultivation area used to grow hybrid varieties accounted for over 60% of rice production and 52% of rice cultivation area in the 2000's (Fan et al., 2005; Spielman et al., 2012). The success of hybrid rice production in China, regarding both yield gain in the field and expansion of the sown area, has encouraged other developing countries to strive for growth in rice production (Mottaleb et al., 2015). The extent and progress of hybrid rice variety adoption and its impact on local and national rice production are thus helpful for a better understanding of the relationship between agricultural technology development and changes in rice farming in China.

The number of hybrid rice varieties released and certificated has increased tremendously in China in recent years. Approximately 300 new hybrid rice varieties are officially released every year, and hybrid rice varieties account for nearly 70% of the total rice varieties produced (Ma and Yuan, 2015). In total, over 490 hybrid rice varieties were widely adopted at farm level in 2011. The rapid development of hybrid rice varieties has spurredresearch on the breeding, management, and cultivation techniques, as well as the development of the seed industry in China, which has substantially expanded the hybrid rice area in the last few decades (Ma and Yuan, 2015; Yin et al., 2018). By 1984, all southern provinces[1] with rice-producing areas were growing hybrid rice varieties. However, the number of hybrid rice varieties and expansion of the hybrid rice area across the main rice-producing areas in China is uneven and unequal, which may raise concerns about resource wastage (Huang, 2022a). The yield advantage of hybrid rice plays an important role in ensuring national food supplies despite decreasing rice-cultivating areas in the last few decades and substantial changes in rice cropping patterns across different rice-producing areas (Chen et al., 2020). The adoption of hybrid rice varieties has led to changes in cropping patterns and contributed to the transition of food systems in emerging economies, and in this context, the spatial dimensions of technology diffusion help identify the spillover and crowding effects to implement improved extension strategies and achieve industry development (Ward and Pede, 2015; Huang, 2022a). With more types of male sterility being exploited, hybrid rice production in China has become more diversified (Cheng et al., 2007). The changes and relationship between variety adoption and land use as well as rice production are yet to be examined.

This study analyzed the changes in hybrid rice adoption in the main rice-producing provinces and evaluated the effect of hybrid rice adoption on rice production within the provinces and across regions. The contributions of the study are: first, taking the number of hybrid rice varieties as the variable, we mapped the changes in hybrid rice technology adoption in each rice-producing province from 1984 to 2011. China is a country that has successfully promoted long-term commercial hybrid rice production on a large scale. Detailed information on changes in hybrid rice technology development is helpful to better understand the diffusion and effects of variety adoption on total rice production. The results of the study provide a reference for other countries to design strategies for hybrid rice technology extension. Second, the effects of hybrid rice technology on rice production changes have remained an open question. The changes in cropping patterns in the main rice-producing provinces in China vary considerably. For instance, the share of double-cropping rice areas at the national level decreased substantially from 31% in 1984 to 20% in 2011. In Hunan province, it declined from 46% in 1984 to 36% in 2011; in contrast, the share almost remained constant in Jiangxi province. Although the wide adoption of hybrid rice varieties compensates for the reduction of the rice area in China, the effects of hybrid rice adoption on the

1 Regions in China are categorized into two types based on geographical and economic divisions. Geographically, China is divided into seven regions including northeast China, such as Heilongjiang, Jilin, and Liaoning, east China, such as Anhui, Fujian, Jiangsu, and Zhejiang, north China, such as Beijing, Hebei, and Shanxi, central China of Henan, Hubei and Hunan, south China, such as Guangdong, Guangxi, and Hainan, southwest China, such as Gansu and Shaanxi, and northwest China, such as Chongqing, Guizhou, Sichuan, and Yunnan. Economically, China is divided into four regions including the eastern regions, such as Guangdong, Jiangsu, and Zhejiang, the central regions, such as Anhui, Hunan, and Jiangxi, the western regions, such as Guangxi, Sichuan, and Yunnan, and the northeast region of Heilongjiang, Jilin, and Liaoning. We opted for the geographical division in the study.

rice area and production may vary across provinces. Evaluation of the impact of hybrid rice technology on rice production is thus important to understand these changes, specifically, both spatial and temporal effects, which need to be measured for a better understanding of the effects of variety adoption. Geographically and temporally weighted regression was applied to measure the effects caused by the time and space variables. Based on the results, the implications of seed commercialization and technology transfer system development for ensuring food security in China in the future are discussed, considering the relevance of this relationship for public policy and early work on the theoretical framework of induced innovation in agriculture.

This study is organized as follows: a literature review is presented in Section 2, followed by the section on data and methods. Section 4 presents the results, and Section 5 summarizes the implications based on the findings and draws a conclusion for the study.

2. Literature review

There is a rich body of literature examining the development and diffusion of hybrid rice technology in developing countries, and a large number of recent research projects have focused on the factors influencing the adoption of hybrid rice at the farm level (Cheng et al., 2007; Spielman et al., 2017). Very few studies are based on data at the macro level, which could provide the bigger picture of policy design. Hybrid rice has been widely adopted in China, India, Bangladesh, Vietnam, Indonesia, and other countries (FAORAP, 2014; Shah et al., 2016; Hu et al., 2022). Fan et al. (2005) found that the improvement in rice varieties has contributed to increases in rice production in China and India. Lin (1991a) studied the diffusion of hybrid rice with family samples from Hunan province, China, and examined the impact of the administrative intervention on farmers' decisions regarding hybrid rice adoption. Lin (1991b) found a significant positive effect of education on farmers' adoption of hybrid rice in Hunan. Similarly, Spielman et al. (2017) conducted a study based on a series of unstructured interviews to investigate the effect of an innovation system on hybrid rice development in India and Bangladesh. In China, planting pattern is an important factor affecting the adoption of hybrid rice (Huang et al., 2021). Chen and Chen (2011) found that the yield gain of super rice could have better market value and benefit farmers more than regular rice. Anwar et al. (2021) confirmed the potential of hybrid rice to increase productivity and farmers' income. However, most studies are based on household-level data, and the site-specific findings may be insufficient to show the dynamic changes of technology adoption in the long run across different regions (Lin, 1992; Wang et al., 2021; Huang, 2022a).

Changes in hybrid rice production and variety adoption vary across regions in China (Zeng et al., 2019). While the adoption of hybrid rice has contributed greatly to Chinese food security over the past 30 years, the distribution of hybrid rice production has become scattered and diversified (Cheng et al., 2007; Ma and Yuan, 2015). The spread of hybrid rice cultivation to different provinces and in different periods has been significantly different (Huang and Scott, 1993). In the early 1980's, the hybrid rice industry developed rapidly, and the sown area of hybrid rice was stable (Li, 2010). The number of combinations of major male sterile lines increased substantially with a few dominant lines, such as Zhenshan 97A, which accounted for 85% of the total number of combinations in China in 1990, after which its proportion declined (Mao et al., 2006). Hybrid rice is mostly grown in southern China as the area of cultivation is a main factor determining the intensity of hybrid rice adoption (Lin, 1992). The site-specific topography and diversified ecological conditions significantly affect the distribution of the hybrid rice area in Sichuan province (Luo, 1994). Xiao and Li (2014) found a spatial correlation between agricultural production in China, especially in the provinces, with similar agricultural technology adoption. Gao and Song (2014) discovered a trend in spatial convergence of technical efficiency in grain production in the process of technology extension, which may indicate the interaction of production across different producing areas. Taking rice seedling-throwing technologies as an example, Yu et al. (2017) found that a significant spillover effect existed among neighboring provinces. As a classic agricultural technology innovation in China, the effect of hybrid rice popularization and diffusion on regional rice production remains to be studied.

Econometric methods have been applied to investigate the spillover effect of technology diffusion. Spatial autocorrelation coefficients, like the Moran index, have often been used for impact evaluation (Mamiit et al., 2020; Zhang et al., 2021). Based on this index, the interrelationship of technological innovation among regions can be displayed vividly on geographical maps. However, the spillover effects across regions remain to be measured (Bjørkhaug and Blekesaune, 2013; Allaire et al., 2015). Xiao et al. (2022) used the spatial Durbin model (SDM) and threshold model to analyze the efficiency of agricultural green production following technological progress. Bao et al. (2021) used the spatial autoregressive (SAR) model to analyze the influencing factors of the total factor productivity of grain production. Spatial econometric models such as SAR and SDM incorporate spatial terms of dependent variables into the model, which may cause estimation bias due to the endogeneity. Thus, the spatial lag of the X (SLX) model, by introducing the spatial term of independent variables, has been suggested to correct this estimation bias (Halleck Vega and Elhorst, 2015). Besides, Brunsdon et al. (1996) proposed geographically weighted regression (GWR) as a local variation modeling technique to capture the spatial variation (Huo et al., 2022). To deal with both spatial and temporal heteroscedasticity simultaneously, a geographically and temporally weighted regression (GTWR) method has been adopted in this study for capturing interactions across different provinces in different years (Huang et al., 2010).

3. Data and methodology

3.1. Analytical framework

Rice production was first categorized into hybrid and conventional rice production to separate the effect of hybrid rice development on rice production in each area. Rice production in each province is presented as follows:

$$Prod_i = Prod^i_{HR} + Prod^i_{CR} = Area^i_{HR} \times Yield^i_{HR} + Area^i_{CR} \times Yield^i_{CR} \tag{1}$$

where i represents a specific rice-producing province. The subscripts, HR and CR, refer to hybrid rice and conventional rice, respectively.

Rice is widely grown in China under different production systems and climates ranging from warm sub-tropics to cool temperate climates with the center of the rice-cultivating area moving from southern China to northeast China (Fang and Sheng, 2000; Deng et al., 2019). The expansion of the rice-cultivating area in certain regions of China is crucial to increase national rice production despite a reduction in the total cultivating area (Liu et al., 2013). We assume that the development of hybrid rice production not only affects the conventional rice production within the same province but also both hybrid and conventional rice production in other provinces. From the perspective of food security, both hybrid and conventional rice can be viewed as substitute goods. We thus assume that the substitution effect between hybrid rice and conventional rice in a given province is α_i and the effect may vary across provinces as the levels of input and output of rice production in different provinces are different. The equation was presented as follows:

$$Prod^i_{CR} = \alpha_i Prod^i_{HR} \tag{2}$$

where α_i is the function of hybrid rice and conventional rice production within and outside the given province, which is presented as:

$$\alpha_i = h\left(Prod^i_{HR},\ Prod^i_{CR}, Prod^{j-i}_{HR}, Prod^{j-i}_{CR}\right) \tag{3}$$

The development of hybrid rice varieties in the i^{th} province is likely to affect the rice yield in other provinces as improved and new hybrid rice varieties can be introduced and adopted in different provinces through different ways, such as collaborative breeding programs, technology diffusion systems, seed companies, and farmers' seed exchanges. Therefore, the rice yield in one province could be affected by both the variety adoption within and outside the province. Huang and Scott (1993) argued that Chinese farmers usually decide on variety selection (i.e., whether hybrid rice or conventional rice), cropping system (i.e., double cropping or single cropping pattern), and agricultural inputs right before the planting season begins; therefore, the variety adoption decision is an input rather than an output variable for rice farming. Rice yield is thus presented as the function of variety adoption as follows:

$$Yield^i_{HR} = f(HR_i, HR_{j-i}, \mathbf{X}) \tag{4}$$

$$Yield^i_{CR} = g(CR_i, CR_{j-i}, \mathbf{X}) \tag{5}$$

where i and j refer to the i^{th} and j^{th} province, and $\mathbf{X}$ refers to the agricultural inputs.

Taking the equations into the function, Equation (1) can be transformed as follows:

$$\begin{aligned} Prod_i &= Prod^i_{HR} + Prod^i_{CR} = (1+\alpha_i)Prod^i_{HR} \\ &= [1 + h\left(Prod^i_{HR},\ Prod^i_{CR}, Prod^{j-i}_{HR}, Prod^{j-i}_{CR}\right)]Prod^i_{HR} \end{aligned} \tag{6}$$

and

$$Prod^i_{HR} = Area^i_{HR} \times Yield^i_{HR} = Area^i_{HR} \times f\left(HR_i, HR_{j-i}, \mathbf{X}\right) \tag{7}$$

$$Prod^i_{CR} = Area^i_{CR} \times Yield^i_{CR} = Area^i_{CR} \times g\left(CR_i, CR_{j-i}, \mathbf{X}\right) \tag{8}$$

Furthermore, we assumed that the rice area in the i^{th} province can be described as the function of rice yield and agricultural inputs, which is $Area^i_{HR} = A(Yield^i_{HR}, Yield^i_{CR}, \mathbf{X})$.

Total rice production in the i^{th} province is affected not only by the development of rice varieties locally but also by those in other provinces. Rice production in the i^{th} province can be transformed into the function of the development of different rice varieties and agricultural inputs, that is:

$$Prod_i = F(HR_i, CR_i, HR_{j-i}, CR_{j-i}, \mathbf{X}) \tag{9}$$

where HR_i and CR_i refer to the development of hybrid rice and conventional rice varieties in the i^{th} province. HR_{j-i} and CR_{j-i} represent the hybrid and conventional rice varieties in other provinces excluding the i^{th} province.

3.2. Model specification

The specification of rice production in a given province is assumed to be a function of local technology development (measured by the number of hybrid and conventionally bred rice varieties) and agricultural inputs and described as follows, without considering the interaction effect from other provinces:

$$Y_{it} = \beta_0 + \beta_{1i}HR_{it} + \beta_{2i}CR_{it} + \beta_{3i}HR_{it} \times CR_{it} + \mathbf{X}'\boldsymbol{\theta} + \mu_i + \varepsilon_{it} \tag{10}$$

where Y_{it} denotes the rice production of the i^{th} province in the t^{th} year, which is measured by the variable of production (*prod*), area (*area*), and yield (*yield*) separately in the models. HR_{it} represents the number of hybrid rice varieties adopted by farmers in the i^{th} province in the t^{th} year. CR_{it} represents the number of conventional rice varieties adopted by farmers in the i^{th} province in the t^{th} year. $\boldsymbol{X}$ is a vector of the control variable, including agricultural inputs and rice cropping pattern, which is measured by the share of the sown area of double-cropping rice (*doublecrop*), the number of agricultural laborers (*agrlabor*), total fertilizer expenditure in rice farming (*fert*), the irrigated rice area (*irri*), and the damaged rice area due

TABLE 1 Summary of statistics of variables included in the empirical analysis.

Variables	Overall (1984–2011)		Period I (1984–1991)		Period II (1992–2001)		Period III (2002–2011)	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Yield (t/ha)	5.92	1.00	5.37	0.89	6.06	0.94	6.22	0.98
Sown area (million hectares)	2.24	0.97	2.50	1.03	2.27	0.90	2.01	0.95
Rice production (million tons)	13.37	6.21	13.72	6.40	13.85	6.00	12.61	6.24
The number of hybrid rice varieties	32.84	36.77	8.27	5.17	21.78	14.53	63.57	44.84
The number of conventional rice varieties	18.01	11.62	21.07	11.14	16.48	11.78	17.08	11.46
Share of sown area of double-cropping rice (%)	25.96	20.06	28.56	20.37	27.50	20.12	22.34	19.39
Rice effective irrigated area (million hectares)	0.73	0.36	0.80	0.38	0.71	0.34	0.69	0.35
Rice disaster area (million hectares)	0.61	0.38	0.66	0.40	0.65	0.37	0.53	0.36
Numbers of agricultural workers (million people)	16.53	7.26	17.06	7.93	17.49	7.64	15.13	6.07
Total fertilizer expenditure for rice (million dollars)	14.88	6.49	15.39	6.68	15.08	6.21	14.28	6.62

Data source: China Rural Statistical Yearbook, Chinese data from the Farm Production Costs and Returns Survey (FPCRS), Ministry of Agriculture and Rural Affairs.
The Chinese yuan is converted to United States dollars (USD) using the exchange rates for 1 USD in 2022: CNY (7).

to disasters (*disarea*) (Table 1). β_{1i}, β_{2i}, β_{3i}, and $\boldsymbol{\theta}$ are the coefficients to be estimated. μ_i represents the province fixed effect, and ε_{it} is the random error term. In addition, we applied a technique of applying clustering standard errors to deal with the possible cross-sectional heteroskedasticity (Bertrand et al., 2004; Huang, 2017). We corrected the standard errors for clustering by province cell.

In addition to the local adoption of rice varieties, rice production in a given province could be affected by the spillover effects of rice production in other provinces. Farmers in a province tend to adopt the same type of rice varieties if they have knowledge and access to those varieties with considerable yield gain that are widely adopted by farmers in another province. Spillovers of farmers' knowledge of variety adoption result in spatial effects across farmers (Ward and Pede, 2015). The above specification can be extended to the following equation by introducing the interaction effects from other rice-producing provinces.

$$Y_{it} = \beta_0 + \beta_{1i}HR_{it} + \beta_{2i}CR_{it} + \beta_{1j}HR_{jt} + \beta_{2j}CR_{jt} + \beta_{3i}HR_{it} \times CR_{it} + \mathbf{X}'\boldsymbol{\theta} + \varepsilon_{it} \quad (11)$$

where i and j refer to the given province and other rice-producing areas, respectively. As the effects of rice production in different provinces in the given province may be varied, a spatial weight is assigned to each province. The sum of weighted effects aims to show the overall effect from other areas. The equation can be rewritten as follows:

$$Y_{it} = \beta_0 + \sum_{j=1}^{m} \beta_{1j} w_{ij} \times HR_{jt} + \beta_{2i}CR_{it} + \beta_{3j} \sum_{j=1, j\neq i}^{m} w_{ij} \times CR_{jt} + \sum_{k=1}^{K} \theta_k x_{ik} + \varepsilon_{it} \quad (12)$$

where m refers to the number of rice-producing provinces and w_{ij} is the spatial weighted effect of rice production in the j^{th} province on that in the i^{th} province. Based on the laws of geography (Tobler, 1970), the spatial weight was measured by the reciprocal value of distance. Therefore, if $j = i$, then w_{ij} refers to the effect of technology development on rice production in the same province, i.e., $w_{ij} = 1$. If $j \neq i$, then $w_{ij} = 1/D_{ij}$.

The effects of technology development in a given province on rice production in other areas may also vary across provinces due to the diversified economic and environmental conditions as well as different distances. Following the methods provided by Brunsdon et al. (1996), the geographically weighted regression (GWR) model was introduced to estimate specific local coefficients for each province by extending the traditional regression framework as follows:

$$Y_{it} = \beta_0(u_i, v_i) + \sum_{j=1}^{m} \beta_{1j}(u_i, v_i) w_{ij} HR_{jt} + \beta_{2i}(u_i, v_i) CR_{it} + \sum_{j=1, j\neq i}^{m} \beta_{3j}(u_i, v_i) w_{ij} CR_{jt} + \sum_{k=1}^{K} \theta_k(u_i, v_i) x_{ik} + \varepsilon_{it} \quad (13)$$

where (u_i, v_i) denotes the coordinates of the center in the i^{th} province ($i=1,\ldots,m$), $\beta_0(u_i, v_i)$ is the intercept value, and

$\beta_{1j}(u_i, v_i)$ is a set of coefficients to measure the effects of technology development in other areas on rice production in the i^{th} province. $\beta_{2i}(u_i, v_i)$ and $\beta_{3j}(u_i, v_i)$ are coefficients to be estimated to identify the local and interaction effects of conventionally bred rice varieties in the i^{th} province, respectively. The coefficient estimated in this model varies across provinces, which allows for the identification of local effects (Huang et al., 2010). However, the effects of technology development on rice production change over time, which results in temporal heterogeneity. Taking the method introduced by Huang et al. (2010) as a reference, a GTWR model was used to capture both the spatial and temporal heterogeneity of rice technology development in rice production. The equation is presented as follows:

$$\begin{aligned} Y_{it} &= \beta_0(u_i, v_i, t_i) + \sum_{j=1}^{m} \beta_{1j}(u_i, v_i, t_i)\, w_{ij} HR_{jt} + \beta_{2i}(u_i, v_i, t_i)\, CR_{it} \\ &+ \sum_{j=1, j \neq i}^{m} \beta_{3j}(u_i, v_i, t_i)\, w_{ij} CR_{jt} + \sum_{k=1}^{K} \theta_k(u_i, v_i, t_i)\, x_{ik} \\ &+ \varepsilon_{it} \end{aligned} \quad (14)$$

The estimates of $\beta(u_i, v_i, t_i)$ are coefficients for each variable with space-time location; (u_i, v_i, t_i) presents the coordinates of the time-space location for the i^{th} province. The estimation of $\beta(u_i, v_i, t_i)$ can be estimated using ordinary least square regression and expressed as follows based on Huang et al. (2010):

$$\hat{\boldsymbol{\beta}}(\mu_i, \nu_i, t_i) = [\mathbf{X}^{\mathbf{T}}\mathbf{W}(\mu_i, \nu_i, t_i)\mathbf{X}]^{-1}\mathbf{X}^{\mathbf{T}}\mathbf{W}(\mu_i, \nu_i, t_i)\mathbf{Y} \quad (15)$$

where $W(\mu_i, \nu_i, t_i)$ is the space-time weighted matrix. In the space-time coordinate system, it is assumed that the effect of observed data "close" to the given i^{th} province has a greater influence than those located farther from the i^{th} province. In this sense, both temporal closeness and spatial closeness need to be defined and measured in the GTWR model (Huang et al., 2010). The spatio-temporal distance function of d_{ij}^{ST} and spatio-temporal weight matrix w_{ij}^{ST} are thus defined based on the space-time function and Gaussian distance-decay-based functions method as follows:

$$d_{ij}^{ST} = \sqrt{\gamma[(\mu_i - \mu_j)^2 + (\nu_i - \nu_j)^2] + \delta(t_i - t_j)^2} \quad (16)$$

$$w_{ij}^{ST} = \exp\left\{-\left(\frac{\gamma[(\mu_i - \mu_j)^2 + (\nu_i - \nu_j)^2] + \delta(t_i - t_j)^2}{b_{ST}^2}\right)\right\} \quad (17)$$

Of them, t_i and t_j are observed times at locations i and j and b^{ST} is a coefficient of spatio-temporal bandwidth, which is defined and measured by the cross-valuation method (CV) by Fotheringham et al. (2002). The bandwidth is estimated when the least square error is calculated.

$$CV = \sum_{i}^{n} [y_i - \hat{y}_i(b)]^2 \quad (18)$$

3.3. Data

The socioeconomic and agricultural input data were obtained from the *China Rural Statistical Yearbook* and Chinese data from *the Farm Production Costs and Returns Survey (FPCRS)*. The number of rice varieties released and adopted by the farmers was obtained from the *Ministry of Agriculture and Rural Affairs*. The data used in the study covered the period from 1984 to 2011 (Table 1). The total fertilizer expenditure in rice production was deflated by a price index, which was constructed using regional retail price indexes of farm inputs (Tian and Wan, 2000). The number of rice varieties adopted by farmers was the mega varieties with a sown area of over 100,000 *mu* (around 6,667 hectares). In total, the rice area planted with mega varieties including hybrid and conventional rice varieties accounted for 43.7 and 31.8% of the national rice area in 2011, respectively.

Rice was widely grown in 14 provinces in China in 2011. Heilongjiang and Jilin provinces are located in northern China without hybrid rice; therefore, the two provinces were not included in the study. In total, 12 provinces with both hybrid and conventional rice production were included. Of them, four provinces were selected to compare the site-specific effects of technology adoption on rice production: Hunan province, Jiangxi province, Guangdong province, and Sichuan province (Figure 1). Hunan was taken as the start and center of hybrid rice development. Jiangxi province is located in central China and is well-known for having the biggest rice-cultivating area associated with the double-cropping system. Sichuan province, located in northwest China with a low economic development level, has a large-scale hybrid rice seed production and variety adoption level. Guangdong province, located in southern China, is regarded as a developed area with a large rice-cultivating area. The four provinces accounted for ∼2-5ths of the national rice cultivation area and rice production in 2011. In terms of hybrid rice production, the four provinces accounted for over 80% of hybrid rice varieties and more than half of the hybrid rice area in 2011 (Table 2). Overall, the share of the hybrid rice-cultivating area of the total rice-cultivating area increased from 23.4% in 1984 to 43.7% in 2011. The development of hybrid rice areas varied across provinces. In 2011, the hybrid rice area accounted for 52.3, 55.6, 45.2, and 78.1% of the local rice area in Hunan, Jiangxi, Guangdong, and Sichuan provinces, respectively (Table 2).

4. Results

4.1. Trends of rice production in China

Rice production in China increased from 178.3 million tons in 1984 to 202.9 million tons in 2011 (Table 2). The improvement of rice yield played an important role as the total rice-cultivating area decreased. The share of double-cropping rice areas decreased from over 30% in 1984 to 20% in 2011. Rice yield improved quickly between 1992 and 2011, while the national rice-cultivating area declined. However, the changes in rice production in different provinces varied. The share of double cropping in rice-cultivating areas in Jiangxi province was almost constant in the past few decades, while the total rice area in Jiangxi was maintained at over

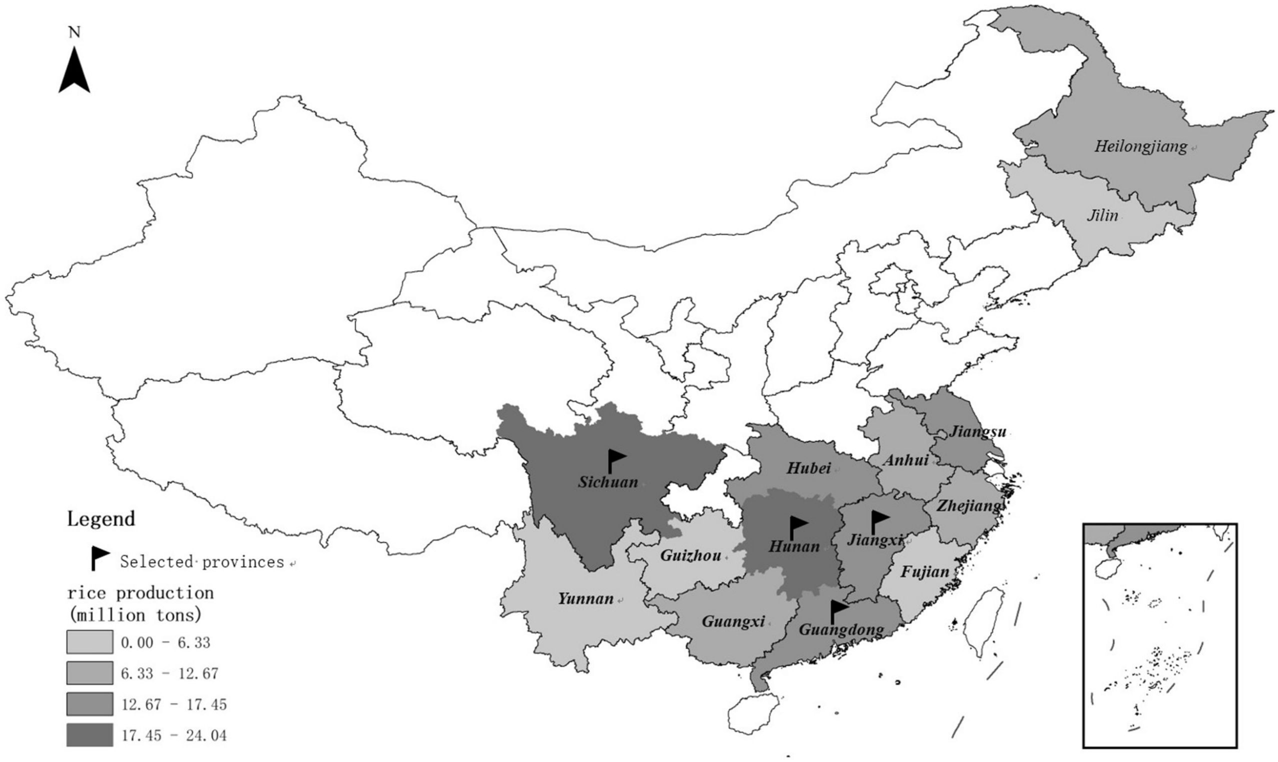

FIGURE 1
Distribution of main rice-producing provinces in China. To keep the consistency of data caliber, the data of Chongqing and Hainan were merged into Sichuan and Guangdong respectively.

3.3 million ha. In Hunan, which is well-known for its development of hybrid rice production, the share of double-cropping rice area decreased from 46% in 1984 to 36% in 2011, while the rice-cultivating area reduced from 4.4 million ha in 1984 to 4.2 million ha in 2011. Although Hunan and Jiangxi are two neighboring provinces with similar climatic conditions and economic levels, the changes in their rice production are different. Guangdong province experienced a significant reduction in its rice-cultivating area, declining from 3.5 million ha in 1984 to nearly 2.2 million ha in 2011, although the share of double-cropping rice area declined by only 5%. The rice system in Sichuan province has been dominated by the single rice cropping system and the rice area declined from nearly 4 million ha in 1984 to 2.6 million ha in 2011.

Changes in rice yield have varied across rice-producing areas in China. Overall, China has achieved substantial progress in its yield improvement, and the average national rice yield increased from 5.4 t/ha in 1984 to 6.7 t/ha in 2011. Sichuan province had the highest rice yield for decades, with 6.4 t/ha in 1984 and 7.5 t/ha in 2011, which was much higher than in other provinces. The rice yield in Guangdong province was maintained at a stable level lower than the national yield level, of 5.1 and 5.5 t/ha in 1984 and 2011, respectively. The rice yield in Hunan province increased from 5.5 t/ha in 1984 to 6.3 t/ha, which was close to the national yield level. Similarly, Jiangxi province improved its rice yield from 4.5 t/ha (1984) to nearly 6 t/ha (2011). Due to the varied progress in rice yield, the contribution of rice production from individual provinces to national rice production changed considerably.

The development of hybrid rice varieties is considered to be one of the main achievements of agricultural technology development in rice production. Hybrid rice varieties are a typical type of HYVs with yield gain and potential advantages. In China, the number of mega hybrid rice varieties adopted by farmers increased by over 10-fold from 1984 to 2011. In the 1980's, only a few hybrid rice varieties were developed and adopted by farmers with a large area, which might be attributed to both the breeding technology and seed industry development. In 2011, the number of hybrid rice varieties adopted by farmers with large-scale adoption, i.e., a sown area not <100,000 *mu* (around 6,667 ha), was nearly 500. After 20 years since Mr. Yuan Longping developed the hybrid rice variety in 1976, the number of hybrid rice varieties adopted by farmers has increased tremendously. Hunan province accounted for nearly 40% of the number of mega hybrid rice varieties, followed by Jiangxi and Sichuan provinces. The number of mega hybrid rice varieties in Guangdong province was much less than that in the three provinces and accounted for 40% of that in Hunan province.

Compared to the development and widespread adoption of hybrid rice varieties, the share of hybrid rice area of the total rice sown area increased rapidly in the 1990's and gradually reached a peak by 2006. The share of rice area used for growing hybrid rice increased from 23% in 1984 to 44% in 2011, followed by a decline in the total rice-cultivating area. With the rapid development of hybrid rice varieties, conventional rice varieties also made considerable achievements. However, the development of conventional rice varieties has been much slower than that of

TABLE 2 Rice production and varietal adoption in the country and selected provinces.

Variables	National				Hunan				Jiangxi				Guangdong				Sichuan			
	1984	1992	2002	2011	1984	1992	2002	2011	1984	1992	2002	2011	1984	1992	2002	2011	1984	1992	2002	2011
Yield (t/ha)	5.37	5.80	6.19	6.69	5.49	5.79	5.98	6.33	4.49	4.94	5.21	5.89	5.10	5.36	5.65	5.51	6.35	7.15	7.29	7.51
Sown area (million hectares)	33.18	32.09	28.20	30.34	4.40	4.19	3.54	4.16	3.33	2.98	2.79	3.44	3.51	3.29	2.45	2.20	3.99	3.12	2.78	2.60
Share of double-cropping rice area (%)	31.28	28.49	23.28	20.16	45.65	47.04	42.47	35.74	43.40	46.75	45.43	43.82	56.56	46.08	54.30	52.41	1.50	1.41	0.11	0.02
Rice production (million tons)	178.26	186.22	174.54	202.88	24.17	24.23	21.19	26.34	14.93	14.74	14.52	20.26	17.93	17.62	13.82	12.10	25.34	22.29	20.24	19.53
Number of mega hybrid rice varieties	37	74	216	499	5	25	56	196	1	11	39	176	10	30	43	79	7	6	20	139
Share of hybrid rice area (%)	23.38	46.94	50.48	43.66	30.90	56.84	62.06	52.31	19.28	34.32	71.67	55.58	39.74	41.44	42.06	45.20	42.21	87.71	83.78	78.13
Number of mega conventional rice varieties	238	229	224	274	19	29	25	23	38	6	14	20	37	34	35	24	10	0	0	8
Share of conventional rice area (%)	43.30	32.44	26.66	31.79	29.64	33.65	20.31	23.01	57.69	10.80	6.03	9.51	43.89	42.51	34.40	21.98	19.60	0.00	0.00	2.67
GDP per capita (USD)	100	332	1,350	5,145	74	228	962	4,109	71	210	833	3,736	118	528	2,211	7,239	70	211	841	3,734

Data source: China Rural Statistical Yearbook, Chinese data from the Farm Production Costs and Returns Survey (FPCRS), Ministry of Agriculture and Rural Affairs.
The Chinese yuan is converted to United States dollars (USD) using the exchange rates for 1 USD in 2022: CNY (7).
The share of hybrid rice area is computed by the mega hybrid rice area to the total rice area.
The share of conventional rice area is computed by mega conventional rice area to the total rice area.

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hybrid rice. An increasing number of hybrid rice varieties increased the hybrid rice-cultivating areas, which may have crowded out the planting of conventional rice varieties. On average, over 200 conventional rice varieties were adopted by farmers and these varieties accounted for <½ of the total rice cultivated areas, on average. Hybrid rice varieties have significant yield advantages over conventionally bred rice; however, the grain quality of hybrid rice is not as good as that of conventional rice (Hu et al., 2016), which may restrict the further expansion of hybrid rice-cultivating areas in the context of changing consumer demands. With better income and economic growth, Guangdong province was considered more developed than Hunan, Jiangxi, and Sichuan provinces. High-quality rice with good taste and aroma was preferred by local consumers and thus was given priority by local breeders. In contrast, the lower the level of economic development, the higher the adoption of hybrid rice varieties. Sichuan province is located in the northwest of China with lower economic development and its hybrid rice-cultivating area accounted for nearly 80% of the provincial rice area. Similarly, in Jiangxi province, the share of the hybrid rice area was 56%. However, the share of the hybrid rice-cultivating area of the total rice area in Guangdong province was the lowest, at <50%. With the rapid development of hybrid rice technology and the widespread adoption of hybrid varieties, the number of conventional rice varieties adopted by farmers has decreased along with a decrease in conventional rice-cultivating areas. Particularly in Jiangxi province, the share of conventional rice area decreased from 58% in 1984 to <10% in 2011. To some extent, this demonstrates a crowding out effect between hybrid rice and conventional rice technology adoption, especially in developing areas.

4.2. Effects of hybrid rice adoption on rice production at national and provincial levels

Table 3 shows the results of the effects of hybrid rice adoption on rice production. Four regressions using the OLS method were implemented to investigate the overall effects from 1984 to 2011 and three individual effects in different periods, i.e., effects in the periods of 1984–1991, 1992–2001, and 2002–2011. The number of hybrid rice varieties adopted by farmers had a significant positive effect on rice yield and rice production. Increased adoption of hybrid rice resulted in improved rice yield and an increase in rice production. However, the effect of hybrid rice adoption on the rice area was negative. Particularly, hybrid rice adoption reduced the rice-cultivating area in the first period of 1984–1991. The effects of hybrid rice adoption on yield were greater than that on rice production as the coefficients were bigger.

There was also an interaction between the adoption of hybrid rice and conventional rice technology, which may have affected local rice production as well. The results showed that the adoption of hybrid rice varieties usually had a direct impact on rice production as the estimated coefficients of interaction between hybrid rice adoption and conventional rice adoption were mostly smaller than those of hybrid rice adoption in the regressions. Average rice yield changed with different numbers of rice varieties adopted by farmers associated with the changes of the sown area due to the yield advantage of hybrid rice, i.e., a high level of hybrid rice variety adoption increased its sown area and consequently improved the local average rice yield. Such effects included the contribution of hybrid rice adoption and substitution effects of hybrid rice adoption on conventional rice. Because the coefficient of interaction variable in the overall model of hybrid rice adoption was −0.01 (Table 3, row 3, column 1) compared to the value of 0.20 (Table 3, row 1, column 1), the increase in the average national yield should mostly be attributed to the adoption of hybrid rice varieties.

Table 4 shows the results of the regression of the effects of hybrid adoption on rice yield, area, and production at the provincial level without considering the interaction effect of rice production across different areas. It was assumed that provincial rice production will be affected by local technology development and the results were based on Equation (10) using the OLS method. In a given province, the effects of local hybrid rice adoption on the changes in rice production are mixed. The increased number of hybrid rice varieties adopted by farmers in Hunan and Jiangxi provinces significantly contributed to the local rice yield increase. The estimated marginal effect of hybrid rice variety adoption in Jiangxi province was 0.28 (Table 4, column 3), which was the highest followed by 0.15 (Table 4, column 1) in Hunan province. Rice yield in Sichuan province was not affected significantly by the local hybrid rice variety adoption, which was probably related to the local high level of rice yield due to the desired climate conditions. Sichuan province has had the largest area for hybrid rice seed production for 20 years and accounted for one-fourth of the national area for hybrid rice seed production. The effect of hybrid rice adoption on rice yield in Guangdong province was insignificant, which may be due to the slow progress of hybrid rice adoption associated with the changes in the rice cropping system as well as the increasing demand regarding the quality of rice. Therefore, maintaining conventional rice production and rice yield may not be prioritized in Guangdong province as much as in other provinces.

Regarding the changes in rice-cultivating areas, local hybrid rice adoption has enlarged the rice area in Hunan province while reducing those in Guangdong and Sichuan provinces. The results of the effects of the interaction between hybrid rice and conventional rice adoption are mixed. Farmers with large-scale rice areas may benefit more from the yield-gain advantage of hybrid rice adoption. Both Hunan and Jiangxi provinces have a long history of rice production and are viewed as the center of rice production in China to ensure national food security. Rice production in these two provinces accounted for 23% of national rice production in 2011. Besides, Hunan province has led the hybrid rice variety breeding and extension programs, and the local government has also made great efforts to support the technology development (Zeng and Liu, 2006). Within Hunan province, the adoption of hybrid rice varieties has positively affected rice production but has had negative effects in Guangdong and Sichuan provinces. However, with Jiangxi being adjacent to Hunan province, the spillover effect of agricultural technology development in Hunan province could have affected rice production in Jiangxi province through technology development cooperation and/or farmers' exchange of seeds and so on (Jing et al., 2013). Without considering the interaction effects of hybrid rice adoption across the provinces, the effects of hybrid rice adoption on rice production can be biased.

TABLE 3 Effects of hybrid rice variety adoption on rice production at the national level using the OLS model.

Variables	Overall (1984–2011)			Model 1 (1984–1991)			Model 2 (1992–2001)			Model 3 (2002–2011)		
	Yield	Area	Prod	Yield	Area	Prod	Yield	Area	Prod	Yield	Area	Prod
HR	0.20***	−0.03**	0.06***	0.99***	0.24*	0.63***	0.26**	0.06	0.18***	0.13***	0.02	0.06**
	(0.03)	(0.01)	(0.01)	(0.36)	(0.12)	(0.18)	(0.11)	(0.05)	(0.05)	(0.05)	(0.02)	(0.02)
CR	−0.12***	0.05***	−0.00	−0.56***	0.18***	−0.01	−0.05	−0.02	−0.04*	−0.17	−0.06	−0.11*
	(0.03)	(0.01)	(0.02)	(0.20)	(0.06)	(0.08)	(0.06)	(0.02)	(0.02)	(0.10)	(0.05)	(0.06)
HRCR	−0.01	−0.00	0.03**	−0.82**	0.23**	−0.05	−0.08	−0.08**	−0.09**	0.13**	0.02	0.06***
	(0.03)	(0.01)	(0.01)	(0.32)	(0.10)	(0.14)	(0.06)	(0.03)	(0.03)	(0.05)	(0.02)	(0.02)
Doublecrop	−0.54***	0.29***	0.23***	0.07	−0.18	0.02	−0.23	0.22***	0.19**	0.29	−0.15	−0.06
	(0.09)	(0.04)	(0.04)	(0.49)	(0.15)	(0.23)	(0.18)	(0.07)	(0.07)	(0.23)	(0.10)	(0.11)
Agrlabor	0.35***	0.09***	0.18***	0.46***	−0.11*	0.04	−0.09	0.11**	0.08	0.09	0.02	0.00
	(0.09)	(0.03)	(0.03)	(0.17)	(0.06)	(0.06)	(0.22)	(0.05)	(0.10)	(0.31)	(0.08)	(0.10)
Fert	0.42***	0.14***	0.25***	0.11	0.15**	0.19**	0.31***	0.06*	0.16***	0.29*	0.20***	0.25***
	(0.06)	(0.04)	(0.04)	(0.12)	(0.06)	(0.08)	(0.06)	(0.03)	(0.04)	(0.16)	(0.05)	(0.06)
Irri	−0.80***	0.57***	0.24***	−0.43**	0.58***	0.38***	−0.63***	0.63***	0.41***	−0.47**	0.13	0.07
	(0.09)	(0.05)	(0.06)	(0.21)	(0.10)	(0.11)	(0.20)	(0.09)	(0.11)	(0.21)	(0.12)	(0.14)
Disarea	−0.14***	0.03*	−0.02	−0.13**	−0.03**	−0.06**	−0.11**	0.02	−0.03	−0.20***	0.01	−0.04
	(0.04)	(0.01)	(0.02)	(0.05)	(0.01)	(0.03)	(0.05)	(0.01)	(0.02)	(0.07)	(0.02)	(0.03)
_cons	0.00	0.00	−0.00	0.18	0.32***	0.38***	0.22***	0.04*	0.13***	0.17**	−0.24***	−0.17***
	(0.02)	(0.01)	(0.01)	(0.27)	(0.08)	(0.12)	(0.05)	(0.02)	(0.02)	(0.08)	(0.05)	(0.05)
No. of observations	336	336	336	96	96	96	120	120	120	120	120	120
Marginal effect of HR	0.196***	−0.034**	0.061***	0.769**	0.297***	0.611***	0.269**	0.070	0.193***	0.122***	0.015	0.055**

The results are based on Equation (10) using the OLS regression.
***, **, *Refers to the significance level of 1%, 5%, and 10%, respectively.
Standard errors are in parentheses and are computed by the clustering of the error term by province cell.
Marginal effects are computed by coefficients of HR and HRCR and the mean of CR.

The following section, therefore, presents the spatial and temporal effects of hybrid rice adoption for a better understanding of the impact of hybrid rice technology diffusion.

4.3. Spatio-temporal effects of hybrid rice adoption in the selected provinces

Taking the example of the four selected provinces, the results showed that the development of hybrid rice adoption in a specific province may have different effects on rice production in other areas. Table 5 shows the average interaction effects of hybrid rice adoption on rice production using the data at the provincial level by pair grouping regression using the OLS method. To include all rice-producing areas in the model and capture both the spatial and temporal heterogeneity of hybrid rice adoption, the GTWR model was applied to measure the effects. We found that the interaction effects among the four selected provinces were greater than others. The development of hybrid rice variety adoption in Hunan province had a greater and wider influence on rice production across different areas in terms of the value of estimated coefficients and the number of provinces being affected. In addition to the spatial effects of hybrid rice adoption, the temporal effects varied in different periods as well. Overall, the development of hybrid rice varieties in the 1990's has had a greater influence on rice yield improvement and rice production, which to some extent indicates that it takes several years, almost a decade, for a large-scale extension of hybrid rice varieties. In the 2000's, the increase in rice yield tapered down, which is consistent with the yield potential of variety breeding progress (Hu et al., 2016; Huang, 2022b).

4.3.1. Hunan province

In the 1980's and 1990's, the adoption of hybrid rice varieties in Hunan province had a reducing positive impact on rice yield in most rice-producing provinces (Figures 2A–C). The magnitude of changes varied across different provinces. For instance, the effect of hybrid rice variety adoption in Hunan on the rice yield of Sichuan province was 6.45 (Figure 2A) during 1984–1991 and decreased to 1.84 (Figure 2B) during 1992–2001, which was higher than those of other provinces. The effect became negative in the 2000's. In contrast, hybrid rice variety adoption in Hunan province always positively affected the rice yield in Guangdong province to a certain extent in the last few decades. From the diffusion of effects over time, the areas where rice yield was most affected by

TABLE 4 Effects of local hybrid rice variety adoption on rice production within the province using the OLS model.

Variables	Yield				Area				Production			
	Hunan	Sichuan	Jiangxi	Guangdong	Hunan	Sichuan	Jiangxi	Guangdong	Hunan	Sichuan	Jiangxi	Guangdong
HR	0.17***	0.32**	0.29***	0.07	0.09**	−0.12**	−0.02	−0.41*	0.20***	0.02	0.13***	−0.29
	(0.04)	(0.15)	(0.05)	(0.41)	(0.03)	(0.05)	(0.02)	(0.22)	(0.04)	(0.08)	(0.03)	(0.34)
CR	0.01	0.22	−0.03	−0.20	0.10	0.14	0.05**	−0.00	0.11	0.23*	0.03	−0.10
	(0.08)	(0.20)	(0.03)	(0.15)	(0.06)	(0.08)	(0.02)	(0.08)	(0.08)	(0.11)	(0.02)	(0.12)
HRCR	−0.01	0.32**	−0.07*	−0.02	−0.11***	−0.07**	0.03	−0.06	−0.11***	0.07	−0.01	−0.06
	(0.04)	(0.13)	(0.04)	(0.21)	(0.03)	(0.03)	(0.02)	(0.12)	(0.04)	(0.06)	(0.03)	(0.17)
Doublecrop	0.53*	−4.45*	−0.27	0.30	−0.62*	−5.40***	0.87**	−0.39	−0.20	−7.75***	0.55**	−0.13
	(0.29)	(2.45)	(0.54)	(0.72)	(0.31)	(1.06)	(0.34)	(0.23)	(0.36)	(1.83)	(0.26)	(0.50)
Agrlabor	−0.27	0.23*	−0.11	−0.33	0.57**	0.15**	0.46**	0.15	0.34	0.29***	0.32	−0.01
	(0.21)	(0.12)	(0.32)	(1.17)	(0.27)	(0.06)	(0.17)	(0.64)	(0.28)	(0.10)	(0.22)	(1.01)
Fert	0.03	0.78***	0.23**	0.04	0.12	0.22*	0.13**	0.42***	0.14	0.59***	0.22***	0.39*
	(0.09)	(0.25)	(0.08)	(0.34)	(0.08)	(0.12)	(0.05)	(0.09)	(0.09)	(0.18)	(0.06)	(0.22)
Irri	−0.44***	−1.24***	−1.31***	−0.29	0.76***	0.82***	1.08***	0.08	0.41***	0.24	0.19	−0.10
	(0.12)	(0.29)	(0.29)	(0.39)	(0.11)	(0.16)	(0.17)	(0.14)	(0.14)	(0.21)	(0.19)	(0.28)
Disarea	−0.03	−0.37***	−0.10**	−0.07	−0.01	0.04	0.02	0.04	−0.03	−0.13**	−0.03**	0.01
	(0.03)	(0.08)	(0.04)	(0.12)	(0.02)	(0.03)	(0.02)	(0.07)	(0.02)	(0.05)	(0.02)	(0.11)
_cons	0.40*	−4.42	0.15	−0.64	0.49*	−6.39***	−0.60	0.72*	0.68**	−8.98***	−0.27	0.26
	(0.21)	(3.27)	(0.85)	(1.14)	(0.25)	(1.46)	(0.49)	(0.37)	(0.31)	(2.47)	(0.50)	(0.78)
No. of observations	28	28	28	28	28	28	28	28	28	28	28	28
Marginal effect of HR	0.154***	−0.079	0.278***	0.050	−0.022	−0.026	−0.020	−0.471***	0.084**	−0.057	0.131***	−0.347

The results are based on Equation (10) using the OLS regression.
***, **, *Refers to the significance level of 1%, 5%, and 10%, respectively.
Heteroscedasticity-robust standard errors are in parentheses.
Marginal effects are computed by coefficients of HR and HRCR and the mean of CR in each province.

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TABLE 5 Interaction effects of hybrid rice variety adoption at province level by pairs using the OLS model.

Dependent variables	Provinces	Provinces											
		Hunan	Jiangxi	Guangdong	Sichuan	Anhui	Fujian	Guangxi	Guizhou	Hubei	Jiangsu	Yunnan	Zhejiang
Yield	Hunan	–	0.039	−0.402***	0.181***	0.233	0.027	−0.046	−0.100	0.051	0.022	0.152	0.108
	Jiangxi	0.019	–	−0.331***	−0.054	0.257	0.062	−0.137	0.045	−0.035	0.078	0.180	0.066
	Guangdong	−0.096	0.224**	–	0.681***	0.342	0.110	0.674	−0.034	0.890*	0.697*	−0.025	0.294
	Sichuan	0.049	0.239***	−0.262**	–	0.174	0.067	0.137	0.055	0.016	0.088	0.179	0.124
Area	Hunan	–	0.004	−0.170***	−0.035*	0.041	−0.066**	−0.100***	−0.009**	0.017	−0.045	0.003	0.040
	Jiangxi	0.132	–	−0.181***	−0.047	−0.009	−0.019	−0.092***	−0.010	0.022*	−0.138***	0.009*	−0.003
	Guangdong	0.274**	0.009	–	−0.003	0.111	−0.000	−0.167	−0.022	−0.058	−0.179**	−0.009	−0.009
	Sichuan	0.160***	−0.025	−0.205***	–	−0.001	−0.007	−0.100***	−0.018**	0.005	−0.104***	−0.002	−0.002
Production	Hunan	–	0.027	−0.331***	0.040	0.106	−0.052**	−0.105**	−0.018	0.048	−0.051	0.028	0.063
	Jiangxi	0.137**	–	−0.301***	−0.084	0.076	−0.005	−0.132***	−0.004	0.025	−0.147	0.038	−0.008
	Guangdong	0.211	0.130	–	0.308***	0.220	0.025	0.104	−0.018	0.291	0.033	−0.016	0.060
	Sichuan	0.185***	0.105***	−0.278***	–	0.060	0.005	−0.035	−0.010	0.021	−0.101	0.026	0.009

The results are based on Equation (11) using the OLS regression and show the interaction between two provinces by pair grouping.
The coefficients indicate the average effect of the number of hybrid rice varieties on rice production including yield, area, and production.
The regression results are omitted in the publication and will be provided upon request.
Heteroscedasticity-robust standard errors are applied.
***, **, *Refers to the significance level of 1%, 5%, and 10%, respectively.

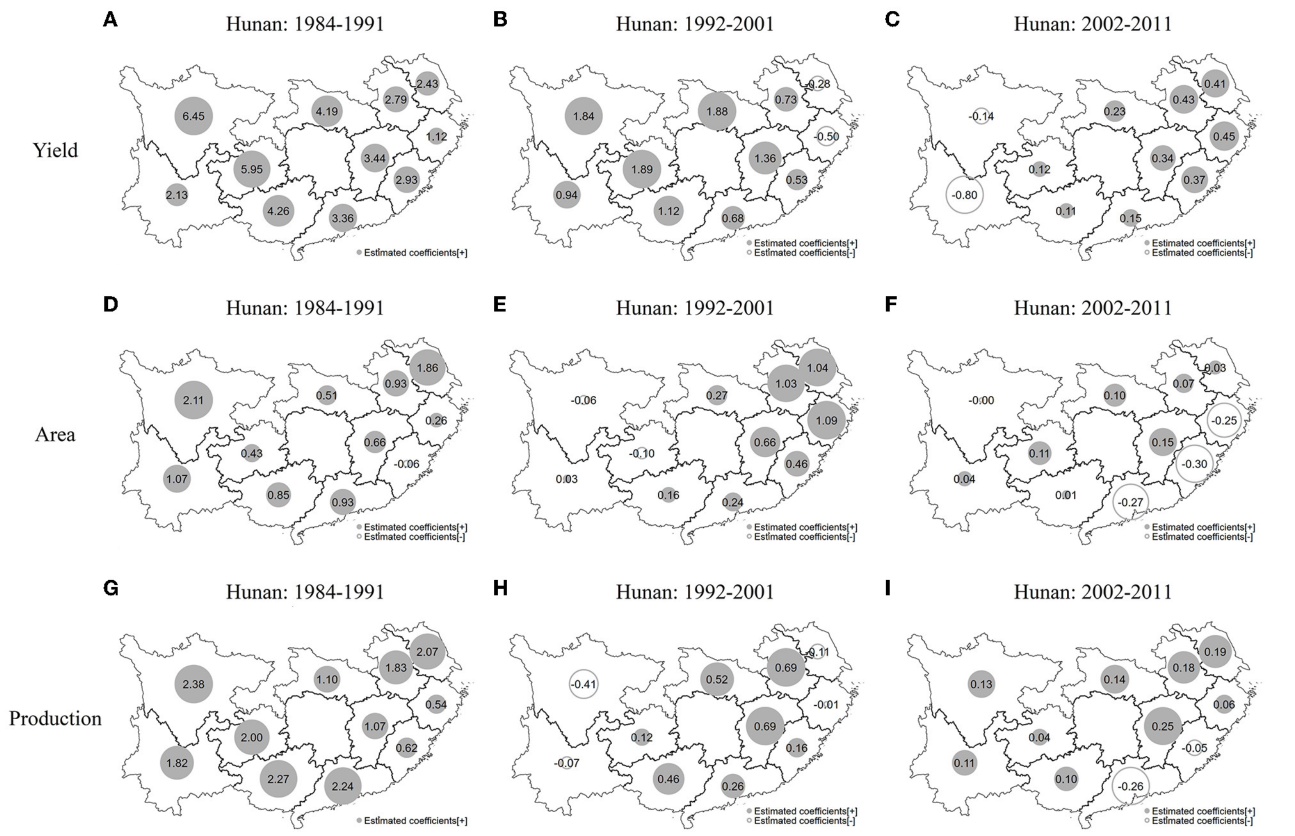

FIGURE 2
Spatio-temporal distribution of regression coefficients of hybrid rice adoption in the Hunan province using the GTWR model from 1984 to 2011. **(A–C)** Represent the spatial distribution of regression coefficients with rice yield from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively; **(D–F)** represent the spatial distribution of regression coefficients with rice area from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively; **(G–I)** represent the spatial distribution of regression coefficients with rice production from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively. The values in the circles are the estimated coefficients of the number of hybrid rice varieties. The circles with shadow mean the estimated effects are positive, while those with blank mean negative.

the development of hybrid rice variety adoption gradually moved from west to east. Between 2002 and 2011, Zhejiang province's rice yield was most affected by Hunan province, although the estimated coefficient in Figure 2C was only 0.45 and much lower than in earlier periods. Regarding the changes in rice yield, the development of hybrid rice variety adoption in Hunan province had a bigger influence on rice production in the provinces located in southern China, particularly in developed areas.

The trend of the spatio-temporal effect of hybrid rice variety adoption on rice area is similar to that of rice yield (Figures 2D–F). However, the extent of changes over time tended to be facilitated. This to some extent shows how hybrid rice adoption has affected change in rice-cultivating areas over time. In the 1980's, the development of hybrid rice variety adoption in Hunan province had a bigger positive impact on provinces farther away, such as Sichuan, Jiangsu, and Yunnan provinces. In the 1990's, the areas that affected other areas more shifted to provinces with better economic development or main rice-producing areas like Jiangxi and Anhui provinces. In the 2000's, the effects changed substantially as many estimated coefficients were negative although the values were much smaller compared to those in the 1980's. For example, the rice area in Sichuan province was positively affected by hybrid rice variety adoption in Hunan province in the 1980's with an estimated coefficient of 2.11 (Figure 2D) at the highest level, but thereafter, the effect diminished and turned negative which was insignificant.

Overall, the development of hybrid rice variety adoption in Hunan province substantially contributed to the increase in rice production in China as the estimated coefficients on rice production across provinces have mostly been positive (Figures 2G–I). However, the contribution has shrunk over time as the values of estimated coefficients have become smaller. However, the trend of effects on rice production across different provinces has been different compared to those of rice yield and rice area. In general, most effects of hybrid rice variety adoption on rice production followed the laws of geography and the effects were usually bigger for provinces that were closer to Hunan province.

4.3.2. Sichuan province

Sichuan is one of the main rice seed production areas and one of the first provinces to widely adopt hybrid rice varieties. The development of hybrid rice varieties in Sichuan

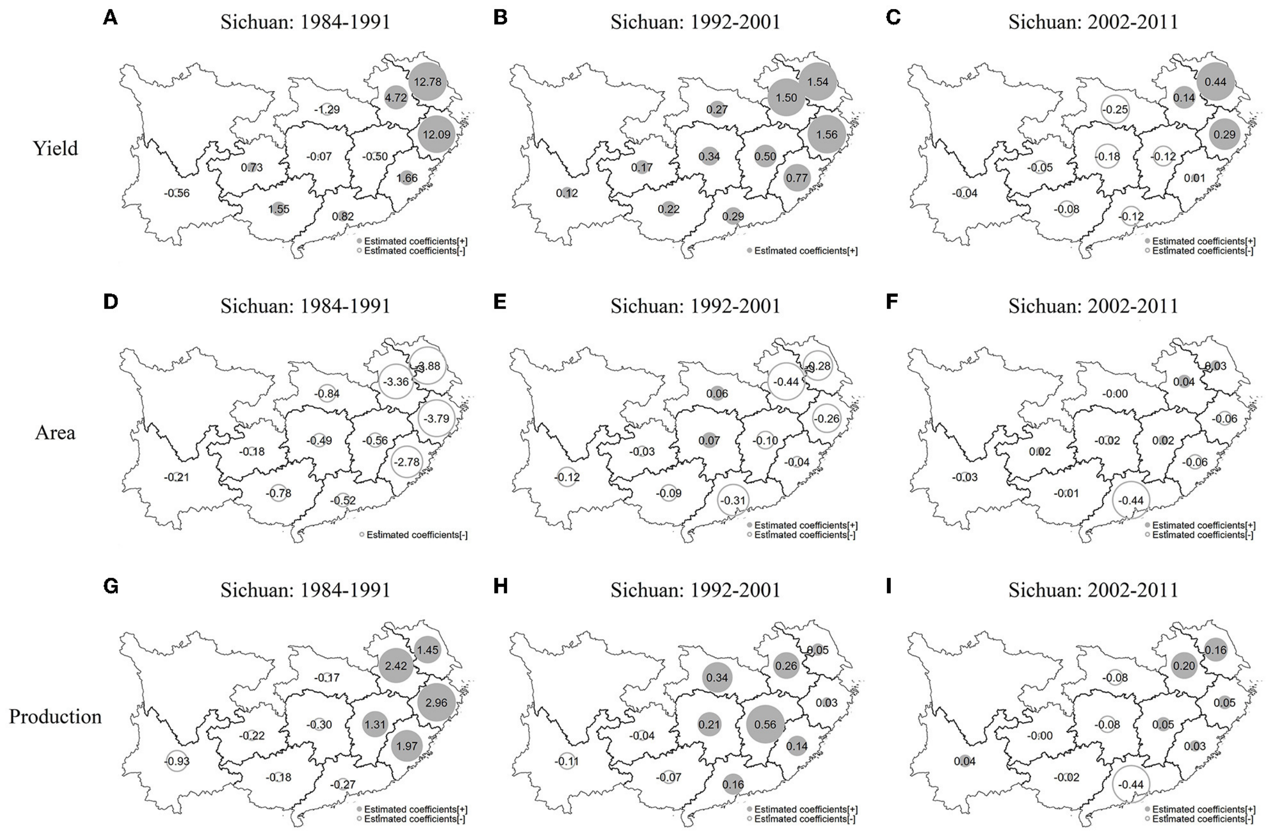

FIGURE 3
Spatio-temporal distribution of regression coefficients of hybrid rice adoption in Sichuan province using the GTWR model from 1984 to 2011. **(A–C)** Represent the spatial distribution of regression coefficients with rice yield from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively; **(D–F)** represent the spatial distribution of regression coefficients with rice area from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively; **(G–I)** represent the spatial distribution of regression coefficients with rice production from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively. The values in the circles are the estimated coefficients of the number of hybrid rice varieties. The circles with shadow mean the estimated effects are positive, while those with blank mean negative.

province enabled the provision of quality seeds to other rice-producing areas (Jing et al., 2013). Thus, taking the number of varieties adopted by farmers as a proxy for agricultural technology development, Sichuan province was expected to contribute to rice production in other provinces, especially the main rice-producing areas.

In general, the effect of hybrid rice variety adoption in Sichuan province has reduced over time (Figure 3). Our results showed that hybrid rice adoption in Sichuan province positively contributed to the rice yield in most rice production provinces in the 1980's, but had a bigger impact on provinces farther from Sichuan, particularly the provinces in eastern China including Jiangsu and Zhejiang (Figures 3A–C). Compared to the effect's distribution, the variation of estimated coefficients in Sichuan province in the 1980's, ranging from negative to the value of 12.78 in Figure 3A, was much bigger than that in Hunan province. In the 1990's, the development of hybrid rice variety adoption in Sichuan had positive effects on the rice yield in all rice-producing provinces although most estimated coefficients were smaller than 1 (Figure 3B). In the 2000's, only Zhejiang, Jiangsu, and Anhui provinces remained positively affected with low estimated coefficient values of <0.5 (Figure 3C). Overall, the effects of hybrid rice adoption in Sichuan province on the rice area across different provinces have been minimal in the last few decades.

The development of hybrid rice variety adoption in Sichuan province contributed considerably to rice production in the 1980's and 1990's, as nearly half of the estimated coefficients were positive (Figures 3G–I). The effects increased with distance, defying the first law of geography. The adoption of hybrid rice varieties in Sichuan province had a significant effect on rice production in Anhui and Jiangxi provinces in the 1990's and 2000's. The development of hybrid rice varieties in Sichuan province had a negative effect on rice production in the neighboring provinces, including Guangxi and Guizhou provinces, which might have been caused by the compensation effect among different provinces (Figures 3D–I).

Our results were not always consistent with the law of geography, in that the degree of influence diminished with distance. There might be three reasons for this. First, the collaborative breeding technology program among scientists and institutions

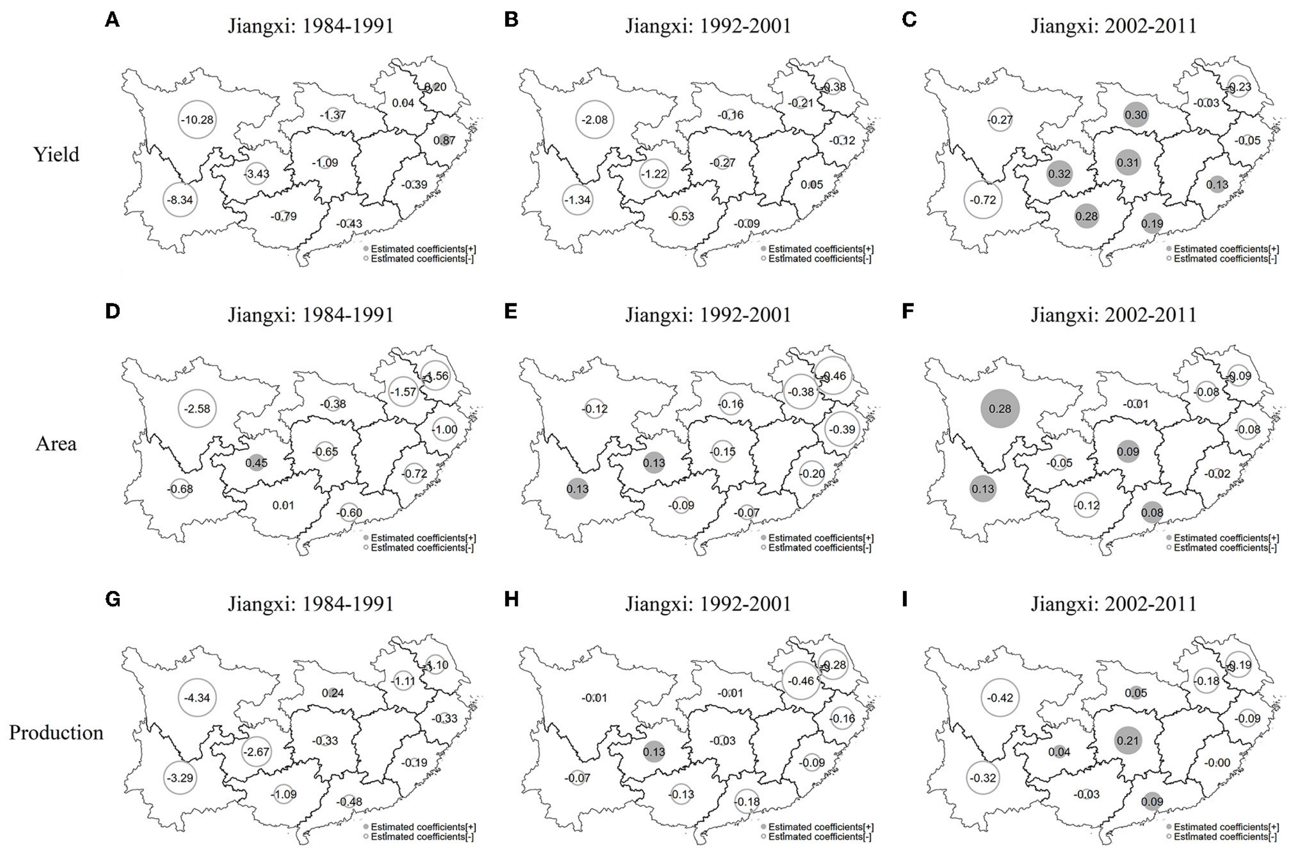

FIGURE 4
Spatio-temporal distribution of regression coefficients of hybrid rice adoption in Jiangxi province using the GTWR model from 1984 to 2011. **(A–C)** Represent the spatial distribution of regression coefficients with rice yield from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively; **(D–F)** represent the spatial distribution of regression coefficients with rice area from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively; **(G–I)** represent the spatial distribution of regression coefficients with rice production from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively. The values in the circles are the estimated coefficients of the number of hybrid rice varieties. The circles with shadow mean the estimated effects are positive, while those with blank mean negative.

was usually attributed to the social network and research interest instead of distance. The cooperation among the breeders and agronomists potentially facilitated the exchange of research materials and the development of hybrid rice varieties. Second, the development of seed companies may have affected the diffusion of hybrid rice varieties substantially as commercialization was essential for hybrid rice variety adoption. Third, local government support and relevant policy could have equally had a biased influence. Further study would be necessary to consider the three factors and help investigate how the spatial effects of hybrid rice variety adoption across provinces are affected.

4.3.3. Jiangxi and Guangdong provinces

Jiangxi province is an important rice-producing area in China, accounting for ∼10% of the rice area and rice production. The rice-cultivating area in Jiangxi province increased in the last few decades, while in most other provinces, it declined. Double rice cropping area was promoted in 2020 (Xu et al., 2022). Compared to Hunan province, Jiangxi province had much less effect on other rice-producing areas (Figure 4). This result was different from previous ones based on the regression using Equation (10) by pair grouping regression (Table 5). Jiangxi province might have been the neighbor that benefited more from the spillover effect of the development of hybrid rice technology in Hunan province instead of being a contributor.

In contrast to the effects of hybrid rice development in Hunan province, the increased adoption of hybrid rice varieties in Jiangxi province had a negative effect on rice yields in the 1980's and 1990's in other provinces (Figures 4A, B). In the 2000's, the development of hybrid rice varieties in Jiangxi province started to have a positive impact on rice yields in Hunan, Hubei, Guizhou, Guangxi, Guangdong, and Fujian provinces (Figure 4C). The effects on the provinces including Hunan, Hubei, and Guizhou provinces located closer to Jiangxi with a lower economic development level were larger, while the effects on the rice area caused by hybrid rice variety adoption in Jiangxi province were different from that on rice yields (Figures 4D–F). The variation may have been caused by the local development of rice production, which requires further study. The results also revealed the positive effects of hybrid rice variety adoption in Jiangxi province in the 2000's (Figures 4G–I); however, it is unlikely that such effects could be attributed to hybrid rice technology that has been developed for over 20 years and farmers have become familiar with the hybrid

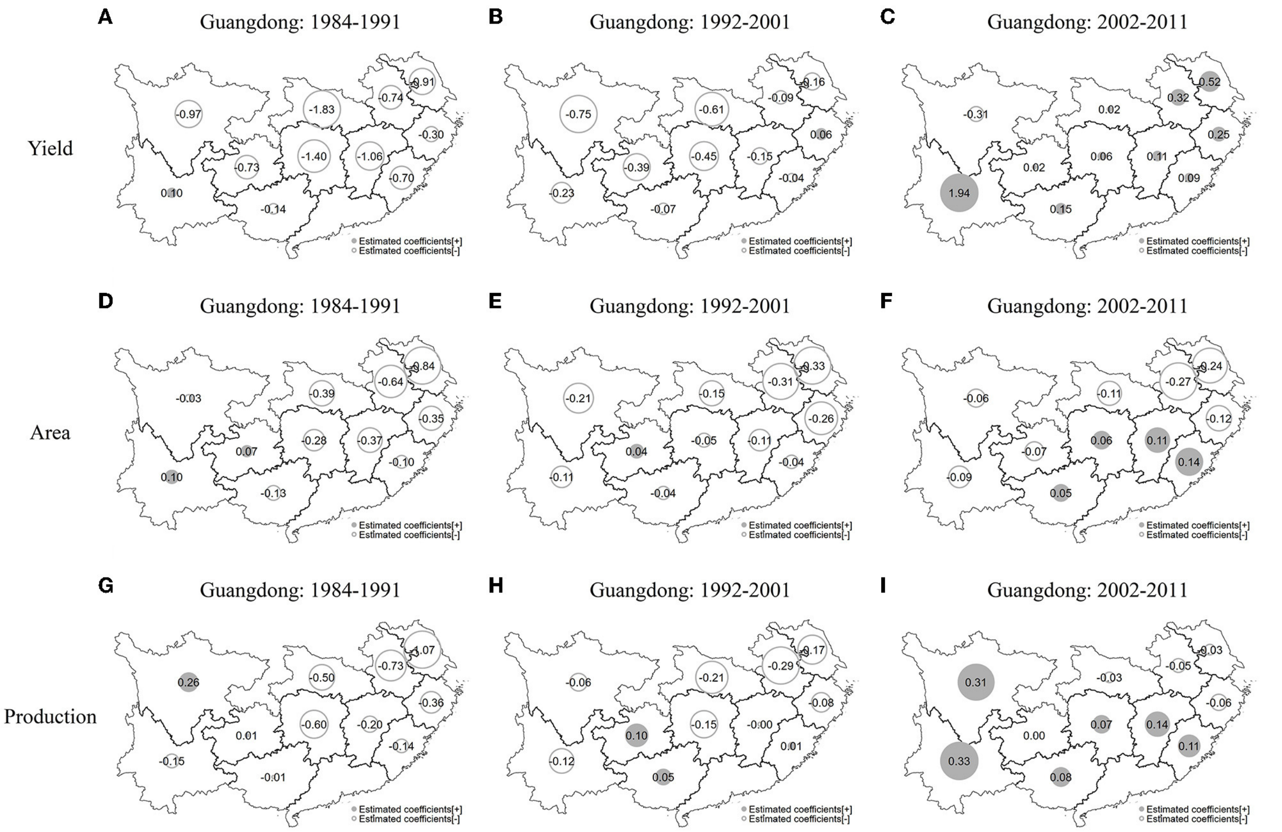

FIGURE 5
Spatio-temporal distribution of regression coefficients of hybrid rice adoption in Guangdong province using the GTWR model from 1984 to 2011. **(A–C)** Represent the spatial distribution of regression coefficients with rice yield from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively; **(D–F)** represent the spatial distribution of regression coefficients with rice area from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively; **(G–I)** represent the spatial distribution of regression coefficients with rice production from 1984 to 1991, from 1992 to 2001, and from 2002 to 2011, respectively. The values in the circles are the estimated coefficients of the number of hybrid rice varieties. The circles with shadow mean the estimated effects are positive, while those with blank mean negative.

rice varieties. The possible contribution of Jiangxi province might be the base for new and improved hybrid rice variety adoption due to its large-scale double-cropping rice area. A large number of hybrid rice varieties adopted in Jiangxi province could have facilitated the development of seed companies and information exchange among farmers. Therefore, the increase in the number of hybrid rice varieties in Jiangxi province had a significant positive effect on both rice yield in Hunan and Guangdong provinces in the 2000's (Figure 4I). On the other hand, the development of hybrid rice production in Jiangxi may have also contributed to the reduction of rice production in other areas in the context of urbanization and reduced the availability of agricultural land for rice farming.

Of the selected four provinces, the development of hybrid rice production in Guangdong province witnessed slow progress in terms of the amount of hybrid rice variety adoption and share of hybrid rice area (Figure 5). Although hybrid rice variety adoption in the Guangdong province has had an insignificant effect on the rice areas in developing areas such as Jiangxi province, it has had a positive effect on the rice yield in developed areas such as Jiangsu province (Table 5).

4.4. Robust analysis

As mentioned earlier, the GTWR model was applied to identify both the spatial and temporal effects of technology adoption compared to OLS and the GWR model. We compared the results of different methods. First, the results from OLS, GWR, and GTWR regression[2] were mostly consistent, which showed that the results from the GTWR regression were reliable and robust. The results from ANOVA[3] showed that the residual sum of squares of the GTWR model was lower than that of the GWR model, which indicated that the GTWR model was an appropriate method (Brunsdon et al., 1999). Second, the effects of technology adoption may be biased without considering the temporal effects. The coefficients of GWR regression present the average value of spatial effects across provinces. The impacts of hybrid rice adoption in Hunan, Sichuan, and Anhui provinces on rice yield were both negative in the OLS and GWR regressions but were positive in the

2 The results of OLS, GWR, and GTWR based on Equations (12–14) are shown in Supplementary Tables 2–4.

3 The results of ANOVA tests are shown in Supplementary Table 1.

GTWR regression. At the beginning of the hybrid rice adoption, a demonstration effect played a dominant role which resulted in the extension of the hybrid rice cultivation areas. Subsequently, as most regions began adopting large-scale hybrid rice production, there was competition among the main rice-producing areas and a crowding effect gradually affected the distribution of rice production given the total amount of rice demand. From the perspective of technology development, rice yield potential has recently reached its ceiling (Cassman et al., 2003; Licker et al., 2010; Neumann et al., 2010; Van Wart et al., 2013). The yield advantage of hybrid rice was different in the 2010's compared to the 1980's when the hybrid rice variety achieved both significant yield gain and the potential to be improved continuously. Simultaneously, the yield potential of conventional rice has also increased and the average yield of conventional rice reached 5.8 t/ha in 2009 (Deng, 2012). Meanwhile, consumers' increasing demand for particular rice qualities significantly affected farmers' hybrid rice production due to increases in economic growth and income. The results showed that extensive adoption of hybrid rice varieties in the country happened in the 1990's, which promoted rice yield and increased rice production associated with increasing agricultural inputs. The further extension of hybrid rice in the 2000's was stagnant and declined in some provinces such as Jiangsu, Jiangxi, and Guangxi. Without considering the temporal effects, the impacts of hybrid rice adoption could be biased because the effects of agricultural technology adoption have varied over time.

5. Discussion

Taking the number of mega hybrid rice varieties adopted by farmers as a measurement of new technology adoption, this study provided a detailed analysis of the dynamic changes in hybrid rice adoption and its impact on rice production in China. Hunan, Sichuan, Jiangxi, and Guangdong provinces, which first promoted and supported large-scale commercial hybrid rice production[4] (Ma and Yuan, 2015; Xie and Zhang, 2018) were taken as examples to estimate the effects of hybrid rice adoption and interaction of variety adoption across regions. The number of mega hybrid rice varieties in the four provinces accounted for 47% of the total hybrid rice varieties for large-scale commercial production.

The number of hybrid rice varieties adopted for large-scale production, to some extent, reflected the level of commercialization of hybrid rice and indicated the advantage of yield gain due to the heterosis advantage. The results confirmed the positive effect of hybrid rice adoption on national rice yield and production. In addition, widespread adoption reduced rice-cultivating areas substantially, which is consistent with the findings of previous studies (Huang et al., 2021).

The cropping pattern of rice production changed substantially due to the rapid expansion of hybrid rice production. In developed provinces like Guangdong, a net importer of rice, the adoption of hybrid rice satisfied its food security in the early stages, and later on, rice area and labor saved in hybrid rice production were used for various other income-generating activities such as cash crops or non-farm activities (FAORAP, 2014; Hu et al., 2022). In contrast, the widespread adoption of hybrid rice varieties increased the rice-cultivating area and continuous increases in rice production in Hunan, Jiangxi, and Sichuan provinces for decades. This indicated the advantages of rice production across the main rice-producing areas, i.e., the larger the number of hybrid rice varieties, the better the rice production in the developing provinces and economies of scale. Undoubtedly, other socioeconomic factors, such as the development of non-agricultural sectors and climatic conditions have contributed significantly to the change in rice cropping patterns (Pingali, 2012; Hu et al., 2022), which require further study to identify the complex effects of different factors impacting rice cultivation.

The spatial effect of hybrid rice adoption on rice production was identified in the study. Being the center of hybrid rice technology development, the effects of the rapid adoption of hybrid rice in Hunan province on rice production trends in Guangdong, Sichuan, and Jiangxi provinces varied. Previous studies have established the spillover effects of agricultural technology development (Hu et al., 2022), and similarly, the province with rapid extension and adoption of hybrid rice varieties had a positive effect on its neighboring provinces. With the increasing number of hybrid rice varieties adopted in Hunan province, rice production in adjacent Jiangxi province was affected more than in other provinces. This is consistent with the laws of geography (Tobler, 1970).

Large-scale commercial hybrid rice production also positively encouraged the participation of the private sector and seed companies (Cheng et al., 2007; Pingali, 2012). In the early 1980's, hybrid rice varieties were mostly extended and promoted by the government when seed companies had just started (Lin, 1991a; Singh et al., 2018). More seed companies were established and encouraged by the returns in seed production (Huang et al., 2002). By 2011, over 1,250 hybrid rice varieties were being farmed on a large scale. Although the studies on hybrid rice breeding and management technology are collaborative, both spillover and crowding effects were identified in the analysis influencing rice yield, rice-cultivating area, and rice production. The two effects from a given province could happen simultaneously and affect the target province differently. Further studies are imperative to determine how the different effects interact with each other in any given province. In addition, the status and development of seed companies involved in hybrid rice technology were not covered in our study due to data limitations. A study focused on the impact of seed companies on rice cultivation and cropping choices and patterns might be helpful for a better understanding of the number of varieties distributed across different areas. Furthermore, climate change should be included in future analyses since it has affected the center of rice production and the adoption of rice varieties in China (Huang et al., 2021), which may also influence the effect of hybrid rice adoption on rice production. Overall, our results demonstrate the variations in hybrid rice adoption and its spatial effect on rice production in China, which can be used as a reference to monitor and evaluate the effects of new technology adoption in developing

4 Although the first rice variety named Nanyou no.2 was officially released in Guangxi province, we did not take Guangxi province as an individual case considering the importance of rice production and technology development of rice varieties. The rice area and production in Guangxi province accounted for 8.3 and 7.1% in 1982 and 6.6 and 5.2% in 2011, which was lower than that in Guangdong province.

countries and design agricultural extension strategies for the long term to ensure food security. However, further study is necessary to identify the mechanism of technology diffusion in the complex context of economic development and climate change for a better strategy and design.

There are also several limitations in this study. First, the data used in the analysis is limited to secondary data. The estimation might be influenced by the application of proxy variables. For instance, irrigation is important for rice production, while irrigated rice area is not available in the secondary data and has been computed based on the share of the rice area within the arable land area. Although it suggests, to some extent, the different levels of irrigation in rice farming across provinces, the possible gap between computation and the real situation may influence the estimation. Second, we attempted to identify the important factors impacting rice farming in different provinces. A better measurement of the complex environment associated with the ecological system would be desirable. Third, the results of the econometric regression may be affected by omitted variables, such as seed commercialization and industry development. The seed industry and technology extension service are both important for local farmers to access improved rice variety adoption, especially for farmers who grow hybrid rice as they have to buy seeds every year. The lack of specific information on the seed market, including the number of seed companies, the amount and value of hybrid rice seed production, and relevant policies may limit the application of results. Finally, the small sample size that was applied in the analysis at the provincial level to identify the effects of hybrid rice adoption within a specific province would raise concerns. The dataset with longer period data may be needed to produce more reliable results.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

The original work of formal analysis and original draft writing of methodology was performed by QW. The literature review, draft writing of results, revision of analysis, and methodology were contributed by BB. The conceptualization, introduction, and conclusion as well as the manuscript draft and editing were undertaken by HW. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1071234/full#supplementary-material

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