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The role of highway construction in influencing agricultural green total factor productivity in China: agricultural industry structure transformation perspective

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Highway construction is vital in agricultural production, directly influencing food security and public health. This study utilized the Epsilon-based measurement-global-Malmquist-model (EBM-GML) and the spatial econometrics model with 31 Chinese provinces' panel data from 2002 to 2020 to investigate the impacts and the mechanisms of low-grade and high-grade highways on the agricultural green total factor productivity (AGTFP). Research findings indicated that (1) low-grade and high-grade highway construction significantly promote the AGTFP through technological progress, and the high-grade highway exerts a significant positive spillover effect on the adjacent areas' AGTFP. (2) The mechanisms of low-grade and high-grade roads on the AGTFP are heterogenous. Low-grade roads could improve the AGTFP by encouraging the rationalization of the agricultural industry structure. High-grade highways promote the AGTFP by upgrading the industry structure. And each-grade road could promote the AGTFP by stimulating the integration of planting and breeding. (3) Both low-grade and high-grade highways improved the AGTFP in non-main-grain-producing areas but inhibited it in main-grain-producing areas. Therefore, this study provided practical policy recommendations for green development in China's agricultural sector and valuable insights for other developing countries.

KEYWORDS

highway construction, agricultural industry structure, agricultural green total factor productivity, EBM-GML, spatial econometrics

1 Introduction

Agriculture is the primary sector of the national economy, and its sustainable development is highly related to the citizens' food security and economic growth (Fu and Zhang, 2022; Babu et al., 2023). Specifically, China's agriculture provides food for 22% of the world's population, with only 10% of the arable land worldwide (Chen et al., 2021), which is crucial in the global economy. China has made remarkable achievements in agricultural growth in the past 40 years, with an average annual growth rate of 4.6% (Gao et al., 2022). However, China's agricultural development under the circumstance of high resource consumption for a long time caused severe waste and environmental pollution (Su et al., 2020; Koondhar et al., 2021), such as excessive fertilization, water pollution, which seriously restricts the agricultural green development (Chen et al., 2021; Liu et al., 2021). Moreover, these pollutants also account for a large proportion of the world's pollution. For example, the ratio of China's agricultural carbon emissions (CO_2) in total volume worldwide was 17%, which was the world's largest source in 2019 (Gao et al., 2022). Therefore, analyzing the measures to promote green production in China's agriculture is extraordinarily urgent and significant for sustainable development worldwide and has become the focus of governments and academic circles (Song et al., 2022; Luo et al., 2023). Agricultural green total factor productivity (AGTFP) is an indicator to measure the sustainability level of agricultural development, considering the economic output and environmental outputs simultaneously (Liu and Feng, 2019; Ye et al., 2023).

Many scholars have calculated the AGTFP and explored the influencing factors (Chen et al., 2021; Liu et al., 2021). Generally, there were two kinds of methodology commonly used to calculate AGTFP , which are data envelopment analysis (DEA) and stochastic frontier analysis (SFA) (Li and Yang, 2018). Compared with the method of SFA, DEA has the advantage of non-parameter estimates without setting the actual production function (Razzaq et al., 2019). Besides, the methodology of DEA could consider multiple inputs and outputs simultaneously (Emrouznejad and Yang, 2018), so it was often combined with the Malmquist index to calculate agricultural production efficiency (Coelli and Rao, 2005; Tipi and Rehber, 2006; Rezitis, 2010). However, the traditional DEA approaches are radial models, requiring the input and output to change in the same proportion. Besides, this method could only consider desired output, not include undesired parts. To overcome these problems, Tone (2001) built a non-radial slack-based measurement (SBM) model to calculate efficiency. Many researchers used the SBM-DEA model to measure AGTFP (Liu et al., 2020; Pishgar-Komleh et al., 2021). For example, Liu et al. (2020) estimated the eco-efficiency in the agricultural sector (AEE) by utilizing the super-SBM model in China from 1978 to 2017, and the results showed that the AEE increased from 0.405 to 0.713, with an increase of around 76%.

The above agricultural productivity studies primarily utilized radial or non-radial measurements, which could overestimate or underestimate the efficiency improvements. Tone and Tsutsui (2010) constructed the epsilon-based measure (EBM) model to consider the radial and non-radial characteristics comprehensively, which measures the efficiency more accurately (Wu et al., 2019). Then, this model was widely used in calculating the eco-efficiency of the city (Zhang Y.Z. et al., 2022), transportation carbon efficiency (Zhao et al., 2022), industrial GTFP (Wang and Wang, 2023), etc. Although the EBM model has been utilized to calculate the efficiency in various research fields, it has rarely been used in measuring the efficiency in the agricultural sector.

Expect measuring AGTFP, the influencing factors analysis of it is another research question that scholars have been widely concerned about. Some research proposed that technological progress is an essential factor in promoting AGTFP (Bachewe et al., 2018; He et al., 2021; Shi et al., 2023). However, Hamid et al. (2023) proposed that technical efficiency restricts the AGTFP. Therefore, strengthening the research inputs in agricultural science and technology is essential for promoting the AGTFP (Liu et al., 2021). Additionally, some researchers found that the government is critical in improving agricultural production efficiency. Xu L. Y. et al. (2023) proposed that financial support helps raise the AGTFP. However, Deng et al. (2023) found that fiscal expenditures significantly increased the AGTFP mainly through enhancing rural infrastructure. Meanwhile, the environmental regulation proposed by the government is also effective in promoting the AGTFP (Liu Z. et al., 2023; Liu G. J. et al., 2023; Tang et al., 2023). Moreover, it is also essential for the government to help transform and upgrade the industrial structure in the agricultural sector to solve the factor misallocation problem for improving the AGTFP (Lei et al., 2023). In addition, some socioeconomic factors are also considered the critical factors influencing the AGTFP, such as urbanization, human capital, digital development level, etc. (Fu and Zhang, 2022; Shen et al., 2022; Li L. et al., 2023; Li X. H. et al., 2023).

Moreover, some researchers proposed that transportation development is vital for agricultural production (Limi, 2022). First, highway construction helps agricultural production materials flow into rural areas, such as seeds, chemical fertilizers, pesticides, etc., thereby directly promoting agricultural production efficiency (Gollin and Rogerson, 2014; Aggarwal, 2018; Shamdasani, 2021). Second, highway construction can also encourage agricultural technicians to come to rural areas for guidance, promoting the level of technology (Teng and Li, 2020). Thirdly, highway construction also helps surplus rural labor transfer to urban areas, improving agricultural productivity (Liu et al., 2015; Zhang et al., 2021). However, highway construction also adversely affects agricultural production, such as land fragmentation (Bacior and Prus, 2018). Li et al. (2015) proposed that road expansion brought about the total carbon stock loss in the Democratic Republic of Congo, with 316 Tgc. Zhou et al. (2021) discovered that rural road construction negatively affects the environmental sustainability in China's regional agriculture due to the overuse of fertilizers. Therefore, the influence of highway construction on the AGTFP is uncertain and deserves further exploration.

The current literature has fully explored the AGTFP and its influencing factors, which gives a deep understanding of the AGTFP and provides some practical policy implications for the sustainable development of agriculture. However, this kind of research still has some limitations. For example, based on the heterogeneity characteristics of transportation, limited literature has analyzed the influence mechanism of different grades of transport on agricultural production. Besides regional heterogeneity in the natural environment and economic development level, the highway's impact on agricultural production is heterogeneous; however, there is limited research analyzing the different effects among various regions. This study's theoretical contribution mainly contains three aspects.

First, analyze the heterogenous effect and mechanism of the low-grade and high-grade highway on the AGTFP. Although existing literature has attached importance to the influence of highway construction on agricultural production (Tong et al., 2013; Aggarwal, 2018; Shamdasani, 2021), there is limited study on its effect on AGTFP. Meanwhile, there is a lack of research to analyze the heterogeneous influence and mechanism of the different grades of highways on agricultural production. The path of the effect of low-grade and high-grade highways on agriculture is different. The low-grade road is an important channel to connect the city and countryside, directly affecting agricultural production. Meanwhile, the high-grade road indirectly affects agricultural production by strengthening regional correlations. Thus, it is essential to distinguish each grade highway's influence and mechanism on the AGTFP.

Second, empirically analyzing the spillover effects of the highway construction on the AGTFP. Previous literature explored the influence of rural road and expressway connectivity on the local area's agricultural production (Aggarwal, 2018; Teng and Li, 2020), but there is a lack of analysis of the impacts of highway construction on the other areas. Generally, highway construction aims to shorten the distance and strengthen the connections between regions; the increased communication is likely to stimulate the spatial impact on the adjacent areas and is worth analyzing. Therefore, we constructed the spatial econometrics model to investigate highway construction's direct and spillover effects on AGTFP.

Thirdly, we compared the heterogenous effect of highway construction on the AGTFP in the main-grain-producing and non-main-grain-producing areas. Existing literature mainly focused on the impact of highway construction on agricultural production in the main-grain-producing area (Luo et al., 2020; Liu and Xiao, 2021), with less attention on the non-main-grain-producing regions and a lack of comparative analysis between them. Given the differences in natural conditions and production tasks in the various areas, it is also necessary to compare the heterogeneous effect of highway construction on each production area for formulating the targeted policy for different regions.

The specific research objectives of this study were to explore the direct and spillover effects of different highway construction on the sustainable development of agriculture in China. Specifically, we calculated AGTFP by utilizing the EBM-GML model to measure the sustainability level of agriculture, which has consistency with the method in the most current studies. Firstly, we theoretically analyzed the different influence mechanisms of low-grade and high-grade highways on the AGTFP. Then, we utilized the spatial econometrics model to analyze the direct and spillover effect of highway construction on AGTFP. Moreover, we examined the mechanism of highway construction on AGTFP by using the mediation effect model. Finally, we explored the heterogeneous impacts on the various producing areas. This study provides valuable empirical evidence for the Chinese government to conduct a rational transportation plan to realize sustainable agricultural development. Meanwhile, the heterogeneity analysis of AGTFP in different regions could also provide significant references for developing countries in various stages of agricultural development.

2 Mechanism analysis

2.1 Highway construction and AGTFP

2.1.1 Low-grade highway construction and AGTFP

Generally, constructing transportation infrastructure is essential for reducing transportation costs and promoting market transaction efficiency (Holl, 2016; Ghani et al., 2017). The low-grade highway is an important channel connecting urban and rural markets and reducing transportation costs, which promotes transaction efficiency in their factor and product markets to a certain extent (Dorosh et al., 2012; Aggarwal, 2018).

For the factor market, low-grade highway construction provides convenience for labor, capital, and technology flow in urban and rural markets. First, constructing low-grade roads promotes the surplus rural labor flow into the urban industrial sector, thereby improving agricultural production efficiency (Lewis, 1954). Then, the reduction of transaction costs brought about by the low-grade highway construction also promotes the inflow of capital into the agricultural sector and directly invests in agricultural production to improve agricultural technical efficiency. Moreover, the low-grade highways also greatly facilitate agricultural technicians to guide the farmers (Luo and Peng, 2016; Teng and Li, 2020), thus improving production technology levels.

For the product market, the low-grade roads have promoted the flow of industrial products, such as fertilizers, pesticides, seeds, etc., into the agricultural sector, directly encouraging agricultural production efficiency (Limi, 2022). Besides, constructing low-grade highways reduces the intermediate loss of agricultural products transported to the city, which expands the agricultural products market (Gollin and Rogerson, 2014) and promotes its production efficiency.

Overall, low-grade highway construction has improved agricultural production efficiency and technical level by promoting the flow of factors and products, which could further boost the AGTFP. Therefore, we proposed the Hypothesis 1:

> *Hypothesis 1 (H1)*: Low-grade highway construction could promote the AGTFP

2.1.2 High-grade highway construction and AGTFP

The construction of high-grade highways promotes the connection between cities, improving the transaction efficiency of a broader range of factor and product markets, significantly impacting AGTFP. For the factor market, constructing a high-grade highway promotes the mutual exchange of labor, capital, and technology among cities, stimulating the optimal factor allocation among regions (Morando, 2023). For the product market, the construction of high-grade highways promotes the trade of agricultural products between cities, which helps each area carry out specialized production according to its comparative advantages (Adamopoulos, 2011), thus improving agricultural production efficiency. Therefore, strengthening high-grade highway construction could promote the optimal allocation of factors and product structure between regions to improve agricultural production efficiency and achieve efficient agricultural production. Thus, we proposed Hypothesis 2.

> *Hypothesis 2 (H2)*: High-grade highway construction could promote the AGTFP

The high-grade highway construction has also increased regional communication and produced a spatial spillover effect. First, high-grade highways facilitate people's flow, transferring knowledge and technology from developed regions to surrounding areas (Shamdasani, 2021). The reason is that local farmers could conveniently move to developed areas for agricultural technology training (Aggarwal, 2018). Then, the construction of high-grade highways will also help more advanced agricultural production materials flow into surrounding areas, thereby promoting the overall sustainable development of agriculture. Thus, we proposed Hypothesis 3.

> *Hypothesis 3 (H3)*: High-grade highway construction could exert spatial spillover effects on the adjacent areas.

2.2 Highway construction, agricultural industry structure, and the AGTFP

The reduction of transportation costs caused by highway construction also impacts the production decision-making and planning of farmers and policymakers and then has a specific impact on AGTFP.

For farmers, the decline in transportation costs will affect their decision to adopt modern agricultural production modes (Damania et al., 2017; Shamdasani, 2021). On the one hand, there are some costs of converting from traditional to modern agricultural production mode, including purchasing agricultural equipment and learning new technologies. On the other hand, modern agriculture will improve production efficiency to a certain extent, such as mechanization production, thus increasing farmers' income. With the reduction of transportation costs, the conversion cost of farmers will also decrease, which will encourage farmers to adopt modern agricultural production modes. Modern agriculture could promote the reduction of intermediate consumption, realize the upgrading of the agricultural industry structure, and affect production efficiency. Therefore, we proposed Hypothesis 4a.

> *Hypothesis 4a (H4a)*: Highway construction could promote AGTFP by stimulating the upgrade development of the agricultural industry structure.

Policy planners aim to maximize the benefits of the whole region's agricultural sector. Regional agricultural development costs include production costs of each product and transportation costs to reach the market (Jacoby, 2000; Helmstädter, 2010). Due to the characteristics of each agricultural product, its transportation cost has specific differences. The continuous improvement of highway construction also exerted heterogeneity in reducing the transportation costs of various products. Therefore, policy planners need to change their production layout based on the extent of the reduction of transportation costs for different agricultural products to adjust the distance of each product to the market to maximize the overall benefit (Rivera-Padilla, 2020). Adjusting the agricultural industry structure layout could bring about optimal resource allocation in the spatial scope and improve agricultural production efficiency. Thus, we proposed Hypothesis 4b.

> *Hypothesis 4b (H4b)*: Highway construction could promote AGTFP by stimulating the rationalization of agricultural industry structure.

Policymakers also usually consider how to promote the integration of various industrial sectors to achieve overall benefits. Highway construction has enabled the integration of various agricultural sectors (Huang et al., 2020). Before integrated development, highway construction reduced the communication cost between different industrial sectors and improved their integration efficiency. During the integrated development, highway construction could not only strengthen the connection of the entire industrial chain and reduce uncertainty but also promote the sharing of resources among various industrial sectors to reduce agricultural production costs and promote efficiency (Jiang et al., 2023). Therefore, we proposed the Hypothesis 4c.

> *Hypothesis 4c (H4c)*: Highway construction could promote the AGTFP by promoting the integrated development of agricultural industry sectors.

2.3 Heterogenous effects of highway construction on the AGTFP

There are five temperature zones in mainland China, and it has different agricultural production environments. Meanwhile, China's economic development gap exists between the North-South and the East-West (Yin et al., 2022). Therefore, the influence of highway construction on agricultural production in various areas will also be different. According to the natural production conditions in China, the government categorized 13 provinces as the main-grain-producing regions. Thus, because of its natural environment, which is suitable for agricultural production, this area undertakes more grain production tasks (Zhang et al., 2021). For this area, highway construction has promoted the agricultural machinery operating cross-region, which has realized large-scale agricultural production and increased total grain output value (Luo et al., 2018). However, large-scale production activities will produce much environmental pollution in this area, which inhibits AGTFP (Zhang et al., 2019).

Meanwhile, because most main-grain-producing areas have a relatively low economic development level, the negative environmental output of their growth will vastly exceed the economic effect, which will have a side effect on the local AGTFP. However, highway construction will bring in more agricultural production resources for non-main-grain-producing areas, which could help them expand the production scale, and it is also conducive to improving their technology due to their developed economic status, thereby promoting the continuous rise of the AGTFP. Thus, we proposed Hypothesis 5.

> *Hypothesis 5 (H5)*: Highway construction exerts a heterogenous effect on the AGTFP in different production areas.

According to the analysis above, we drew the mechanism analysis framework in Figure 1.

3 Method and variables

3.1 Study area

The scope of this research is 31 provinces in mainland China. At the same time, China has divided 13 main-grain-producing provinces to adapt to the new grain production and distribution pattern changes so that these areas can take advantage of their geographical resources. Therefore, this study also compared the heterogeneity of highway construction's impact on the AGTFP in different regions. Figure 2 presents the specific division of the study area.

3.2 Econometric model

3.2.1 Fixed-effect regression model

To investigate the relationship between highway construction and AGTFP, we first constructed the fixed-effect regression model by

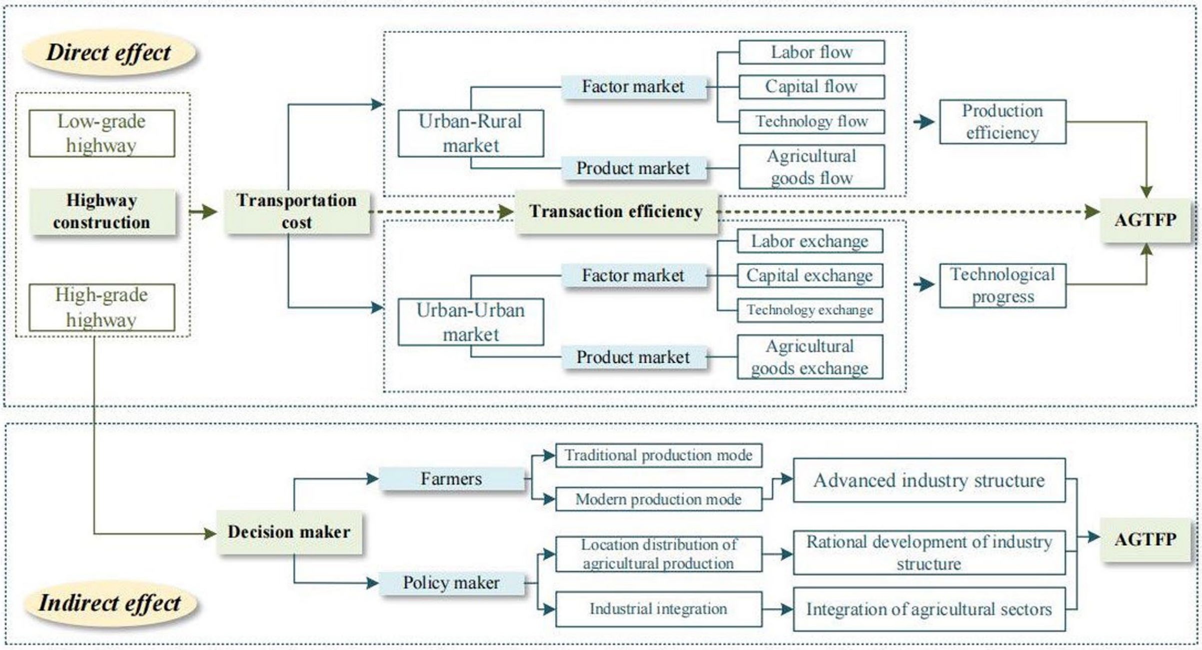

FIGURE 1
Mechanism analysis framework.

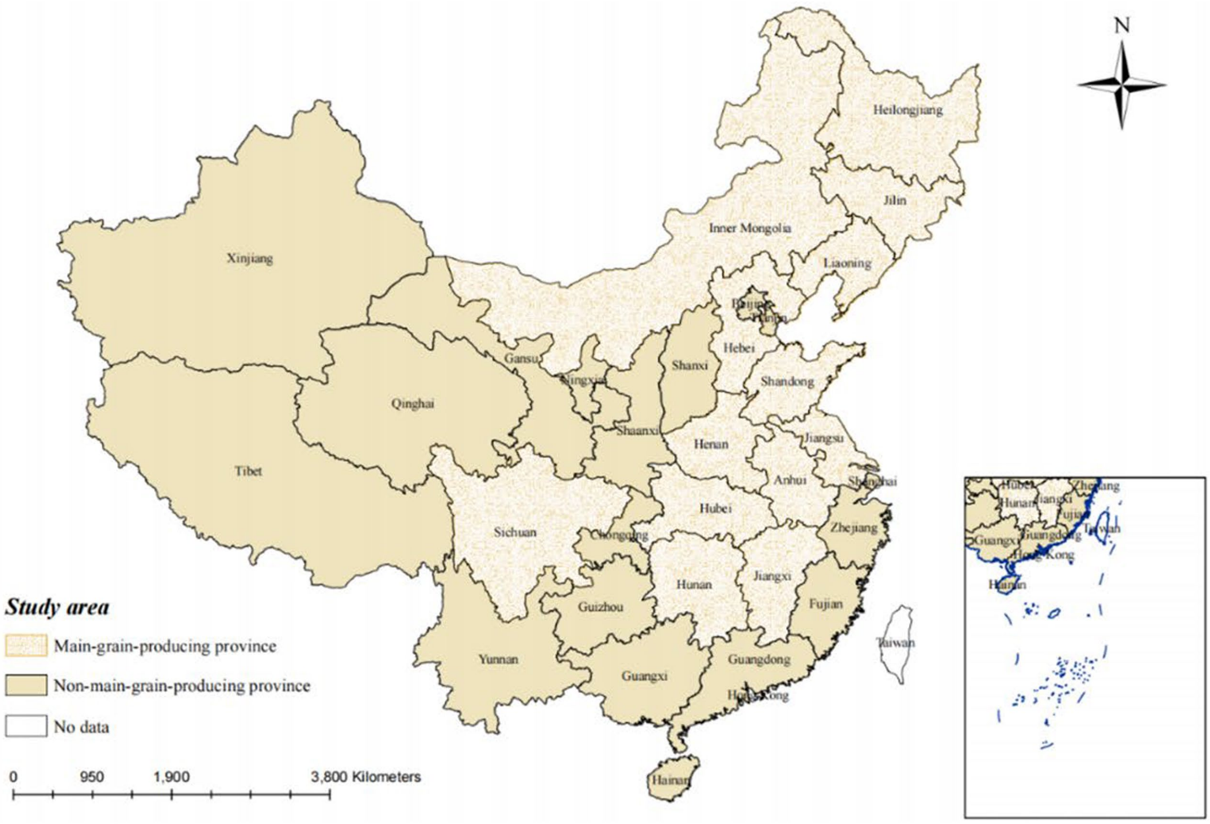

FIGURE 2
Study area.

taking the AGTFP as the dependent variables, highway construction as the core independent variable, and financial support, urbanization, and other variables directly impact the AGTFP as the control variables. Then, we utilized the fixed effect regression model to analyze the impacts by simultaneously controlling the individual (province) fixed and time (year) fixed effects. We first fixed some regional variables that do not change with time, such as regional farming culture, terrain characteristics, etc. These variables are difficult to measure and do not vary over time, so we controlled the individual effects. Then, we added the time effect to fix the influence of factors that change over time, such as macroeconomic situations and national policy shocks. Controlling the above two effects could reduce the missing variable bias, and the model is represented as Eq. (1).

$$\text{AGTFP}_{it} = \beta_1 \text{highway}_{it} + \beta X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (1)$$

where AGTFP_{it} is the dependent variable, which denotes the AGTFP in province i, year t; highway_{it} represents the highway construction; X_{it} is the vector of control variables; β reflects the influencing coefficients of each factor; $\propto_i$ and v_t are the individual and time-fixed effects; ε_{it} reflects the error term.

3.2.2 Spatial econometrics model

We utilized spatial econometrics to explore the impacts of highway construction on the AGTFP by considering the spillover effect. Generally, the spatial Durbin model (SDM) is the general form of the spatial econometrics model, including the spatial interaction of dependent and independent effects simultaneously (LeSage and Pace, 2008). When the model only exists the spatial lag effect of the dependent variable, it will transform into the spatial autoregression model (SAR). Moreover, if the model only has the spatial error effect, it will change into the spatial error model (SEM). The SDM model is represented as Eq. (2):

$$\begin{aligned}\text{AGTFP}_{it} &= \rho W\text{AGTFP}_{it} + \beta_1 \text{highway}_{it} + \beta X_{it} \\ &+ \theta_1 W\text{highway}_{it} + \theta W X_{it} + \mu_i + v_t + \varepsilon_{it}\end{aligned} \quad (2)$$

where W is the spatial weight matrix reflecting the spatial correlations among regions; ρ and θ represent spatial lag effect coefficients of AGTFP and highway construction, respectively.

Two kinds of spatial weight matrices were utilized in this paper. The first is the geographic distance matrix ($W1$), with the element w_{ij} representing the geographical distance between the two provinces. According to Liu and Lin (2019), the distance is calculated by the latitude and longitude of the provincial capital city. The second is the economic distance matrix ($W2$). Based on Cai et al. (2022), the economic distance is calculated by the per capital GDP gap between two provinces.

In addition, Elhorst (2010) proposed that the model can be applied to decompose the spillover effect in the spatial econometrics model. Eq. (3) shows that we could decompose the coefficients of each factor into direct and indirect effects.

$$\begin{aligned}&\text{AGTFP}_{it} = \\ &\left(I-\rho W\right)^{-1}\left(\beta_1\text{highway}_{it} + \beta X_{it} + \theta_1 W\text{highway}_{it} + \theta W_{it}\right) \\ &+ \left(I-\rho W\right)^{-1}\mu_i + \left(I-\rho W\right)^{-1}v_i + \left(I-\rho W\right)^{-1}\varepsilon_i\end{aligned} \quad (3)$$

Then, the partial derivatives of the i-th independent variable are shown in Eq. (4):

$$\begin{aligned}&\left[\frac{\partial \text{AGTFP}}{\partial \text{highway}_{it}} \frac{\partial \text{AGTFP}}{\partial X_{1t}} \cdots \frac{\partial \text{AGTFP}}{\partial X_{nt}}\right] = \\ &\begin{bmatrix} \frac{\partial \text{AGTFP}_1}{\partial \text{highway}_{1t}} & \frac{\partial \text{AGTFP}_1}{\partial X_{1t}} \cdots & \frac{\partial \text{AGTFP}_1}{\partial x_{nt}} \\ \vdots & \ddots & \vdots \\ \frac{\partial A\text{GTFP}_n}{\partial \text{highway}_{1t}} & \frac{\partial \text{AGTFP}_n}{\partial X_{1t}} \cdots & \frac{\partial \text{AGTFP}_n}{\partial X_{nt}} \end{bmatrix} \\ &= \left(I-\rho W\right)^{-1} \begin{bmatrix} \beta_t & w_{12}\lambda_t & \ldots\ w_{1n}\lambda_t \\ w_{21}\lambda_t & \beta_t & \ldots\ w_{2n}\lambda_t \\ \vdots & \vdots & \ldots\ \vdots \\ w_{n1}\lambda_t & w_{n2}\lambda_t & \ldots\ \beta_t \end{bmatrix}\end{aligned} \quad (4)$$

When the explanatory variables in Eq. (3) change, it will drive the explained variable change, generate a direct effect, and affect the dependent variables of other units to exert a spillover effect.

3.2.3 Mediation effect model

The previous discussion of the mechanism of highway construction may affect the AGTFP by upgrading the agricultural industry structure, promoting the rationalization of the agricultural industry structure, and integrating agricultural sectors. To test the mediation effects, we constructed the following models referring to Baron and Kenny (1986) and Gao et al. (2023) to investigate the mechanism of the influence of highway construction on the AGTFP carefully.

$$\begin{aligned}M_{it} &= \tau W M_{it} + \alpha_1 \text{highway}_{it} + \alpha X_{it} \\ &+ \gamma_1 W\text{highway}_{it} + \gamma W X_{it} + \mu_i + v_t + \varepsilon_{it}\end{aligned} \quad (5)$$

$$\begin{aligned}\text{AGTFP}_{it} &= \eta W\text{AGTFP}_{it} + \delta_1 M_{it} + \delta_2 \text{highway}_{it} + \delta X_{it} \\ &+ \kappa_1 W M_{it} + \kappa_2 W\text{highway}_{it} + \kappa W X_{it} + \mu_i + v_t + \varepsilon_{it}\end{aligned} \quad (6)$$

Considering the inter-regional linkages brought about by the highway construction, it may exert a spillover effect on the inter-regional agricultural industrial structure. Therefore, we added the spatial lag variable of mediation variables in the Eq. (5) to construct a spatial econometric model. M_{it} is the mediation variable, WM_{it} is the spatial lag variable of M. The coefficient β_1 in Eq. (2) illustrates the total effect of the highway construction on the AGTFP, and the coefficient α_1 in Eq. (5) means the effect of highway construction on the mediation variable. When the coefficient α_1 is significant, indicating that highway construction promotes the mediation effect and vice versa. After that, we put the mediation variable, core independent variable, and their spatial lag variables in the Eq. (6) while considering the spillover effects caused by the highway construction. The coefficient δ_2 in the Eq. (6) is the direct effect of highway construction on the AGTFP. The coefficients δ_1 in Eq. (6) represents the coefficient of the mediating effect. When the coefficients α_1, and δ_1 are significantly positive, representing that a mediation effect exists.

3.3 Variables selection

3.3.1 Dependent variable

Generally, DEA is a kind of methodology for assessing efficiency with multiple inputs and outputs. Charnes et al. (1978) first constructed the CCR DEA model with a fixed-scale returns assumption based on the concept of boundary proposed by Farrell (1957). Then, Banker et al. (1984) extended the premises to reveal a BCC model to calculate technical and scale efficiency. However, CCR and BCC models are radial DEA, ignoring non-radial slacks. Tone (2001) utilized a difference variable to measure the slack in the input and output and a scalar in the non-radial estimation methods called the slack-based measurement (SBM) method. However, this model failed to consider the parts with the same radial proportions. To solve these problems, Tone and Tsutsui (2010) constructed the method of EBM, which integrated the radial and non-radial parts of the distance function and could reflect the ratio of objective and actual value and the difference between various inputs and outputs simultaneously. The development path of DEA is presented in Figure 3.

Meanwhile, considering the agricultural sector's long cycle and continuous production process, we utilized the global Malmquist Luenberger (GML) to calculate the AGTFP. The Malmquist index was calculated to represent the dynamic productivity during one period (Malmquist, 1953). Combined with the DEA model, this index was set to represent the changing productivity trend over time (Färe et al., 1992). However, the ML index is limited to noncircular geometric averages and linear programming infeasibility. Thus, Pastor and Lovell (2005) employed the GML index to solve this problem. Therefore, we measured the AGTFP by constructing the EBM-GML model using 31 provincial data in China from 2001 to 2020. The detailed calculation process is as follows:

Step 1: Applying the EBM method to calculate the agricultural green production efficiency. The Eq. (7) is:

$$\gamma^* = \min \frac{\theta - \varepsilon_x \frac{1}{\sum_{i=1}^{m}\omega_i^-} \sum_{i=1}^{m} \frac{\omega_i^- s_i^-}{x_{ik}}}{\varphi + \varepsilon_y \frac{1}{\sum_{r=1}^{q}\omega_r^g} \sum_{r=1}^{q} \frac{\omega_r^g s_r^g}{y_{rk}} + \varepsilon_z \frac{1}{\sum_{t=1}^{p}\omega_t^b} \sum_{t=1}^{p} \frac{\omega_t^b s_t^b}{z_{tk}}} \quad (7)$$

$$\text{s.t.} \quad \begin{aligned} & X\lambda - \theta x_k + s_i^- = 0 \\ & Y^g\lambda - \varphi y_k - s_r^g = 0 \\ & Z^g\lambda - \varphi Z_k + s_t^b = 0 \\ & \lambda \ge 0,\ s_i^- \ge 0,\ s_r^g \ge 0,\ s_t^b \ge 0 \end{aligned}$$

where $0 \le \gamma^* \le 1$ reflects the value of green production efficiency; X, Y^g, and Z^g represent the matrices of the input, desirable output, and undesirable output, respectively; θ and φ are the parameters of the radial part; S_i^-, S_r^g, and S_t^b denote the slack-based variable of the related inputs or outputs; λ is the weight; ω_i^-, ω_r^g, and ω_t^b represent the relative weight of X, Y^g, and Z^g; ε_x, ε_y, and ε_z are the weight of the non-radial part.

Step 2: Calculating the GML index, which is shown in Eq. (8):

$$\begin{aligned} & \text{AGTFP}^{t,t+1}\left(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1}\right) \\ & = \left(1 + D_G^T\left(x^t, y^t, b^t\right)\right) / \left(1 + D_G^T\left(x^{t+1}, y^{t+1}, b^{t+1}\right)\right) \end{aligned} \quad (8)$$

where AGTFP represents the change rate of the green production efficiency for each province. And we could get the $D_G^T(x,y,b) = \max\{\beta | (y + \beta y, b - \beta b) \epsilon P_G(x)\}$ according to the global baseline production possibilities set. In particular, AGTFP > 1 indicates the improvement of the green production situation, and AGTFP < 1 means the deterioration of the green production situation. Then, we decomposed the GML index into the combination of the global production technology set with the ML index according to Oh (2010), and the formula is presented as follows:

$$\begin{aligned} & \text{AGTFP} = \left(x^{t+1}, y^{t+1}, b^{t+1}, x^t, y^t, b^t\right) \\ & = \left[\frac{\vec{s^t}\left(x^{t+1}, y^{t+1}, b^{t+1}\right)}{\vec{s^t}\left(x^t, y^t, b^t\right)} \times \frac{\vec{s^{t+1}}\left(x^{t+1}, y^{t+1}, b^{t+1}\right)}{\vec{s^t}\left(x^t, y^t, b^t\right)}\right]^{\frac{1}{2}} = \text{TC} \times \text{TEC} \end{aligned} \quad (9)$$

where TC denotes the technological progress, TEC represents the technical efficiency.

As for the indicators for measuring AGTFP, there are some differences among the current studies. Most researchers selected land, labor, and capital as the input variables (Deng et al., 2023; Luo et al., 2023), which are the traditional production factors. In particular, the machinery is commonly considered as the capital factor (Wang et al., 2017). Meanwhile, fertilizer, agricultural film, and pesticides are also crucial inputs in agricultural production (Huang et al., 2022; Liu Z. et al., 2023; Liu G. J. et al., 2023). And some scholars added resource factors in the input indicator system, such as water (Huang et al., 2022; Liu Z. et al., 2023; Liu G. J. et al., 2023). As for the desired output, agricultural production output is widely considered (Coluccia et al., 2020; Wu et al., 2020). However, the undesired part has not formed the consensus. Some researchers have chosen nonpoint source pollution as the undesired output (Zhang et al., 2023). However, most scholars selected agricultural CO_2 as the undesired output (Lei et al., 2023; Shen et al., 2023). Zhang Z.X. et al. (2022) simultaneously utilized the agricultural CO_2 and nonpoint source pollution as the undesired outputs, comprehensively measuring AGTFP. This study selected the relevant input and output variables according to the existing literature and the situation. As for input variables, this paper selected traditional factors, namely labor, land, and capital, and considered energy, water resources, and climate factors. As for agricultural pollution, according to the research of Yu et al. (2023), we considered nonpoint source pollution and CO_2 simultaneously. In addition, the detailed introduction of the selected input and output variables for measuring the AGTFP is depicted in Table 1 and Figure 4.

3.3.2 Core independent variables

In this study, the core independent variable is the situation of highway construction. Due to the different roles and tasks of the various grade highways, we explored each grade highway's effect. Referring to "Technical Standards for Highway Engineering, China" (JTG B01-2014), the road could be divided into five grades: expressway, first-grade highway, secondary road, tertiary highway, and township road, and detailed information is shown in Table 2.

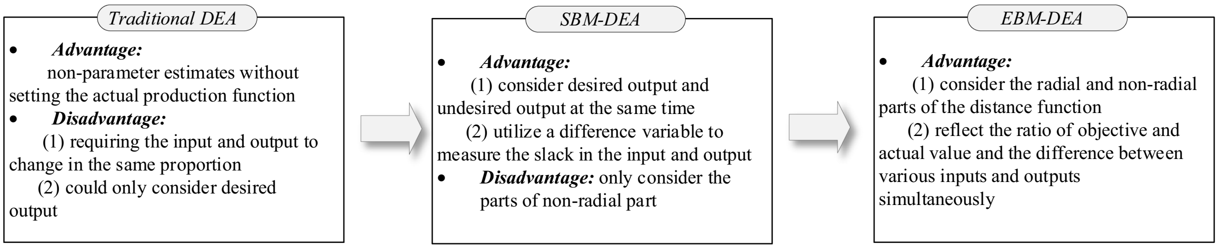

FIGURE 3
The advantages and disadvantages of the DEA method.

TABLE 1 Variables of input and output.

Input/output	Variables	Proxy indicators	Unit
Input	Labor	The number of laborers in the agricultural sector	10,000 people
	Land	Crop sown and aquaculture area	1,000 hectares
	Capital	Total agricultural machinery power	100,000 kilowatts (kW)
		Quantity of the agricultural chemical fertilizer	Tons
		Usage of the pesticide	Tons
		Usage of agricultural film	Tons
	Energy	Diesel consumption	Tons
		Electricity consumption	kWh
		Water consumption	100 million cubic meters (m^3)
	Climatic factors	Average temperature	Celsius
		Precipitation	mm
Output	Desirable output	Gross output value in the agricultural sector	100 million CNY
	Undesirable output	Non-point source pollution	10,000 m^3
		Carbon emissions	10,000 tons

In particular, the main task of expressways and first-grade highways, denoted as high-grade highways, is to connect the cities. The tertiary and township roads are low-grade highways, which mainly strengthen the relationships between city-rural and rural–rural areas. Besides, the secondary road connects with the rural road, enhancing the relationship between the city and rural areas. Therefore, we also regard the secondary road as a low-grade highway directly affecting agricultural production. The proxy variable of highway construction is low-grade and high-grade highway density, calculated by using the proportion of the length of the road and the provincial area.

In addition, because the Ministry of Transport of China does not disclose the data on graded roads in prefecture-level cities and counties, only some provinces (such as Shanxi, Henan, Hunan, etc.) have published the statistics on graded roads in prefecture-level cities. Thus, the statistical caliber is inconsistent, with many missing values. Considering data acquisition and quality, this paper selects provincial data for empirical analysis.

3.3.3 Mediator variables

3.3.3.1 Rationalization of agricultural industry structure

The rationalization of the agricultural industry structure reflects the degree of coordination of each internal sub-industry (Jin and Jin, 2020; Cao and Nie, 2021). According to the literature of Yang et al. (2022), we chose the portion of cash and grain crops, the percentage of beef and mutton to total meat output, the rate of aquaculture output to the whole agricultural sector's production, and the ratio of the output value of forestry, animal husbandry, and fishery to the total output value of the entire agricultural industries, and utilize the methodology of entropy weight to standardize each variable. The weighted summation is the indicator that reflects the rationalization of the agricultural industry structure.

3.3.3.2 Upgrading of agricultural industry structure

The essence of transitioning from traditional to modern agriculture is increasing production efficiency. According to the literature of Yang and Qiao (2021), we selected the proportion of value-added of the whole agricultural industries and intermediate consumption to represent their respective production efficiencies. After that, we also applied the methodology of entropy weight to standardize the indicators and use the weighted summation as the variable for denoting the upgrading of the agricultural industry structure.

3.3.3.3 Integration of planting and breeding

Combining planting and breeding is the focus of agricultural industry integration development, essential for green growth.

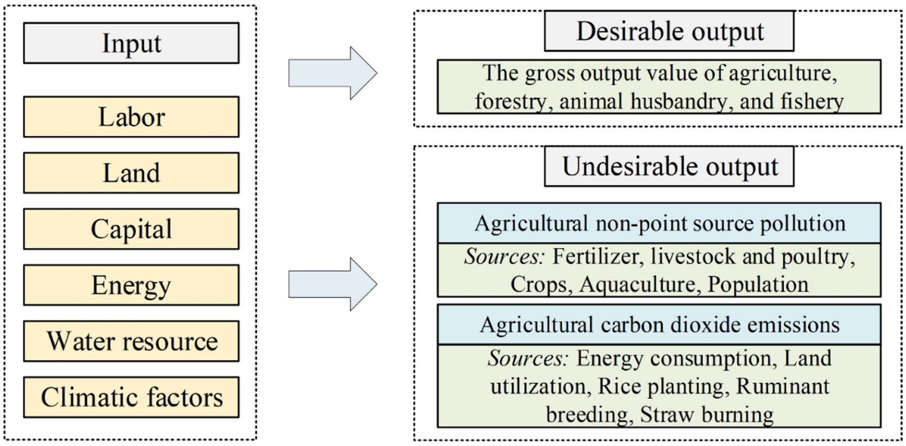

FIGURE 4
Input and output variables.

TABLE 2 The definition of high-grade and low-grade highway.

Highway classification	Highway grade	Main function	Explanation
High-grade highway	Expressway	Connecting politically, economically, and culturally significant cities and regions	Connecting city to city
	First-grade highway	Connecting with significant political and economic centers	
Low-grade highway	Secondary road	A trunk road connecting political and economic centers, large industrial and mining areas, or a suburban road with heavy transportation	Connecting city and countryside
	Tertiary highway	General trunk roads connecting counties and towns	
	Township road	Feeder roads connecting countries, townships, villages, etc	

The information sources are from the Chinese highway engineering technical standard (JTG B01-2014).

Regarding the measurement method of Li (2022), we selected the level of integration of planting and animal husbandry. The specific measurement method is the coupling coordination degree of the gross production value of planting and animal husbandry. The calculation equation of coupling coordination degree is:

$$pbc = \sqrt{C \times T}, T = af(x) + bg(x), C = \sqrt{f(x)g(x) / \left[\left(f(x) + g(x)\right)/2\right]^2} \quad (10)$$

where pbc represents the coordination degree of the planting and animal husbandry; T is the coupling degree; C denotes the coordination degree; $f(x)$ and $g(x)$ are the total output in the planting industry and animal husbandry industry, respectively; a and b are the sector's importance in the system, and we set $a = b = 0.5$ with considering their equal importance.

3.3.4 Control variables

With the reference of the existing studies, we have controlled some variables that affect AGTFP (Wu et al., 2020; Fang et al., 2021; Song et al., 2022) to avoid the missing variables bias, such as economic development level (lnaagri), industrialization (indus), urbanization (lnurban), trade openness (lninexport), human capital (lnceduc), financial support (financial), and disaster (lndisaster). The detailed information is presented in Table 3.

Previous research indicated that socioeconomic factors are the critical variables that influence sustainable agricultural development. We selected four factors to reflect the socio-economic level: economic development, industrialization, urbanization, and trade openness. (1) Economic development level (lnaagri), we measured by using agricultural production value *per capita*. Generally, the developed areas usually receive more financial support, directly affecting technological progress and infrastructure improvements (Sadorsky, 2013). (2) Industrialization (indus), we calculated by the proportion of industrial added value and gross regional product value. Industrialization could directly improve rural production and living equipment, essential in promoting agricultural economic development (Guo et al., 2020). (3) Urbanization (lnurban), we measured by using the ratio of the urban population to the total population. Urbanization stimulated the flow of rural surplus labor force to the city, which helped to promote resource allocation efficiency (Fang et al., 2021). (4) Trade openness (lninexport), we utilized the percentage of the sum volume of the import and export in each province and regional GDP to measure. With the strengthening of openness, the exchange of agricultural products in the market could promote technical interactions between regions to improve the local agricultural technology level and help each area

TABLE 3 Variable names and definitions.

Variables	Symbol	Definitions of variables
Agricultural green total factor productivity	AGTFP	Agricultural green total factor productivity is estimated with the EBM-GML model introduced in section 3.3.1
Technological progress	TC	Decomposition of AGTFP by using Eq. (9) in section 3.3.1
Technical efficiency	TEC	Decomposition of AGTFP by using Eq. (9) in section 3.3.1
Low-grade highway density	lnrural	The total length of the secondary road, tertiary highway, and township road/the provincial area (km/km^2), taking the logarithm
High-grade highway density	lnhighway	The total length of the expressway and first-grade highway/the provincial area (km/km^2), taking the logarithm
Expressway density	lnhigh	The length of the expressway/the provincial area (km/km^2), taking the logarithm
First-grade highway density	lnfirst	The length of the first-grade highway/the provincial area (km/km^2), taking the logarithm
Secondary road density	lnsecond	The length of the secondary road/the provincial area (km/km^2), taking the logarithm
Tertiary highway density	lnthird	The length of the tertiary highway/the provincial area (km/km^2), taking the logarithm
Township road density	lnfourth	The length of township road/the provincial area (km/km^2), taking the logarithm
Rationalization of the agricultural industry structure	rais	Utilize the entropy method to calculate the summation indicator by using the variables of the portion of cash and grain crops, the percentage of beef and mutton to total meat output, the rate of aquaculture output to the whole agricultural sector's production, and the ratio of the output value of forestry, animal husbandry, and fishery to the total output value of the entire agricultural industries
Upgrading of agricultural industry structure	aais	Utilize the entropy method to calculate the summation indicator by using the variables of the proportion of value-added of the whole agricultural industries and intermediate consumption to represent their respective production efficiencies
Integration of planting and breeding	pbc	The coupling coordination degree of the gross production value of planting and animal husbandry is calculated using Eq. (10)
Financial support for agriculture	financial	The percentage of fiscal support for agriculture in the total budgetary expenditure
Human capital	lnceduc	Average years of education *per capita*, taking the logarithm
Urbanization	lnurban	The ratio of the urban population to the total population
Openness	lninexport	The percentage of the sum volume of the imports and exports in each province and regional GDP
Disaster rate	lndisaster	The percentage of the area is influenced by the disaster and crop-planted area
Agricultural output value *per capita*	lnaagri	Agricultural production value *per capita*, taking the logarithm
Industrialization	indus	The proportion of industrial-added value and gross regional product value

boost resource allocation efficiency based on their comparative advantage (Xu L.Y. et al., 2023).

Additionally, some studies found that education significantly impacts agricultural production. Adnan et al. (2018) pointed out that farmers with higher education levels could easily accept new technologies and promote green production in agriculture. Therefore, this study selected human capital (lnceduc) as one control variable, measured by average years of education *per capita* (Fang et al., 2021). Moreover, government plays a critical role in agricultural production. Financial support could provide the capital for the farmers to improve their production equipment and promote technological progress, directly benefiting sustainable agricultural development (Song et al., 2022). We used the percentage of the fiscal support for agriculture in the total budgetary expenditure to represent the financial support level (financial). Also, natural disasters often influence agricultural production (Khanal et al., 2021). Suresh et al. (2021) also found that natural disasters will hurt the farmers' enthusiasm, which could hurt agricultural technological progress and productivity. Therefore, we controlled the influence of disaster (lndisaster), which was measured by the percentage of the area influenced by the disaster and crop planted area.

3.3.5 Data source

The data for calculation of the AGTFP is from the "China Rural Statistical Yearbook," the relevant data on highways is sourced from the "China Transportation Statistical Yearbook," and the data on regional economic development is collected from the "China Regional Statistical Yearbook." Table 4 shows the basic descriptive statistics for each variable.

4 Empirical results

4.1 Benchmark empirical results

Table 5 represents the benchmark econometrics results of the influence of different grades of highways on the AGTFP. First, the model (1) to (2) tabulates the fixed effect results, which presents both

TABLE 4 Basic descriptive statistics of variables.

Variables	Variables	Obs.	Mean	Stand. dev.	Min.	Max.
Dependent variables	AGTFP	589	2.3216	1.1393	0.7375	6.0640
	TC	589	1.3892	0.1893	1.0697	1.8268
	TEC	589	0.9986	0.1531	0.4099	1.8048
Core independent variables	lnrural	589	8.9042	0.8510	6.6065	11.3048
	lnhighway	589	5.8473	1.1007	2.3247	8.2018
	lnhigh	577	5.3080	1.0562	1.5472	7.9741
	lnfirst	577	4.7819	1.3780	0.8350	7.2969
	lnsecond	589	6.6703	0.9407	4.5836	9.1368
	lnthird	589	6.8810	0.8894	4.2383	9.5706
	lnfourth	589	8.5508	0.9384	5.6928	10.9609
Mediator variables	rais	589	0.3411	0.1722	0.1015	0.9369
	aais	527	0.5262	0.1299	0.1594	0.9640
	pbc	577	0.3461	0.2651	0.0000	1.0000
Control variables	financial	589	0.0874	0.0513	0.0042	0.2038
	lnceduc	589	7.6774	0.7115	4.7424	9.9122
	lnurban	589	0.5164	0.1528	0.1980	0.8960
	lninexport	589	4.4172	1.8785	−0.9086	7.8568
	lndisaster	589	0.2116	0.1480	0.0024	0.9356
	lnaagri	589	8.5649	0.7390	6.7664	10.5168
	indus	589	0.4463	0.0865	0.1583	0.6148

the low-grade and high-grade highways that promote the AGTFP, with coefficients of 0.3315 and 0.3557, respectively. The results mean that the road density of low-grade and high-grade highways will increase by 1%, and the AGTFP will improve by 33.15% and 35.57%, respectively. In this model, we controlled the province and year fixed effect to reduce the influences from the individual variables, such as farming culture, and some impacts from the variables change with time, such as economic condition and policy shock. These variables significantly affect agricultural production but are challenging to measure. Therefore, we controlled the province and year-fixed effect simultaneously, which could reduce the missing variable error. However, this model has ignored the spatial correlations within regions, which would lead to the inaccuracy of the estimated coefficients. Then, we constructed the spatial econometrics models, and the results are represented in the model (3) to (4). The robust LM tests show no spatial error effect but have the spatial lag effect; thus, we chose the spatial autocorrelation regression (SAR) model to analyze the influence of highways on the AGTFP. The results also represent a positive effect of highways on the AGTFP at the 1% significance level.

However, the coefficients have some changes compared to the fixed effect results; the coefficient of a low-grade highway (0.3642) is slightly higher, but the coefficient of a high-grade highway (0.2149) is lower. The proper reason is that the high-grade highway construction also exerts a spillover effect on the other areas. All the results verify the Hypothesis 1 to 2. To find detailed information about the mechanism of the impacts of highway construction on the AGTFP, we analyzed its effects on the technological progress (TC) and the technical efficiency (TEC), and the regression results are presented in Table 6. It indicates that both the low-grade and high-grade highways improved the AGTFP through the improvement of technological progress. Meanwhile, we could find that the spatial autocorrelation coefficient is also significantly positive, which means surrounding areas' AGTFP will affect the local AGTFP. Therefore, the regions need to strengthen the relationships to realize coordinated development in the agricultural sector.

4.2 Spatial spillover effects analysis results

From Table 5, we found a spatial autocorrelation effect of the AGTFP. Besides, this study also analyzed each grade of highway's direct, indirect, and total impact on the AGTFP (see Table 7). It shows that low-grade highway significantly impacts the local AGTFP , but the spillover effect is insignificant. However, the direct and indirect impacts of high-grade highways are positive. The possible reason is that the high-grade road mainly connected the cities, which could spill over the advanced experience and technology to the adjacent areas.

Moreover, we also found that except for the tertiary highway and township road, the other three kinds of road (expressway, first-grade highway, secondary road) directly and indirectly affect the local area's AGTFP and the adjacent area's AGTFP. From the description of grade roads above, we could find that the role of expressways and

TABLE 5 Benchmark empirical results.

Variable	FE		SAR	
	(1)	(2)	(3)	(4)
lnrural	0.3315***		0.3642***	
	(3.9600)		(8.7400)	
lnhighway		0.3557***		0.2149***
		(3.1000)		(5.9300)
financial	0.5865	0.6532	−0.4406	−0.7300
	(0.4900)	(0.5700)	(−0.3800)	(−0.6100)
lnceduc	1.7362*	1.8115*	1.9849***	1.2527*
	(1.7300)	(1.8500)	(2.7200)	(1.6600)
urban	2.6793	2.5344	1.6036**	2.4577***
	(1.6500)	(1.4600)	(2.2800)	(3.3700)
lninexport	−0.0336	−0.0819	0.0467	0.0229
	(−0.2400)	(−0.5700)	(0.8100)	(0.3800)
disaster	−0.2926	−0.2621	−0.1244	−0.1872
	(−1.4300)	(−1.2900)	(−0.7300)	(−1.0600)
lnaagri	0.4738*	0.4251*	0.6504***	0.5000***
	(2.0100)	(1.7800)	(6.2800)	(4.6100)
lnindus	−5.1387***	−4.8386***	−3.3846***	−3.8879***
	(−5.4300)	(−5.4800)	(−7.6700)	(−8.4100)
ρ			0.3572***	0.1610***
			(5.6700)	(17.0400)
_cons	−7.1509***	−5.8587**		
	(−3.0000)	(−2.4600)		
Hausman	125.7400***	98.9600***	114.6176***	89.7067***
LM-Spatial Lag			80.6447***	80.7997***
Robust LM-Spatial Lag			14.4039***	13.8517***
LM-Spatial Error			67.0048***	67.8779***
Robust LM-Spatial Error			0.7639	0.9298
Province	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	589	579	589	589
R^2	0.7987	0.8025	0.8066	0.8004

The t-statistics value is in parentheses; *, **, *** represent the p-value is 0.1, 0.05, and 0.01, respectively.

first-grade highways is to connect the big cities, and secondary roads connect the urban and rural areas, which could spill the effect to other regions through factors and product exchange. Therefore, we also verified Hypothesis 3 that the high-grade highway exerts a positive spillover impact on the neighboring areas' AGTFP. Besides, we also found that it is essential to construct high-grade roads to connect the regions and realize the sustainable agricultural development of the whole region.

Moreover, this study also analyzed the spillover effects of different geographical distances. In this paper, regarding Wu et al. (2021) and Cai et al. (2022), the distance threshold is set based on the geographical distance spatial weight matrix, with 200 km as the initial value and 200 km as the step length. When the geographical distance of the provincial capital city is within the threshold range, the weight element is set to 1; otherwise, it is 0. Table 8 shows that the scale of the indirect impact of high-grade highways is around 1,000 km. Meanwhile, the value of the spillover effects presents a U shape in geographical distance.

4.3 Mechanism analysis results

In addition, we also analyzed the internal mechanism of highway construction on the AGTFP by constructing the mediation effect model; the results are shown in Tables 9, 10. The internal mechanism differs entirely from the low-grade and high-grade highways on the AGTFP.

From Tables 9, 10, we found that the coefficients of the low-grade and high-grade highways on the rais are significantly positive, indicating highway construction could improve the rationalization of industrial structure. However, the coefficients of the rais are just considerably positive in the econometric model of low-grade highway construction, representing that the mechanism test only passes in the effect of low-grade highway construction on the AGTFP. Besides, the results show that low-grade and high-grade highway construction could promote advanced development in the agricultural sector. Meanwhile, the mechanism test only passes in the effect of the high-grade highway. Based on the results above, we concluded that low-grade highway construction promotes the AGTFP by adjusting the industrial structure for rationalized development in the agricultural sector; high-grade highway construction promotes the AGTFP by upgrading the agricultural industry structure. The possible reason is that low-grade highways mainly strengthen the relationships among rural areas in a single region. However, the high-grade road is a significant channel for the developed regions to modernize agricultural production equipment or technology in the developing areas, which promotes the upgradation of agricultural industry structures in the whole region.

In addition, we also analyzed the mechanism of integrating planting and breeding and found that the low-grade and high-grade highways could promote the AGTFP through this mechanism. The results indicate that highway construction is vital in providing knowledge and information to rural areas, causing the farmers to adopt the new production mode for sustainable development in the agricultural sector.

4.4 Robustness test

In addition, we made the following tests to ensure the robustness of the empirical results: replace the dependent variable and the spatial weight matrix (see Table 11). First, we utilized the slack-based measurement (SBM) method to calculate the AGTFP and set it as the explained variable to investigate the influence of highway construction on the AGTFP. Second, we used the economic spatial weight matrix to reflect the spatial relations between regions and explore the effect of highway construction on the AGTFP. Table 11 shows that both the

TABLE 6 Empirical results of the impacts of highway construction on TC and TEC.

Variable	TC		TEC	
	(1)	(2)	(3)	(4)
lnrural	0.0198***		0.0018	
	(7.4732)		(0.1369)	
lnhighway		0.0095***		−0.0088
		(4.1776)		(−0.7910)
financial	0.3404***	0.2990***	0.7111**	0.7139**
	(4.9062)	(4.1930)	(2.1949)	(2.2105)
lnceduc	−0.2064***	−0.2314***	−0.4483*	−0.4639**
	(−4.4678)	(−4.8804)	(−1.9014)	(−1.9766)
urban	0.4458***	0.4648***	−0.0574	−0.0709
	(10.6033)	(10.7091)	(−0.2850)	(−0.3511)
lninexport	−0.0123***	−0.0119***	−0.0599***	−0.0063***
	(−3.3925)	(−3.1541)	(−3.3023)	(−3.4163)
disaster	0.0015	0.0021	0.0396	0.0398
	(0.14405)	(0.2021)	(0.7837)	(0.7881)
lnaagri	0.0150**	0.0126*	−0.0016	−0.0015
	(2.2983)	(1.8777)	(−0.0546)	(−0.0489)
lnindus	−0.0806**	−0.0768**	−0.1073	−0.0591
	(−2.5473)	(−2.2380)	(−0.7713)	(−0.4033)
ρ	0.4012***	0.4523***	0.1732**	0.1731**
	(6.9397)	(8.2014)	(2.5556)	(2.5548)
Hausman	25.1347*	152.9550***	25.7318***	29.0951***
LM-Spatial Lag	362.9394***	315.5219***	269.0677***	268.9251***
Robust LM-Spatial Lag	318.2562***	289.0916***	11.9135***	11.3352***
LM-Spatial Error	51.9769***	36.3544***	258.2434***	258.5201***
Robust LM-Spatial Error	7.2938***	9.9241***	1.0892	0.9302
Province	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	589	589	589	589
R^2	0.9865	0.9856	0.4133	0.4140

The t-statistics value is in parentheses; *, **, *** represent the significance level is 0.1, 0.05, and 0.01, respectively.

low-grade and high-grade highway construction positively affect the AGTFP, which is the same as the results in Table 5, and verified the results above are robust.

4.5 Endogeneity test

The spatial econometric model could solve endogeneity problems brought about by the spatial correlation among regions, but it cannot solve the issue caused by reverse causality. Generally, areas with completed highway construction have better economic and agricultural development conditions. Considering the endogeneity between highway construction and AGTFP, this study selected the following instrumental variables to solve the endogenous problem: highway construction lagging by one stage and the product of geographical distance (Jiang and Huang, 2020; Li et al., 2020; Fu and Zhang, 2022). Since the geographical distance does not change with time, this study multiplies the distance and time by calculating the instrumental variables. Table 12 shows the endogeneity test results. Models (1) and (3) represent the regression results of the first stage of the effect of instrumental variables on constructing low-grade and high-grade highways. It indicates that the lag variable of highway construction and the instrumental variable significantly impact the highway construction variable. The Cragg–Donald Wald F value of the first stage is much larger than 10, indicating no weak instrumental variable. In addition, the Sargan test result showed that the p-value is more significant than 0.1, and the coefficients of Anderson LM tests were significant, indicating that there was no over-identification issue and the instrumental variable was rigorously exogenous. Moreover, the coefficients of highway construction in all the regressions are significantly positive, verifying that the results are robust.

4.6 Heterogenous analysis results

Agriculture is highly dependent on natural resources, and various natural endowments will lead to heterogeneous agricultural production modes, leading to different effects on the AGTFP. In addition, each production area has its own development goals and tasks; thus, the role of highway construction is different in various regions. Therefore, we explored the influence of highway construction on the AGTFP in the areas of main-grain-producing and non-main-grain-producing (see Table 13).

Table 13 shows that the impact of the low-grade highway on the AGTFP is adverse but insignificant in main-grain-producing areas, and high-grade road negatively impacts the AGTFP in this area. In addition, low-grade and high-grade highways negatively affect the AGTFP of the adjacent regions. The results indicate that although a high-grade road strengthens the regional connection and stimulates agricultural production, the expanded scale brings more negative environmental output, inhibiting the AGTFP. Besides, the improvement of transportation accessibility brought about by the highway construction also exerts a siphoning effect on the surrounding areas.

However, the results are different in non-main-grain-producing areas. Table 13 represents low-grade and high-grade highway construction that could promote the AGTFP. Moreover, each grade of highway positively affects the adjacent areas' AGTFP. These results illustrate that highway construction is vital in stimulating green production in non-main-grain-producing areas. Meanwhile, this study also compared the coefficient difference between the two groups, and the p-value was obtained by Bootstrap 1,000 times. The result in Table 13 shows a significant difference in the impact of low-grade and high-grade highway construction on AGTFP in main-grain-producing and non-main-grain-producing areas.

The heterogeneity analysis results indicate that highway construction has opposite effects on main-grain-producing and

TABLE 7 Direct, indirect, and total effects.

Effects	Low-grade highway	High-grade highway	Expressway	First-grade highway	Secondary road	Tertiary highway	Township road
Direct	0.3719***	0.2335***	0.2493***	0.2210***	0.3794***	0.3541***	0.3603***
	(8.2500)	(6.0000)	(5.7600)	(7.1500)	(8.0200)	(8.4800)	(8.6700)
Indirect	0.1370	0.4453***	0.3840**	0.4778***	0.3186*	0.1659	0.1515
	(0.9000)	(2.7500)	(2.3900)	(3.7400)	(1.9300)	(1.1900)	(1.1100)
Total	0.5088***	0.6788***	0.6333***	0.6988***	0.6981***	0.5199***	0.5112***
	(2.9000)	(33.7900)	(3.5400)	(4.9500)	(3.6500)	(3.2700)	(3.2800)

The *t*-statistics value is in parentheses; *, **, *** represent the *p*-value is 0.1, 0.05, and 0.01, respectively.

TABLE 8 The effects of different spatial distances.

Effects	<200 km	400 km	600 km	800 km	1,000 km	>1,000 km
Direct	0.1960***	0.1701***	0.1333***	0.1588***	0.1819***	0.1443***
	(4.8100)	(4.4098)	(3.8964)	(4.5203)	(5.0052)	(3.2936)
Indirect	0.0977	0.0900**	0.0478**	0.0509*	0.0608**	−0.0563
	(1.5007)	(2.3842)	(2.0902)	(2.0318)	(2.4614)	(−0.0871)
Total	0.2937***	0.2600***	0.1811***	0.2097***	0.2427***	0.0881
	(4.0295)	(5.3645)	(5.1252)	(4.9362)	(5.7807)	(0.1321)

The *t*-statistics value is in parentheses; *, **, *** represent the significance level is 0.1, 0.05, and 0.01, respectively.

TABLE 9 Mediation effect analysis results of the low-grade highway.

Variables	rais	AGTFP	aais	AGTFP	pbc	AGTFP
rais		0.9129***				
		(3.7543)				
aais				0.3604		
				(0.8400)		
pbc						3.2588***
						(6.8800)
lnrural	0.0144**	−0.0176	0.0254***	0.3127***	0.0131***	0.3394***
	(2.3747)	(−0.4628)	(5.5700)	(6.7800)	(3.5900)	(8.1900)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
ρ	0.4720***	0.4050***	0.0508	0.4364***	0.4613***	0.3913***
	(10.1051)	(7.8708)	(0.6400)	(16.0000)	(8.2500)	(6.4000)
Hausman	4.6282	100.6556***	32.4806**	162.3376***	2.4736	7.2402
LM-Spatial Lag	144.7427***	6.5726**	26.1795***	60.6774***	2.8635*	120.3054***
Robust LM-Spatial Lag	7.9311***	2.8684*	22.3083**	20.7002***	4.6646**	39.9534***
LM-Spatial Error	138.4486***	4.5079**	10.9862***	40.0279***	8.5210***	84.3294***
Robust LM-Spatial Error	1.6370	0.8037	7.1150***	0.0507	10.3222***	3.9774**
Province	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	589	589	527	527	570	570
R^2	0.5560	0.5966	0.1197	0.7839	0.5713	0.8269

The *t*-statistics value is in parentheses; *, **, *** represent the significance level is 0.1, 0.05, and 0.01, respectively.

TABLE 10 Mediation effect analysis results of the high-grade highway.

Variables	rais	AGTFP	aais	AGTFP	pbc	AGTFP
rais		0.2069				
		(0.3868)				
aais				0.7600*		
				(1.7800)		
pbc						3.0200***
						(6.1600)
lnhighway	0.0092*	0.2050***	0.0098**	0.1427***	0.0217***	0.3523***
	(1.8711)	(5.3080)	(2.5700)	(3.9000)	(5.9500)	(7.9300)
Control	Yes	Yes	Yes	Yes	Yes	Yes
ρ	0.2780***	0.1263*	0.0613	0.1815*	0.4953***	0.2968***
	(4.6398)	(1.8386)	(0.7700)	(1.9000)	(9.1500)	(4.5000)
Hausman	31.3133**	60.5715***	28.9385**	62.1052***	3.6863	31.6946**
LM-Spatial Lag	21.0394***	24.0073***	23.1035***	60.8697***	85.5477***	120.1571***
Robust LM-Spatial Lag	11.5443***	3.2716*	15.4911**	16.1856***	6.4627**	39.6087***
LM-Spatial Error	14.3504***	25.2281***	11.5735***	44.8071***	160.4074***	84.7360***
Robust LM-Spatial Error	4.8553**	4.4924**	3.9611**	0.1230	81.3224***	4.1876**
Province	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	589	589	527	527	570	570
R^2	0.6645	0.8876	0.0795	0.7762	0.5790	0.8339

The t-statistics value is in parentheses; *, **, *** represent the significance level is 0.1, 0.05, and 0.01, respectively.

non-main-grain-producing areas' AGTFP. The following part analyzes the possible reasons for the results. Table 14 represents the effect of highways on the economic and environmental output in different areas. Table 15 is the mechanism analysis of the main-grain-producing and non-main-grain-producing areas.

As for economic production, low-grade roads negatively affect each area. The mechanism analysis above indicates that low-grade highways are significant in rationalizing the structure of the agricultural industry. The result demonstrates that low-grade roads will stimulate the farmers to adjust their agricultural industry structure, such as soybean replacing corn, which causes the total output to decrease. Meanwhile, the low-grade highway reduces non-point source pollution and CO_2. Whereas the adverse economic effects are more significant than the environmental effects, causing the decline of the AGTFP in the main-grain-producing area.

However, Table 14 also shows that the high-grade highway significantly increased the economic output in the whole region. The high-grade road is vital for modern agricultural development, which enlarges agricultural production. Meanwhile, the high-grade highway also brings a large amount of agricultural pollution to the main-grain-producing area, causing a decrease of AGTFP. Meanwhile, Table 15 also shows that the high-grade highway stimulates the upgrading of the agricultural industry in the main-grain-producing area, which inhibits the AGTFP. Therefore, the main main-grain-producing area must focus on adjusting the agricultural industry structure to reduce the opposite effect of the highway construction.

In non-main-grain-producing areas, low-grade highways have brought about the adjustment of the proportion of agricultural industrial structure, the decline of the total agricultural output value, and the reduction of non-point source pollution. As seen from Table 14, the total effect of the decrease in economic output is smaller than that of the decline of non-point source pollution. In addition, the impact of reducing economic output comes from the direct effect. In contrast, the effect of the reduction of non-point source pollution comes from the indirect effect, which is the effect of other areas in the non-main-grain-producing areas. The possible reason for this result is that for non-main-grain-producing areas, small-scale production exists in most areas, and there will be a "diseconomy of scale" in terms of fertilizer input efficiency, resulting in a direct positive effect in some areas. Although some areas have reduced emissions due to the adjustment of agricultural industrial structure, the overall positive and negative effects have offset, resulting in no significant direct environmental effects. For the whole region of non-main-grain-producing areas, the internal interlinkages will bring scale effects and reduce environmental output, showing that the indirect effect coefficient from environmental production is negative.

4.7 Discussion

From the results of the above analysis, highway construction promotes the AGTFP. Furthermore, some aspects deserve further discussion. From the perspective of influence mechanisms of different

TABLE 11 Robustness test results.

Variables	Replacing independent variable		Replacing spatial weight matrix	
	(1)	(2)	(3)	(4)
lnrural	0.3846***		0.3552***	
	(3.6400)		(8.3400)	
lnhighway		0.2284**		0.2538***
		(2.4600)		(6.3736)
lnfinancial	−8.1823***	−5.3290*	−1.2946	−0.0532
	(−3.2400)	(−1.7300)	(−1.0200)	(−0.0445)
lnceduc	5.1211***	4.7693**	2.5415***	1.0178
	(2.7700)	(2.4700)	(3.4300)	(1.2982)
lnurban	−3.5250**	−3.2622*	1.8935***	3.6201***
	(−2.2400)	(−1.7500)	(2.6500)	(4.9878)
lninexport	0.5335***	0.5218***	0.0342	−0.0877
	(3.7400)	(3.3800)	(0.5900)	(−1.4125)
lndisaster	0.0460	−0.2138	−0.1421	−0.1388
	(0.1200)	(−0.4700)	(−0.8300)	(−0.8117)
lnaagri	2.0059***	2.2820***	0.5639***	0.3033***
	(8.4500)	(8.2400)	(5.3000)	(2.8018)
lnindus	0.1618	−1.3961	−4.1122***	−3.5251***
	(0.1400)	(−1.1800)	(−9.2600)	(−6.5575)
ρ	−0.2401*	0.2265***	0.1911***	0.1161***
	(−1.8600)	(3.5500)	(4.6100)	(2.8375)
Hausman	13.9612	14.5139	74.3552***	228.7720***
LM-Spatial Lag	33.1363***	36.8681***	8.0173***	8.0331***
Robust LM-Spatial Lag	7.9604***	22.6841***	30.4361***	40.9247***
LM-Spatial Error	25.6497***	19.7222***	20.5505***	21.5457***
Robust LM-Spatial Error	0.4737	5.5382**	42.9693***	54.4373***
Province	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	589	589	589	589
R^2	0.5662	0.6636	0.8043	0.8909

The t-statistics value is in parentheses; *, **, *** represent the significance level is 0.1, 0.05, and 0.01, respectively.

TABLE 12 Endogeneity test results.

Variables	(1)	(2)	(3)	(4)
	First stage	Second stage	First stage	Second stage
L.lnrural	0.9262***			
	(42.0500)			
lnrural _IV	0.0058*			
	(1.7700)			
L.lnhigh			0.8898***	
			(37.1600)	
lnhigh _IV			0.0126***	
			(3.1000)	
lnrural		0.2969***		
		(6.2300)		
lnhighway				0.1394***
				(3.2100)
lnfinancial	0.2252	−0.3897	−0.1252	0.1260
	(0.6300)	(−0.5500)	(−0.2900)	(0.1800)
lnceduc	0.0897	0.8971	−0.1135	0.8001
	(0.2400)	(1.2000)	(−0.2500)	(1.0400)
lnurban	0.8967**	1.8142**	0.1115	2.0731***
	(2.4600)	(2.4900)	(0.2500)	(2.7800)
lninexport	0.0671**	−0.0581	0.0718*	−0.0275
	(2.1400)	(−0.9800)	(1.8900)	(−0.4500)
lndisaster	−0.0888	−0.1279	−0.1675	−0.1077
	(−1.0500)	(−0.7600)	(−1.6500)	(−0.6200)
lnaagri	−0.1131**	0.3661***	−0.1379**	0.3524***
	(−2.1500)	(3.6500)	(−2.1800)	(3.4100)
lnindus	0.1037	−3.9290***	0.6593**	−3.7487***
	(0.4700)	(−8.9800)	(2.4200)	(−7.9400)
ρ	−0.1030***	0.3490***	0.0233	0.3168***
	(−2.8200)	(5.1800)	(0.5200)	(4.1700)
Hausman	51.4200***		30.2300***	
Sargan	0.3800		2.0290	
	0.5374		0.1543	
Cragg–Donald Wald F	884.1000		777.0100	
Anderson canon. Corr. LM (Under identification test)	407.7720***		395.4400***	
N	558	558	558	558
Centered R^2	0.8092		0.7983	

The t-statistics value is in parentheses; *, **, *** represent the significance level is 0.1, 0.05, and 0.01, respectively.

grades of highways on the AGTFP, low-grade and high-grade highways have exerted the heterogeneous influence path. Generally, the low-grade highway promotes resource integration in rural areas, making each region adjust the structural proportion based on their own resource endowment and market demand, benefiting the rationalization of resource allocation, which could promote the AGTFP (Lei et al., 2023). Meanwhile, high-grade highways strengthen the connections between regions, providing the opportunity to spill over the advanced technology of developed areas to the surrounding areas and then improve the overall technology level to promote agricultural production efficiency. The above findings could provide detailed information for the government to set the transportation plan for promoting the sustainable development of agriculture.

Then, we found that agricultural industry structure adjustment is significant in promoting green production in agriculture, including

TABLE 13 Heterogeneous analysis results in main-grain and non-main-grain-producing areas.

Variable	Main-grain-producing area		Non-main-grain-producing area	
	(1)	(2)	(3)	(4)
lnrural	−0.0910		0.3890***	
	(−0.6431)		(8.4800)	
lnhighway		−0.5936***		0.5053***
		(−4.0101)		(10.2200)
Control	Yes	Yes	Yes	Yes
ρ	−0.2720***	−0.1969**	0.4996***	0.2434***
	(−3.0820)	(−2.2881)	(5.4900)	(3.5000)
Hausman	38.7627***	17.1564	3.9325	12.7496
LM-Spatial Lag	2.5939	4.0504**	47.6304***	48.0789***
Robust LM-Spatial Lag	11.0895***	12.7657***	12.1172***	11.4778***
LM-Spatial Error	2.2409	1.3084	36.6677***	37.5938***
Robust LM-Spatial Error	10.7366***	10.0236***	1.1545	0.9927
Coefficient difference	0.6510*	0.7020**		
	(p = 0.0760)	(p = 0.0430)		
N	247	247	323	323
R^2	0.9339	0.9368	0.7629	0.8191

The t-statistics value is in parentheses; *, **, *** represent the significance level is 0.1, 0.05, and 0.01, respectively.

TABLE 14 The effects of heterogeneous analysis.

Variables	Main-grain-producing regions			Non-main-grain-producing regions		
	Direct	Indirect	Total	Direct	Indirect	Total
AGTFP						
lnrural	−0.0391	−0.6836*	−0.7227*	0.4316***	0.3800**	0.5175***
	(−0.2638)	(−1.7750)	(−1.9999)	(7.6200)	(2.3800)	(3.2300)
lnhighway	−0.5381***	−0.9768**	−1.5148***	0.5417***	0.5475***	1.0635***
	(−3.9278)	(−2.3847)	(−3.1723)	(10.0400)	(3.8800)	(5.4100)
Agricultural output						
lnrural	−0.0788***	0.1383**	0.0595	−0.0258*	−0.0273	−0.0531*
	(−3.5300)	(2.4200)	(0.9300)	(−1.7800)	(−1.6000)	(−1.7200)
lnhighway	0.1357***	0.3002***	0.4359***	0.0459***	0.1061***	0.1520***
	(5.6900)	(3.1700)	(3.8800)	(2.9300)	(2.6400)	(3.0300)
Non-point source pollution						
lnrural	−0.2040**	−0.1619	−0.3659**	−0.0222	−0.1627***	−0.1849**
	(−2.4100)	(−1.0300)	(−2.2700)	(−0.8500)	(−2.8600)	(−2.5200)
lnhighway	0.4655***	0.9200***	1.3855***	0.0560**	0.0525	0.1085
	(5.5600)	(3.0600)	(3.8700)	(2.1400)	(0.8400)	(1.3900)
Agricultural CO_2						
lnrural	−0.1768**	−0.2677	−0.4445	−0.0246	−0.1740	−0.1985
	(−2.3400)	(−0.9600)	(−1.3900)	(−0.6300)	(−1.1400)	(−1.0600)
lnhighway	0.2153**	0.6171	0.8323	0.0366	0.1033	0.1399
	(2.1400)	(1.1900)	(1.3800)	(0.9400)	(0.6300)	(0.7100)

The t-statistics value is in parentheses; *, **, *** represent the significance level is 0.1, 0.05, and 0.01, respectively.

TABLE 15 Heterogeneous mechanism analysis results in different areas.

Variable	Main-grain-producing area				Non-main-grain-producing area			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	rais/aais	AGTFP	rais/aais	AGTFP	rais/aais	AGTFP	rais/aais	AGTFP
rais		−0.3947		−0.3725		1.4018***		0.8197
		(−0.6400)		(−0.5900)		(5.2521)		(1.3300)
lnrural	−0.0616***	−0.2398*			0.0325***	0.3541***		
	(−4.4700)	(−1.7700)			(3.6087)	(7.8926)		
lnhighway			0.0661***	−0.3759***			−0.0033	0.5251***
			(5.6600)	(−2.9200)			(−0.8600)	(10.4100)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	247	247	247	247	323	323	323	323
R^2	0.3417	0.1807	0.3686	0.8873	0.8300	0.8774	0.0244	0.7838
aais		−0.2474***		−5.0858***		2.0018***		2.1062***
		(−4.9400)		(−7.4600)		(3.3300)		(3.6800)
lnrural	0.0126	−0.0011			0.0394***	0.3083***		
	(1.1700)	(−0.1300)			(7.7700)	(5.4000)		
lnhighway			0.0184**	−0.4402***			0.0308***	0.3770***
			(2.1500)	(−4.5300)			(6.0400)	(7.0700)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	221	221	221	221	289	289	289	289
R^2	0.2087	0.8292	0.2205	0.9065	0.2681	0.7736	0.2099	0.8024

The *t*-statistics value is in parentheses; *, **, *** represent the significance level is 0.1, 0.05, and 0.01, respectively.

rationalization and upgrading of agricultural industrial structure. This finding is consistent with the findings of many other studies (Lei et al., 2023; Liu Z. et al., 2023; Liu G. J. et al., 2023). However, the heterogeneous analysis results indicate that upgrading the agricultural industry structure could inhibit the AGTFP in the main-grain-producing area, one path where a high-grade highway has negatively affected the AGTFP. The possible reason is that the reduced transportation cost brought by high-grade highways has stimulated the cross-regional operation of agricultural machinery, which reduces the intermediate consumption value of agricultural production and brings large-scale production (Liu et al., 2021). However, large-scale production would exert environmental pollution (Luo et al., 2020) and then inhibit the green development of agriculture in main-grain-producing areas. The results showed that upgrading the agricultural industrial structure could not always promote the AGTFP, which should be under the reasonable production scale.

5 Conclusion

This study aimed to analyze highway construction's impact on the AGTFP and its internal mechanism. First, we used the EBM-GML method to calculate the AGTFP based on data from 31 Chinese provinces from 2002 to 2020. Then, we utilized spatial econometrics to explore the direct and indirect effects of low-grade and high-grade highways on the AGTFP. Moreover, we constructed the mediation effect model to verify the mechanisms empirically: rationalization of agricultural industry structure, upgrading agricultural industry structure, and integration of planting and breeding. After that, we analyzed the heterogenous effect in the main-grain-producing provinces and other regions. According to the above analysis, we drew the following conclusions.

(1) Both low-grade and high-grade highway construction significantly promotes the AGTFP through stimulating technological progress. Meanwhile, high-grade highway construction also exerts a positive spillover effect on the adjacent areas, meaning that the high-grade highway construction could also promote green production in the agricultural sector of the surrounding areas and the geographical distance scale of 1,000 km.

(2) The mechanism of low-grade and high-grade highways promotes the AGTFP was heterogeneous. In detail, a low-grade highway raises the AGTFP by improving the level of rationalizing the agricultural industry structure, and a high-grade road promotes the AGTFP by stimulating the upgrading of the agricultural industry structure. Moreover, low-grade and high-grade highway construction could encourage the integration of planting and breeding to realize green production.

(3) Highway construction significantly exerted a positive direct and indirect impact on the AGTFP in non-main-grain-producing areas. However, low-grade and high-grade highway construction inhibits the AGTFP in the main-grain-producing area. For further exploration, it was found that the low-grade highway negatively affects

agricultural production by adjusting the agricultural industry structure, which negatively affects the AGTFP. Moreover, the high-grade highway construction brought much agricultural pollution through promoting modern agriculture's development and inhibited the AGTFP.

Through the above analysis, we found that highway construction has adversely affected the AGTFP in main-grain-producing areas in China. Thus, the government needs to take measures to achieve the overall sustainable development of Chinese agriculture. First, it is essential to enhance cooperation within main-grain-producing areas and encourage all regions to give full play to their comparative advantages and achieve specialized production. For one thing, large-scale production could promote production efficiency. For another, talent gathering could promote the technical level. Then, the government should set the corresponding policy support to the main-grain-producing areas to rationalize the agricultural industry structure. The above conclusions also provide some policy references for developing countries at a low economic development level but with abundant agricultural resources.

The above findings contribute to a better understanding of the influence of highway construction on the AGTFP. However, there are still some limitations in this study, and they need to be further analyzed in the future. First, this study only focused on China's agricultural green development without considering other countries because the data has no consistent source in the global aspect. Thus, in the future, it is necessary to find valuable data to evaluate the effect of highway construction on agricultural green development in different countries and give detailed measures for each country. Besides, we mainly analyzed the effect and mechanism of highway construction on the AGTFP based on the macro aspect. However, it is more accurate to understand the impact of highway construction on farmers' choice of production mode from the micro level. In the future, with the continuous improvement of survey data of rural residents in China, we could further discuss the impact of highway construction on agricultural production from the micro level. Third, considering the difficulty of data acquisition and the rationality of provincial data utilization, this paper adopts provincial panel data for empirical analysis. However, the municipal or county level could accurately reflect the factor or product flow between urban and rural areas. In the future, more granular levels of data could be used for analysis when China's statistics continue to improve.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ZZ: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Software, Visualization, Writing – original draft. JD: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. SG: Formal analysis, Validation, Writing – original draft, Writing – review & editing. RL: Formal analysis, Project administration, Supervision, Writing – review & editing.

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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.

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