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Spatio-temporal Distribution of Influencing Factors of Agricultural Sustainable Development in China

Przestrzenno-czasowy rozkład czynników wpływających na zrównoważony rozwój rolnictwa w Chinach

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Abstract

Guided by the United Nations Sustainable Development Goals, the research focuses on the sustainable development of agriculture. Based on the data of China's agricultural and economic development from 2013 to 2022, using entropy method to build the agricultural green development index (AGDI) system. Furthermore, the geographically and temporally weighted regression (GTWR) model was used to analyze the impact of seven factors on AGDI, namely, Urbanization rate (UR), Financial support for agricultural level (FSAL), Number of village health clinics (NVHC), Sulfur dioxide emissions (SDE), Chemical oxygen demand emissions (CODE), Education funding (EF), and educational attachment (EA). The results show that (1) AGDI in different regions is highly consistent in temporal evolution, but the spatial distribution is significantly different, showing a pattern of high in the south of the east – secondary high in the middle – low in the northwest and northern parts of the region. (2) The influence of each factor on AGDI has obvious spatiotemporal heterogeneity. For example, SDE had a negative impact throughout the investigation period, with the largest fluctuation amplitude; The effects of FSAL and NVHC are relatively stable. (3) The impact of EA remains consistent in different regions in 2013 and 2022. The impact of FASL and NVHC is mainly in the east and northeast, the impact of CODE is mainly in the east and central, and the impact of EF and SDE is mainly in the northeast. The research results not only reveal the spatiotemporal characteristics of green development in Chinese agriculture, but also provide reference for policy-making.

Key words: sustainable development of agriculture, entropy method, geographically and temporally weighted regression, green development, environmental sustainable development

Streszczenie

Kierując się Celami Zrównoważonego Rozwoju ONZ, badania koncentrują się na zrównoważonym rozwoju rolnictwa. Na podstawie danych dotyczących chińskiego rozwoju rolniczego i gospodarczego w latach 2013–2022, wykorzystano metodę entropii do zbudowania systemu indeksu zielonego rozwoju rolnictwa (AGDI). Ponadto, model regresji ważonej geograficznie i czasowo (GTWR) został użyty do analizy wpływu siedmiu czynników na AGDI, a mianowicie: wskaźnika urbanizacji (UR), wsparcia finansowego dla poziomu rolnictwa (FSAL), liczby wiejskich przychodni zdrowia (NVHC), emisji dwutlenku siarki (SDE), emisji chemicznego zapotrzebowania na tlen (CODE), finansowania edukacji (EF) i przywiązania edukacyjnego (EA). Wyniki pokazują, że (1) AGDI w różnych regionach jest wysoce spójne w ewolucji czasowej, ale rozkład przestrzenny jest znacząco różny, pokazując wzór wysoki na południu wschodu – wtórny wysoki w środku – niski w północno-zachodniej i północnej części regionu. (2) Wpływ każdego czynnika na AGDI ma oczywistą heterogeniczność czasoprzestrzenną. Na przykład SDE miało negatywny wpływ przez cały okres objęty badaniem, z największą amplitudą wahań; skutki FSAL i NVHC są stosunkowo stabilne. (3) Wpływ EA pozostaje spójny w różnych regionach w 2013 i 2022 r.

Wpływ FASL i NVHC występuje głównie na wschodzie i północnym wschodzie, wpływ CODE występuje głównie na wschodzie i w centrum, a wpływ EF i SDE występuje głównie na północnym wschodzie. Wyniki badań nie tylko ujawniają przestrzenno-czasowe cechy zielonego rozwoju w chińskim rolnictwie, ale także stanowią punkt odniesienia dla kształtowania ogólnej polityki.

Słowa kluczowe: zrównoważony rozwój rolnictwa, metoda entropii, regresja ważona geograficznie i czasowo, zielony rozwój, zrównoważony rozwój środowiskowy

1. Introduction

With the continuous promotion of China's ecological civilization construction, the green and sustainable development of agriculture has achieved certain results. Agricultural green development emphasizes the synergy of green and development; The current agriculture must change from intensive agriculture with high input, high environmental impact and low resource utilization efficiency to more sustainable agriculture. Agricultural production is the foundation of China's national economy. Agricultural green production is the driving force for the development of green economy and the premise for realizing green behavior and sustainable ecology (Liu et al, 2020). Liu et al. (2020) proposed the importance of linking the suggestions and practices of green ecological environment with the high priority sustainable development goals of the United Nations. In this context, China's *belt and road* initiative and the International Green Development Alliance promote the 2030 agenda for sustainable development (Wang et al., 2023).

The pursuit of sustainable development has become an imperative, with the three interrelated pillars of environment, society and economy forming the cornerstone of this ambitious vision. The agricultural sector, as a key component of human society, plays a pivotal role in the process of achieving the sustainable development goals. The impact of agriculture on the well-being of society cannot be underestimated, as it is directly related to food security, provides a source of livelihood for a large number of people, and profoundly shapes the landscape and development of rural areas. Therefore, an in-depth study of the factors influencing the green and sustainable development of agriculture in China and its spatial and temporal distribution is of great significance for a comprehensive understanding of the mechanisms of sustainable agricultural development, the coordination of the interests of various parties and the promotion of society as a whole in the direction of sustainability.

Compared with the existing research, the innovation of this study mainly has three aspects. On the one hand, it is the innovation of the evaluation system. For a long time, researchers have mainly focused on the ecological environment, scientific and technological innovation, socio-economic aspects and the green and sustainable development of agriculture. The evaluation system lacks consideration of aspects such as livelihood security. This study constructed 12 evaluation indicators of agricultural green development from four aspects of agricultural resources, economic benefits, scientific and technological innovation, and life security. Secondly, in terms of the selection of influencing factors, researchers mainly focus on a single environment, such as natural environment and social environment, and lack the combination of the two environments. This research takes both into account and selects seven influencing factors. In addition, it is the innovation of research perspective. Most scholars mainly focus on the sustainable development of agriculture in a single region, but lack of consideration of regional differences, and analyze it from the perspective of the whole country. This study uses GTWR model to analyze the sustainable development of agriculture from the perspective of time and space. This paper is divided into five parts. The second part reviews the literature on the impact of natural environment on agricultural sustainable development. Then, the third part describes the research design, including research methods, index selection and data sources. The fourth part describes the temporal and spatial distribution of AGDI, and focuses on the specific impact of environment on agricultural sustainable development. The fifth part mainly summarizes the conclusions and puts forward some countermeasures for different factors, which provides a useful reference for the sustainable development of agriculture.

2. Literature review

2.1. Green development of Agriculture

Agricultural sustainable development is closely related to human survival and development. The existing research mainly focuses on the measurement and influencing factors of agricultural green development level. For example, Chen and Zhang (2023) used the entropy weight comprehensive evaluation method to build 15 agricultural green development evaluation indicators from the three levels of social economy, scientific and technological progress, and resources and environment to determine the development level of green agriculture. Green provinces develop in advanced provinces, and the effect of agricultural economic transformation path selection is good. It is scientific and reasonable to take green agriculture development as a new development mode of traditional agricultural economy (Luo, 2020). Wang et al. (2024) constructed 19 agricultural green development evaluation indicators from three levels of green investment, green production and green products. Wang (2022) constructed 12 evaluation indexes of agricultural green development from three aspects of ecological agriculture, green production and output benefit. Pan et al. (2024) used entropy method to evaluate the total index of agricultural green development. Hou and Wang (2022) used entropy grey correlation method to calculate the level of agricultural green development. Kasztelan and Nowak (2020) used the linear ranking method to construct the comprehensive index of agricultural green performance. Yan et al. (2023) used spatial Markov chain analysis to explore spatial differences and dynamic evolution trends. In terms of the distribution of agricultural green development, regional dynamic trends and differences vary, and there is a significant spatial spillover effect (Shao et al., 2024). Wan etc. (2023) pointed out that future research will include air pollution emissions into the evaluation model to improve the scientificity and universality of the model. In terms of the influencing factors of agricultural green development level, innovation has significantly promoted the green growth of agriculture (Ren et al, 2023). Zheng et al. (2024) pointed out that maintaining a strong symbiotic relationship is essential to improve the awareness of green technology innovation and the ability of resource allocation within enterprises, and ultimately promote green development. Fu et al. (2024) pointed out that the digital technology revolution is the catalyst for China's green agriculture transformation and global sustainable development efforts.

2.2 Influence of environment on agricultural green development

With climate change, scarcity of natural resources, environmental degradation, labor shortage and changing social needs, agriculture is facing increasingly severe challenges (Ye et al. 2023). Among them, the shortage of water resources is particularly prominent, which has become a major constraint on the agricultural ecosystem in arid areas (Zhang et al., 2024). Li et al. (2022) pointed out that the conflict between limited water supply and growing water demand posed a serious challenge to the collaborative management of agricultural water and land resources. Meanwhile, Ye et al. (2023) also stressed that the impact of water shortage on regional agricultural development is becoming more and more obvious.

In this context, economic development and population growth have further intensified the demand for water and land resources. Feng et al. (2023) pointed out that in the context of global warming and resource scarcity, the complex relationship between water, land, energy and carbon dioxide makes it crucial to develop effective management processes in sustainable agricultural systems. In addition, the development of industrialization has also brought many problems to agriculture. Tan and Qi (2023) pointed out that the development of industrialization has overwhelmed the ecological environment destroyed by modern agricultural methods. Although chemical fertilizers and pesticides have played an important role in promoting the development of agricultural production, the side effects of agricultural development have always been environmental pollution and the uncontrolled use of natural resources (Futa et al., 2024).

At present, the heavy dependence of agricultural development on labor and resources makes the transformation of labor structure a key factor affecting progress (Wen et al., 2024). In this case, it is particularly critical to alleviate the shortage of water resources and promote the practice of sustainable water resources management, especially in meeting the demand for agricultural water and alleviating the problem of water balance (Kotb et al., 2024). Luo et al. (2024) advocated seeking a balance between productivity and environmental protection, and pointed out that this may guide the government to optimize land use policies and promote green technologies for sustainable agriculture.

In summary, although some scholars have studied the relationship between the environment and the green sustainability of agriculture, most have focused on individual regions without considering the uneven development among different areas in China, and have not analyzed from a national perspective. Moreover, when examining the impact of the environment on the green sustainability of agriculture, they have failed to take a comprehensive view of environmental factors and construct an evaluation system. Therefore, it is crucial to consider the differences between regions, calculate a comprehensive index of environmental impact, analyze the spatiotemporal distribution characteristics of the influence of the environment on the green sustainability of agriculture, and propose region-specific prevention and control policies.

3. Research design

3.1. Definition of variables

This research selects indicators such as Per capita arable land for grain sowing, Cultivated Land Replanting Index, The proportion of water-saving irrigation area, Total power of agricultural machinery per unit sown area, Fertilizer application intensity, Grain yield per unit area, Total output value of agricultural machinery per unit sown area, The growth rate of grain production, Agricultural labor productivity, Level of mechanization, Rural electricity growth rate, and Net income per capita of farmers as indicators of green agricultural development, from four dimensions: agricultural resources, economic benefits, technological innovation, and livelihood security. It applies the entropy method to construct an evaluation system for green agricultural development and calculates the Green Agricultural Development Index (AGDI). From an environmental perspective, indicators such as Urbanization rate (UR), Financial support for agriculture level (FSAL), Number of village health clinics (NVHC), Sulfur dioxide emissions (SDE), Chemical oxygen demand emissions (CODE), Education funding (EF), and Educational attainment (EA) are selected. The source variables for the level of green agricultural development, environmental perspective variables, and their descriptive statistics are presented in Tables 1, 2, and 3. From Table 3, it can be seen that the range of AGDI values is from 0.123 to 0.562, with an average value of 0.3.

Table 1. AGDI variable description statistics

Variables	*Min*	*Q1*	*Median*	*Mean*	*Q3*	*Max*
Per capita arable land for grain sowing	0.112	0.312	0.476	0.573	0.66	0.285
Cultivated Land Replanting Index	0.566	0.947	0.946	1.343	1.649	2.389
The proportion of water-saving irrigation area	0.204	0.351	0.542	0.565	0.748	1.198
Total power of agricultural machinery per unit sown area	2.892	4.76	4.133	6.605	7.931	13.87
Fertilizer application intensity	0.08	0.266	0.349	0.364	0.427	0.8
Grain yield per unit area	1.83	2.985	3.577	3.677	4.456	6.846
Total output value of agricultural machinery per unit sown area	1.616	4.165	5.856	7.801	9.131	45.3
The growth rate of grain production	-0.335	-0.01	0.008	0.005	0.023	0.236
Agricultural labor productivity	0.846	2.113	2.896	3.268	4.214	8.718
Level of mechanization	0.306	0.542	0.819	0.877	1.183	1.849
Rural electricity growth rate	-0.991	0.013	0.04	0.065	0.077	3.184
Net income per capita of farmers	-1044	1414	2288	2894	384.8	12816

Table 2. Natural and social environmental variables

Variables	*Units*	*Definition*
UR	percentage	Urbanization rate
FASL	percentage	Financial support for agriculture level
NVHC	piece	Number of village health clinics
SDE	ten thousand tons	Sulfur dioxide emissions
CODE	ten thousand tons	Chemical oxygen demand emissions
EF	ten thousand yuan	Education funding
EA	percentage	Educational attainment

Table 3. Descriptive statistics of initial indicators for various influencing factors

Variables	*Min*	*Q1*	*Median*	*Mean*	*Q3*	*Max*
AGDI	0.123	0.211	0.298	0.3	0.371	0.562
UR	0.379	0.54	0.603	0.617	0.675	0.896
FASL	0.04	0.09	0.114	0.113	0.133	0.19
NVHC	1142	10268	16440	20981.386	26300.25	62311
SDE	0.11	8.558	16.8	30.134	40.583	164.5
CODE	1.97	15.555	33.865	56.488	88.198	184.8
EF	1.57E+06	7.72E+06	1.14E+07	1.37E+07	1.68E+07	6.19E+07
EA	0.834	0.937	0.956	0.95	0.969	0.989

The United Nations sustainable development goals provide a clear direction for global development. Increased greening of agriculture is a key driver for achieving Sustainable Development Goal 2 (Zero hunger). A high level of green development implies efficient use of resources and eco-friendly production, ensuring a stable supply of food, while at the same time promoting the upgrading of the agricultural industry and creating more employment and income opportunities. In addition, the green development of agriculture has a close relationship with the social economy, as agriculture is the foundation of society and the lifeblood of the economy, and its development has a profound impact on social stability and economic vitality. The indicator system of agricultural green development constructed in this paper includes socio-economic factors, and the two are mutually reinforcing. At the social level, green agriculture gives rise to new industries, such as organic cultivation, ecological processing, rural tourism, etc., which provide farmers with channels to increase their income, attract the return of labour and optimize the employment structure. The increase in farmers' income can improve the quality of life and enhance the ability of society to cope with food security issues. A comprehensive social security system in rural areas ensures access to food for vulnerable groups and promotes the implementation of SDG 2 at the social level. At the economic level, the multi-dimensional indicators covering scientific and technological inputs, industrialisation levels, etc., have contributed to the development of green agriculture. Through resource optimisation and scientific and technological innovation, green agriculture reduces production costs, increases added value, enhances market competitiveness, stabilises the supply and prices of agricultural products, attracts social capital investment, provides economic support for sustainable agricultural development, and ensures that the goal of SDG 2 is achieved.

This paper is centred on the United Nations SDG 2, according to the official website of the United Nations, the specific implementation goals of SDG2 are as follows:

1) By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round.
2) By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons.
3) By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.
4) By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.
5) By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed.
6) Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries.
7) Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round.
8) Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility.

Table 4. Variables and UN Sustainable development goals

Variables	*United Nations Sustainable Development Goals*
UR	Goal 1: End poverty in all its forms
	Goal 9: Infrastructure, industrialization
	Goal 11: Cities
FASL	Goal 2: Zero Hunger
NVHC	Goal 3: Health
SDE	Goal 3: Health
	Goal 12: Sustainable consumption and production
	Goal 13: Climate Action
CODE	Goal 6: Water and Sanitation
	Goal 12: Sustainable consumption and production
	Goal 13: Climate Action
	Goal 15: Biodiversity, forests, desertification
EF	Goal 4: Education
EA	Goal 4: Education
	Goal 10: Inequality

Table 4 details the internal links between the indicators studied in this paper and the UN sustainable development goals. Specifically, CODE is an important indicator for measuring water quality and is directly related to SDG6 (Water and Sanitation). The United Nations has proposed to reduce pollution, improve water quality and ensure the cleanness and health of human water by 2030. In addition, chemical oxygen demand emissions are also associated with goals 12 (Sustainable consumption and production), 13 (Climate Action) and 15 (Biodiversity, forests, designation), and their control and reduction are important links to achieve these goals. As an important indicator to measure air pollution, SDE is closely related to goal 3 (Health) and affects people's respiratory health. At the same time, it is also closely linked with goal 12 (Sustainable consumption and production) and goal 13 (Climate Action). Reducing SDE is an important measure to deal with climate change and achieve sustainable production. NVHC reflects the medical and health conditions in rural areas and directly affects the achievement of goal 3 (Health), providing basic medical services for rural residents and ensuring their health level. EF and EA are closely related to goal 4 (Education). The improvement of education level can cultivate more high-quality agricultural practitioners, promote agricultural technology innovation, promote green development of agriculture, so as to provide support for the realization of multiple sustainable development goals.

In summary, as shown in Table 4, the indicators selected in this paper are based on the sustainable development goals of the United Nations, and the relationship between the AGDI and the indicators is deeply studied. By strengthening the innovation of agricultural technology, optimizing the allocation of resources, improving the level of education and reducing pollution emissions, we can make positive contributions to the realization of sustainable development goals and promote the sustainable development of global agriculture.

3.2. Research methodologies

3.2.1. Entropy method

In order to construct the evaluation system of agricultural green development, AGDI was calculated by entropy method. Entropy method (EM) is an objective weighting method. The principle is: in the process of index evaluation, the amount of information is reflected according to the variation degree of each index value, so as to determine the weight. The smaller the entropy, the greater the amount of information, and the greater the weight of the index; On the contrary, the larger the entropy, the smaller the amount of information and the smaller the corresponding index weight. The calculation steps of entropy method are as follows:

(1) Standardize data

(2) Construct the judgment matrix P matrix of the evaluation indexes of each year:

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \quad (1)$$

(3) Calculate index information entropy E_j:

$$E_j = -k \sum_i^n P_{ij} \ln P_{ij} \quad (2)$$

(4) Calculate the difference coefficient of index value D_j:

$$D_j = 1 - E_j \quad (3)$$

(5) Calculate weight W_j:

$$W_j = \frac{D_j}{\sum_{i=1}^{n} D_j} \quad (4)$$

Where, X_{ij} is the jth index of the ith year, $k = \frac{1}{lnm}$, m is the number of evaluation years, and n is the number of indicators.

3.2.2. Spatiotemporal geographically weighted regression model （GTWR）

In order to explore the spatiotemporal heterogeneity of environment on agricultural sustainable development, the spatiotemporal geographically weighted regression (GTWR) model was used in this study. Geographically weighted regression (GWR) and time weighted regression (TWR) are commonly used in existing research to deal with the problems of spatial heterogeneity and temporal heterogeneity. Huang et al. (2010) proposed the GTWR model, which is an improvement of GWR and TWR. By applying panel data regression, it can analyze the spatiotemporal heterogeneity at the same time. In addition, the study of Bai et al. (2016) verified the superiority of GTWR over GWR in regression analysis. The calculation formula of GTWR method is as follows:

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{P} \beta_k(u_i, v_i, t_i)x_{ik} + \varepsilon_i \quad (5)$$

where ui and vi are the longitude and latitude coordinates of the observation point respectively; (ui, vi, ti) is the space-time coordinates of the i-th sample point; β0 is the regression constant of sample point i, that is, the constant term of GTWR; βk is the k-th regression parameter of point i, and xik is the value of independent variable xk at point i, that is, the value of each explanatory variable in the GTWR model.

3.3. Data sources

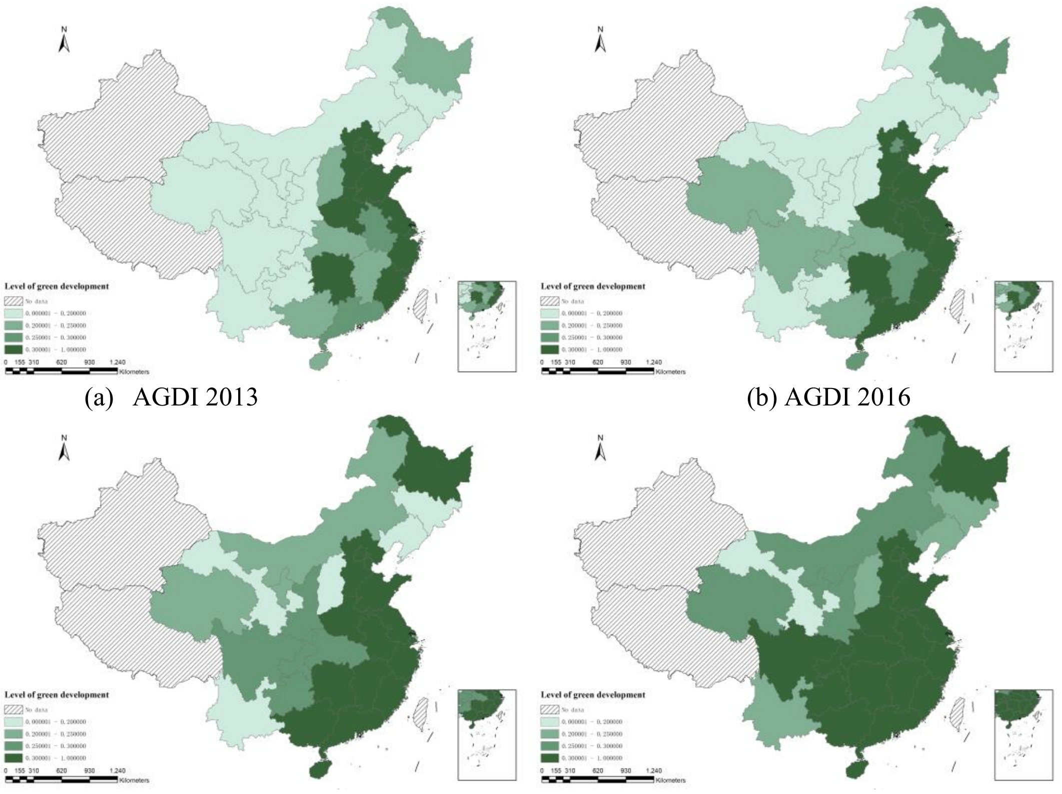
The research area of this study is the administrative division of China. According to the definition of the National Bureau of statistics, China's 34 provincial administrative units can be divided into five regions, namely, the East, central, West, northeast, Hong Kong, Macao and Taiwan. The data comes from the China Statistical Yearbook and the China Environmental Statistical Yearbook issued by the National Bureau of statistics of China, covering 29 provinces of China from 2012 to 2022 (excluding Hong Kong, Macao, Taiwan, Xinjiang and Tibet). Due to the lack of data in some regions, the study areas are the East, central, West and northeast. The data type is panel data, in which the dependent variable is AGDI and the other environmental regulation variables are independent variables. Due to the lack of some data, the mean interpolation method has been adopted.

4. Results

4.1. Temporal and spatial distribution of AGDI

4.1.1. Development trend of AGDI

The AGDI of different regions is calculated by entropy method. Specifically, the higher the AGDI value, the higher the degree of green development of agriculture, and vice versa. Figure 1 shows the AGDI values of different provinces in China from 2013 to 2022, and the data is visualized. The time evolution of AGDI in different regions is highly consistent. Judging from the index over the years, AGDI in most provinces showed a steady upward trend.



(a) AGDI 2013 (b) AGDI 2016

(c) AGDI 2019 (d) AGDI 2022

Figure 1. Trends in AGDI for different regions from 2013 to 2022, own computing

The development index is the first and fastest growing in the eastern region. From 2016 to 2019, the central and northeast regions began to develop gradually. By 2022, most of the eastern regions reached a high level of development, and the central region basically reached a medium level of development. In addition, the provincial index difference is very obvious. From the index over the years, the eastern region has the highest development efficiency, followed by the central region, the northeast region, and the western region. This shows that the eastern region is in the forefront of agricultural green development, while other regions are gradually catching up. Although the western region started late, it also showed a positive growth trend, showing the overall progress of green agricultural development nationwide.

The timeframe of this study covers the COVID-19. It is worth mentioning that the epidemic, a very destructive and specific variable, swept through all areas of agriculture like a storm, creating an all-encompassing and deep impact on agricultural production and distribution, the industrial chain, policy inputs, and the labour force. For example, at the production and distribution end, the transport of agricultural materials was blocked. On the industrial chain, the upstream agricultural enterprises have difficulties in purchasing raw materials, and the downstream processing enterprises have shortages of raw materials and shrinking demand, reducing the scale of production. In addition, there is a time lag in the implementation of policies due to poor information and cumbersome procedures, and social capital is less willing to invest due to market uncertainty, and some agro-related projects are shelved. The labour market is also in disarray, with restrictions on the movement of rural labour, which affects production schedules during critical farming hours, and a shortage of workers in urban agribusinesses, which reduces the efficiency of agricultural product processing and marketing.

However, the epidemic has not reversed the upward trend of green development in agriculture, but has instead become an opportunity for innovation and breakthrough. Localities are actively exploring green production models, accelerating the replacement of chemical fertilisers with organic fertilisers, and using rural waste to make high-quality organic fertilisers, which not only reduces reliance on chemical fertilisers, reduces surface pollution, but also improves soil fertility. At the same time, the emergence of circular agriculture model, to build a combination of planting and raising, agriculture and animal husbandry docking ecological cycle system, to achieve resource recycling and zero emissions of waste. The circulation of agricultural products through e-commerce to expand channels, live with goods, community group purchases and other modes to break the geographical restrictions, reduce intermediate links, enhance sales efficiency and added value. Various regions have strengthened green brand building, enhanced product quality and credibility through quality supervision, traceability systems, green certification, and created distinctive brands. Industry chain enterprises also increase green technology research and development and deep processing investment. The upstream launch of environmentally friendly green agricultural materials, downstream development of high value-added green processing products, promote the agricultural industry chain to green, high-end. So that green development has become a strong engine for agriculture to continue to promote in a complex environment.

4.1.2. Spatial distribution of AGDI

In order to explore the spatial distribution differences of AGDI, the AGDI values of different regions from 2013 to 2022 are visualized in Figure 2, which shows the distribution of AGDI in China's provinces from 2013 to 2022. The figure clearly shows the advantages of the eastern coastal areas in AGDI. The index of these areas is high, indicating that the degree of green development of agriculture is good. Although the central region is not as good as the eastern region, its index is at a medium level compared with the western and northwestern regions, showing a certain development trend. The AGDI values of the western and northwestern regions and some northern regions are relatively low, indicating that there is still much room for improvement in the green development of agriculture in these regions. On the whole, the spatial distribution pattern of *high in the south of the East - secondary high in the middle - low in some regions of the northwest and North* has been formed, which reflects the differences in agricultural green development in different regions.

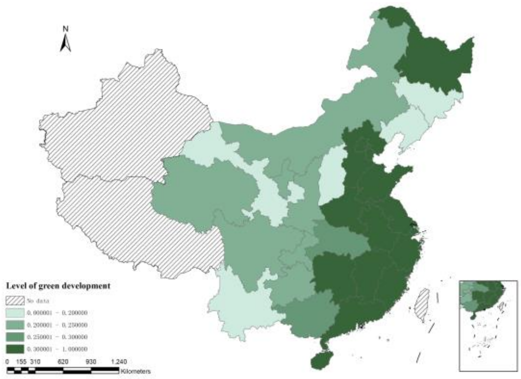


Figure 2. Average AGDI trend in different regions from 2013 to 2022, own computing

4.2. Model evaluation

Considering the imbalance of regional development in China, AGDI model is applied to explore the influencing factors and temporal and spatial distribution of AGDI. The OLS, TWR, SWR and GTWR models were established by using ArcGIS software, and the model fitting results were compared.

In order to compare different models, the R-square is selected, AICC and RSS are used as critical criteria to determine the goodness of fit of the model, where RSS is the sum of squares of residuals. In the model selection, the larger the R square, the smaller the AICC and RSS values, indicating that the model fitting effect is better. Compared with the standardized data, the results are shown in Table 5. The OLS model without considering the spatial relationship has better fitting effect, the fitting effect of TWR and GWR is better than OLS, and the goodness of fit of gtwr is significantly better than the other three models, and its adjusted R factor reaches 0.98.

Table 5. Model evaluation

Model	*R^2*	*AICc*	*RSS*
OLS	0.505167	-693.735	1.46909
TWR	0.6393541	-803.6392015	1.055368243
GWR	0.9604391	-1548.77923	0.080817753
GTWR	0.9829675	-1949.169258	0.020318695

4.3. Temporal and spatial distribution of influencing factors

Table 6 lists the descriptive statistics of the regression coefficient estimation results calculated by ADGI. For example, from an average point of view, UR, FSAL, NVHC, CODE and EF are positive effects, and SDE and EA are negative effects. From the value range of the coefficient, the minimum value of each variable is negative, and the maximum value is positive. Therefore, it is necessary to further study the temporal and spatial differences of the impact of environmental horizon on ADGI.

Table 6. Description statistics of GTWR results

Variables	*Min*	Q_1	*Median*	*Mean*	Q_3	*Max*
Intercept	-4.697	-0.003	0.169	0.129	0.348	1.294
UR	0.436	0.088	0.285	0.376	0.567	4.193
FSAL	-1.577	-0.094	0.032	0.029	0.162	1.225
NVHC	-2.367	-0.003	0.149	0.102	0.279	5.875
SDE	--8.238	-0.577	-0.135	-0.316	0.017	5.06
CODE	-0.638	-0.049	0.022	0.021	0.094	1.382
EF	-6.073	-0.190	0.058	0.048	0.334	15.692
EA	-0.889	-0.274	-0.106	-0.095	0.037	4.025

4.3.1. Temporal evolution of environmental influences on AGDI

Figure 3 shows the time evolution trend of the impact of various variables on AGDI from the perspective of environment. Different variables have significant fluctuation characteristics, among which SDED and EF have the most prominent fluctuations. SDES had a negative impact on AGDI from 2013 to 2022, and the negative impact reached -0.85421 in 2022, with the strongest inhibitory effect; The impact direction of EF changes frequently. It is positive in 2013 and 2016-2019, and negative in other years, which has an unstable effect on AGDI. The impact of UR shows a fluctuating upward trend, and the positive driving effect gradually highlights; CODE and FSAL fluctuate slightly, CODE has a weak positive impact for a long time, and FSAL fluctuates slightly in the positive and negative range; NVHC mainly has weak positive effects, with moderate fluctuations, while EA mostly has negative effects, and its inhibition on AGDI is persistent but limited. On the whole, the impact of environmental factors on agricultural green development has significant time heterogeneity.

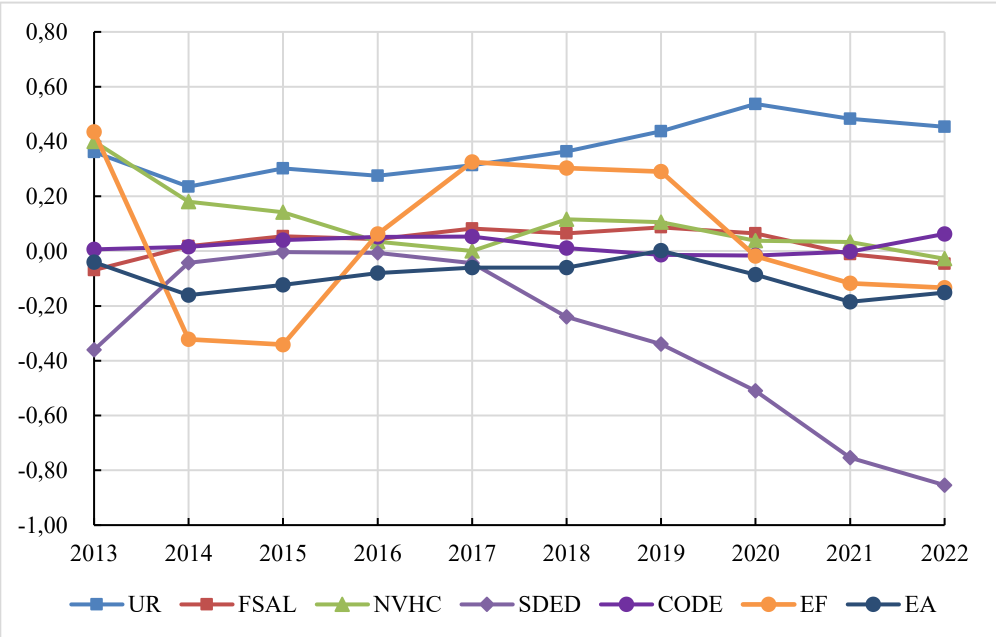
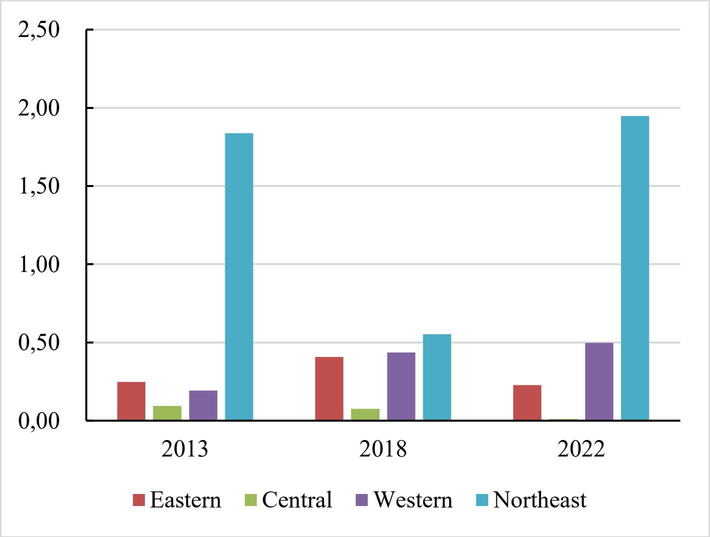


Figure 3. Temporal evolution of environmental influences on AGDI

4.3.2. The influence of UR on AGDI

As shown in Figure 4 (a), the impact of urbanization on agricultural green development in 2013, 2018 and 2022 has obvious regional heterogeneity: in 2013 and 2022, the coefficient in Northeast China was significantly high (up to 1.84), indicating that urbanization has a strong positive driving effect on agricultural green development; The eastern region showed a positive impact in 2013 and 2018, and the impact weakened in 2022; The western region showed a positive effect in 2018 and 2022, and the impact increased in 2022; The coefficient of each year in the central region is close to 0, and the effect of urbanization on agricultural green development is negligible.

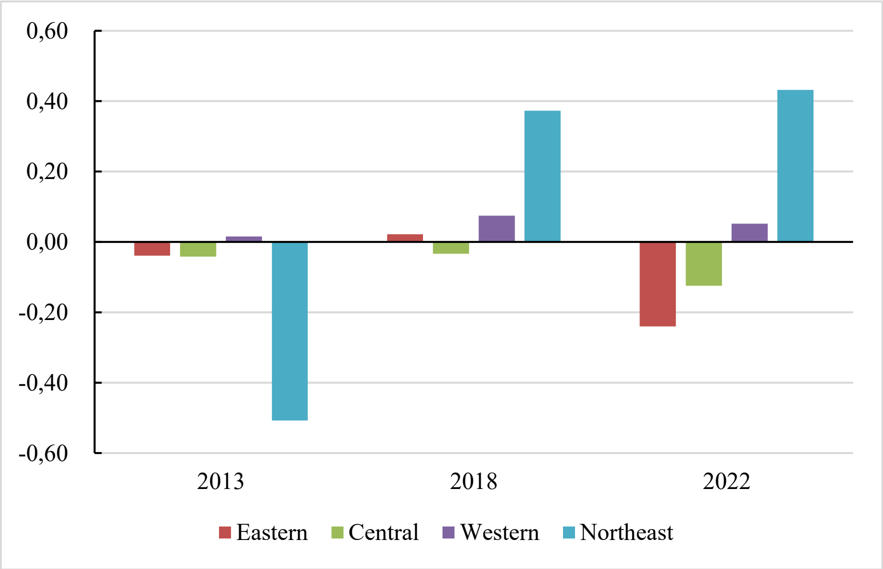
This difference may be explained by the different synergy modes of regional urbanization and agricultural development. For example, in the process of urbanization in Northeast China, industrial agglomeration may drive the investment in agricultural science and technology and the efficient utilization of resources (such as the development of large-scale green agriculture), which has strengthened the role of promoting the green development of agriculture; In the early stage of urbanization in the eastern region, agricultural upgrading was promoted by factor agglomeration, but in the late stage, the marginal benefit of urbanization on agricultural green development was reduced because the industrial structure was inclined to non-agricultural fields; Urbanization in the western region is accompanied by the implementation of ecological protection policies (such as returning farmland to forests and supporting green industries), gradually releasing the driving potential of urbanization for the green transformation of agriculture; The central region may not be able to form an effective driving force for green agricultural development due to the low quality of urbanization and insufficient linkage of urban and rural resources.



(a) UR

Figure 4a. The influence of UR on EPCI

4.3.3. The influence of FSAL on ADGI



(b) FSAL

Figure 4b. The influence of FSAL on EPCI

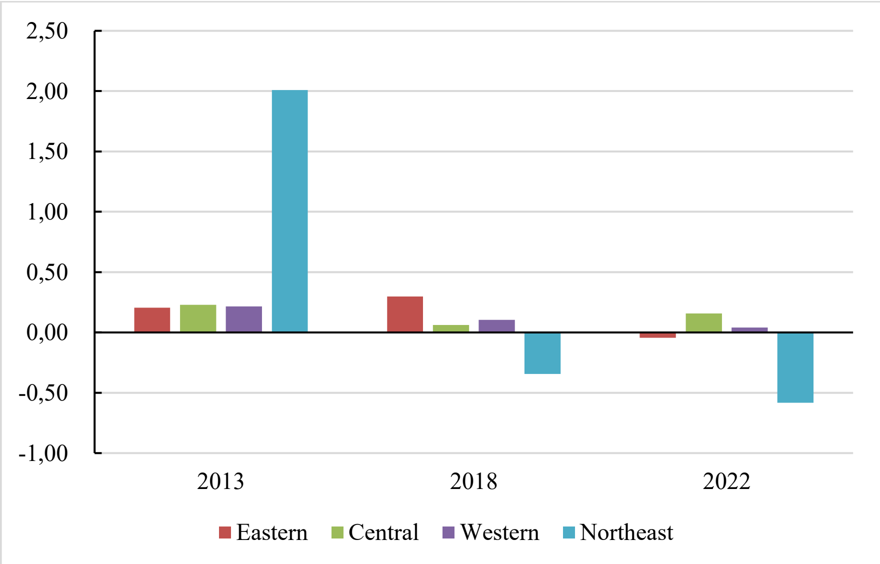
As shown in Figure 4 (b), the impact of fiscal support for agriculture on the level of agricultural green development in different regions in 2013, 2018 and 2022 showed significant spatio-temporal heterogeneity: in 2013, the northeast region showed a strong negative impact, indicating that the driving effect of fiscal support for agriculture on agricultural green development at this stage did not meet expectations; In 2018, the northeast region turned positive, and in 2022, the positive impact was further strengthened, becoming a key driving force. In other regions, the eastern region has a negative impact in 2022, or is restricted by the regional development focus inclining to non-agricultural industries; The effect of fiscal support for agriculture on agricultural green development is weak in Central China; The western region showed a certain positive impact in 2018, but the effect was significantly weakened in 2022.

The possible reasons for such regional differences are related to the foundation of agricultural development and the adaptability of policies. For example, Northeast China, as the main agricultural production area, has gradually released its role in promoting the green development of agriculture as the financial support for agriculture gradually inclines to green fields such as the promotion of ecological agricultural technology and agricultural pollution control; Due to the obvious trend of non-agricultural industrial structure in the eastern region, the financial support for agriculture is relatively insufficient for the resource investment of agricultural green development, resulting in a negative impact; The central region may fail to effectively promote the green transformation of agriculture due to the limited scale and inefficient use of financial funds for agriculture.

4.3.4. The influence of NVHC on AGDI

As shown in Figure 4 (c), the impact of the number of village clinics on the level of green agricultural development in 2013, 2018 and 2022 showed significant regional heterogeneity: in 2013, the northeast region showed a strong positive impact, and the increase in the number of village clinics played a positive role in promoting green agricultural development; However, in 2018 and 2022, the impact in Northeast China turned negative, and the negative degree further deepened in 2022. In other regions, the coefficients of each year in the eastern, central and western regions tend to be close to 0 or only show a weak positive, and the overall impact is not significant.

The possible reason for this spatial-temporal difference is related to the collaborative relationship between regional public service resource allocation and agricultural green development. In 2013, the construction of village clinics in Northeast China may indirectly promote labor force to participate in green agricultural production by improving the health level of rural population; However, after 2018, if the resource input of village clinics is not effectively connected with the demand for agricultural green development (such as the promotion of ecological agricultural technology and rural environmental governance), or if resources are idle due to the outflow of rural population, it will have a negative effect on agricultural green development. The linkage mechanism between the layout of village clinics and the green development of agriculture in the East, middle and West is not prominent, and the overall impact is always weak.



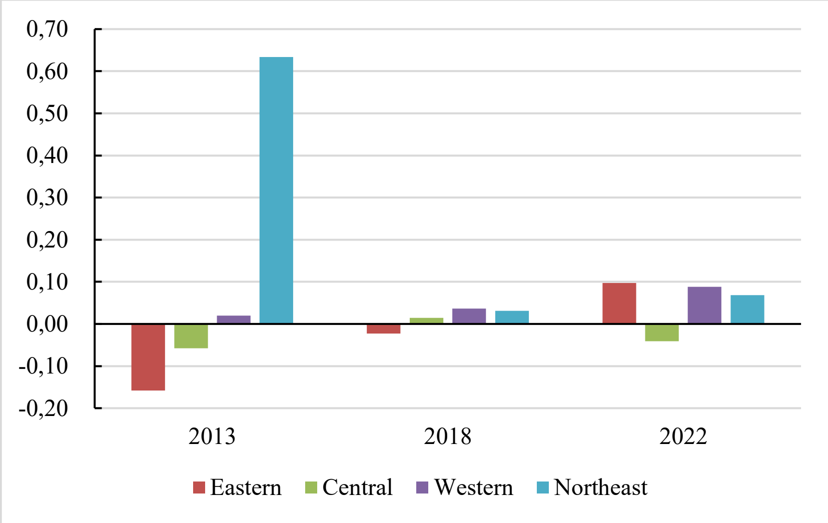
(c) NVHC

Figure 4c. The influence of NVHC on EPCI

4.3.5. The influence of CODE on AGDI

As shown in Figure 4 (d), the impact of sulfur dioxide emissions on agricultural green development in 2013, 2018 and 2022 showed obvious regional heterogeneity: in 2013, the coefficient of Northeast China was significantly positive (up to 0.6), indicating that sulfur dioxide emissions at this stage had a positive impact on agricultural green development, while the eastern region had a negative impact; In 2018, the regional coefficients were close to 0, and the overall impact was weak; In 2022, the eastern region turned positive, and other regions still had no significant effect.

This difference may be due to the correlation between regional industrial structure and pollution control capacity. In 2013, industrial emissions may drive regional economic development in Northeast China, indirectly providing financial support for agricultural green technology investment, forming a *emissions economy agricultural greening* link; Because the eastern region faced environmental constraints earlier, sulfur dioxide emissions had a negative pressure on agricultural ecology. In 2022, the East will have a positive impact, or the upgrading of pollution control technology will form a new synergy between industrial emissions and agricultural green development (such as the green transformation of agriculture driven by cleaner production). The overall impact in 2018 is weak, which may be that the pollution control in each region is in the adjustment period, and the relationship between emissions and agricultural green development is not clearly apparent.

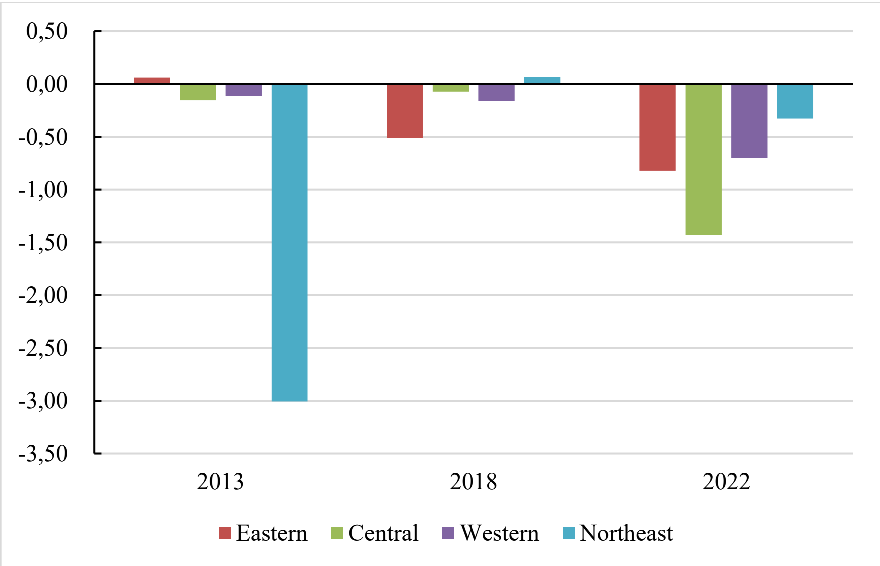


(d) CODE

Figure 4d. The influence of CODE on EPCI

4.3.6. The influence of SDE on AGDI

As shown in Figure 4 (e), the impact of chemical oxygen demand emissions on the level of green agricultural development in 2013, 2018 and 2022 showed significant regional heterogeneity: in 2013, the northeast region showed a very strong negative impact, and the chemical oxygen demand emissions significantly inhibited the green agricultural development; In 2018, there was a negative impact in the eastern region; In 2022, the negative impact in the central region is particularly prominent (the coefficient is close to -1.5), while the impact in other regions is relatively weak.



(e) SDE

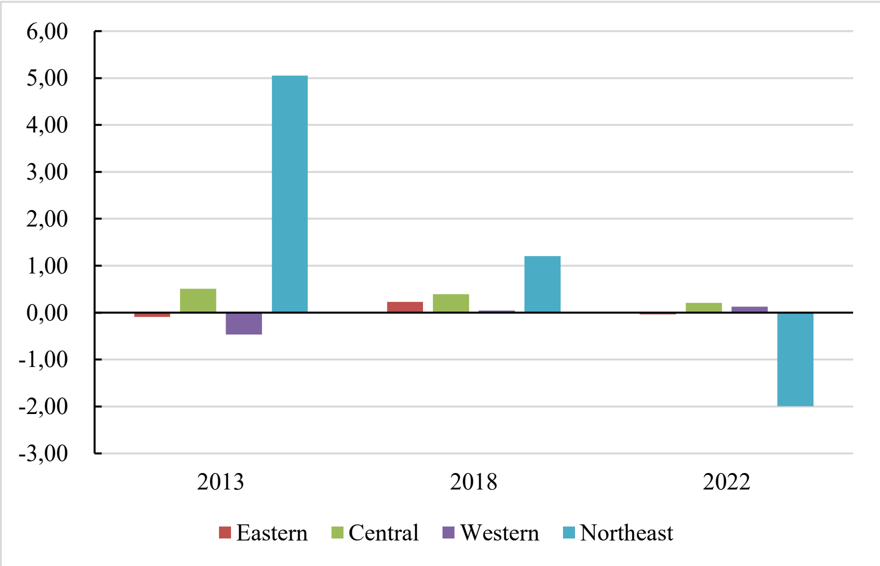
Figure 4e. The influence of SDE on EPCI

This difference may be due to the correlation between regional pollution characteristics and agricultural ecological sensitivity. In 2013, the chemical oxygen demand in Northeast China may exceed the standard due to industrial wastewater and agricultural non-point source pollution (such as aquaculture wastewater), which will directly damage the agricultural ecological environment; The negative impact of the eastern region in 2018 is related to its high degree of industrialization and wastewater discharge polluting farmland water quality; In 2022, the central region was significantly negative, or the accumulation of chemical oxygen demand was aggravated, which was restricted by the excessive use of agricultural chemical inputs and the insufficient treatment of rural domestic sewage.

4.3.7. The influence of EF on AGDI

As shown in Figure 4 (f), there is significant regional heterogeneity in the impact of education funds on the level of green agricultural development in 2013, 2018 and 2022: in 2013, the coefficient of Northeast China was as high as about 5.0, and education funds formed a strong positive drive on green agricultural development; In 2018, the northeast region still maintained a positive role; In 2022, the impact in Northeast China will turn negative. In other years, the coefficients of the eastern, central and western regions tend to be close to 0 or only show weak fluctuations, and the overall impact is not significant.

The possible reason for this difference is that the investment direction of education funds is related to the matching degree of regional agricultural development needs. In 2013, the education funds in Northeast China may focus on the research and development of green agricultural technology and the cultivation of farmers' ecological consciousness, which will directly promote the green transformation of agriculture; The positive impact continued in 2018, reflecting the sustained effect of education investment. However, the negative impact in 2022, or the deviation of the use of education funds from the core needs of agricultural green development (such as excessive emphasis on non-agricultural Education), failed to form an effective support. The eastern, central and western regions have always been weak in driving the green development of agriculture due to the insufficient scale of education investment or the failure to accurately match the demand for green development of agriculture (such as the lack of eco agricultural technology training).



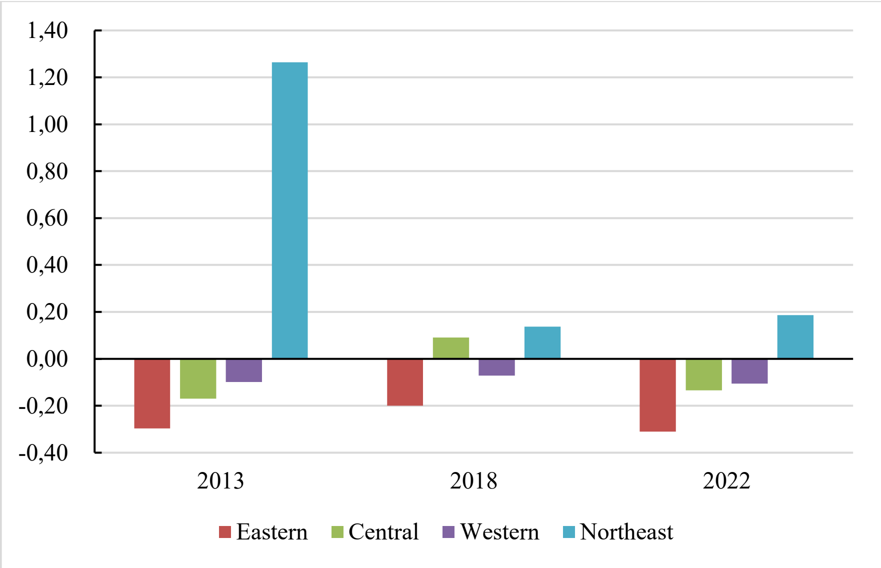
(f) EF

Figure 4f. The influence of EF on EPCI

4.3.8. The influence of EA on AGDI

As shown in Figure 4 (g), the impact of education level on agricultural green development level in 2013, 2018 and 2022 has significant regional heterogeneity: in 2013, the coefficient of Northeast China reached more than 1.2, and education level has a strong positive drive on agricultural green development; In 2018, the northeast region still maintained a positive effect, while the impact of other regions was weak; In 2022, the northeast region maintained a positive impact, while the eastern region showed a negative fluctuation. The coefficient of each year in the central and western regions tended to be close to 0, and the overall effect was not significant.

The possible reason for this difference is that education is related to the supporting direction of agricultural green development. In 2013, the improvement of education level in Northeast China may strengthen farmers' cognition and application ability of green agricultural technology (such as ecological planting and efficient utilization of resources), and directly promote the green transformation of agriculture; From 2018 to 2022, the continuation of the positive impact of Northeast China reflects the long-term penetration of education into agricultural green development. The negative fluctuation in the eastern region in 2022, or the lack of targeted education for agricultural green development due to the inclination of educational resources to non-agricultural industries. The central and western regions may have limited investment in education or poor connection between education content and agricultural green technology promotion, which may make it difficult to show the driving effect on agricultural green development.



(g) EA

Figure 4g. The influence of EA on EPCI

5. Conclusions

Based on the data of 29 provinces in China (excluding Hong Kong, Macao, Taiwan, Xinjiang and Tibet) from 2013 to 2022, this paper analyzes the impact of environmental perspective on AGDI. The main conclusions are as follows. First, the time evolution of AGDI in different regions is highly consistent, and the ADGI in different regions are different, forming a distribution pattern of *high in the south of the East – secondary high in the middle – low in some regions of the northwest and North*. Second, the impact of various factors on the AGDI is different, and the variables show different effects in different periods. Specifically, FSAL and NVHC have the smallest fluctuations, and NVHC has a negative impact only in 2022. During the investigation period, SDED has a negative impact, and the impact fluctuation is the largest. In 2022, the negative impact is the largest, reaching -8.5421. UR has a positive impact during the investigation period. The impact direction of EF has changed many times during the investigation period. EA has a positive impact only in 2019 and a negative impact in other years. Third, the impact of some variables has obvious temporal and spatial heterogeneity. The impact of UR in different regions is consistent, and the impact of EA in different regions in 2013 and 2022 is consistent. FASL and NCHC are mainly affected in the East and northeast, CODE is mainly affected in the East and central, and EF and SDE are mainly affected in the northeast.

Based on this, the following practical policy suggestions are put forward for different regions. In the eastern and northeast regions, we should improve the degree of financial support for agriculture and improve the medical level of village clinics. In the central region, we should strengthen the control of pollution sources, improve sewage treatment capacity, promote ecological agriculture and green agricultural technology, and reduce agricultural pollution to water bodies. For the northeast region, we should increase the investment in education to limit the mining and use of high sulfur coal and optimize the energy structure.

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