



Environmental decentralisation, environmental regulation, and agricultural carbon intensity: an empirical study based on Chinese provincial panel data

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Abstract

Agricultural carbon emission reduction is inseparable from discussions about government systems, especially in countries with distinctive institutional arrangements such as China. Environmental regulation may influence the impact of environmental decentralisation on agricultural carbon intensity. Using panel data from 30 provinces in mainland China from 2000 to 2015, this paper depicts the spatiotemporal pattern and dynamic evolution of environmental decentralisation, environmental regulation, and agricultural carbon intensity. It uses the spatial Durbin model to empirically study the internal connections between the three. The empirical results show that the enhancement of environmental decentralisation, environmental administrative decentralisation, environmental supervision decentralisation, and environmental monitoring decentralisation is not conducive to reducing agricultural carbon intensity. The results also show that the enhancement of the intensity of environmental regulation of “terminal governance type” and “front-end governance type” is conducive to reducing agricultural carbon intensity, but this effect has a negative “space spillover” phenomenon. Other findings are as follows: (1) the enhancement of the two types of environmental regulation intensity is conducive to changing the impact of environmental decentralisation on agricultural carbon intensity from a “grabbing-hand” to a “helping-hand”; (2) compared with balanced grain-producing and marketing areas and major grain-marketing areas, environmental decentralisation and two types of environmental regulations have a greater negative impact on the agricultural carbon intensity of major grain-producing areas. Therefore, the central government should change how it evaluates political performance; accelerate the construction of a diversified performance evaluation system; increase the weight of low-carbon, green, and other indicators that reflect the friendly development of agriculture in the system; and encourage local governments to adjust the direction of agricultural production.

Keywords Environmental decentralisation · Environmental regulation · Agricultural carbon intensity · Spatial Durbin model · China

1 Introduction

Global warming brings challenges to the sustainable development of the global economy, society, and environment. Air pollution caused by intensive production activities and high energy consumption production modes has aroused global concern. In order to control global warming within 2 °C and prevent climate disasters, 195 countries around the world have chosen to join the Paris Agreement and continue to promote carbon reduction and emission reduction projects (Jakučionytė-Skodienė & Liobikienė, 2022). China is already the world's biggest carbon emitter and energy consumer (Ma et al., 2019; Mallapaty, 2020). Meanwhile, its carbon emissions are still in the “climbing” stage, even though most developed countries have achieved a carbon peak. This is due to their different stages of development. As a major greenhouse gas emitter, China pledged at the 75th session of the United Nations General Assembly to peak its carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. While industrial emissions contribute the most to carbon emissions, agricultural emissions account for about 17% of China's total greenhouse gas emissions (Huang et al., 2019). Therefore, under the “dual carbon” target, China's agricultural production has a huge space for carbon emission reduction and the prospect of developing low-carbon agriculture. Characteristically, agricultural production is highly dependent on resources and the environment. The increase of resource input and production efficiency are the main sources of output growth. Ensuring adequate food supplies has been the most pressing challenge facing China. It has been trying to feed 21% of the world's population on 7% of the world's arable land (He et al., 2019; Ye et al., 2020). Fortunately, China has managed to feed its 1.4 billion people, with its total grain output rising from 113 million tons in 1949 to 664 million tons in 2018 (Lal, 2018). Since 2003, China has recorded 16 consecutive years of grain production growth (Li et al., 2021b). However, *the Bulletin on China's Ecological and Environmental Conditions (2018)* shows that the utilisation rate of chemical fertilisers and pesticides in China's three major food crops is only about 38%. The agricultural energy utilisation efficiency is also at a low level. Overuse of pesticides, fertilisers, and mulch, as well as reliance on traditional fossil fuels, are among the main sources of agricultural carbon emissions behind China's high grain yields (Wang et al., 2019; Zhang et al., 2017). Since 2015, the Ministry of Agriculture and Rural Affairs of the People's Republic of China has carried out a zero-growth campaign for the use of chemical fertilisers and pesticides. While the use of pesticides and chemical fertilisers in China has begun to decrease year by year (Jiao et al., 2018), agricultural energy input continues to increase due to increased food demand (Wu et al., 2020c). If China continues to follow the old road of “petroleum agriculture”, the contradiction between the rapid development of agriculture and the protection of the ecological environment will become more and more prominent. Therefore, how to balance the reduction of agricultural carbon emissions and ensure the stable development of agriculture is an important content of the Chinese government's current consideration.

Agricultural carbon emission reduction is inseparable from discussions about government systems, especially in countries with unique institutional arrangements such as China. In 2008, the reform of China's government institutions leads to the adjustment of the State Environmental Protection Administration to the Ministry of Environmental Protection, which means that the reform of China's environmental decentralisation system has gradually improved and constituted an important part of “Chinese-style decentralisation” (Zhang et al., 2018). Environmental decentralisation reflects local governments' actual autonomous decision-making power in environmental governance affairs (Wu et al., 2019).

According to the theory of environmental federalism, improving the environmental management rights of local governments helps to improve the pertinence and effectiveness of environmental pollution control (Oates, 2001). The Chinese government improves the efficiency of environmental governance at all levels of government by giving local governments more power in environmental affairs (Hong et al., 2019; Millimet, 2013). Under such a system, local governments can not only acquire more environmental property rights, including administrative, supervision, and monitoring powers, but also formulate self-interested environmental policies and pollution control countermeasures according to the local economic development goals and ecological environment status (Hao et al., 2019; Ran et al., 2020). Therefore, as an important subject to participate in and achieve regional agricultural energy carbon emission reduction, the influence of local governments' behaviour on agricultural energy carbon emission cannot be ignored. In this context, it is necessary to investigate the impact of environmental decentralisation on agricultural carbon emissions (Cui et al., 2018; Liu & Feng, 2021; Yang et al., 2022).

Under the environmental decentralisation system, the environmental protection behaviour of local governments is key to environmental governance. Environmental regulation has been effective in reducing carbon emissions, improving energy efficiency, and addressing the externalities of environmental pollution (Chen & Chang, 2020; Wu et al., 2020a; You et al., 2019). However, under the Chinese-style decentralisation system, the central government has the right to promote local officials (Xie et al., 2022). At the same time, political and financial incentives still make "GDP" the main indicator of assessment in the process of promotion of local officials (Jiang & Li, 2021). To improve local economic development and personal interests, local governments and officials are more inclined to sacrifice non-economic functional goals to achieve short-term economic interests. This induces incomplete enforcement and "race to the bottom" competition such as environmental monitoring (Ran et al., 2020; You et al., 2019), eventually leading to inefficient carbon emission reduction in agriculture. Therefore, environmental decentralisation may be an important factor against agricultural carbon emission reduction. However, most studies believe that environmental decentralisation is not conducive to carbon emission reduction, but lack further thinking on the conditions under which it can promote carbon emission reduction (Liu & Yang, 2021; Xu & Li, 2022). This paper argues that environmental regulation, as the embodiment of local governments' environmental protection awareness and pollution control ability, appropriately increases the intensity of environmental regulation. It also posits that environmental decentralisation can better consider the interests of carbon emission reduction and economic development and play a role in reducing agricultural carbon intensity. Therefore, it is necessary to study the impact and mechanism of environmental decentralisation and environmental regulation on agricultural carbon emissions. Moreover, the essence of agricultural carbon emission reduction is to coordinate the relationship between agricultural carbon emissions and agricultural economic development. In this study, agricultural carbon intensity, the index that can comprehensively reflect agricultural economic growth and agricultural carbon emissions, is selected. The influence mechanism of environmental decentralisation and environmental regulation on agricultural carbon intensity is discussed on the basis of considering the spatial spillover effect. This research is expected to provide policy suggestions for reference to optimise the environmental decentralisation system and coordinate the development of agricultural economy and agricultural carbon emission reduction.

This study has three main contributions to the literature. The first contribution is that this paper discusses the mechanism of environmental decentralisation on agricultural carbon intensity and finds out the regulatory variables that affect the role of environmental

decentralisation. Therefore, the conclusions of this study help to better clarify the internal mechanisms of environmental decentralisation, environmental regulation, and agricultural carbon intensity. So far, there is no literature studying their relationship in China in this context. The second contribution is to expand environmental decentralisation to the field of agriculture. Most scholars have studied environmental decentralisation, examined its impact on economic growth, or discussed its relationship with carbon emissions. However, few scholars have considered both agricultural economy and agriculture in discussions about carbon emissions. The third contribution is to study the carbon reduction effect of environmental regulation from the two dimensions of front-end and end-end governance.

The rest of this paper is set up as follows. Section 2 briefly introduces the literature synthesis and research hypotheses. Section 3 measures China's agricultural carbon intensity, environmental decentralisation, and environmental regulation and briefly explains the estimation methods and data used in this study. Section 4 presents the empirical results and discussion. Section 5 provides conclusions and related policy implications.

2 Literature review and research hypotheses

2.1 Environmental decentralisation and agricultural carbon intensity

Since 1990, China's central government has delegated power to local governments to seek a balance between organisational unity and autonomy (Feng et al., 2020). The environmental decentralisation reflects the distribution of environmental management powers between the central and local governments (Feng et al., 2022). Although, no one has paid attention to the relationship between environmental decentralisation and agricultural carbon intensity. However, the academic research on environmental decentralisation and environmental governance has been very rich, thus providing a certain research basis for this paper. The governance effect of environmental decentralisation has formed a debate between "good" and "bad", that is, whether environmental decentralisation is conducive to improving environmental conditions or not (Goel et al., 2017; Sigman, 2007). For example, Li et al. (2021a) believe that environmental decentralisation will promote economic development, reduce pollutant emissions, and produce a strong Porter effect; Xia et al. (2021) found that environmental decentralisation can reduce carbon emissions, but environmental decentralisation in neighbouring areas will increase carbon emissions in the region. On the contrary, Ran et al. (2020) found that environmental decentralisation promoted carbon emissions and believed that China's current environmental decentralisation system was not conducive to carbon emission reduction; Hao et al. (2022) found that environmental decentralisation, environmental administrative decentralisation, environmental supervision decentralisation, and environmental supervision decentralisation all have negative impacts on environmental emergencies. To sum up, most of the existing studies focus on the relationship between environmental decentralisation and environmental pollution and discuss the effect of environmental decentralisation on pollutant control. Although no consistent conclusions have been reached, most studies on environmental decentralisation are based on the perspective of welfare economics (Levaggi et al., 2020; Wu et al., 2020b). Therefore, this study analyses the impact mechanism of environmental decentralisation on agricultural carbon intensity from the perspective of welfare economics.

The impact of environmental decentralisation on agricultural carbon intensity is multifaceted. First, improving the level of environmental decentralisation means that local

governments have more autonomous management rights of environmental public affairs. The theory of federal environmentalism points out that environmental decentralisation can better select the most appropriate environmental governance policies according to local residents' preferences, to improve the effect of environmental governance (Oates, 1972). However, China's "GDP-only" promotion mechanism and absolutely authoritative government governance model make local officials prefer economic development, even though such development comes at the expense of ecological environment (Qi & Zhang, 2014; Yang & Muyang, 2013; Zhou, 2004). On the one hand, as the level of environmental decentralisation improves, local governments have sufficient incentives to convert environmental protection funds into "universal funds", triggering the "sticky flypaper effect" and directly leading to insufficient investment in agricultural environmental protection funds (Pan et al., 2020). Therefore, the impact of environmental decentralisation on agricultural carbon intensity in agricultural provinces may be more pronounced than in other provinces. On the other hand, improving local governments' environmental management power is likely to breed a series of corruption and rent-seeking behaviours (Huang & Liu, 2014; Jiang et al., 2020). Relying on the expanding power of environmental management, local governments can adjust and directly lower environmental protection standards and consciously reduce the intensity of environmental law enforcement. At the same time, China's environmental governance has an obvious urban–rural "dual" structure (Xi et al., 2015). Most local governments adopt the "focusing on cities and ignoring rural areas" strategy when dealing with environmental pollution, which may be even more unfavourable to reducing agricultural carbon intensity. Therefore, the following hypothesis is proposed:

H1 An increase in the degree of environmental decentralisation is not conducive to reducing agricultural carbon intensity.

2.2 Environmental regulation and agricultural carbon intensity

Environmental regulation was first proposed by Pigou, a famous British economist, who believed that taxation could reduce the pollution emissions of enterprises (Hahn & Stavins, 1992). Since then, environmental regulation has become an important means for governments to control environmental pollution. At present, there are few direct studies on environmental regulation and agricultural carbon intensity, with most studies focusing on the relationship between environmental regulation and agricultural pollution (Smith & Siciliano, 2015; Sneeringer, 2009). Moreover, most scholars believe that environmental regulation is beneficial to reduce agricultural pollution (He et al., 2022; Zhou et al., 2021). For example, Slabe-Erker et al. (2017) found that agricultural conservation taxes are effective, albeit to a limited extent, in reducing pesticides in groundwater; Liu and Xie (2018) pointed out that chemical fertiliser tax policy and ecological compensation policy alleviated the negative impact of input factors such as chemical fertiliser and pesticide on cultivated land to a certain extent. Zhang et al. (2021) and Guo et al. (2021) found that subsidy policies solve the problem of food security and reduce agricultural pollution emissions. In general, environmental regulation is an important way of improving agricultural ecological environment.

Agricultural environmental regulation currently includes three main types: command and control; economic incentive; and public participation. These three types of environmental regulation also have different effect paths on agricultural carbon intensity. First,

for the command-and-control type, the government strictly and mandatorily controls the carbon emissions of agricultural energy through laws and regulations to reduce agricultural carbon intensity (Waxman & Markey, 2009). For example, the “*American Clean Energy and Security Act*” promulgated by the USA in 2009 made binding regulations on carbon emissions in agricultural production. Secondly, as far as economic incentives are concerned, the government mainly promotes the transformation of agricultural producers’ production mode from traditional to ecological through economic interests (Eisner, 2004; Shortle & Dunn, 1986), thus achieving the goal of reducing agricultural carbon intensity. For example, agricultural financial subsidies help reduce energy consumption and carbon dioxide emissions in the agricultural sector (Lin & Xu, 2018; Searchinger et al., 2020). Finally, in terms of public participation, the government actively participates in the process of reducing agricultural energy carbon emissions by mobilising the enthusiasm of the public (Hou & Hou, 2019; Yang et al., 2019). Examples of this are the “*Public Participation Policy*” issued by the USA in 2003 and the “*Guidelines on Public Access to Environmental Information*” issued by the European Union in 2004. In order to reduce agricultural carbon emissions, China has successively promulgated a series of laws, regulations, and action plans, among which three are the most representative, namely the “*Law of the People’s Republic of China on the Prevention and Control of Air Pollution*”, the “*National Agricultural Sustainable Development Plan (2015–2030)*”, and the “*Implementation Plan for Reducing and Fixing Carbon in Agricultural Villages*”. From the perspective of the measures proposed in the relevant policy documents, China is mainly dominated by command-and-control environmental regulations, supplemented by economic incentive and public participation environmental regulations. In general, no matter what type of environmental regulation is conducive to reducing agricultural carbon intensity. However, since agricultural carbon emissions are composed of scattered, ambiguous and non-single sources, their environmental regulation effects are typically non-exclusive. At the same time, under the background of the political competition system and the pursuit of rapid economic development, “I emit, you control” has become the priority of local governments. This makes environmental regulations a “free-rider” in agricultural carbon emission reduction. Although environmental regulation helps to reduce agricultural carbon intensity, environmental regulation presents a negative “spatial spillover” effect due to local governments’ “free-rider” behaviour. Therefore, the following hypothesis is proposed:

H2 The increase in the intensity of environmental regulation is conducive to reducing agricultural carbon intensity, but this effect has a negative “spatial spillover” phenomenon.

2.3 Environmental decentralisation, environmental regulation, and agricultural carbon intensity

Incorporating environmental decentralisation and environmental regulation into a unified framework to discuss their action mechanism on agricultural carbon intensity is the focus of this study. In the context of the political competition system and the pursuit of rapid economic development, an “I emit, you govern” strategy has become the first choice of local governments. This facilitates the “race to the bottom” and “mutual imitation” phenomenon in environmental regulations (Woods, 2020). At the same time, since agricultural carbon emissions are composed of scattered, unclear, and non-single sources, and their environmental regulation effects are typically non-exclusive, the phenomenon of “free riders” may become the norm.

Environmental regulation embodies local governments’ environmental protection awareness and pollution control ability. By appropriately increasing the intensity of environmental regulation, environmental decentralisation can better consider the interests of carbon emission reduction and economic development and play a role in reducing agricultural carbon intensity. Therefore, the following hypothesis is proposed:

H3 The increase in the intensity of environmental regulation is conducive to changing the impact of environmental decentralisation on agricultural carbon intensity from a “grabbing-hand” to a “helping-hand”.

In addition, this study provides a mechanism analysis diagram to more intuitively reflect the relationship between environmental decentralisation, environmental regulation, and agricultural carbon intensity (see Fig. 1).

3 Research methods and data

3.1 Calculation of agricultural carbon intensity

3.1.1 Calculation of agricultural carbon emissions

Since China does not have statistical data on agricultural carbon emissions, this study calculates China’s agricultural carbon emissions. According to previous literature, the sources of agricultural carbon emissions include four types. The first is agricultural energy input, which mainly includes raw coal, gasoline, diesel oil, electricity, pesticides, fertilisers, and agricultural film. The second is methane emissions caused by rice cultivation. The third is methane and nitrous oxide emissions from livestock production. The fourth is nitrous oxide, which is released from the soil during crop cultivation.

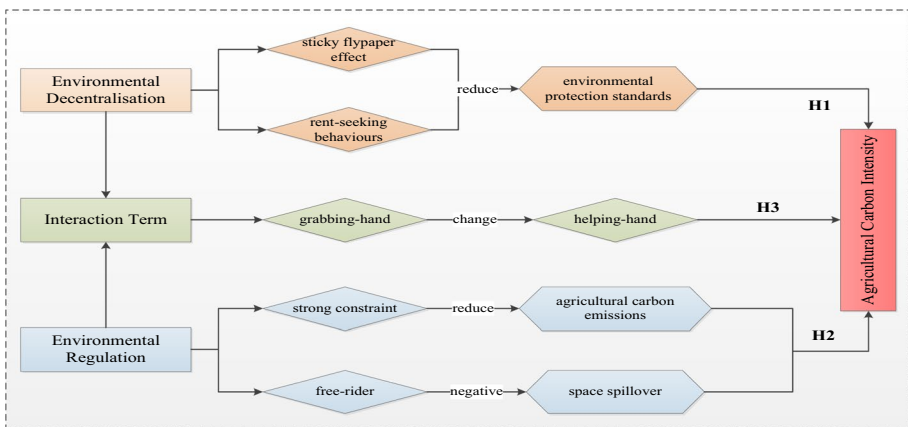


Fig. 1 Mechanism analysis of environmental decentralisation, environmental regulation, and agricultural carbon intensity

This study is based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). This paper also draws on the agricultural carbon emission equation proposed by Tian et al. (2014) and Zhang et al. (2019b):

$$\text{CO}_2 = \sum_{i=1}^n \text{CO}_{2,i} = \sum_{i=1}^n C \times \beta_i \times \frac{44}{12} \quad (1)$$

CO_2 is the agricultural carbon dioxide emission, $\text{CO}_{2,i}$ is the carbon dioxide emission of the i th carbon source, C is the agricultural carbon emission, and β_i is the emission coefficient of the i th carbon source. This study refers to the carbon emission coefficients of previous studies (Luo et al., 2017; Ma et al., 2019; Paustian et al., 2006; Xin-min, 2011). Among them, the carbon emission factor of China's provincial power is taken from the "2010 China Regional and Provincial Power Grid Average Carbon Dioxide Emission Factors".

3.1.2 Calculation of agricultural carbon intensity

An effective way to achieve low-carbon development of China's agriculture is to reduce agricultural carbon intensity. Therefore, this study draws on Zhou et al., (2019) and Zhang et al., (2019a) to define agricultural carbon intensity as:

$$\text{ACI} = \text{CO}_2 / \text{AV} \quad (2)$$

ACI represents the agricultural carbon intensity, which is also the dependent variable of this study, CO_2 is the agricultural carbon dioxide emissions calculated according to formula (1), and AV represents the added value of the primary industry.

3.2 Explanatory variables and data

3.2.1 Environmental decentralisation

Environmental decentralisation reflects the division mechanism of environmental management powers among governments at all levels. To better measure the impact of environmental decentralisation on the allocation of environmental supervision authority, and based on the particularity of China's administrative management and the rationality and availability of data. This study draws on Zhang and Li (2020) and Wu et al., (2020a) in the measurement of environmental decentralisation and uses the personnel distribution characteristics of different levels of government environmental protection departments to describe the indicators of environmental decentralisation. To alleviate the endogeneity problem caused by the differences in economic development in various regions, this study also simultaneously uses $[1 - (\text{GDP}_{it}/\text{GDP}_t)]$ to deflate all decentralisation indicators. The specific environmental decentralisation calculation formula is as follows:

$$\text{ED}_{it} = \left[\frac{\text{LSP}_{it}/\text{POP}_{it}}{\text{LSP}_t/\text{POP}_t} \right] \times [1 - (\text{GDP}_{it}/\text{GDP}_t)] \quad (3)$$

ED_{it} is the index of environmental decentralisation; LSP_{it} and LSP_t are the number of personnel of environmental protection agencies in China and province i in year t , respectively; and POP_{it} and POP_t are the population size of the country and province i at the end of year t , respectively.

This paper further subdivides environmental decentralisation into environmental administrative decentralisation (EAD), environmental supervision decentralisation (ESD), and environmental monitoring decentralisation (EMD). The calculation of the three subdivision indicators is the same as formula (3). The only difference is that the number of environmental protection system personnel is replaced by the number of environmental protection administrative personnel, environmental supervision personnel, and environmental monitoring personnel, respectively.

3.2.2 Environmental regulation

Most studies mainly measure the intensity of environmental regulation from the two dimensions of terminal governance and front-end governance (Ren et al., 2018; Song et al., 2021). Therefore, when considering data availability, the ratio of environmental protection investment amount of completed environmental protection acceptance projects to GDP in the current year is adopted to measure the first type of environmental regulation. We refer to Zhang et al., (2019c, 2020). The ratio of the environmental protection investment of the completed environmental protection acceptance project to GDP is used to measure the “terminal governance type” environmental regulation. Meanwhile, the ratio of environmental pollution control investment to GDP measures the “front-end governance type” environmental regulation. ER(1) and ER(2) represent both measurements.

3.2.3 Control variables

To find suitable control variables, IPAT and STIRPAT models, which have been proposed to study the effects of various factors on CO₂ emissions, were referenced in this study (Dietz & Rosa, 1994; Liu & Song, 2020). IPAT model is a famous model for assessing environmental stress and takes population, affluence, and technology as three factors affecting environmental quality. The STIRPAT model is an extension of the IPAT model, allowing for the decomposition of population, affluence, and technology. It also introduces other factors that might affect the environment. Therefore, this study divided control variables into population, affluence, and technology and other factors according to IPAT and STIRPAT models. Referring to the studies of Abbasi et al. (2020), Du et al. (2019), and Chang (2015), this study selected employment structure, urbanisation rate, and rural population density to represent population variables, and technological level to represent technical indicators. Per capita GDP, industrial structure, and per capita added value of primary industry were selected to represent economic indicators. In addition, Lin and Chen (2020) found that transportation infrastructure has an important impact on energy and environmental efficiency, which in turn affects carbon dioxide emissions. Therefore, road traffic infrastructure is selected as one of the control variables in this study. The specific meanings, symbols, and measured values of these variables are shown in Table 1.

3.2.4 Samples and data sources

In this study, 30 provinces in Mainland China (excluding Tibet, Hong Kong, Macao and Taiwan) were selected as the investigation samples, and the data sample was from 2000 to 2015. It should be noted that after 2017, the “*China Environmental Statistical Yearbook*”

Table 1 Definition of all relevant variables used in the study

Symbol	Variables	Definition	Unit of measurement
Explained variable			
ACI	Agricultural carbon intensity	Agricultural CO ₂ emissions/value-added of primary industry	Ton/10 thousand yuan
Explanatory variable			
ED	Environmental decentralisation	See formula (3)	–
ER(1)	Environmental regulation (1)	Completed environmental protection acceptance project environmental protection investment in that year/GDP	%
ER(2)	Environmental regulation (2)	Environmental pollution control investment/GDP	%
Control variable			
URB	Urbanisation rate	Proportion of provincial urban population in the total population	%
ES	Employment structure	Employment in primary industry/total employment	%
IS	Industrial structure	Added value of the primary industry/GDP	%
PGDP	Per capita GDP	GDP/total population	10 thousand yuan
RPD	Rural population density	Rural permanent population/cultivated area	Person/hectare
TI	Technique level	Technology R&D Investment/GDP	%
PAPI	Per capita added value of primary industry	Added value of the primary industry/employees in primary industry	10 thousand yuan/person
RTI	Road traffic infrastructure	Road mileage per unit area in each province	km/km ²

Table 2 Descriptive statistics for the variables

Variables	<i>N</i>	Mean	Std. deviation	Minimum	Maximum
ACI	480	4.450	3.286	1.037	29.944
ED	480	1.333	1.281	0.272	8.142
ER(1)	480	0.349	0.259	0.013	2.038
ER(2)	480	1.363	0.677	0.400	5.165
URB	480	47.638	15.219	13.885	89.275
ES	480	42.022	15.986	3.281	81.834
RS	480	12.866	6.724	0.400	37.900
PGDP	480	2.748	2.168	0.266	10.796
RPD	480	6.602	4.058	0.991	34.833
TI	480	0.197	0.367	0.012	2.299
PAPI	480	0.462	0.288	0.081	1.538
RTI	480	1.375	1.680	0.106	9.966

will not publish the data of environmental system practitioners at all levels. Therefore, the index value of environmental decentralisation is calculated until 2015. The data in this study are from *China Environmental Statistical Yearbook*, *China Energy Statistical Yearbook*, *China Rural Statistical Yearbook*, *Provincial Statistical Yearbook*, and *China Science and Technology Statistical Yearbook*. To avoid heteroscedasticity, the indexes were logarithmically processed. Due to inflation, indicators related to the price index were adjusted to constant prices for the year 2000. Descriptive statistics of variables involved in this study are shown in Table 2.

3.3 Construction of spatial econometric model

3.3.1 Spatial autocorrelation test

To discuss the spatial effects of environmental decentralisation, environmental regulation, and agricultural carbon intensity, it is necessary to first conduct spatial autocorrelation test on agricultural carbon intensity. In this paper, global Moran's I index is used to conduct the spatial autocorrelation test (Moran, 1950). The calculation formula of global Moran's I index is as follows:

$$I = \frac{n}{\sum_{i=1}^n \sum_{j=1}^n w_{ij}} \times \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (aci_i - \overline{aci})(aci_j - \overline{aci})}{\sum_{i=1}^n (aci_i - \overline{aci})^2} \quad (4)$$

I is the global Moran index, *n* is the number of observations, w_{ij} is the spatial weight matrix of positions i and j , aci_i and aci_j are the observations in the i region and the j region, respectively, and \overline{aci} is the average value of aci .

3.3.2 Setting up the spatial econometric model

Anselin (1988) pointed out that ignoring the spatial correlation between regions will lead to the deviation of model setting, which makes the spatial econometric model widely concerned by the academic community. The commonly used spatial models are three types: spatial lag model (SAR), spatial error model (SEM), and spatial Durbin model (SDM). The SAR model takes the spatial lag term of the dependent variable as the independent variable, while the SEM model introduces the spatial lag term of the error term as the independent variable. The SDM model simultaneously introduces the spatial lag term of the dependent variable and the spatial lag term of the error as independent variables. The formula of the SDM model in this paper is as follows:

$$\begin{aligned}
 ACI_{it} = & \alpha_0 + \alpha_1 \ln ED_{it} + \alpha_2 \ln ER_{it} + \alpha_3 \ln ED_{it} \times \ln ER_{it} + \alpha_4 \ln URB_{it} + \alpha_5 \ln ES_{it} \\
 & + \alpha_6 \ln RS_{it} + \alpha_7 \ln PGDP_{it} + \alpha_8 (\ln PGDP_{it})^2 + \alpha_9 \ln RPD_{it} + \alpha_{10} \ln TI_{it} \\
 & + \alpha_{11} \ln PAPI_{it} + \alpha_{12} \ln RTI_{it} + \rho W ACI_{it} + \theta_1 W \ln ED_{it} + \theta_2 W \ln ER_{it} \\
 & + \theta_3 W \ln ED_{it} \times \ln WER_{it} + \theta_4 W \ln URB_{it} + \theta_5 W \ln ES_{it} + \theta_6 W \ln RS_{it} \\
 & + \theta_7 W \ln PGDP_{it} + \theta_8 W (\ln PGDP_{it})^2 + \theta_9 W \ln RPD_{it} + \theta_{10} W \ln TI_{it} \\
 & + \theta_{11} W \ln PAPI_{it} + \theta_{12} W \ln RTI_{it} + \varepsilon_{it}; \varepsilon_{it} = \rho W_{it} \varepsilon_i + \gamma_{it}
 \end{aligned} \tag{5}$$

where i is the i th province, with $i = 1, 2, \dots, 30$, t is the year (2000–2015), W is the spatial weight matrix, ρ and α are the coefficients of the spatial lag terms of the dependent and independent variables, γ_{it} is the random error term, and the rest of the variables and signs remain the same as above.

3.4 Quality control and quality assurance

To verify hypothesis 1 and hypothesis 2, this paper obtains the estimated coefficient of environmental decentralisation and environmental regulation on agricultural carbon intensity through formula (5) (delete the interaction between environmental decentralisation and environmental regulation). In verifying hypothesis 3, this paper discusses the impact of environmental decentralisation on agricultural carbon intensity under the influence of environmental regulation by adding the interaction between environmental decentralisation and environmental regulation to the original formula. In setting the model method, this paper verifies the rationality of the spatial econometric model through spatial autocorrelation test, Lagrange multiplier (LM) tests, Wald test, LR test, and Hausman test. In the aspect of data processing, this paper logarithmises the data to avoid heteroscedasticity. At the same time, this paper adjusts the data related to the price index to the constant price in 2000 due to the uncertainty of the estimated coefficient caused by inflation. In terms of result analysis, this paper tests the rationality of empirical results by building a theoretical analysis framework (see Fig. 1).

4 Results

4.1 Analysis of dynamic evolution characteristics

Using nonparametric kernel density estimation formula and Stata16 software, the kernel density curves of agricultural carbon energy intensity, environmental regulation, and environmental decentralisation at the provincial level in China in 2000, 2005, 2010, and 2015 were drawn (end governance environmental regulation (ER(1)) was selected to report due to space limitations). To characterise the temporal dynamic evolution characteristics (see Fig. 1). (1) From the gravity centre position of the annual kernel density curve, agricultural carbon intensity moved consistently to the left from 2000 to 2015; environmental regulation first moved to the right and then to the left; and environmental decentralisation first moved to the left and then to the right. This shows that agricultural carbon intensity is the evolution of continuous decline, environmental regulation is the evolution of upward and then downward movement, and environmental decentralisation is the evolution of downward and then upward movement. (2) From the peak height of the main peak of the curve, agricultural carbon intensity increased continuously from 2000 to 2015, and environmental regulation and environmental decentralisation increased and decreased. This shows that the differences in agricultural carbon intensity are continuously decreasing, and the differences in environmental regulation and environmental decentralisation are first decreasing and then expanding. (3) In terms of the number of curve peaks, agricultural carbon intensity and environmental regulation showed a two-peak coexistence with one main peak and one other peak. Meanwhile, environmental decentralisation showed a multi-peak coexistence with one main peak and several other peaks. This shows that agricultural carbon intensity and environmental regulation have polarisation characteristics, and environmental decentralisation has the characteristics of multi-polarisation. (4) From the point of curve about trailing, 2000–2015, agriculture in carbon intensity, environmental regulation and the separation of the right side of the trail is greater than the left side of the trail, in the tail length of agricultural carbon intensity and environment on the separation of the shortened, environmental regulation in the expansion, shows that high value decentralisation dropped agricultural carbon intensity and environment, the high value area environmental regulation has increased. In general, agricultural carbon intensity decreased from 2000 to 2015, and gradually showed a balanced development. From 2000 to 2015, the intensity of environmental regulation increased first and then decreased, forming a double-polarisation trend. From 2000 to 2015, the degree of environmental decentralisation decreased first and then increased, forming a trend of multi-pole differentiation.

4.2 Analysis of spatial and temporal patterns

To intuitively analyse the spatial–temporal pattern evolution of agricultural carbon intensity, environmental decentralisation, and environmental regulation at the provincial level in China, this study used ArcGIS10.2 to present the spatial distribution of agricultural carbon intensity, environmental decentralisation, and environmental regulation in 30 provinces in 2000, 2005, 2010, and 2015 (see Fig. 2). Table 9 shows the names of Chinese provinces and their corresponding abbreviations. This study draws on Feng et al. (2019), adopts a unified standard to classify agricultural carbon intensity, environmental regulation, and environmental decentralisation, and divides them into four grades.

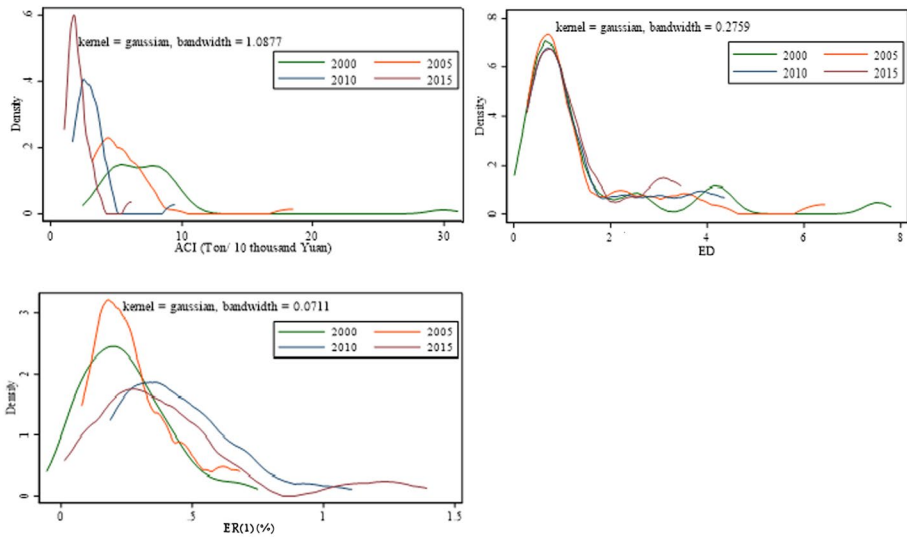


Fig. 2 Dynamic evolution characteristics of agricultural carbon intensity, environmental regulation, and environmental decentralisation

Based on the 4-year spatial distribution of agricultural carbon intensity, the following conclusions can be drawn. First, China's agricultural carbon intensity showed a downward trend from 2000 to 2015, with higher agricultural carbon intensity in the northern region and lower agricultural carbon intensity in the southern region. Second, provinces with high agricultural carbon intensity in 2000 and 2005 were mainly located in the north-west and south-west regions, with the highest in Heilongjiang, Xinjiang, and Shanxi. Meanwhile, provinces with faster economic growth, such as southern and eastern coastal provinces, had lower agricultural carbon intensity. Finally, provinces with higher agricultural carbon intensity in 2010 and 2015 were mainly located in the north-west and some northern regions, with the highest in Qinghai, Gansu, and Inner Mongolia. This indicates that agricultural carbon intensity is highly correlated with the industrial structure and economic development level of each province.

Based on the 4-year spatial distribution of environmental decentralisation, the following conclusions can be drawn. First, the degree of environmental decentralisation in China from 2000 to 2015 showed a trend of first decreasing and then increasing. The north-west region had a higher degree of environmental decentralisation, while the northern and eastern regions had a lower degree. Second, provinces with a high degree of environmental decentralisation in 2000 and 2005 were mainly located in north-west China and north China, with Beijing, Shanghai, and Qinghai being the highest. Finally, the provinces with a high degree of environmental decentralisation in 2010 and 2015 were still located in the north-west and north China, with the highest in Beijing, Tianjin, and Ningxia.

The following conclusions can be drawn from the 4-year spatial distribution of environmental regulations. First, China's environmental regulation from 2000 to 2015 showed a trend of rising first and then falling. The intensity of environmental regulation in the northern region was higher, and the intensity in the southern region was lower. Second, the provinces with higher environmental regulation intensity in 2000 and 2005 were mainly located in the north-west region, with the highest in Ningxia, Xinjiang, and Qinghai. Meanwhile,

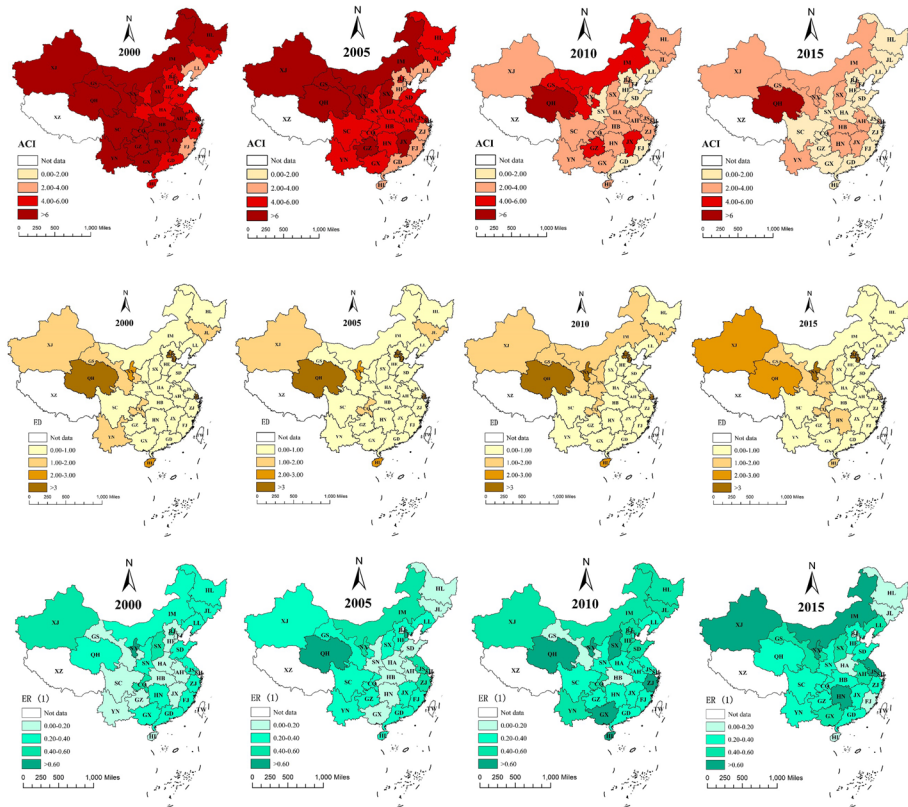


Fig. 3 Spatial distribution of agricultural energy carbon intensity, environmental regulation, and environmental decentralisation in China

Table 3 Global Moran’s index of agricultural carbon intensity in China from 2000 to 2015

Year	Moran’s index	Z-statistics	p value	Year	Moran’s index	Z-statistics	p value
2000	0.101	2.442	0.007	2008	0.121	2.223	0.013
2001	0.105	2.325	0.010	2009	0.139	2.678	0.004
2002	0.111	2.476	0.007	2010	0.117	2.152	0.016
2003	0.104	2.503	0.006	2011	0.139	2.457	0.007
2004	0.111	2.369	0.009	2012	0.127	2.188	0.014
2005	0.115	2.236	0.013	2013	0.117	1.930	0.027
2006	0.136	2.505	0.006	2014	0.138	2.140	0.016
2007	0.121	2.307	0.011	2015	0.108	1.776	0.038

the central region had lower environmental regulation intensity. Finally, provinces with high environmental regulation intensity in 2010 and 2015 were mainly located in north China and north-west China, with the highest in Jiangsu, Xinjiang, and Inner Mongolia (Fig. 3).

4.3 Spatial autocorrelation test

The global Moran index of provincial agricultural carbon intensity in China from 2000 to 2015 was calculated using Stata16 software. Table 3 shows that the global Moran index of China's agricultural carbon intensity from 2000 to 2015 was positive and significant at the 5% level. The distribution of China's agricultural carbon intensity is spatially positively auto-correlated and spatially clustered rather than randomly distributed. Therefore, when studying the influencing factors of China's agricultural carbon intensity, its spatial effect must be considered, also indicating that the choice of the spatial econometric model in this paper is correct. At the same time, the global Moran index of China's agricultural carbon intensity showed an upward trend from 2000 to 2015. In terms of stages, the global Moran index of agricultural carbon intensity showed an upward trend from 2000 to 2006. In 2007–2015, the global Moran index of agricultural carbon intensity showed a fluctuating downward trend, and the spatial correlation began to weaken, indicating that the agricultural carbon intensity in China during this period tended to develop in a balanced way.

4.4 Empirical results and analysis

4.4.1 Model selection

Choosing a specific spatial econometric model requires a series of tests (see Table 4). According to the principles proposed by Elhorst (2003), this study used Stata16 software to first perform Lagrange multiplier (LM) tests (LM-LAG and LM-ERR) and their robustness tests (robust LM-LAG and robust LM-ERR) to examine whether nonspatial panel data models ignore the spatial effects of the data. As shown in Table 4, the LM test, Wald test, and LR test all passed the significance test at the 5% level, indicating that it is reasonable to set the model as the SDM model. At the same time, the Hausman test ($p < 0.05$) found that the fixed-effects model was better than the random-effects model. Finally, this study was found to fit the spatiotemporal double fixed-effects SDM model by LR-IND ($p < 0.10$) and LR-TIME ($p < 0.01$).

Table 4 LM test, Wald test, Hausman test, and LR test results

Test	
LM-LAG	304.23***
Robust LM-LAG	163.04***
LM-ERR	146.37***
Robust LM-ERR	5.18**
Wald-SAR	111.32***
Wald-SEM	106.55***
LR-SAR	99.29***
LR-SEM	96.20***
Hausman	39.60**
LR-IND	41.24*
LR-TIME	389.83***

***Indicates that the estimated coefficients passed the Z-test at the 1% levels of significance

Table 5 Empirical results on agricultural carbon intensity, environmental decentralisation, and environmental regulation

Variable	Environmental decentralisation		Environmental administrative decentralisation		Environmental supervision decentralisation		Environmental monitoring decentralisation	
	(1)	(2)	(3)	(4)				
lnED	2.091*** (5.08)	1.826*** (4.56)	0.444 (1.62)	0.872*** (4.75)	0.798*** (4.44)	0.578** (2.04)	0.512** (1.85)	
lnER(1)	-0.305*** (-2.94)	-0.263** (-2.48)	-	-0.304*** (-2.93)	-	-0.253** (-2.40)	-	
lnER(2)	-	-0.609*** (-3.14)	-0.638*** (-3.22)	-	-0.742*** (-3.81)	-	-0.626*** (-3.17)	
lnURB	0.367 (0.52)	0.361 (0.53)	0.337 (0.48)	0.188 (0.27)	0.224 (0.330)	0.344 (0.48)	0.366 (0.53)	
lnES	-2.189** (-2.14)	-2.057** (-2.06)	-0.780 (-0.80)	-0.419 (-0.43)	-0.589 (-0.62)	-0.450 (-0.45)	-0.575 (-0.59)	
lnIS	2.482*** (2.95)	1.954** (2.28)	2.498*** (2.95)	1.140 (1.34)	1.820** (2.16)	1.710** (1.97)	2.270*** (2.65)	
lnPGDP	1.971** (2.20)	1.521* (1.67)	2.637*** (2.86)	0.998 (1.11)	2.209** (2.43)	1.588* (1.72)	2.660*** (2.87)	
(lnPGDP) ²	0.902*** (6.67)	0.946*** (6.78)	0.903*** (6.57)	0.817*** (5.98)	0.786*** (5.84)	0.910*** (6.58)	0.880*** (6.47)	
lnRPD	-0.082 (-0.13)	-0.174 (-0.26)	-0.288 (-0.44)	-0.346 (-0.54)	-0.392 (-0.62)	-0.239 (-0.36)	-0.345 (-0.54)	
lnITI	-0.266 (-1.11)	-0.288 (-1.20)	-0.063 (-0.27)	-0.209 (-0.88)	0.018 (0.08)	-0.296 (-1.20)	-0.065 (-0.27)	
lnPAPI	-7.259*** (-8.02)	-6.744*** (-7.34)	-7.076*** (-7.78)	-6.018*** (-6.61)	-6.502*** (-7.20)	-6.583*** (-6.87)	-6.948*** (-7.39)	
lnRTI	0.567** (2.22)	0.920*** (3.67)	0.812*** (3.32)	0.538** (2.10)	0.455* (1.81)	0.964*** (3.89)	0.846*** (3.51)	
W*lnED	2.921* (1.88)	-0.748 (-1.06)	-0.547 (-0.80)	1.319*** (2.79)	1.009** (2.18)	-1.829* (-1.77)	-1.637 (-1.63)	

Table 5 (continued)

Variable	Environmental decentralisation		Environmental administrative decentralisation		Environmental supervision decentralisation		Environmental monitoring decentralisation	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
W*lnER(1)	-0.302 (-1.18)	-0.130 (-0.50)	-0.308 (-1.21)	-	-0.081 (-0.32)	-	-	-
W*lnER(2)	-	2.201*** (4.17)	-	2.205*** (4.09)	1.949*** (3.64)	-	2.274*** (4.24)	-
W*lnURB	-10.010*** (-5.90)	-10.351*** (-6.51)	-10.865*** (-6.27)	-10.781*** (-6.62)	-10.495*** (-6.56)	-11.066*** (-6.38)	-10.986*** (-6.77)	-
W*lnES	-5.995** (-2.18)	-4.762* (-1.77)	-4.983* (-1.80)	-4.314 (-1.59)	-2.624 (-0.98)	-5.076* (-1.82)	-4.360 (-1.61)	-
W*lnRS	4.451** (2.24)	3.370* (1.74)	3.319 (1.64)	2.548 (1.29)	0.944 (0.48)	3.399* (1.66)	2.627 (1.32)	-
W*lnPGDP	3.465 (1.38)	1.455 (0.59)	2.997 (1.17)	1.076 (0.43)	1.070 (0.42)	2.315 (0.89)	0.552 (0.22)	-
W*(lnPGDP) ²	-0.810** (-2.51)	-0.665** (-2.09)	-0.989*** (-3.01)	-0.857*** (-2.65)	-0.956*** (-2.98)	-0.842*** (-2.94)	-0.842*** (-2.60)	-
W*lnRPD	-1.546 (-0.99)	-2.465 (-1.59)	-2.310 (-1.45)	-2.927* (-1.86)	-2.501 (-1.60)	-2.643 (-1.63)	-3.276** (-2.05)	-
W*lnTI	-0.914 (-1.48)	-1.018* (-1.68)	-0.573 (-1.91)	-0.718 (-1.18)	-0.638 (-1.04)	-0.465 (-0.72)	-0.626 (-1.00)	-
W*lnPAPI	-7.663*** (-3.02)	-5.916** (-2.39)	-7.558*** (-2.90)	-6.045** (-2.37)	-5.128** (-1.99)	-3.787 (-1.50)	-6.938** (-2.11)	-
W*lnRTI	-0.110 (-0.17)	0.271 (0.42)	0.719 (1.11)	1.002 (1.58)	-0.351 (-0.52)	0.488 (0.76)	0.814 (1.29)	-
ρ	-0.281*** (-3.34)	-0.290*** (-3.44)	-0.255*** (-2.99)	-0.264*** (-3.10)	-0.304*** (-3.59)	-0.299*** (-3.53)	-0.259*** (-3.05)	-0.268*** (-3.16)
R ²	0.7509	0.7639	0.7467	0.7583	0.7524	0.7646	0.7475	0.7597

Table 5 (continued)

Variable	Environmental decentralisation	Environmental administrative decentralisation	Environmental supervision decentralisation	Environmental monitoring decentralisation
	(1)	(2)	(3)	(4)
log-likelihood	-676.9547	-667.2745	-676.0646	-674.1469
Observations	480	480	480	480

*, **, and *** Indicate that the estimated coefficients passed the Z-test at the 10%, 5%, and 1% levels of significance, respectively

4.4.2 Analysis of spatial spillover effect

Table 5 shows that during the study period, agricultural carbon intensity was significantly positively correlated with environmental decentralisation (ED), industrial structure (IS), per capita GDP (PGDP), quadratic term of per capita GDP, and road traffic infrastructure (RTI). Environmental regulation (ER (1) and ER (2)), employment structure (ES), and per capita added value of primary industry (PAPI) were significantly negatively correlated. At the same time, environmental decentralisation (ED), “front-end governance type” environmental regulation (ER (2)), and industrial structure (IS) in neighbouring areas significantly promoted the local agricultural carbon intensity. Urbanisation rate (URB), employment structure (ES), quadratic term of per capita GDP, technology level (TI), and per capita added value of primary industry (PAPI) have significant inhibitory effects on local agricultural carbon intensity. In addition, environmental administrative decentralisation (EAD), environmental monitoring decentralisation (ESD), and environmental monitoring decentralisation (SMD) all showed significant positive correlations with local agricultural carbon intensity. Environmental monitoring decentralisation (ESD) showed a significant positive correlation with agricultural carbon intensity in adjacent areas. Environmental monitoring decentralisation (SMD) showed a significant negative correlation with agricultural carbon intensity in adjacent areas. Due to the spatial lag term, the estimated coefficients of the SDM cannot represent the marginal effects of the independent variables. Instead, it is necessary to decompose the spatial spillover effects of independent variables on agricultural carbon intensity, namely direct effects, indirect benefits, and total effects.

4.4.3 Decomposition results of spatial spillover effect

Table 6 shows that columns (4)–(7) are the decomposition effects of environmental decentralisation (ED, EAD, ESD, EMD) and two types of environmental regulation (ER(1), ER(2)). From column (4) of the table, it can be concluded that environmental decentralisation (ED) is not conducive to reducing agricultural carbon intensity. Thus, hypothesis 1 is verified, a similar result to the research conclusion of Zhang and Li (2020); both “terminal governance type” and “front-end governance type” environmental regulations are conducive to reducing agricultural carbon intensity, and “front-end governance type” environmental regulation (ER(2)) has a negative “spatial spillover” effect. Hypothesis 2 is also verified. At the same time, it can be seen from columns (5)–(7) of the table that both types of environmental regulations are conducive to reducing agricultural carbon intensity in the direct effect; three types of environmental decentralisation (EAD, ESD, EMD) are not conducive to reducing agricultural carbon intensity, which is similar to the research conclusion of Wu et al. (2020a). This result may be because environmental decentralisation endows local governments with more “discretion” in environmental governance. Under the “egoistic” motivation of local governments, such “discretion” will not be conducive to the inhibition of environmental regulation on agricultural carbon intensity. In the indirect effect, the coefficient of environmental supervision decentralisation (ESD) is significantly positive, indicating that environmental supervision decentralisation (ESD) is not only unfavourable to reduce local agricultural carbon intensity, but also unfavourable to reduce agricultural carbon intensity in surrounding areas. On the contrary, in the indirect effect, the coefficient of environmental monitoring decentralisation (EMD) is significantly negative, indicating that it is not conducive to reducing local agricultural carbon intensity, but is beneficial to reducing agricultural carbon intensity in surrounding areas. This may be due to the

Table 6 Direct effect, indirect effect, and total effect of factors influencing agricultural carbon intensity

Variable	Environmental decentralisation		Environmental administrative decentralisation		Environmental supervision decentralisation		Environmental monitoring decentralisation	
	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Direct effect								
InED	1.997*** (4.68)	1.764*** (4.23)	0.667** (2.29)	0.480* (1.69)	0.825*** (4.37)	0.766*** (4.14)	0.669** (2.31)	0.596** (2.10)
InER(1)	-0.300*** (-3.02)	-0.729*** (-3.89)	-0.265*** (-2.62)	-0.748*** (-3.92)	-0.298*** (-2.99)	-0.856*** (-4.52)	-0.257** (-2.54)	-0.740*** (-3.88)
InER(2)		YES	YES	YES	YES	YES	YES	YES
Control variable								
Indirect effect								
InED	2.023 (1.48)	1.382 (1.05)	-0.721 (-1.13)	-0.514 (-0.84)	0.892** (2.21)	0.663* (1.67)	-1.622* (-1.80)	-1.442* (-1.65)
InER(1)	-0.190 (-0.92)		-0.064 (-0.30)		-0.187 (-0.93)		-0.020 (-0.10)	
InER(2)		1.945*** (4.59)		1.973*** (4.43)		1.762*** (4.14)		2.028*** (4.56)
Control variable	YES	YES	YES	YES	YES	YES	YES	YES
Total effect								
InED	4.020*** (2.92)	3.146*** (2.40)	-0.054 (-0.08)	-0.034 (-0.05)	1.717*** (3.97)	1.429*** (3.35)	-0.952 (-1.02)	-0.846 (-0.93)
InER(1)	-0.490*** (-2.10)		-0.329 (-1.37)		-0.485** (-2.13)		-0.277 (-1.18)	
InER(2)		1.216*** (2.80)		1.225*** (2.69)		0.906** (2.06)		1.287*** (2.83)
Control variable	YES	YES	YES	YES	YES	YES	YES	YES

* and *** indicate that the estimated coefficients passed the Z-test at the 10% and 1% levels of significance, respectively

phenomenon of “race to the bottom” of local governments in environmental monitoring rights, and this effect has a negative “spatial spillover” phenomenon. Although environmental monitoring rights may reduce the authenticity of environmental monitoring data, it will improve local governments’ ability to share environmental information, which is conducive to reducing agricultural carbon intensity in space. In addition, it is interesting that in the indirect effects of column (4)–(6), the coefficients of “front-end governance type” environmental regulation (ER(2)) are significantly positive, while the coefficients of “terminal governance type” environmental regulation (ER(1)) are negative and insignificant. This shows that the phenomenon of “free riding” among local governments is more obvious in “front-end governance type” environmental regulation (ER(2)).

4.4.4 Further empirical analysis

Since China’s reform and opening up, the “delegation of power and transfer of profits” has given local governments a certain level of free decision-making power. So, is this environmental power necessarily detrimental to reducing agricultural carbon intensity? As the embodiment of local government’s environmental governance behaviour, can environmental regulation affect the effect of environmental decentralisation? We add the interaction term of environmental decentralisation and environmental regulation to the model to further explore their relationship.

Table 7 shows that columns (8)–(11) are the decomposition effects after adding the interaction terms of environmental decentralisation and environmental regulation. Column (8) of the table shows that the coefficients of environmental decentralisation (ED) are all significantly positive in the direct effect. Also, both types of environmental regulation are significantly negative, and their interaction terms are significantly negative. This shows that the improvement of the intensity of environmental regulation is conducive to the transformation of the impact of environmental decentralisation on agricultural carbon intensity from the “grabbing-hand” to a “helping-hand”. Hypothesis 3 is verified. Hypothesis 3 has been verified, indicating that the negative impact of “GDP only” can be weakened by appropriately increasing the intensity of environmental regulation, and the negative impact of environmental decentralisation on agricultural carbon intensity can be improved. As can be seen from column (10), the coefficients of environmental supervision decentralisation (ESD) and “front-end governance type” environmental regulation (ER(2)) are significantly positive among the indirect effects, while the coefficient of their interaction term is significantly negative. This indicates that “front-end governance type” environmental regulation (ER(2)) weakens the effect of environmental supervision decentralisation (ESD) on agricultural carbon intensity in surrounding areas. It is also unfavourable to reduce agricultural carbon intensity in surrounding areas, and there is a “green paradox” effect. As can be seen from column (11), in the direct effect, the coefficient of environmental monitoring decentralisation (EMD) is significantly positive, the coefficient of “front-end governance type” environmental regulation (ER(2)) is significantly negative, and the coefficient of their interaction term is significantly negative. This indicates that the increase in the intensity of front-end governance-based environmental regulation is conducive to weakening the adverse impact of environmental monitoring decentralisation (EMD) on agricultural carbon intensity.

Table 7 Empirical results after adding the interaction term of environmental decentralisation and environmental regulation

Variable	Environmental decentralisation		Environmental administrative decentralisation		Environmental supervision decentralisation		Environmental monitoring decentralisation	
	(8)	(9)	(10)	(11)				
Direct effect								
InED	1.323*** (3.14)	1.872*** (4.47)	0.011 (0.04)	0.563* (1.95)	0.240 (1.04)	0.810*** (4.45)	-0.152 (-0.49)	0.714** (2.49)
InER(1)	-0.168* (-1.70)	-0.138 (-1.38)	-0.138 (-1.38)	-0.254** (-2.57)	-0.254** (-2.57)	0.007 (0.06)	0.007 (0.06)	
InER(1)*InED	-0.608*** (-5.66)	-0.604*** (-5.88)	-0.604*** (-5.88)	-0.356*** (-4.22)	-0.356*** (-4.22)		-0.633*** (-6.23)	
InER(2)		-0.751*** (-4.01)		-0.751*** (-3.93)		-0.900*** (-4.73)		-0.659*** (-3.41)
InER(2)*InED		-0.434*** (-2.10)		-0.307 (-1.58)		-0.213 (-1.34)		-0.404** (-2.13)
Control variable	YES	YES	YES	YES	YES	YES	YES	YES
Indirect effect								
InED	1.785 (1.42)	1.543 (1.25)	-0.423 (-0.71)	-0.300 (-0.49)	0.944* (1.90)	0.659* (1.76)	-1.057 (-1.22)	-1.267 (-1.49)
InER(1)	-0.183 (-0.88)	-0.126 (-0.57)	-0.126 (-0.57)	-0.143 (-0.69)	-0.143 (-0.69)		-0.071 (-0.32)	
InER(1)*InED	0.015 (0.08)	0.162 (0.84)	0.162 (0.84)	2.169*** (4.63)	0.090 (0.56)	1.877*** (4.30)	0.048 (0.26)	2.399*** (4.92)
InER(2)		2.211*** (5.09)		-0.580 (-2.34)		-0.776* (-1.92)		-0.786 (-1.52)
InER(2)*InED		-1.173** (-2.34)		-0.580 (-2.34)		-0.776* (-1.92)		-0.786 (-1.52)
Control variable	YES	YES	YES	YES	YES	YES	YES	YES
Total effect								

Table 7 (continued)

Variable	Environmental decentralisation		Environmental administrative decentralisation		Environmental supervision decentralisation		Environmental monitoring decentralisation	
	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
InED	3.109** (2.38)	-0.412 (-0.64)	1.184** (2.20)	-1.209 (-1.33)	1.469*** (3.52)	-0.553 (-0.62)		
InER(1)	-0.351 (-1.51)	-0.265 (-1.05)	-0.397* (-1.69)	-0.064 (-0.26)				
InER(1)*InED	-0.594*** (-3.28)	-0.441** (-2.26)	-0.265* (-1.72)	-0.585*** (-3.02)				
InER(2)			1.418*** (2.89)	0.978** (2.15)	1.740*** (3.36)			
InER(2)*InED			-1.607*** (-3.03)	-0.989** (-2.32)	-1.191** (-2.14)			
Control variable	YES	YES	YES	YES	YES	YES	YES	YES

* and *** Indicate that the estimated coefficients passed the Z-test at the 10% and 1% levels of significance, respectively

Table 8 Empirical results at the level of region

Variable	Major grain-producing areas		Balanced grain-producing and marketing areas		Major grain-marketing areas	
	(12)	(13)	(13)	(14)	(14)	(14)
Direct effect						
lnED	0.416* (1.75)	-0.020 (-0.13)	0.917 (0.82)	4.587*** (3.95)	-0.245 (-1.20)	-0.038 (-0.18)
lnER(1)	-0.077 (-1.22)		0.269 (1.04)		-0.068* (-1.72)	
lnER(1)*lnED	0.161 (1.39)		-0.947*** (-2.73)		-0.110** (-3.03)	
lnER(2)		-0.377*** (-3.18)		0.209 (0.42)		-0.143** (-2.49)
lnER(2)*lnED		0.563*** (2.93)		-4.095*** (-5.65)		-0.069 (-1.22)
Control variable	YES	YES	YES	YES	YES	YES
Indirect effect						
lnED	0.839** (2.40)	0.189 (0.86)	-3.516** (-2.11)	-6.851*** (-3.33)	-1.059*** (-3.94)	-1.079*** (-4.16)
lnER(1)	0.117 (1.45)		-0.090 (-0.13)		-0.070 (-1.27)	
lnER(1)*lnED	0.393** (2.43)		0.628 (0.76)		0.001 (0.02)	
lnER(2)		0.206 (1.20)		1.627 (1.40)		-0.020 (-0.25)
lnER(2)*lnED		0.571 (1.58)		3.323** (2.14)		0.010 (0.13)
Control variable	YES	YES	YES	YES	YES	YES
Total effect						
lnED	1.255*** (2.88)	0.169 (0.73)	-2.599* (-1.75)	-2.265 (-1.03)	-1.304*** (-3.20)	-1.118*** (-2.78)
lnER(1)	0.040 (0.46)		0.179 (0.26)		-0.138* (-1.69)	
lnER(1)*lnED	0.554*** (3.00)		-0.318 (-0.37)		-0.109 (-1.61)	
lnER(2)		-0.172 (-0.87)		1.836 (1.59)		-0.162 (-1.44)
lnER(2)*lnED		1.134*** (3.10)		-0.771 (-0.41)		-0.058 (-0.55)
Control variable	YES	YES	YES	YES	YES	YES

* and ***Indicate that the estimated coefficients passed the Z-test at the 10% and 1% levels of significance, respectively

4.4.5 Empirical results at the regional level

Due to China's vast territory, there is a big gap in each region's resource endowment, natural environment, and agricultural economic development. To compare whether there are differences in the impacts of environmental decentralisation and environmental regulation on agricultural carbon intensity among regions, the samples are divided into major

grain-producing areas, balanced grain-producing and marketing areas, and major grain-marketing areas for empirical analysis. Table 1 lists the specific provinces by region. Due to space limitations, this paper only reports the estimation results of environmental decentralisation (ED) and two types of environmental regulation (ER(1), ER(2)).

By comparing columns (12)–(14) in Table 8, it can be seen that, among the direct effects, only major grain-producing areas and balanced grain-producing and marketing areas have a significantly positive environmental decentralisation (ED) coefficient. In the indirect effect, the environmental decentralisation (ED) coefficient of major grain-producing areas was significantly positive, while that of balanced grain-producing and marketing areas and major grain-marketing areas was significantly negative. This shows that environmental decentralisation (ED) is more unfavourable for reducing the agricultural carbon intensity of major grain-producing areas compared with the other two region types. Also, this impact is more prominent in the “spatial spillover” effect. This may be because major grain-producing areas shoulder the task of producing stable and high-yield grains, thus causing local governments to pursue high-yield and tolerate the excessive use of pesticides and fertilisers in agricultural production. In the direct effect, “terminal governance type” environmental regulation (ER(1)) is beneficial to reduce the agricultural carbon intensity of major grain-marketing areas and main grain-marketing areas, while “front-end governance type” environmental regulation (ER (2)) is beneficial to reduce the agricultural carbon intensity of major grain-producing areas and balanced grain-producing and marketing areas. In terms of the total effect, environmental decentralisation (ED) is not conducive to reducing agricultural carbon intensity in major grain-producing areas, while “terminal governance type” environmental regulation (ER(1)) is conducive to reducing agricultural carbon intensity in major grain-marketing areas. This indicates that environmental decentralisation (ED) and environmental regulation (ER(1), ER(2)) have a greater negative impact on agricultural carbon intensity in major grain-producing areas than in major grain-marketing areas and balanced grain-producing and marketing areas.

5 Discussion

Clarifying the relationship between environmental decentralisation, environmental regulation, and agricultural carbon intensity has important guiding value for promoting the development of low-carbon agriculture and formulating effective, accurate, and operable agricultural carbon emission reduction policies. In this study, 30 provinces in Chinese Mainland (excluding Tibet, Hong Kong, Macao, and Taiwan) were taken as the sample to study the spatial relationship between environmental decentralisation, environmental regulation, and agricultural carbon intensity. The results of this study can provide research support for China and other developing countries to effectively implement agricultural carbon emission reduction policies.

First, agricultural carbon intensity has significant spatial correlation, which is clustered in space rather than randomly distributed. In fact, the spatial spillover effect of agricultural carbon intensity has been verified in many studies (Li & Li, 2022; Zhong et al., 2022). Second, there is a “green paradox” effect in environmental decentralisation, and the improvement of environmental administrative decentralisation, environmental monitoring decentralisation, and environmental monitoring decentralisation is not conducive to reducing agricultural carbon intensity. This view is similar to the research conclusion of Ran et al., (2020). In terms of the impact of environmental regulation on agricultural carbon intensity,

this study explored the impact of environmental regulation on agricultural carbon intensity from the two dimensions of “terminal governance type” and “front-end governance type” and found that improving environmental regulation intensity can effectively reduce agricultural carbon intensity. However, there is a negative “space spillover” phenomenon. This view is similar to the conclusion of Chang et al., (2022) and Zhang and Zhao (2022). This study also provides new evidence for the view that environmental regulation reduces agricultural carbon intensity. Of course, unlike other studies, it only discusses the direct or indirect impact of environmental decentralisation on carbon emissions (Ran et al., 2020; Yuan et al., 2022). This study creatively indicates that the impact of environmental decentralisation on agricultural carbon intensity will change from a “grabbing-hand” to a “helping-hand” with the improvement of environmental regulation intensity. Specifically, in the context of relatively loose environmental regulations, environmental decentralisation makes local governments prefer economic development, and this development is mostly at the cost of damaging the ecological environment. However, with the improvement of the intensity of environmental regulation, its own binding characteristics are further reflected, and this extensive development will be restrained to a certain extent. Therefore, this study is helpful to provide a certain reference basis for relevant government departments to formulate agricultural carbon emission reduction policies or measures, and take “weakening the environmental management authority of local governments and improving the intensity of environmental regulation” as the goal orientation of policy implementation.

In addition, this study quantitatively studies the nonlinear effects of environmental decentralisation and environmental regulation on China’s agricultural carbon intensity, but there are some limitations that can inspire further research. First, to ensure the reliability of agricultural carbon emission accounting, the coefficient mainly refers to the carbon emission reference coefficient published by the Chinese government as available in widely cited literature. However, coefficients below the provincial level are still uncertain, which may affect the reliability of the results. Second, since the relevant data of environmental decentralisation indicators are statistically available after 2015, the research period of this paper was only 16 years. Finally, since there are obvious gaps in agricultural development in different regions of a province, the link between environmental decentralisation, environmental regulation, and agricultural carbon intensity can be more accurate and explanatory when data from cities or counties are obtained.

6 Conclusions and policy recommendations

6.1 Conclusion

Based on the panel data of 30 provinces in Chinese Mainland from 2000 to 2015, this study empirically examined the internal relationship between environmental decentralisation, environmental regulation, and agricultural carbon intensity by building a spatial Durbin model. The results of this study are as follows:

1. During the study period, agricultural carbon intensity showed a continuous downward trend, with higher agricultural carbon intensity in northern China and lower agricultural carbon intensity in southern China. The intensity of environmental regulation in northern China is higher than in southern China. The degree of environmental decentralisa-

- tion decreased first and then increased. The degree of environmental decentralisation was higher in north-west China, and lower in north China and eastern China.
2. Enhancing environmental decentralisation, environmental administrative decentralisation, environmental supervision decentralisation, and environmental monitoring decentralisation is not conducive to reducing agricultural carbon intensity. However, enhancing the intensity of environmental regulation of “terminal governance type” and “front-end governance type” is conducive to reducing agricultural carbon intensity, but this effect has a negative “space spillover” phenomenon.
 3. Improving the intensity of environmental regulation helps to transform the influence of environmental decentralisation on agricultural carbon intensity from “grabbing-hand” to “helping-hand”.
 4. Compared with balanced grain-producing and marketing areas and major grain-marketing areas, environmental decentralisation and two types of environmental regulations have a greater negative impact on the agricultural carbon intensity of major grain-producing areas.

6.2 Policy recommendations

Based on these findings, this study makes the following policy recommendations:

1. The central government should formulate low-carbon and reasonable agricultural development policies and guide local governments to shift the focus of development to low-carbon agricultural transformation projects to a certain extent. This will help to reduce agricultural carbon emissions to the greatest extent and ensure food security.
2. The central government should maintain a certain degree of centralisation in local environmental management and improve the rights of environmental management. At the same time, a differentiated carbon emission governance system should be formulated according to the agricultural development of each region, to improve the governance performance of agricultural carbon emissions.
3. The central government should change the way it appraises performance, strengthen the constraint and supervision over local governments, and accelerate the construction of a diversified performance appraisal system. It should also increase the weight of low-carbon, green, and other environmentally friendly indicators in the system; encourage local governments to adjust the direction of their behaviour; and consider the coordinated development of economy and environment.
4. The central government should further eliminate the negative impact of “GDP only” and let local governments fully realise that the country and people want high-quality, cost-effective, and green GDP, and should pay more attention to improving quality and efficiency, improving scientific and technological innovation capacity, and optimising economic structure.

Appendix 1

See Table 9.

Table 9 Chinese provincial names and corresponding abbreviations

Province	Anhui (AH)	Hebei (HE)	Henan (HA)	Heilongjiang (HL)	Hunan (HN)	Hubei (HB)	Jilin (JL)
Major grain-producing areas	Jiangsu (JS)	Jiangxi (JX)	Liaoning (LN)	Inner Mongolia (IM)	Shandong (SD)	Sichuan (SC)	
Balanced grain-producing and marketing areas	Shanxi (SX)	Guangxi (GX)	Chongqing (CQ)	Guizhou (GZ)	Yunnan (YN)	Shaanxi (SN)	Gansu (GS)
Major grain-marketing areas	Qinghai (QH)	Ningxia (NX)	Xinjiang (XJ)	Tibet (XZ)			
Other areas	Shanghai (SH)	Tianjin (TJ)	Zhejiang (ZJ)	Guangdong (GD)	Beijing (BJ)	Hainan (HI)	Fujian (FJ)
	Macao (MO)	Taiwan (TW)	Hong Kong (HK)				

() is the abbreviation of province

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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