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Impact of formal and informal environmental regulations on agricultural carbon emissions: Empirical evidence from China

*Yumiao Zhang, Qi Yin, Yufan Wu, Kun Ma**

School of Economics and Management, Hebei University of Science and Technology, Shijiazhuang, P.R. China

**Corresponding author: hebust237699822@163.com*

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Abstract: Agricultural carbon emissions (ACE) is a critical contributor to global greenhouse gas emissions, which have already become a common challenge for global carbon reduction. As a major agricultural producer and largest carbon emitter, China has made great efforts to reduce ACE. Using the panel data of 30 provinces in China from 2011 to 2022, this study explores the heterogeneous impacts of formal environmental regulations (FER) and informal environmental regulations (IER) on ACE. The results reveal that both FER and IER have significant effect on reducing ACE, with FER showing a more pronounced effect. The mechanism analysis indicates that agricultural technological innovation and planting structure adjustment play important mediating roles in this impact mechanism. The effect of FER is more remarkable in major grain producing areas than in non-major grain producing areas, while the effect of IER is completely opposite. Compared with coastal regions, both FER and IER have significant inhibitory effect on ACE in inland regions. Additionally, the marketisation level may reinforce the inhibitory effect of both FER and IER on ACE. Based on the empirical results, this study suggests to strengthen the synergistic effect of FER and IER, promote agricultural technology innovation, and formulate targeted policies according to regional differences.

Keywords: carbon emissions reduction; environmental policy; mediating effect model; threshold model

As the trend of global warming intensifies, the impact of climate change on the environment and socio-economic systems has become a global concern. Intergovernmental Panel on Climate Change (IPCC) assessment report states that anthropogenic greenhouse gas emissions is the main driver of global warming, and agriculture, as the second-largest source of global carbon emissions, contributes approximately 21% of the total net anthropogenic greenhouse gas emissions. Without controls, the agricultural sector is likely to overtake manufacturing industry as the world's largest source of carbon emissions in the future (Farajian et al. 2018). It is a common challenge for agricultural sectors of different countries, and imperative for them to take measures to mitigate agricultural carbon emissions (ACE) and alleviate the pressure of temperature increasing. China is the largest carbon emitter in the world: according to the Biennial Transparency Report on Climate Change of China (BTR) to the United Nations Framework Convention in 2024, its total carbon emissions in 2021 is about 14.314 billion tonnes. Among these, ACE are about 931 million

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tonnes, which is more than the total carbon emissions of Germany and accounts for approximately 12% of global agricultural greenhouse gas emissions. Therefore, China is expected to make great contribution to the global efforts to reduce ACE.

As the world's largest developing country, agriculture plays a fundamental and important role in China's national economy. In recent years, China's agricultural production has made great progress through agricultural mechanisation and the widespread use of pesticides and fertilisers (An et al. 2023). However, such extensive production mode has also brought negative impacts on the environment, especially the ACE has gradually become a serious problem (Campi et al. 2021). According to the BTR, China's ACE in 2021 increased by 12.4% over 2010. ACE in China primarily consist of methane (CH_4) emissions from livestock enteric fermentation, rice cultivation, and manure management, as well as nitrous oxide (N_2O) emissions from synthetic fertiliser use and other agricultural activities (Streimikiene et al. 2021). Among them, emissions by livestock enteric fermentation and rice cultivation accounted for more than 60% of the ACE. Besides, confined by different production mode, resource endowment, and socio-economic development, the ACE exhibited substantial variation among provinces (Xue et al. 2024). Due to intensive rice farming and animal husbandry, East, Central and Southwest China are the main sources of ACE in China, contributing about 60% of the country's agricultural greenhouse gas emissions (Gao et al. 2025).

The carbon source complexity and spatial heterogeneity of ACE increase the difficulty of controlling ACE. The Chinese government has implemented a series of environmental protection policies and measures aiming at reducing ACE (Table 1). Measures such as the 'The 14th Five-Year Plan of National Agricultural Green Development' and the 'Circular Economy Promotion Law of People's Republic of China' have outlined specific measures to promote sustainable agricultural development and reduce carbon emissions. These relevant policies and regulations constrain the carbon emissions practices of enterprises and industries directly. Besides, with the improvement of Chinese people's education level and the popularisation of mobile Internet, the social concern to environmental protection is increasing, and the recognition, acceptance and support for energy

Table 1. Policies and regulations related to agricultural carbon emissions reduction in China

Time	Documents	Category
2007	China's National Climate Change Program	whole fields
2008	Circular Economy Promotion Law of People's Republic of China	whole fields
2011	Responding to Climate Change: China's Policies and Actions	whole fields
2014	Regulation on the Prevention and Control of Pollution from Large-scale Breeding of Livestock and Poultry	agricultural field
2015	National Sustainable Agricultural Development Plan (2015–2030) Action Plan for Zero Growth in Chemical Fertiliser Use by 2020 Action Plan for Zero Growth in Pesticide Use by 2020	agricultural field
2016	The 13th Five-Year Plan for Controlling Greenhouse Gas Emissions	whole fields
	Reformation Plan for Establishing a Green and Ecology Oriented Agricultural Subsidy System	agricultural field
2017	Opinions on Innovating System and Mechanism to Promote Agricultural Green Development	agricultural field
2021	Action Plan for Carbon Emission Peak Before 2030 Guiding Opinions on Establishing and Improving a Green, Low-Carbon and Circular Development Economic System	whole fields
	The 14th Five-Year Plan of National Agricultural Green Development	agricultural field
2022	The 14th Five-Year Comprehensive Energy Conservation and Emission Reduction Work Plan	whole fields
	Implementation Plan for Reducing Emissions and Increasing Carbon Sequestration in Agriculture and Rural Areas	agricultural field

Source: Authors' own processing

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conservation, emissions reduction and green transformation also become stronger. As a result, the public, the media, environmental groups and other non-governmental organisations play a more important role in supervising and restraining corporate behaviour than before (Kong et al. 2020). Both formal regulatory restrictions and informal social oversight are crucial for controlling carbon emissions (Cole et al. 2005).

Given the urgency of achieving carbon peaking and carbon neutrality goals, along with the practical need for green development of agriculture, it is crucial to systematically analyse the actual effects of formal environmental regulations (FER) and informal environmental regulations (IER) of China on promoting agricultural carbon reduction. This research is conducive to better leveraging both formal and informal forces to tackle ACE problems in China, and also provide policy inspiration for developing countries to promote the development of low-carbon agriculture and effectively control the ACE.

Literature review

In recent years, ACE have become an important topic in the study of global climate change. Previous studies have shown that the primary contributors of ACE include pesticide and fertiliser inputs, the consumption of fossil energy during agricultural machinery operation, and the growth and output processes of agricultural products (Aday et al. 2016). IPCC emission coefficient approach, input-output modelling, and carbon footprint accounting based on life cycle assessment are applied to estimate the total ACE (Hu et al. 2023). Besides, spatial distribution characteristics of ACE are also explored and compared by different watersheds, food-producing areas, economic zones (Pu et al. 2021; Wen et al. 2022; Xue et al. 2024). Given the growing concern about carbon emissions from agriculture, the factors affecting ACE are also widely discussed. The improvement of agricultural production and management practices such as agricultural technological progress (Zhu et al. 2024), agricultural mechanisation (Rymaniak et al. 2021), and large-scale operation of farmland (Li et al. 2022b) may contribute to the reduction of ACE, while changes in population size (Åby et al. 2014) and energy consumption structure (Yu et al. 2020) have also been identified as key factors influencing ACE.

Environmental regulation, as a major tool and powerful instrument for solving environmental problems, has been widely studied and applied in the field of reducing carbon emissions. The notion of environmental regulation was initially defined as a government policy to balance environmental protection and economic development (Kathuria 2006), and the concept has been continuously extended with the development of various regulatory instruments. According to the different functioning modes, environmental regulation can be divided into command type and market-based type (Li and Ramanathan 2018). The former mainly refers to environmental protection laws and regulations involving emission standards, technical standards etc. (Blackman et al. 2018), and the latter mainly includes carbon tax, carbon emission trading and other market means (Jaffe et al. 2002). However, this classification method only takes the government as the main implementation body into consideration, ignoring the power of the public and non-governmental organisations. Thus, according to the different entities involved, environmental regulation can be further divided into two categories: formal environmental regulations (FER) and informal environmental regulations (IER) (Cole et al. 2005). FER refers to relevant policies and laws which are formulated by the governmental departments to protect and improve the environment and implemented through public power to intervene and control the environmental behaviour of enterprises. FER is a 'hard constraint' on enterprises (Hepburn 2010; Li and Shi 2022). IER refers to social awareness that the public, the media, environmental protection organisations and other stakeholders raise the importance of environmental protection in the whole society and public supervision by the whole society. IER may exert invisible pressure on the environmental behaviour of enterprises, which is a 'soft constraint' on enterprises (Chen et al. 2021; Tang et al. 2023).

At present, there is no academic consensus on the relationship between environmental regulations and carbon emissions. A number of studies have shown that environmental regulations can reduce carbon emissions, and that this effect is realised through a variety of channels, including energy consumption transformation, industrial structure upgrading and technological innovation (Di et al. 2014; Cheng et al. 2017; Chen et al. 2019). It has also been argued that the impact of environmental regulations on carbon emissions is uncertain and exhibits a non-linear relationship due to differences in regulatory intensity and possible threshold effects (Lu et al. 2022). In addition, as different forms of environmental regulation have their own characteristics, they also have different impacts on carbon emissions (Tian and Feng 2022). However, most of the previous literature focus on exploring the effects

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of different instruments of FER, such as command and market-based environmental regulation, and the findings have been controversial. Some scholars proved that command regulation would be more effective in reducing carbon emissions (Song and Han 2022), while others argued that the lack of flexibility of command regulation may lead to inefficiency, market-based regulation are more conducive in guiding enterprises to reduce emissions through market forces (Peng et al. 2021). There are limited studies which focused on the differential effects of FER and IER on carbon emissions. Dong et al. (2022) demonstrated that both FER and IER had significantly affected carbon emissions, but the two had different impact mechanisms. Wang and Guo (2024) found that FER was more effective in the eastern regions and larger cities, whereas IER played a crucial role in regions with lower carbon emissions.

The impact of environmental regulations on ACE is rarely discussed and only a few studies focus on the effect of FER on ACE, while the effect of IER on ACE causes less attention. Some scholars selected specific forms of FER, such as carbon tax policies, the high-standard farmland construction policy, the agricultural sustainable development experimental demonstration zone policy to analyse their impacts on ACE (Fan et al. 2018; Dumortier and Elobeid 2021; Du et al. 2023; Li et al. 2023). There are some other scholars who tried to construct an indicator system to assess FER and evaluate its inhibitory effect on ACE (Xia et al. 2024). Lu and Dai (2023) adopted the adjusted coefficient of the GDP to measure environmental regulations, investigated its impact on ACE and further examined the threshold effect of trade policy. In addition, Zhang et al. (2020) pointed out that the effects of environmental regulation on ACE may vary across provinces in China due to the large differences in economic development level and environmental protection pressures.

Previous literatures provide useful reference and inspiration for this paper, but the effect of FER and IER on ACE has not been fully explored. The underlying mechanism and regional heterogeneity of the effects are still vague. In addition, the potential role of regional marketisation level has been neglected in the impact mechanism of environmental regulations on reducing carbon emissions. In fact, the marketisation level not only affects the behavioural patterns of agricultural producers, but also determines the efficiency of green technology innovation and environmental regulation (Wang et al. 2021). Based on the above analysis, this paper focuses on the impact mechanisms, heterogeneous effects of FER and IER on ACE in China and also the threshold effect of marketisation level. The marginal contributions of this study can be summarised in three aspects. Firstly, the construction of a comprehensive ACE accounting system with multi-carbon source is helpful to improve the accuracy of ACE measurement. Secondly, the study examines the heterogeneous effects and mechanisms of both FER and IER on ACE. Finally, a panel threshold model is employed to testify the possible non-linear correlation between environmental regulations and ACE across various marketisation levels.

Theoretical analysis and hypothesis

The theoretical framework interpreting the impact mechanisms of FER and IER on reducing ACE is shown in Figure 1.

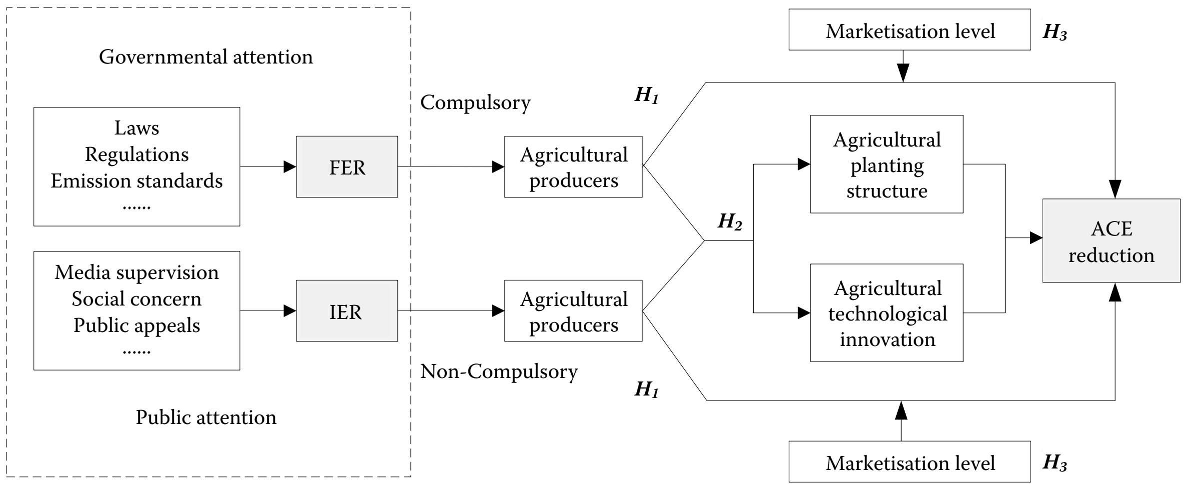

Figure 1. Theoretical framework

ACE – agricultural carbon emissions; FER – formal environmental regulations; IER – informal environmental regulations
Source: Authors' own processing

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Impact of FER and IFR on ACE. FER with clearly defined rules and obligatory penalties by the government, will effectively decrease carbon emissions in the short term. The more attentions and the stricter the policy, the more obvious the short-term effect. However, such compulsory measure may also increase the burden of enterprises, reduce the enthusiasm of enterprises to transform and develop, and bring adverse effects on environmental quality (Balogh 2020). If regulation is not strong enough or the cost of breaking the law is not high, the effect of carbon reduction will be greatly reduced. In the long run, the continuous improvement of environmental protection legislation and the enhancement of law enforcement will inevitably increase the emission costs of enterprises, forcing agricultural producers to adopt low-carbon and more environmental-friendly production methods. To summarise, in the short run, the strict and effective implementation of FER can reduce the strategic emission reduction speculation of enterprises to a certain extent, produce a 'deterrent effect' on enterprises, and in the long run, FER will promote enterprises to carry out substantive energy conservation and emission reduction measures (Carpentier and Suret 2015).

With the enhancement of public awareness of environmental protection, IER may urge the active and transparent disclosure carbon emission information by enterprises through social supervision mechanism and public opinion pressure, which can monitor and influence their carbon emission behaviours (Balsalobre-Lorente et al. 2019). Besides, in order to enhance their social reputation and market perception, the agricultural producers have strong incentives to carry out low-carbon transformation (Rehman et al. 2022). This option would further reduce ACE. However, IER is a non-compulsory measure, so the carbon reduction effect of IER depends mainly on the strength of public power and consciousness and social responsibility of the enterprises. So, the effect of IER on reducing ACE may vary greatly by district and enterprises.

Based on the above analysis, this paper proposes hypothesis H_1 as follows:

H_1: Both FER and IER will have positive effect on reducing ACE, but the degree of effect differs.

Mediating effect of FER and IER on ACE. On one hand, both FER and IER can reduce ACE by stimulating agricultural producers to adopt technological innovations. The traditional view is that FER, by setting emission standards and technical specifications, will increase the operating costs of enterprises, thus inhibiting the innovation activities of enterprises, known as the Cost Compliance Effect (Jaffe et al. 1995). The Porter hypothesis, however, suggests that appropriate FER can stimulate technological innovation, which not only fulfil regulatory requirements, but also potentially brings additional economic benefits, known as the innovation offset effect (Porter and Linde 1995). With the increasing high costs associated with pollution emissions by more stringent environmental regulations, agricultural producers should prioritise their own interests by actively adopting green technological innovations, thereby seeking low-carbon and more environmental-friendly production methods. As public awareness of environmental protection rises, IER can also promote the investment and application of green technology innovation by agricultural producers through public opinion, consumer demand and other mechanisms, so as to comply with market trends and social expectations and reduce carbon emissions.

On the other hand, both FER and IER can reduce ACE by promoting the adjustment of agricultural planting structure. The increasing proportion of food crops or application of diversified crop rotation can reduce the use of high-carbon agricultural materials such as fertilisers and pesticides and improve the carbon retention capacity of soil, reducing the overall ACE on a broader level (Holka et al. 2022). Based on specific emission standards and reward and punishment mechanisms, FER will guide farmers and enterprises to optimise the planting structure by increasing the violation cost. While IER, such as the increased public awareness of environmental protection and appeals for green products, will encourage agricultural producers to adopt more environmental-friendly farmland management and farming practices, such as switching to ecological or organic agriculture, in order to meet the market demand for green agricultural products (Schader et al. 2011).

Based on the above analysis, this paper proposes hypothesis H_2 as follows:

H_2: FER and IER can effectively reduce ACE by promoting agricultural technological innovation and facilitating agricultural planting structure adjustments.

Threshold effect of FER and IER on ACE. The main purpose of environmental regulations is to control ACE and promote a green transformation in agricultural production. However, different marketisation level may affect the effectiveness of FER and IER on reducing ACE. In regions with lower marketisation levels, agricultural producers face stricter resource constraints and production limitations and rely more on traditional agricultural production methods due

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to less advanced production technologies (Xie and Huang 2021). As a result, agricultural producers lack sufficient financial and technical support to effectively respond to mandatory emission standards. Therefore, the effect of FER may be limited. For IER, although public awareness of environmental protection and public opinion monitoring can bring some pressure, agricultural producers are difficult to obtain the necessary market information and technical support due to the low marketisation level, so this non-compulsory pressure cannot effectively reduce ACE.

As the marketisation level increases, the liquidity of information and factors in the agricultural market will increase significantly. Agricultural producers will be able to obtain financial and technical support more easily, as a result, they can adopt low-carbon production technologies and improve production patterns more effectively (Wang et al. 2021). In this case, the effectiveness of FER may be significantly enhanced. In addition, in regions with higher marketisation levels, government and the public are usually more concerned about environmental protection. Driven by both market demand and social pressure, agricultural producers are more likely to adopt green technology and low-carbon production mode, thus further enhancing the carbon emission reduction effect of IER.

Based on the above analysis, this paper proposes hypothesis H_3 as follows:

H_3: The impact of FER and IER on ACE exhibits nonlinear characteristics depending on the marketisation level.

MATERIAL AND METHODS

Methodology

Benchmark regression model. To effectively explore the impact of FER and IER on China's ACE, this paper constructs the following panel fixed effect model as the benchmark regression model:

$$ACE_{it} = \alpha_0 + \alpha_1 FER_{it}(IER_{it}) + \sum \alpha_i Controls_{it} + \\ + \lambda_i + \delta_t + \varepsilon_{it} \quad (1)$$

where: i and t – provincial-level regions and years, respectively; ACE_{it} – the agricultural carbon emissions of province i in year t; FER_{it} and IER_{it} – the formal and informal environmental regulations of province i in year t, respectively; $Controls_{it}$ – the relevant control variables of province i in year t; λ_i and δ_t – individual fixed effects and time fixed effects, respectively; ε_{it} – the random error term.

Mediating effect model. To further investigate the mediating role of agricultural planting structure and technological innovation in the impact of FER and IER on ACE, this paper makes reference to Baron and Kenny's (1986) method and constructs mediating effect model based on the benchmark regression model, as follows:

$$ACE_{it} = \alpha_0 + \alpha_1 FER_{it}\left(IER_{it}\right) + \sum \alpha_i Controls_{it} + \\ + \lambda_i + \delta_t + \varepsilon_{it} \quad (2)$$

$$Mediating_{it} = \beta_0 + \beta_1 FER_{it}\left(IER_{it}\right) + \\ + \sum \beta_i Controls_{it} + \lambda_i + \delta_t + \varepsilon_{it} \quad (3)$$

$$ACE_{it} = \theta_0 + \theta_1 FER_{it}\left(IER_{it}\right) + \theta_2 Mediating_{it} + \\ + \sum \theta_i Controls_{it} + \lambda_i + \delta_t + \varepsilon_{it} \quad (4)$$

where: $Mediating_{it}$– the mediator variable, which is substituted using the agricultural planting structure (APS) and agricultural technology innovation (ATI); α_1 – the total effect of FER or IER on ACE; θ_1 – the direct effect of FER or IER on ACE; $\theta_2 \times \beta_1$ – the indirect effect of FER or IER on ACE through mediator variables.

Equation (3) illustrates the relationship between FER or IER and the mediator variables. Equation (4) captures both the causal relationship between the mediator variables and ACE and the independent effect of FER or IER on ACE.

Panel threshold model. To investigate the non-linear effects of FER and IER on ACE at varying marketisation levels, this paper selects the method of Hansen (1999) to construct the following panel threshold model with the marketisation level (ML) as the threshold variable:

$$ACE_{it} = \gamma_0 + \gamma_1 FER_{it}\left(IER_{it}\right) \times I\left(ML \le \delta_1\right) + \\ + \gamma_2 FER_{it}\left(IER_{it}\right) \times I\left(\delta_1 < ML \le \delta_2\right) \\ + \cdots + \gamma_n FER_{it}\left(IER_{it}\right) \times I\left(\delta_{n-1} < ML \le \delta_n\right) + \\ + \gamma_{n+1} FER_{it}\left(IER_{it}\right) \times I\left(ML > \delta_n\right) \quad (5)$$

where: ML – the threshold variable; $\delta_1 \ldots \delta_n$ – the corresponding threshold values; $I(\cdot)$ – the indicator function that takes the value of 1 when the expression within the parentheses is true and 0 otherwise.

This paper examines the threshold effect of FER and IER on ACE by analysing the plus-minus and magnitude of the coefficient $\gamma_1 \ldots \gamma_{n+1}$.

Variable measurement

The explained variable is agricultural carbon emissions (ACE). In this paper, the emission coefficient method proposed by the IPCC is used to measure ACE by selecting 16 carbon source indicators across five dimensions:

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agricultural materials, crop cultivation, animal husbandry, biomass burning, and energy consumption.

Among them, agricultural materials mainly include fertilisers, pesticides and mulches, with data based on actual usage for the year. Crop cultivation mainly refers to the carbon emissions generated during the process of agricultural ploughing and agricultural irrigation. The data are calculated based on the actual sown area of crops for the year. Animal husbandry involves three major livestock such as pigs, cattle and sheep, with data based on the amount of breeding for the year. Biomass burning is primarily considered in terms of straw burning and selects six major straw crops, which are wheat, rice, corn, soybean, cotton and rapeseed, as the carbon sources for calculation. Energy consumption mainly focuses on carbon emissions resulting from diesel and agricultural electricity usage. The specific formula as follows:

$$ACE = \sum ACE_j = \sum T_j E_j \quad (6)$$

where: ACE – total agricultural carbon emissions; ACE_j – the agricultural carbon emissions generated by the j^{th} carbon source; T_j – the quantity of the j^{th} carbon source input; E_j – the carbon emission coefficient of the j^{th} carbon source, as listed in the Table 2.

The explanatory variables include formal environmental regulations (*FER*) and informal environmental regulations (*IER*). Firstly, as official and authoritative documents, the environmental protection content covered in the government work reports reflects not only the government's policy orientation and implementation strength in environmental governance, but also the comprehensiveness and depth of relevant policies and regulations. Therefore, this paper applies the text analysis method to measure the level of FER. Firstly, the word division of the government work reports of each province is processed. Secondly, the frequencies of the keywords related to environmental regulations are counted. Finally, the ratio of keywords frequencies to the total number of word frequencies is calculated, which is used as the proxy variable for FER. The larger the

Table 2. ACE sources and coefficients

Types of ACE source	ACE indicators	ACE Coefficients	Reference
Agricultural materials	fertiliser	0.896 kg/kg	Oak Ridge National Laboratory
	pesticides	4.934 kg/kg	Oak Ridge National Laboratory
	mulches	5.180 kg/kg	Institute of Resource, Ecosystem, and Environment of Agriculture, Nanjing Agricultural University
Crop cultivation	ploughing	312.600 kg/hm^2	College of Biological Sciences, China Agricultural University
	irrigation	25.000 kg/hm^2	College of Biological Sciences, China Agricultural University
Animal husbandry	pigs	34.091 kg/each year	IPCC
	cattle	415.910 kg/each year	IPCC
	sheep	35.182 kg/each year	IPCC
Biomass burning	wheat	0.160 kg/kg	IPCC
	rice	0.180 kg/kg	IPCC
	corn	0.170 kg/kg	IPCC
	soybean	0.150 kg/kg	IPCC
	cotton	0.130 kg/kg	IPCC
	rapeseed	0.220 kg/kg	IPCC
Energy consumption	diesel	0.593 kg/kg	IPCC
	agricultural electricity	CO_2: 0.792 t/MWh	Ministry of Ecology and Environment of China

ACE – agricultural carbon emissions
Source: Authors' own processing

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ratio, the higher the level of FER dominated by government. The keywords include environmental protection, pollution, energy consumption, emission reduction, sewage, ecology, green, low-carbon, air, chemical oxygen demand, sulphur dioxide, carbon dioxide, PM10, and PM2.5.

Secondly, the Baidu Index is a data set derived from a weighted analysis and collation of the search frequency on Baidu, China's largest search engine website, which can reflect the degree of public attention to specific keywords. This paper uses the Baidu Index value of each province based on the keyword 'environmental protection' as the proxy variable for IER. The higher the value, the higher the level of IER with public and media participation in environmental governance.

The mediator variables include agricultural planting structure (*APS*) and agricultural technological innovation (*ATI*). Compared with other crops, grain crops have a lower demand for fertilisers, pesticides, mulches and other high-carbon agricultural materials. In order to reflect the characteristics of the planting structure that 'grain-oriented', this paper chooses the ratio between the sown area of grain crops and the total sown area of crops to measure the APS. In addition, agricultural technology patents can enhance farmers' technical proficiency through education and knowledge spillover, and reduce carbon emissions caused by low production efficiency (Tao 2012). In this paper, the number of agricultural technology patents is selected to measure the *ATI.*

The threshold variable is marketisation level (*ML*). This paper uses the Marketization Index constructed by Fan et al. (2011) to represent the marketisation level. The higher the value of the index, the higher marketisation level of the region.

The control variables are as follows:

Agricultural industry structure (*AIS*) which is expressed by the ratio of agricultural output value to the total output value of agriculture, forestry, animal husbandry and fisheries.

Degree of openness to the outside world (*DOOW*) which is expressed by the total annual import and export value of each province.

Agricultural land productivity (*ALP*) which is expressed by the ratio of the total output value of agriculture, forestry, animal husbandry and fisheries to the total sown area of crops.

Level of expenditure on science and education (*LESE*) is expressed by the proportion of science and technology expenditure and education expenditure in GDP.

Agricultural productivity per capita (*AGDP*) is represented by the ratio of total agricultural output value to the rural population.

Data sources

After data matching and cleaning, this paper selects the panel data of 30 provinces (autonomous regions and municipalities) in China except Tibet, Hong Kong,

Table 3. Variables summary and descriptive

Type	Variable	Unit	Mean	Max	Min
Explained variable	*ACE*	10 000 tonnes	0.215	0.642	0.005
Explanatory variables	*FER*	–	0.397	0.429	0.368
	IER	–	0.229	0.621	0.014
Mediator variables	*APS*	–	0.657	0.971	0.355
	ATI	piece	0.299	1.665	0.004
Threshold variable	*ML*	–	8.150	12.864	3.359
Control variables	*AIS*	–	0.527	0.721	0.362
	DOOW	billion USD	149.760	1 429.500	0.344
	ALP	thousand USD/ha	13.060	50.030	3.420
	LESE	%	4.560	11.710	2.491
	AGDP	USD/capita	1 685.482	6 243.395	432.718

ACE – agricultural carbon emissions; *AGDP* – agricultural productivity per capita; *AIS* – agricultural industry structure; *ALP* – agricultural land productivity; *APS* – agricultural planting structure; *ATI* – agricultural technological innovation; *DOOW* – degree of openness to the outside world; *FER* – formal environmental regulations; *IER* – informal environmental regulations; *LESE* – level of expenditure on science and education; *ML* – marketisation level

Source: Authors' own processing

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Macao and Taiwan from 2011–2022. The original data are derived from the China Statistical Yearbook, China Rural Statistical Yearbook, China Energy Statistical Yearbook, Statistical Yearbook of Provinces, the official website of provincial governments, the Ministry of Ecology and Environment of China and Baidu Index. Some missing values are filled in by interpolation. The variables summary and descriptive statistics of each variable are shown in Table 3.

RESULTS

The overall level of ACE

Based on Equation (6), this study measured *ACE* in 30 provinces of China from 2011 to 2022. The results are shown in Figure 2. In general, *ACE* shows a downward trend in different provinces, but the overall change is small. Additionally, there are significant differences in *ACE* of different provinces. It can be seen that the high values of *ACE* are mainly concentrated in the inland regions of the central and western China, particularly in Sichuan, Inner Mongolia, Yunnan, and Henan. The reason may be that these provinces are traditional agricultural provinces, with a relatively higher proportion of agricultural production.

Benchmark regression results

Based on Equation (1), this study applied Stata/SE 17.0 to empirically analyse the impact of *FER* and *IER* on *ACE*. The benchmark regression results are shown

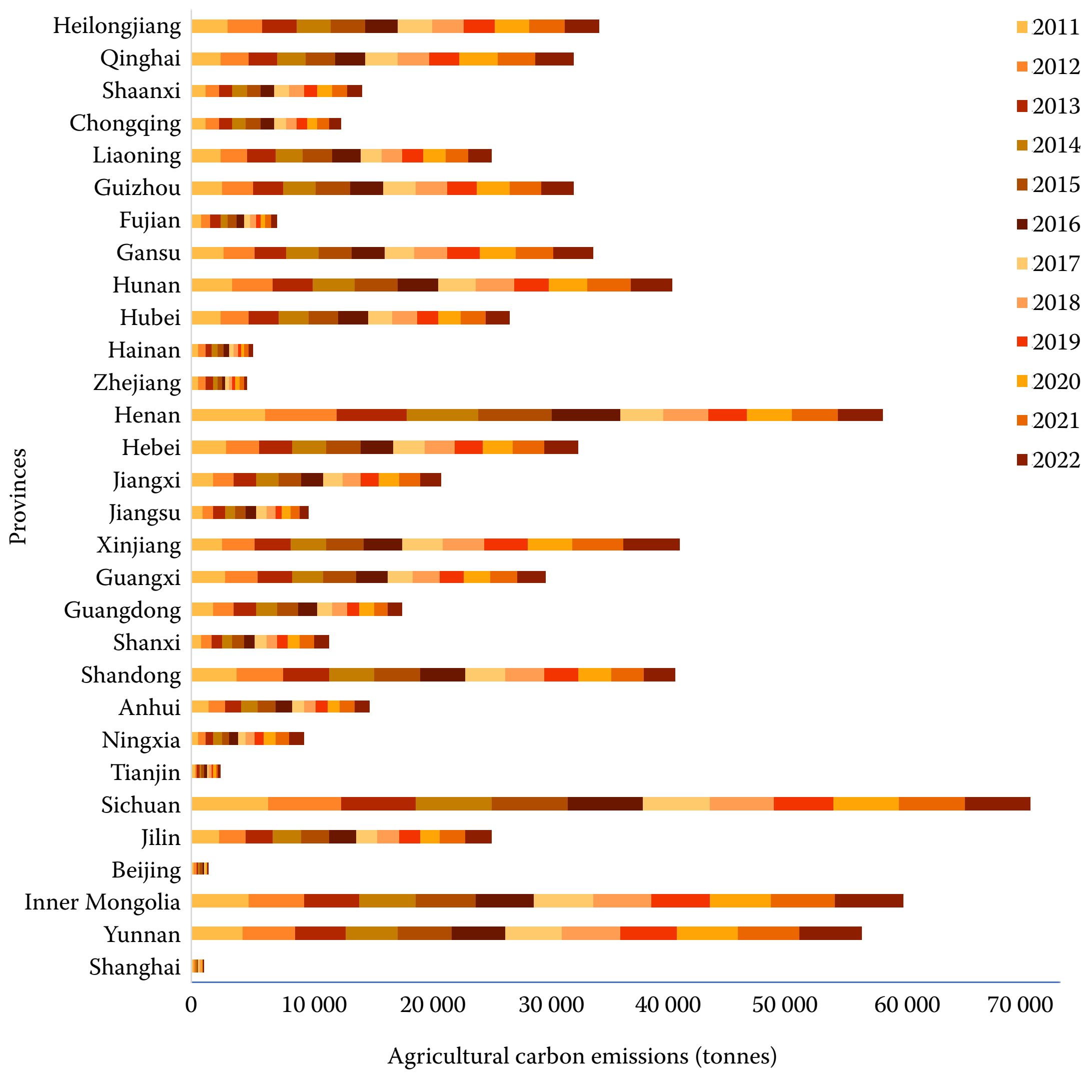

Figure 2. Agricultural carbon emissions in China across provinces

Source: Authors' own processing

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in Table 4. Columns (1 and 2) present the estimated results of *FER* without and with control variables, respectively. Columns (3 and 4) show the results of *IER* under the same conditions. All models include individual fixed effects and time fixed effects. The empirical results show that the regression coefficients of both *FER* and *IER* –0.891 and –0.233 respectively, which are negatively correlated with *ACE* at the 1% significance level. This finding indicates that increasing the level of *FER* and *IER* can significantly reduce *ACE*, with the effect of *FER* being more pronounced. The hypothesis H_1 is verified.

Robustness tests

Endogeneity tests. Benchmark regression may suffer from endogenous problem due to the omission of variables and reverse causal relationships. Therefore, this paper introduced two instrumental variables, one period lagged environmental regulation variable and topographic relief variable, and adopted the IV-GMM method to deal with the endogenous problem.

One period lagged environmental regulation is dynamically linked to the current environmental regulation and does not affect the *ACE* in the current period. This satisfies the relevance and exogeneity conditions required for selecting the instrumental variable. The test results are shown in columns (1 and 2) of Table 5. In terms of the reasonableness of the model selection, the estimated coefficients of both *FER* and *IER* are significantly negative at the level of 1%. In terms of the validity of the instrumental variable, K-P LM statistic, K-P Wald statistic and Hansen J statistic pass the unidentifiable test, the weak instrumental variable test and the over-identification test, respectively. The validity of one period lagged environmental regulation as the instrumental variable is verified.

This paper uses topographic relief as an additional instrumental variable drawing on the research methods

Table 4. Benchmark regression results

Variable	(1)	(2)	(3)	(4)
	ACE	*ACE*	*ACE*	*ACE*
FER	–0.978**	–0.891***	–	–
	(0.417)	(0.320)		
IER	–	–	–0.318***	–0.223***
			(0.090)	(0.079)
AIS	–	–0.451**	–	–0.430**
		(0.178)		(0.173)
DOOW	–	–0.000	–	–0.000
		(0.000)		(0.000)
ALP	–	0.047	–	0.037
		(0.050)		(0.051)
LESE	–	–0.041	–	–0.011
		(0.040)		(0.045)
AGDP	–	0.020	–	0.021
		(0.025)		(0.025)
Constant	0.595***	1.078***	0.263***	0.556*
	(0.159)	(0.328)	(0.013)	(0.326)
Individual fixed effect	yes	yes	yes	yes
Time fixed effect	yes	yes	yes	yes
Observations	360	360	360	360
R-squared	0.172	0.322	0.224	0.324

***, **, and *significance at 1%, 5%, and 10% levels, respectively; *ACE* – agricultural carbon emissions; *AGDP* – agricultural productivity *per capita*; *AIS* – agricultural industry structure; *ALP* – agricultural land productivity; *DOOW* – degree of openness to the outside world; *FER* – formal environmental regulations; *IFR* – informal environmental regulations; *LESE* – level of expenditure on science and education

Source: Authors' own processing

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Table 5. Endogeneity test results

Variable	(1)	(2)	(3)	(4)
	ACE	*ACE*	*ACE*	*ACE*
FER	−4.445***	–	−46.334***	–
	(1.090)		(11.816)	
IER	–	−0.467***	–	−10.053***
		(0.132)		(2.687)
Control variables	yes	yes	yes	yes
Constant	1.233***	−0.773***	17.580***	−5.687***
	(0.451)	(0.110)	(4.576)	(1.441)
Individual fixed effect	yes	yes	yes	yes
Time fixed effect	yes	yes	yes	yes
Observations	330	330	360	360
K-P LM *P*-value	0.000	0.000	0.000	0.000
K-P Wald statistic	220.923	1 066.366	15.973	13.508
Hansen J *P*-value	0.000	0.000	0.000	0.000

***significance at 1% level; *ACE* – agricultural carbon emissions; *FER* – formal environmental regulations; *IER* – informal environmental regulations; K-P LM – Kuiper portmanteau LaGrange multiplier test
Source: Authors' own processing

of Song et al. (2024). In terms of relevance, topographic relief tends to have a significant impact on regional economic development and transport conditions, which may further affect the emission and dispersion of pollutants. Therefore, it may affect the formulation and implementation of environmental regulation measures. In terms of exogeneity, as an objective geographical feature, topographic relief is unlikely to directly affect *ACE*. The results in columns (3 and 4) of Table 5 show that the estimated coefficients of both *FER* and *IER* are significantly negative at the level of 1%, and the relevant statistics on the validity of the instrumental variable pass the test.

In conclusion, the results of the endogeneity test using different instrumental variables show that both *FER* and *IER* maintain a significant inhibitory effect on *ACE*, which is consistent with the benchmark regression results.

Table 6. Robustness test results: Replace the core variable and handling outliers

Variable	(1)	(2)	(3)	(4)
	Replace the core variable		Handling outliers	
FER	−0.108**	–	−0.898***	–
	(0.050)		(0.315)	
IER	–	−0.030**	–	−0.223***
		(0.014)		(0.078)
Control variables	yes	yes	yes	yes
Constant	0.155*	0.090	1.079***	0.548
	(0.082)	(0.059)	(0.328)	(0.326)
Individual fixed effect	yes	yes	yes	yes
Time fixed effect	yes	yes	yes	yes
Observations	360	360	360	360
R-squared	0.395	0.400	0.320	0.322

***, **, and *significance at 1%, 5%, and 10% levels, respectively; *FER* – formal environmental regulations; *IER* – informal environmental regulations
Source: Authors' own processing

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Replace the core variable. This paper replaced the original explained variable of *ACE* with agricultural carbon intensity, which is defined as the ratio of *ACE* to agricultural population. According to the regression results in columns (1 and 2) of Table 6, the impact coefficients of both *FER* and *IER* on agricultural carbon intensity are significantly negative at the 5% level. This finding is in line with the conclusions of the benchmark regression and has passed the robustness test.

Handling outliers. In order to avoid the possible effects of extreme values, this paper applied a 1% reduced-tail treatment to the key variables. The test results are shown in columns (3 and 4) of Table 6. After the reduced-tail treatment, both *FER* and *IER* significantly suppress *ACE* at the 1% level, further verifying the robustness of the previous conclusions.

Mediating effect test

The mediating effects of *FER* and *IER* on *ACE* were tested based on Equations (3 and 4). The results are shown in Table 7 and Table 8. Columns (1 and 2) of Table 7 show that *FER* promote the adjustment of *APS* at the 5% significance level. Furthermore, both *FER* and the adjustment of *APS* inhibit *ACE* at the 5% significance level. This indicates that *APS* plays a partial mediating role between *FER* and *ACE* reduction. The mediating effect is –0.2508 (–0.338 × 0.742), which accounting for 28.15% of the total effect. The estimation results in columns (3 and 4) of Table 7 indicate that *APS* also plays a significant mediating role between *IER* and *ACE* reduction, with the mediating effect is –0.0558 which accounting for 25.01% of the total effect.

The estimation results in Table 8 show that *FER* and *IER* significantly promote *ATI* at the level of 5% and 1%, and correspondingly, *ATI* reduces *ACE* effectively at 5% and 10% levels. In the process of *FER* and *IER* affecting *ACE*, the mediating effects of *ATI* accounts for 15.51% and 26.36% of the total effect respectively, indicating that *ATI* also plays an important mediating role in the impact of both *FER* and *IER* on *ACE* reduction. The hypothesis H_2 is verified.

Heterogeneity test

In order to investigate the heterogeneous effects of FER and IER on ACE between major grain producing areas and non-major grain producing areas, this paper further implemented sub-sample regressions. According to the 'Opinions on Reforming and Improving Several Policy Measures for Comprehensive Agricultural Development' issued by the Ministry of Finance of China, the provinces of Henan, Inner Mongolia, Hunan, Hebei, Sichuan, Jilin, Liaoning, Jiangxi, Shandong, Jiangsu,

Table 7. Mediating effect test results of APS

Variable	(1)	(2)	(3)	(4)
	APS	*ACE*	*APS*	*ACE*
FER	0.742** (0.288)	–0.640** (0.303)	–	–
IER	–	–	0.165* (0.085)	–0.168** (0.075)
APS	–	–0.338** (0.143)	–	–0.338** (0.145)
Control variables	yes	yes	yes	yes
Constant	0.712** (0.283)	1.319*** (0.365)	1.132*** (0.240)	0.940** (0.383)
Individual fixed effect	yes	yes	yes	yes
Time fixed effect	yes	yes	yes	yes
Observations	360	360	360	360
R-squared	0.290	0.371	0.285	0.374
Presence of mediating effect	yes		yes	
Intermediation effect value	–0.251		–0.056	
The proportion of mediating effect	28.150%		25.010%	

***, **, and *significance at 1%, 5%, and 10% levels, respectively; *ACE* – agricultural carbon emissions; *FER* – formal environmental regulations; *IER* – informal environmental regulations; *APS* – agricultural planting structure

Source: Authors' own processing

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Table 8. Mediating effect test results of ATI

Variable	*ATI*	*ACE*	*ATI*	*ACE*
FER	3.004** (1.107)	–0.753** (0.296)	–	–
IER	–	–	1.435*** (0.344)	–0.165* (0.086)
ATI	–	–0.046** (0.019)	–	–0.041* (0.021)
Control variables	yes	yes	yes	yes
Constant	3.652*** (0.879)	0.911*** (0.308)	–1.424** (0.637)	0.499 (0.311)
Individual fixed effect	yes	yes	yes	yes
Time fixed effect	yes	yes	yes	yes
Observations	360	360	360	360
R-squared	0.666	0.346	0.693	0.341
Presence of mediating effect	yes		yes	
Intermediation effect value	–0.138		–0.059	
The proportion of mediating effect	15.510%		26.360%	

***, **, and *significance at 1%, 5%, and 10% levels, respectively; *ACE* – agricultural carbon emissions; *FER* – formal environmental regulations; *IER* – informal environmental regulations; *ATI* – agricultural technological innovation
Source: Authors' own processing

Anhui, Hubei and Heilongjiang are categorised as major grain producing areas. The remaining provinces are categorised as non-major grain producing areas.

The estimation results in columns (1 and 2) of Table 9 show that estimated coefficients of *FER* in major and non-major grain producing areas are –1.019 and –0.155 respectively, and the effect is statistically significant at the 5% level in major grain producing areas, whereas the estimated coefficient for non-major grain producing areas is not significant. It means that *FER* may have a prominent effect in major grain producing areas. Columns (3 and 4) show that the estimated

Table 9. Results of grain producing areas heterogeneity

Variable	(1) major grain producing areas	(2) non-major grain producing areas	(3) major grain producing areas	(4) non-major grain producing areas
FER	–1.019** (0.346)	–0.155 (0.251)	–	–
IER	–	–	0.274 (0.229)	–0.109* (0.055)
Control variables	yes	yes	yes	yes
Constant	1.210* (0.557)	0.456** (0.211)	0.853 (0.687)	0.310* (0.164)
Individual fixed effect	yes	yes	yes	yes
Time fixed effect	yes	yes	yes	yes
Observations	156	204	156	204
R-squared	0.524	0.522	0.523	0.533

** and *significance at 5%, and 10% levels, respectively; *FER* – formal environmental regulations; *IER* – informal environmental regulations
Source: Authors' own processing

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Table 10. Results of regional heterogeneity in coastal and inland regions

Variable	Coastal regions	Inland regions	Coastal regions	Inland regions
FER	–0.668 (0.618)	–1.065** (0.433)	–	–
IER	–	–	–0.066 (0.075)	–0.391*** (0.096)
Control variables	yes	yes	yes	yes
Constant	0.685** (0.284)	1.102* (0.553)	0.415** (0.161)	0.365 (0.462)
Individual fixed effect	yes	yes	yes	yes
Time fixed effect	yes	yes	yes	yes
Observations	132	228	132	228
R-squared	0.645	0.317	0.623	0.340

***, **, and *significance at 1%, 5%, and 10% levels, respectively; *FER* – formal environmental regulations; *IER* – informal environmental regulations
Source: Authors' own processing

coefficient of *IER* in non-major grain producing areas is –0.109 at significant level of 10%. It indicates that *IER* can reduce *ACE* in non-major grain producing areas. But the estimated coefficient of *IER* in major grain producing areas is not significant, which implies that *IER* may not have a distinct effect.

Considering the regional differences in economic development and trade openness, this paper categorises the 30 provinces into coastal regions including Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Zhejiang, Shanghai, Fujian, Guangdong, Guangxi and Hainan, and inland regions for the remaining provinces. The estimation results in Table 10 show that the coefficients of both *FER* and *IER* in inland regions are significant at the level of 5% and 1%, respectively, while the coefficients in coastal regions are not significant. It suggests that impact of both FER and IER in inland regions may be more remarkable than in coastal regions.

Threshold effect test

To further investigate the potential nonlinear impact of environmental regulation on ACE under different marketisation levels, this paper tested the threshold effect of both FER and IER on ACE through Equation (5). The results in Table 11 show that the single threshold effects for both FER and IER passed the significance test, while the double threshold effects were not significant. This indicates that the marketisation level induces a single threshold effect on the relationship between both types of environmental regulations and ACE.

The regression results in column (1) of Table 12 show that *FER* has a significant inhibitory effect on *ACE* on both sides of the marketisation level threshold of 8.368, and when the marketisation level is greater than 8.368, the estimated coefficient changes from –0.469 to –0.584, and the significance level increases from 5% to 1%, indicating that its inhibitory effect is more obvious. Column (2) show that *IER* increase

Table 11. Threshold effect test results

Independent variable	Threshold variable	Threshold number	*F*-value	*P*-value	Threshold value	Critical value		
						10%	5%	1%
FER	*ML*	Single	53.320**	0.023	8.368	31.879	39.204	58.600
		Double	22.820	0.143	4.862	26.119	33.653	54.637
IER	*ML*	Single	89.210***	0.000	8.368	34.164	39.944	53.042
		Double	20.530	0.207	4.862	26.425	30.408	42.170

*** and **significance at 1%, and 5% levels, respectively; *FER* – formal environmental regulations; *IER* – informal environmental regulations; *ML* – marketisation level
Source: Authors' own processing

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Table 12. Threshold effect regression results

Variable	(1)	(2)
	ACE	*ACE*
FER (*ML* ≤ 8.368)	–0.469**	–
FER (*ML* > 8.368)	–	–0.584***
IER (*ML* ≤ 8.368)	0.115**	–
IER (*ML* > 8.368)	–	–0.117***
Control variables	yes	yes
Constant	0.806	0.561
Observations	360	360
R-squared	0.299	0.359

*** and **significance at 1% and 5% levels, respectively; *ACE* – agricultural carbon emissions; *FER* – formal environmental regulations; *IER* – informal environmental regulations; ML – marketisation level
Source: Authors' own processing

ACE at the significance level of 5% when the marketisation level is below 8.368. However, when the marketisation level exceeds 8.368, *IER* significantly reduce *ACE* at the level of 1%. The hypothesis H_3 is verified.

DISCUSSION

This paper first analysed the heterogeneous effects of both FER and IER on ACE. The results indicate that improving the level of FER and IER can significantly reduce ACE. This finding is consistent with previous study of Xia et al. (2024). However, by further comparative analysis, this paper found that compared with IER, FER had a more obvious inhibitory effect on ACE. The possible reason is that FER can exert a strong constraining effect on agricultural production activities and at the same time, it can provide a clear framework for agricultural producers to take action, which improves the efficiency of low-carbon transition. In contrast, the soft constraints imposed by IER through public opinion and social norms are relatively weaker. Consequently, its enforcement and emission reduction effectiveness may be lower than those of FER.

In terms of impact mechanisms, the results show that both FER and IER effectively reduce ACE by promoting agricultural technological innovation and facilitating planting structure adjustment. This conclusion accords with the study of Li et al. (2023). Furthermore, the results show that compared with FER, agricultural technological innovation accounts for a higher proportion of the mediating effect in the impact of IER on ACE reduction. The possible reason is that IER is flexible and closely connected to social members, which induce agricultural producers to be attentive to potential future changes in societal needs and markets. As a result, they are more likely to pursue more extensive technological innovations and enhancements in the production processes for long-term benefits. In contrast, FER exerts direct pressure on the environmental protection behaviour of agricultural producers due to its mandatory and explicit nature. However, this pressure is more inclined to meet the current carbon emission standards rather than being driven by long-term strategic planning (Li et al. 2022a). As a result, agricultural producers tend to be conservative in their innovation efforts in the face of FER. They may focus on adopting some quick and effective methods to reduce current carbon emission instead of promoting broader or deeper technological innovations in low-carbon transformation.

Another major finding is that the impact of FER and IER on ACE has significant regional differences. On one hand, FER has a significant effect on reducing ACE in major grain producing areas, while IER has remarkable effect in non-major grain producing areas. The possible reason is that agricultural production in major grain producing areas is larger and more concentrated, and the government may have better control over it, which facilitate the effective implementation of FER. In contrast, the agricultural structure of non-major grain producing areas may be more diversified and market-oriented, so market factors such as consumer demand and brand reputation may have a greater influence on agricultural producers, making them more inclined to adopt innovative and high value-added agricultural models, which are often better aligned with IER (Zhou and Zhang 2024). This finding demonstrates the differentiated impact of FER and IER on ACE under different agricultural production structures. On the other hand, both FER and IER can significantly reduce ACE in inland regions, but have no obvious impact on coastal regions. The possible reason is that coastal regions have higher levels of industrialisation and urbanisation, and a lower proportion of agricultural production. In addition, coastal regions are highly open to the outside world and exposed to strict environmental standards in the international market earlier. The agricultural producers in coastal regions may have widely adopted green production technologies and efficient management methods, resulting in additional environmental regulation having a small marginal inhibitory effect on ACE. This finding is similar to previous study of Du et al. (2023) who suggested that the ACE reduction effect of environmental regulation is more obvious in cities with larger agricultural output value.

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Moreover, this paper finds that with the enhancement of marketisation level, FER and IER will have a more significant inhibitory effect on ACE. There are several possible explanations for this result. First, under a highly market-oriented environment, agricultural producers can get necessary resources such as technology, capital and talent to reduce carbon emission and improve emission reduction efficiency more easily. Secondly, regions with a higher marketisation level usually have a more advanced legal system and stronger enforcement capacity, which is conducive to the effective implementation of FER. In addition, the improvement of marketisation level is often accompanied by the enhancement of public environmental awareness and strengthening role of IER. This positive relationship between the marketisation level and the effect of FER and IER on ACE reduction highlights the importance of considering the regional marketisation level when formulating relevant policies.

CONCLUSION

This paper conducts theoretical analysis of the impact mechanism of FER and IER on ACE, and makes an empirical test of this mechanism using the panel data of 30 provinces in China from 2011 to 2022. The results show that both *FER* and *IER* can significantly reduce *ACE*, with *FER* having a more pronounced inhibitory effect. *FER* and *IER* can reduce *ACE* effectively through *ATI* and *APS* adjustment. The *FER* can remarkably reduce *ACE* in major grain producing areas, while the impact of *IER* on reducing *ACE* in non-major grain producing areas is more evident. Compared to coastal regions, *FER* and *IER* have a more obvious inhibitory effect in inland regions. Furthermore, as the marketisation level increases, the inhibitory effects of both *FER* and *IER* on *ACE* become more pronounced.

Based on these conclusions, the paper proposes the following policy suggestions: Firstly, FER and IER should be comprehensive applied to enhance the effectiveness of carbon emission governance through diversified strategies. Formulation and enforcement of laws and regulations need to be strengthened, ensuring comprehensive compliance by agricultural producers through strict supervision. Simultaneously, efforts should be made to improve public awareness and encourage public participation in supervision, leveraging social forces to form an effective environmental monitoring mechanism.

Secondly, agricultural technical innovation and the adoption of low-carbon production practices should be motivated. The government should enhance fiscal support and tax reduction for the research and development of low-carbon technologies in agriculture, especially in the areas of precision fertiliser application, smart irrigation and the utilisation of renewable energy. The collaboration between agricultural industries, universities and research institutes should also be encouraged and supported. Meantime, it is necessary to increase the publicity of agricultural green transformation, improve public awareness, and strengthen technical training and guidance for agricultural producers, so as to better promote and apply low-carbon technologies.

Thirdly, differentiated strategies should be formulated according to the agricultural structure and economic development of the regions. For major grain producing areas, the implementation of FER should be strengthened to push the green transformation of large-scale agricultural production. For non-major grain producing areas, IER practices such as promoting green certification, and cultivating green brand, and guiding consumers to choose environmentally friendly products should be promoted and popularised. Besides, the positive role of market mechanism should be taken into consideration. Market-based tools such as carbon trading markets and green finance in the agriculture should be further improved.

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