Heliyon 9 (2023) e21993

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

How environmental decentralization affects the synergy of pollution and carbon reduction: Evidence based on pig breeding in China

Yanjun Jiang [a], Yue Zhang [b,*], Robert Brenya [a], Kai Wang [a]

[a] College of Economics and Management, Nanjing Agricultural University, Nanjing 210095, China
[b] College of Finance, Nanjing Agricultural University, Nanjing 210095, China

ARTICLE INFO

Keywords:
Environmental decentralization
Pollution reduction
Carbon reduction
Synergy
Pig breeding
Breeding scale

ABSTRACT

Reducing pollution and carbon is essential to achieve China's goal of "carbon peaking and carbon neutrality"; however, the collaborative paths of pollution and carbon reduction remain vague and worth exploring. This paper analyses panel data from 30 provinces in China from 2002 to 2017 to determine the impact of environmental decentralization on the synergy of pollution and carbon reduction in pig farming. The result shows that environmental decentralization has a significant 'carbon reduction effect' and 'pollution reduction effect' on pig farming; it is also conducive to promoting the synergistic effect of reducing pollution and carbon emissions through supporting environmental facilities and industrial organisations. Various types of environmental decentralization have significant differences in the synergy of pollution and carbon reduction. The scale of pig breeding plays a positive regulatory role in the impact of environmental decentralization on the synergy of pollution and carbon reduction while showing regional heterogeneity. This research is crucial for advancing the green transformation of pig breeding.

1. Introduction

China's livestock and poultry breeding industry has grown in recent years, and the contradiction between the pollution emissions and the carrying capacity of the ecological environment due to livestock breeding has become increasingly prominent. The *Bulletin of the Second National Pollution Source Survey (2020)* indicates that the chemical oxygen demand, ammonia nitrogen, total nitrogen and total phosphorus discharged by the livestock and poultry breeding industry reached 10.00 million tonnes, 11.09 million tonnes, 596,300 tonnes and 11.97 million tonnes, comprising 93.76 %, 51.30 %, 42.14 % and 56.46 % of the agricultural source emissions, respectively. These amounts represent a substantial pollution source in agricultural and rural areas. At the same time, livestock and poultry breeding is a significant source of greenhouse gas emissions, with biogas and carbon monoxide from livestock and poultry manure accounting for 50 % of agricultural pollution. Pig breeding has always been the core industry of China's livestock and poultry breeding industry, and serious problems exist, such as high energy consumption and waste [1]. According to the *National Pig Production and Development Plan (2016–2020)*, China produces about 600 million tonnes of pig manure, accounting for one-third of the total livestock and poultry manure; however, its comprehensive utilisation rate is less than 50 %, causing severe environmental pollution. Moreover, pig breeding produces high carbon emissions, accounting for about 3 % of the global total carbon emissions yearly.

* Corresponding author.
E-mail address: Moonnzhang@163.com (Y. Zhang).

https://doi.org/10.1016/j.heliyon.2023.e21993
Received 28 June 2023; Received in revised form 25 October 2023; Accepted 1 November 2023
Available online 4 November 2023
2405-8440/

Compared with developed countries, the carbon emissions per pig in Western Europe and North America are 1.55 kg and 2.05 kg higher than the industry average, respectively [2,3]. A green transformation of the livestock and poultry breeding business requires continued encouragement regarding the green and low-carbon development of large-scale pig breeding and recognising the synergy of pollution and carbon reduction.

The *China Ecological Environment Protection Working Conference* in 2021 proposed the concept of 'synergy of pollution and carbon reduction' and noted the importance of achieving an effective synergy between 'carbon neutrality and carbon peak' and 'pollution control'. The synergistic effect of pollution reduction and carbon reduction refers to the fact that pollution reduction policies can improve carbon reduction efficiency, while carbon reduction policies can promote pollution reduction efficiency, and the two can effectively achieve synergy. Thus, the dual environmental benefits of pollution and carbon reduction can be achieved. Furthermore, the policy implementation direction of pollution reduction and carbon reduction can be reasonably balanced, improving policy efficiency and generating multiple social and economic benefits, such as reducing governance costs and improving public health [4].

Different feed formulations and antibiotics used in pig breeding directly led to significant differences in pork quality, faecal pollutants and carbon emissions. From the perspective of source prevention, process control and end treatment, pollutants and greenhouse gas emissions may originate from the same specific production link, with a common source and space transfer effect [4]. Pollution prevention and control are inseparable from carbon reduction. Pollutants from pig breeding and carbon dioxide emissions have the same root, process, frequency, effect and path in governance. Both are related to the overall construction and green development of ecological civilisation.

The Ministry of Agriculture and Rural Affairs and the Ministry of Ecological Environment jointly issued the technical guidelines for the '*Construction of Livestock and Poultry Farm (Household) Manure Treatment Facilities*' and the '*Implementation Plan for the Synergistic and Efficient Reduction of Pollution and Carbon Reduction*', aiming to effectively solve the problem of livestock and poultry non-point source pollution in 2022. The same year, the Ministry of Agriculture and Rural Affairs and the National Development and Reform Commission issued the '*Implementation Plan for Reducing Emissions and Fixing Carbon in Agriculture and Rural Areas*' together. This plan focused on livestock and poultry scale farms to promote low-carbon emission reduction for livestock and poultry and help the smooth completion of carbon emission targets during the '14th Five-Year Plan' period. Moreover, under the macro control of the central government, agricultural non-point source pollution and carbon reduction have achieved some specific results; however, large differences remain in the effectiveness of pollution and carbon reduction between regions. The collaborative pollution and carbon reduction path is still vague and worth exploring; therefore, scientifically allocating the environmental management authority between the central and local governments is important for gradually realising the synergy of pollution and carbon reduction. In the context of environmental federalism, enhancing local governments' environmental management rights can facilitate the implementation of local policies, fully utilise the advantages of local information to identify sources of pollution and enhance the efficiency of environmental governance for pig breeding [5]. China has steadily given local governments more authority over administrative matters related to environmental protection since the 1990s to foster enthusiasm for local environmental protection governance [6]. At this time, local governments gained more power in environmental governance as the environmental decentralization system developed [7]. Environmental decentralization primarily refers to the gradual transfer of certain environmental governance powers from the central government to local authorities in environmental management. This process allows local governments to decide on the specific policy approaches to implement based on their jurisdiction's unique conditions. Furthermore, local governments are empowered to autonomously formulate standards for environmental incentives and penalties [8,9]. The local government can plan social services, such as a pig manure disposal scheme and strict review and distribution of antibiotics and disinfectants according to whether the region is a large hog transfer county. Different regions must choose a precise approach and scheme based on the density and scale of pig breeding to realise the synergy of pig breeding pollution and carbon reduction from the source. The impact mechanism and the degree of different environmental decentralization regarding the synergistic effect of pollution reduction and carbon reduction in pig farming are worth studying.

Compared with the existing literature, this study's marginal contributions include the following points. (1) Based on the bilateral perspectives of 'pollution reduction' and 'carbon reduction', this study investigates the impact mechanism and specific action path of environmental decentralization on the synergistic effect of pollution reduction and carbon reduction in pig farming. Specifically, we analyse the differential effects and effects of different types of environmental decentralization. (2) We explore the regulatory effect of the pig farming scale on the synergistic effect of environmental decentralization on pollution reduction and carbon reduction in pig farming, further identifying the impact of environmental decentralization on the pig farming scale. (3) This study uses the cross-elasticity index of pollution reduction and carbon reduction to measure the degree of synergistic effect of pollution reduction and carbon reduction. We apply the numerator denominator splitting assignment method to solve the ambiguity caused by the ratio results. Furthermore, we use simple joint regression methods in previous studies to avoid the difficulty in distinguishing and measuring the synergistic effect of pollution and carbon reduction.

2. Literature review

Pollution and carbon reduction mainly depend on the government's macro-control measures [10–13], such as legal, administrative and economic. Environmental regulation means the government imposes additional strict restrictions on polluters [14] to establish an external constraint mechanism for pollution discharge. Additionally, environmental regulation directs firms to create and use green technologies, breaking the dependence on technological advancement [15]. This approach improves green productivity and controls pollutant emissions through innovative compensation effects [16]. In industrial production, environmental supervision accelerates energy structure optimisation [17] and efficiency improvement of capacity utilisation [18]. It also plays a positive role in curbing the emission of pollutants, promoting upgrading industrial structure [19] and reducing pollution emissions through improved industrial design [20]. Environmental protection oversight and inspection push firms to limit pollution production and emissions, significantly enhance regional air quality and ensure pollution monitoring and control [21]. A government subsidy plan is a practical and feasible solution to reduce pollution emissions [22], which can help resolve the conflict between agricultural expansion and environmental conservation and increase local businesses' earnings. Furthermore, pollution prevention is being adjusted from end treatment to source prevention. For example, firms may be forced to increase investment in environmental protection equipment by environmental restrictions, including environmental fees and emission standards [23,24]. Moreover, for the pathway of carbon emission reduction, most scholars believe that carbon emission trading is a cost-effective policy tool [25,26], which effectively prevents 'hitchhiking' pollution and contributes to carbon emission reduction practices [27–29]. Energy efficiency improvement is essential in lowering China's carbon emissions, which could offer innovative resources and knowledge innovation [30]. Carbon tax policy [31] and government green investment [32] are also feasible plans to reduce greenhouse gas emissions. Moreover, the low-carbon urban construction policy provides a useful way to resolve the tension between urban development, resource conservation and environmental protection [33].

Environmental decentralization originates from the theory of environmental federalism, which transfers environmental governance from the central to local governments. The local governments develop and carry out environmental policies and regulations within the central government's overarching environmental protection strategy [34]. The academic community has long debated whether environmental governance is more effective through decentralised management or centralised power. Scholars have furthered their research on environmental decentralization and its governance effect. For example, based on the macro perspective, environmental decentralization in pollution control [35,36], green transformation [7,37] and other aspects of governance have achieved remarkable results. Comparatively, local governments can better create policies that align with local reality and accomplish the most efficient distribution of resources for environmental public goods [38]. Furthermore, compared with environmental centralisation, decentralization of environmental management enables local governments to deliver superior environmental services [39,40]. The local government can advance firms' and industries' innovation and environmental protection capacity by better understanding the local environmental situation [41]. Decentralising environmental power can reduce the cost of information transmission between the central and local governments and significantly enhance local pollution control regarding environmental law enforcement [42]. The information advantages of local governments encourage the efficient use of human capital and local resources [43] to improve the working efficiency of the grassroots environmental protection system and establish an efficient environmental monitoring system. Environmental decentralization also increases local financial freedom and fosters technical innovation and interchange through prudent fiscal spending, preferential tax policies and financial subsidies [44]. Some scholars also hold the differentiation perspective; for example, Ran et al. (2020) [45] found that China's current environmental decentralization system may not be conducive to carbon emissions control.

The synergistic emission reduction effect between greenhouse gases and air pollutants has been confirmed in the literature [46,47]. Prior research mainly focused on objectively evaluating the synergistic emission reduction effect of environmental rules in the industrial sphere, while some research explored the shared purpose of lowering pollutants and greenhouse gas emissions [48,49]. For example, Bollen and Brink (2014) [48] analysed the relationship between EU air pollution and climate change policy, finding that climate policy could significantly reduce greenhouse gas emissions by improving energy efficiency, fuel conversion and economic structure transformation. Furthermore, Braspenning Radu et al. (2016) [49] used ten scenarios in the IMAGE framework to explore the impact of future climate and air pollution policies on the emissions of greenhouse gases and air pollutants. They determined that climate change policies substantially impact the emissions of sulfur dioxide and nitrogen monoxide. Additionally, Du and Li (2020) [50] found that China's environmental regulations contribute to pollution reduction and prevent greenhouse gas emissions from businesses due to the synergistic emission reduction impact, while Gao et al. (2022) [51] believed the environmental protection tax law provides convincing evidence for the joint control of greenhouse gases and pollution emissions. Air pollution control policies and low-carbon energy systems can drive a city to transform into carbon neutral and reduce air pollution with synergy [52]. The carbon emission trading policy is conducive to achieving the synergy of air pollution control and climate change mitigation [53] through indirectly altering air quality and carbon emissions by relocating cities' industrial hubs [54].

Existing research has explored the role and effect of differentiated means of pollution control and carbon emission reduction, mainly in the industrial field; however, the following deficiencies remain. (1) Previous literature only focused on the impact of single environmental indicators of environmental decentralization and carbon reduction or pollution reduction from a unilateral perspective [35,36,55]. Few studies have involved the impact mechanism and specific implementation path of environmental decentralization on the synergy of pollution and carbon reduction. (2) Many studies have theoretically analysed the connotation and mechanism of coordinated pollution treatment and carbon reduction [47,50,56,57], from the synergy of pollution reduction measures to carbon reduction [58,59] and carbon reduction measures [60,61]. No method has been established for measuring the synergy between pollution reduction and carbon dioxide emissions, nor can the synergy or anti-synergy between these two factors be determined. (3) The research perspective on environmental decentralization mainly focuses on industrial polluting enterprises and macro-regional perspective and rarely examines micro-investigation of the pig industry. Therefore, investigating how environmental decentralization affects the synergy of pollution and carbon reduction in the pig sector can help extend the theoretical application range. Such investigation can serve as a decision-making guide for the pig breeding industry and reasonably coordinate the rights of central and local governments.

3. Theoretical analysis and research hypothesis

According to the traditional environmental federalism theory [38], the distribution of environmental pollution control and governance authority between the central and local governments is essential for environmental decentralization. Pig breeding is a high pollution and carbon emission industry in China; thus, the vast geographical area leads to more scattered pig breeding, and the government's regulation of pollutant emissions from pig breeding is quite challenging. According to the theory of externalities, the pollutants emitted by pig farmers upstream along a river can directly affect the living environment of downstream farmers, leading to cross-border pollution. Due to the difficulty in determining pollution rights and responsibilities and significant differences in pollution levels due to the length of the river and differences in pollution levels with different scales, environmental policies must be tailored to local conditions [62,63]. Furthermore, due to the vast territory of China, significant differences in terrain and planting structures among farmers result in varying transaction costs caused by the consumption of pig manure. These discrepancies affect the promotion of the synergistic effect of pollution reduction and carbon reduction [64]. Regarding information asymmetry, pig farmers' pursuit of profit maximisation leads to unreasonable pig breeding planning, and the environmental pollution and carbon emissions of pig breeding continue to increase [65,66]. Local governments can use the advantages of the big data platform and information to cope with the pollution caused by pig rearing more flexibly as their autonomy in environmental management continues to grow. Environmental decentralization can reduce carbon emissions and help reduce pollution [67]. The carbon emissions from pig breeding mainly come from the respiratory tract of pigs, feed processing of pig farms, fermentation of pig manure, treatment of sick and dead pigs and energy consumption caused by the transportation of epidemic prevention materials. On the one hand, decentralising the central environmental management authority can help local governments identify high-polluting areas and substandard pig farmers with more accuracy, dismantle the substandard pig farmers and save energy on feed and medication delivery [68].

Similarly, the construction of public septic tanks and harmless treatment facilities for sick and dead pigs should be strengthened with the help of information advantage to reduce each pig's unit carbon emissions. On the other hand, environmental decentralization is conducive to the rational approval of the local government for the transfer of land for pig breeding, the scientific location of pig farms and the encouragement of dry and wet separation of pig manure. It also intensifies the breeding and breeding cycle, promoting the balance between the supply and demand of pig manure in the region and reducing the direct discharge of manure. With the expansion of local governments' autonomy, the space for cooperation between local financial and environmental protection departments to jointly control pollution has expanded, and the environmental protection subsidy policy has been further improved [69]. For example, subsidies have been increased for large machinery and biogas digesters related to pig breeding, and the efficiency of pig manure treatment has been further improved. Additionally, pig farming has a certain degree of pollution concealment. Under decentralization, the local administration informs the public and urges locals to exercise effective supervision to stop the indiscriminate pollution released by pig breeders, especially checking farmers' rainwater and sewage diversion facilities to prevent pig manure from washing away and causing groundwater pollution. Thus, we propose the following hypotheses.

Hypothesis 1. Environmental decentralization helps reduce carbon emissions from pig farming.

Hypothesis 2. Environmental decentralization helps reduce the intensity of pollutant emissions from pig farming.

Environmental decentralization promotes pollution reduction, is conducive to carbon reduction and promotes the synergy of pollution and carbon reduction in many ways (Fig. 1). First, the local government uses the information advantage to delimit prohibited areas for pig breeding and urges farmers in different breeding areas to strengthen the construction supporting environmental protection facilities. By constructing an anaerobic tank, the anaerobic fermentation of pig manure could be strengthened, and the carbon emissions of manure could be reduced. The anaerobic fermented manure could enter the biogas tank to produce biogas, directly reducing the emission of manure while reducing pollution and carbon emission [70]. Second, expanding local government autonomy can help control the excess nitrogen, phosphorus and other minerals in pig feed. Implementing the national environmental protection project oversight pilot in all regions will encourage the 'race to the top'. The Environmental Protection Supervision Department will increase the review of pig feed formula to prevent the excessive addition of nitrogen, phosphorus and other elements in the feed,

Fig. 1. Analysis of mechanism.

thereby reducing the excess nitrogen and phosphorus content in pig manure and avoiding water eutrophication and severe pollution of soil. Simultaneously, increasing the supervision of pig feed can help prevent the excessive addition of other additives, thus reducing the carbon emissions of pig intestines and stomachs. Furthermore, preventing pigs from growing too quickly is also beneficial to reducing the number of animals sold; to a certain extent, it also reduces the total carbon emissions, thus achieving the goal of reducing pollution and reducing carbon synergy. Third, environmental decentralization helps optimise the whole industrial chain of pigs. Decentralization is conducive to the local government formulating preferential policies for introducing leading pig enterprises and continuously promoting the development of pig industrialisation organisations. The 'company and farmer' and 'company and cooperative and farmer' organisational models enable farmers to obtain more financial and technical support, enabling pig farmers to purchase pig manure treatment equipment and effectively reduce the emission of pig-related pollutants. Concurrently, the 'vertical integration of the company' pig breeding mode has realised the development of the whole pig industry chain in pig production, processing and marketing, reducing the energy consumption of pig feed transportation and slaughtering transportation, thereby successfully promoting the pollution and carbon reduction synergies in pig breeding [71]. The scale of pig breeding under decentralization will affect the implementation effect of the pollution reduction policy. When pig breeding is widespread, the scales are easier to attract attention from the government and locals, which tightens environmental protection oversight. It also improves the pig farmers' understanding of environmental protection and employs regular feed and anaerobic fermentation of faecal waste. Additionally, the breeding scale will influence how well the carbon reduction policy is implemented—the larger the scale, the easier it is for pig farmers to obtain financial subsidies for extensive environmental protection facilities. The financial subsidies for organic fertiliser production and biogas digester construction help the resource utilisation of pig manure, thus improving pollution reduction.

According to the cost-benefit theory, pig farmers chiefly pursue profit maximisation, and reducing related transaction costs is the key to promoting pollution reduction and carbon reduction synergy among pig farmers. With the expansion of local environmental decentralization, local governments can alter the cost of pollution reduction and carbon reduction for pig farmers by reducing uncertainties, such as an epidemic's impact and via socialised services for livestock and poultry [72]. On the one hand, local governments strengthen the asset specificity adjustment of pig farming through information advantages. They encourage pig farmers to expand their farming scale by building standardised pig farms and large biogas digesters and vigorously promote the main ways and methods of carbon reduction, using scale effects to achieve the carbon reduction goal. On the other hand, local governments can adjust the targets and projects of socialised services for livestock and poultry at any time and provide targeted assistance to pig farmers to contact farmers to effectively return manure to the field and achieve a dynamic balance of the regional 'farming cycle'. Furthermore, local governments have introduced leading pig enterprises and strengthened the cultivation of pig farmers' reputation demands, utilising social networks and social norms to dynamically constrain pig farmers' behaviour of arbitrary pollutant emissions in real time [73,74].

Therefore, we propose the following hypotheses.

Hypothesis 3. Environmental decentralization positively impacts the synergy of pollution and carbon reduction in pig breeding.

Hypothesis 4. Scale plays a positive regulatory role in the impact of environmental decentralization on the synergy of pollution and carbon reduction in pig farming.

According to the respective roles, the three types of environmental decentralization include environmental administrative decentralization, environmental monitoring decentralization and environmental supervision decentralization. Decentralising environmental administration primarily entails developing and applying environmental policies and mobilising environmental management staff. With the expansion of administrative decentralization, local governments can more flexibly punish unqualified pig farmers and dismantle pig pens with the help of information advantage. Furthermore, environmental administration decentralization reduces the emission of pollutants from the source and timely prevents the random disposal and burning of diseased and dead pigs to accomplish the reduction of carbon emissions target. Expanding local administrative decentralization can also stimulate the implementation of market-incentive environmental protection policies. The establishment of a carbon trading market and the organic combination of biogas fermentation and return to farmland reduce carbon emissions and effectively achieve the fertilisation of pig manure, which is conducive to promoting the green cycle of pig farming and realising the development path of turning waste into treasure [75]. Environmental monitoring decentralization mainly includes monitoring environmental pollution control and improving relevant environmental protection policies, reducing the central government's monitoring cost. However, the relatively high proportion of small-scale pig breeding and retail households in China leads to the problematic widespread and high cost of monitoring pig breeding pollution and the low transparency of pollution emissions. The central government's environmental protection goals and local governments' objectives for economic development are frequently at odds with one another, and little synergy exists between efforts to reduce pollution and carbon emissions. Environmental supervision decentralization mainly includes the assessment and measurement of the environmental pollution degree of each region. Local governments can easily find the pollution source and conduct effective treatment, which helps reduce pollution and carbon; however, as the central government increases the proportion of environmental performance in the assessment of lower-level governments, local governments may hide and tamper with the pollution data, thus increasing the actual pollution and carbon emissions of pig breeding. This situation weakens the positive effect of environmental supervision decentralization on the synergy of pollution and carbon reduction to a certain extent [43,51,76]; thus, the following hypothesis is proposed.

Hypothesis 5. Environmental administrative decentralization significantly impacts the synergy of pollution and carbon reduction in pig breeding. Environmental monitoring decentralization is not conducive to the synergy of pollution and carbon reduction, and the beneficial influence of environmental supervision decentralization on the synergy of pollution and carbon reduction decreases.

4. Research design

4.1. Statistical methods

This study uses a fixed-effect model to examine the impact of environmental decentralization on the synergy of pollution and carbon reduction in pig breeding. The models are as following equations (1)–(3).

$$EYH_{it} = \beta_0 + \beta_1 ED_{it} + \beta_2 DIR_{it} + \beta_3 STP_{it} + \beta_4 YF_{it} + \beta_5 ZLF_{it} + \beta_6 YWD_{it} + \beta_7 JBD_{it} + \beta_8 NAL_{it} + \beta_9 GCL_{it} + \beta_{10} CZL_{it} + Region_i + Year_t + \varepsilon_{it} \quad (1)$$

$$WRZ_{it} = \beta_0 + \beta_1 ED_{it} + \beta_2 DIR_{it} + \beta_3 STP_{it} + \beta_4 YF_{it} + \beta_5 ZLF_{it} + \beta_6 YWD_{it} + \beta_7 JBD_{it} + \beta_8 NAL_{it} + \beta_9 GCL_{it} + \beta_{10} CZL_{it} + Region_i + Year_t + \varepsilon_{it} \quad (2)$$

$$Ec_{it} = \beta_0 + \beta_1 ED_{it} + \beta_2 DIR_{it} + \beta_3 STP_{it} + \beta_4 YF_{it} + \beta_5 ZLF_{it} + \beta_6 YWD_{it} + \beta_7 JBD_{it} + \beta_8 NAL_{it} + \beta_9 GCL_{it} + \beta_{10} CZL_{it} + Region_i + Year_t + \varepsilon_{it} \quad (3)$$

where *i* refers to the region, and *t* refers to time. In equation (1), EYH_{it} refers to the carbon emission intensity of pig breeding. In equation (2), WRZ_{it} refers to the total amount of pollutants in pig breeding. In equation (3), Ec_{it} refers to the synergy of pollution and carbon reduction. ED_{it} refers to the degree of environmental decentralization in *i* region and *t* year. *Controls* refer to a group of control variables, including DIR_{it}, STP_{it}, YF_{it}, ZLF_{it}, YWD_{it}, JBD_{it}, NAL_{it}, GCL_{it} and CZL_{it} (Table 1). $Region_i$ and $Year_t$ refer to the fixed effect of region and year, respectively, controlling the influence of unobservable factors on pollution reduction, carbon reduction and synergy of pollution and carbon reduction in individual and time. ε_{it} represents the disturbance term. We explore whether different types of environmental decentralization will bring differentiated impacts on pig breeding environmental governance by including environmental administrative decentralization, environmental monitoring decentralization and environmental supervision decentralization [45,77].

The scale of pig breeding (*Scale*) should be included to explore the moderator role of breeding scale; hence, we build the following equations (4)–(6).

$$EYH_{it} = \beta_0 + ED_{it} + Scale_{it} + \beta_1 ED_{it} \times Scale_{it} + \beta_2 DIR_{it} + \beta_3 STP_{it} + \beta_4 YF_{it} + \beta_5 ZLF_{it} + \beta_6 YWD_{it} + \beta_7 JBD_{it} + \beta_8 NAL_{it} + \beta_9 GCL_{it} + \beta_{10} CZL_{it} + Region_i + Year_t + \varepsilon_{it} \quad (4)$$

$$WRZ_{it} = \beta_0 + ED_{it} + Scale_{it} + \beta_1 ED_{it} \times Scale_{it} + \beta_2 DIR_{it} + \beta_3 STP_{it} + \beta_4 YF_{it} + \beta_5 ZLF_{it} + \beta_6 YWD_{it} + \beta_7 JBD_{it} + \beta_8 NAL_{it} + \beta_9 GCL_{it} + \beta_{10} CZL_{it} + Region_i + Year_t + \varepsilon_{it} \quad (5)$$

$$Ec_{it} = \beta_0 + ED_{it} + Scale_{it} + \beta_1 ED_{it} \times Scale_{it} + \beta_2 DIR_{it} + \beta_3 STP_{it} + \beta_4 YF_{it} + \beta_5 ZLF_{it} + \beta_6 YWD_{it} + \beta_7 JBD_{it} + \beta_8 NAL_{it} + \beta_9 GCL_{it} + \beta_{10} CZL_{it} + Region_i + Year_t + \varepsilon_{it} \quad (6)$$

Table 1
Meaning and descriptive statistics of variables.

Variable	Code	Definition	Mean	Std.Dev.
Pollutant emissions	WRZ	chemical oxygen demand, suspended solids and ammonia nitrogen (10000 tons)	2.0921	1.7199
Carbon emissions	lnEYH	All carbon emissions (CO_2, N_2O and CH_4) (10000 tons)	1.2306	1.0117
Synergistic effect of pollution reduction and carbon reduction	Ec	Synergistic index of carbon dioxide and total pollutants	−0.5000	1.9385
Environmental decentralization	ED	Environmental decentralization index	0.9771	0.3589
Administration decentralization	EAD	Administration decentralization index	1.3549	1.3094
Monitoring decentralization	EMD	Monitoring decentralization index	1.4256	1.4467
Supervision decentralization	ESD	Supervision decentralization index	1.4064	1.4844
Income level of rural residents	lnDIR	Disposable income of rural residents (yuan)	8.6640	0.6562
Technological progress level	STP	Ratio of patent licensing volume to GDP (%)	1.0702	0.9597
Epidemic risk	lnYF	Total number of pigs killed and culled due to 8 common epidemics (head)	4.2650	2.9991
Abundance of hog feed supply	ZLF	Ratio of corn output to total grain output (%)	31.9073	25.0240
Degree of education	YWD	Farmers with high school education/all farmers (%)	10.5730	3.5182
Transportation convenience	JBD	Total mileage of highways, railways and inland waterways/Land area (%)	0.8299	0.5980
Agricultural labor supply	lnNAL	Number of agricultural labor force (10,000)	6.4619	1.0841
Land bearing capacity	GCL	Area of cultivated land/national cultivated land area (%)	3.0365	2.2004
Urbanization level	CZL	Proportion of urban population in total population (%)	47.0144	15.9038
Supporting degree of environmental protection facilities	HBS	Proportion of gas production from regional biogas digesters to the total gas production from national biogas digesters (%)	3.2991	3.9473
Green Feed Usage Level	LSL	Gross output value of branded feed industry (100 million yuan)	177.4234	216.3299
The degree of pig industrialisation organization	ZZC	Number of pig cooperatives	2075.7480	2607.8350
Pig breeding scale	Scale	The ratio of the number of pig farms with more than 50 pigs to the total number of pig farms (%)	6.5802	6.1666

4.2. Indicator selection

4.2.1. Dependent variable

① Carbon emission intensity of pig breeding comes from the carbon dioxide emission of pig breeding (*lnEYH*). Direct carbon emissions from pig breeding include the CH_4 of pig intestinal emissions and the CH_4 of the faecal management system. The emissions of N_2O and indirect carbon emissions from pig breeding include carbon emissions from the consumption of electricity and feed in the breeding process [78–80]. As a result, the combination of direct and indirect carbon emissions from pig farming constitutes the overall amount of carbon emissions.

② Total amount of pollutants from pig breeding (*WRZ*). Following the Emission Standard of Pollutants from livestock and poultry breeding industry (GB 18596-2001) combined with scientific data availability, we measure *WRZ* by the sum of chemical oxygen demand, suspended solids and ammonia nitrogen in the pig breeding industry.

③ Pig breeding reduces pollution and carbon and synergises efficiency (E_C). Referring to the extant literature [81], we use the cross-elasticity index to measure pollution and carbon reduction synergy. The specific formula is as follows:

$$Ec = \frac{EAC_{\mathrm{ghg}}/AC_{\mathrm{ghg}}}{EPoll_{lap}/Poll_{lap}} \tag{7}$$

In Formula (7), *E*c indicates the coordination control cross elasticity between *Poll* and *AC*. AC_{ghg} refers to the previous year's total carbon emissions and $Poll_{lap}$ refers to the previous year's pollutant emissions. EAC_{ghg} refers to the current year's carbon emissions minus the previous year's emissions. $EPoll_{lap}$ refers to the current year's pollutant emissions minus the previous year's emissions.

*E*c is a ratio; thus, using it to measure pollution and carbon reduction synergy provides ambiguous results. For example, if *E*c is positive, it is difficult to determine whether *Poll* and *AC* decrease or increase simultaneously. It can only be precisely determined by further investigating its numerator and denominator's positive and negative values [81]. Therefore, the degree of synergy is divided into three levels: 'anti-synergy', 'weak synergy' and 'strong synergy'. The values are −1, 0 and 1 respectively. If the numerator and denominator of *E*c are both positive, it means that *AC* and *Poll* increase simultaneously. The value of the *E*c is set to −1, indicating 'anti-synergy'. If the sign of the *E*c numerator and denominator is opposite, the *E*c value is set to 0, indicating 'weak synergy'. Moreover, the numerator and denominator of *E*c are both negative and the value of the *E*c is set to 1, indicating a synergistic effect of pollution and carbon reduction, that is, 'strong synergy'.

The Chinese government implemented the 'Regulations on Prevention and Control of Pollution from Scale Breeding of Livestock and Poultry' in 2014. The strength of environmental regulation (ER) varied considerably between before and after 2014; therefore, it is necessary to analyse the current situation and geographical distribution of the *E*c in China. The data of the first year of 'the 11th Five-Year Plan' period (2006–2010) and the last year of 'the 13th Five-Year Plan' period (2016–2020) are compared to calculate *E*c, as shown in Figs. 2 and 3. Fig. 2 indicates that *E*c is basically 'anti-synergy' in hog breeding in most regions of China during the '11th Five-Year Plan' period, indicating carbon emissions and pollutant emissions increase simultaneously. Furthermore, Fig. 3 shows that the *E*c has made great progress in hog production during the '13th Five-Year Plan' period. In most regions, *E*c is basically a 'strong synergy'; carbon and pollutant emissions are reduced simultaneously. A comprehensive analysis of the two figures shows that strengthening ER is conducive to the green transformation of hog production. Additionally, no apparent change occurs in the *E*c in northwest and southwest China, potentially due to the backward level of economic development; thus, the local government cannot provide the necessary infrastructure and technology for their green transformation.

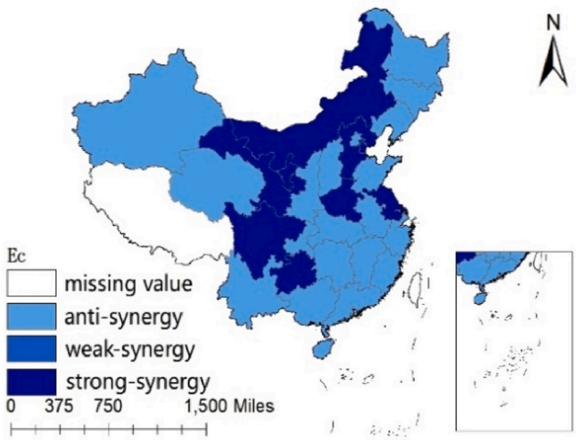

Fig. 2. Synergy of POC and CBR in pig breeding during the "11th Five-Year Plan" period.

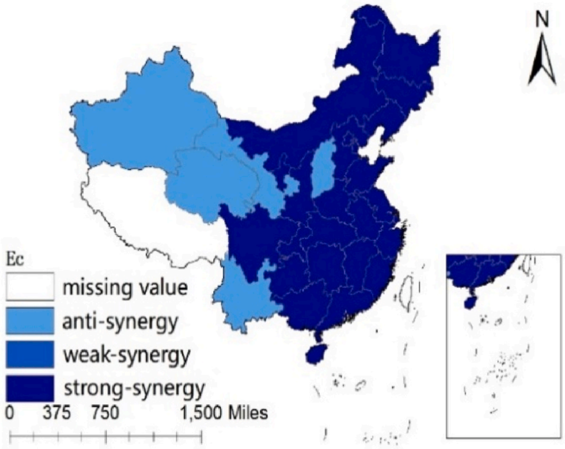

Fig. 3. Synergy of POC and CBR in pig breeding during the "13th Five-Year Plan" period.

4.2.2. independent variable

Management decentralization is one aspect of environmental decentralization; hence, it aligns with its essence to measure environmental decentralization by personnel allocation. Referring to the methods of Wu et al. (2020) [77] and Ran et al. (2020) [45], the degree of environmental decentralization among governments at all levels is measured by the distribution and dynamic change characteristics of the number of personnel of environmental agencies in various regions (equation (8)). There are three specific reasons for this. First, implementing *ER* policies and pollution control relies on personnel from environmental protection agencies at all levels of government. A particular scale and number of personnel of environmental protection agencies are prerequisites for the government to exercise environmental power and effectively respond to the division of regional environmental protection enforcement efforts and environmental rights. Second, a region's environmental affairs determine the organisation of its personnel structure; thus, the environmental protection department's personnel arrangement and overall scale are relatively stable. The position changes of relevant environmental protection personnel only occur between internal departments of the organisation; therefore, changes in the personnel size of environmental protection agencies effectively reflect the division of government environmental powers. Furthermore, the changes in the number and scale of personnel in environmental protection institutions directly reflect the changes in financial investment by governments at all levels in environmental affairs, thereby reflecting the division of environmental protection powers between central and local governments.

Environmental decentralization:

$$ED_{it} = \frac{ESP_{it}/PA_{it}}{HSP_t/PA_t}\left(1 - \frac{GDP_{it}}{GDP_t}\right) \tag{8}$$

To explore the impact of different types of environmental decentralization on the pollutants, carbon emissions, synergy of pollution and carbon reduction in pig breeding, we further divide environmental decentralization (*ED*) into environmental administrative decentralization (*EAD*), environmental monitoring decentralization (*EMD*) and environmental supervision decentralization (*ESD)*. Equations (9)–(11) represent the measurements of *EAD*, *EMD* and *ESD*.

EAD:

$$EAD_{it} = \frac{ESA_{it}/PA_{it}}{HSA_t/PA_t}\left(1 - \frac{GDP_{it}}{GDP_t}\right) \tag{9}$$

EMD:

$$EMD_{it} = \frac{ESM_{it}/PA_{it}}{HSM_t/PA_t}\left(1 - \frac{GDP_{it}}{GDP_t}\right) \tag{10}$$

ESD:

$$ESD_{it} = \frac{ESS_{it}/PA_{it}}{HSS_t/PA_t}\left(1 - \frac{GDP_{it}}{GDP_t}\right) \tag{11}$$

ESP_{it}, ESA_{it}, ESM_{it} and ESS_{it} refer to the total number of environmental protection system personnel, administrative personnel, monitoring personnel and supervision personnel, respectively; *i* represents province (city) and *t* equals year. HSP_t, HSA_t, HSM_t and HSS_t refer to the total number of personnel in the national environmental protection system, the number of environmental protection administrative personnel, the number of environmental protection monitoring and the number of environmental protection supervisors personnel, respectively. PA_{it} represents the region's population size in the *t* year, and GDP_{it} refers to the *i* region's gross domestic product (GDP) in the t year. To avoid endogenous problems, the above measures are deflated by using 1-GDP_{it}/GDP_t.

4.2.3. Adjusting variables

The scale of pig breeding (*Scale*): Scholars have not unified the standard for measuring the scale of pig breeding. Referencing the *China Animal Husbandry and Veterinary Yearbook*, the current situation of pig breeding in China and the measurement method of Zhang et al. (2019) [82], the specific measurement formula is as follow equation (12):

$$scale_{it} = \frac{SFG_{it}}{ALL_{it}} \times 100 \tag{12}$$

In Formula (12), SFG_{it} represents the number of pig farms with more than 50 pigs sold in the i region in the t year, and ALL_{it} represents the total number of pig farms in the i region in the t year.

4.2.4. Control variable

Following the existing research [83,84], the control variables include some provincial-level factors that may affect the carbon and pollution emissions of pig breeding. The natural logarithm of rural inhabitants' disposable income serves as a measure of their income level. The level of scientific and technological progress is expressed by the ratio of patent authorisation to *GDP*. Epidemic risk is expressed by the sum of the number of live pigs killed and killed (head) caused by eight common diseases. The ratio of corn yield to total grain production reflects the quantity of the supply of pig feed. The proportion of rural households with high school education measures the cultural level of farmers. The ratio of the total distance of roads, railroads and inland waterways to the land area is used to gauge traffic convenience. The quantity of the agricultural labour force measures the supply degree of the agricultural labour force. The share of each province's cultivated land area in the nation's total cultivated land area determines the bearing capacity of pig breeding land. The ratio of the urban population to the overall population serves as a gauge for urbanisation levels.

4.3. Data

Due to the lack of data on environmental decentralization measurement indicators in the China Environmental Yearbook after 2017, it is not accessible to measure environmental decentralization indicators after 2017. Therefore, we select panel data of 30 provinces (excluding Tibet, Hong Kong, Macao and Taiwan) in China from 2002 to 2017. The data comes from the *China Environmental Yearbook, China Animal Husbandry and Veterinary Yearbook, China Rural Statistical Yearbook, Veterinary Bulletin, China Rural Household Survey Yearbook* and the *China Statistical Yearbook*. Missing data are supplemented by linear interpolation.

4.4. Description of the study variables

Table 1 displays each variable's definition and statistical breakdown. The pollution and carbon reduction synergy from pig farming is low and requires further improvement. China has a relatively low level of *ED*, suggesting that the decentralization of environmental management authority in different regions is somewhat constrictive and has relatively stable fluctuations.

4.5. Heterogeneity analysis

Due to the differences in the development level, resource endowment and environmental conditions of the pig breeding industry, we divide the sample into four areas according to the *National Pig Production Development Plan (2016–2020)* issued by the Ministry of Agriculture. The zones include key development areas, restricted development areas, potential growth areas and moderate development areas. The key development areas include Hebei, Shandong, Henan, Chongqing, Guangxi, Sichuan and Hainan. The restricted development zones include Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Anhui, Jiangxi, Hubei, Hunan and Guangdong. Furthermore, the potential growth areas include Liaoning, Jilin, Heilongjiang, Neimenggu, Yunnan and Guizhou, while the moderately developed areas include Shanxi, Shaanxi, Gansu, Xinjiang, Tibet, Qinghai and Ningxia. The heterogeneity effect of *ED* on E_C in different development regions was further studied.

4.6. Analysis of spatial spillover effects

To explore whether a spatial spillover effect exists on the impact of *ED* on *Ec* and to pursue scientific and rigorous research conclusions, this paper builds a panel space regression based on Spatial Durbin Model. The SDM model is a statistical method used in spatial econometrics to analyse how one variable's value in a specific location is influenced not only by its own characteristics but also by the characteristics of neighbouring locations. It accounts for spatial dependencies or interactions between observations. In essence, it helps us understand how things in one place are affected by things in nearby places, making it useful for studying phenomena with spatial patterns, such as regional economics, environmental factors, and social interactions. In equation (13), d_{ij} represents the spatial distance between different areas. The smaller the geographical distance between provinces and the more significant the impact between regions, the greater the weight value.

$$W_{ij} = \begin{cases} \frac{1}{d_{ij}}, & i \neq j \\ 0, & i = j \end{cases} \tag{13}$$

5. Results and discussions

5.1. Baseline regression analysis

Table 2 presents the regression results of pollution reduction effects of environmental decentralization (*ED*) and different types of *ED*. *ED* has a significant negative impact coefficient on pig breeding pollution at a 1 % level, suggesting that increasing the degree of *ED* can improve the environmental pollution caused by pig breeding. The reason is that the local government has environmental management autonomy due to *ED* and can fully grasp the development of the local pig breeding industry. Furthermore, they can establish focused environmental policies from the perspectives of pollution reduction and the advancement of green technologies and rely on the 'acquaintance' relationship to increase regional environmental protection monitoring that guides farmers to increase investment in decontamination equipment and realise the green transformation of pig breeding. Unlike existing research, this study is based on the pig farming industry. Expanding local government's independent management authority helps local governments continuously utilise their information advantages to improve socialised services for livestock and poultry. At the same time, it increases the environmental supervision of large-scale pig farmers, thereby promoting the 'breeding and breeding cycle' of pig farming, effectively absorbing pig manure and reducing pollution.

The three decomposition indicators of *ED*, *EAD* and *ESD* have relatively little impact on reducing pollution; however, moderate *EMD* can significantly reduce the pollution of pig rearing. Compared with environmental administration and supervision, the scope of authority of the monitoring department includes the overall coordination and monitoring of environmental issues, which is the most direct and important link to pollution control. The effective operation of local government environmental monitoring is closely related to whether the breeding industry's environmental protection policies can be implemented. As the investment in the transformation of pig manure treatment equipment and the environmental management system of the pig industry can play a significant role, this decentralization index has the most apparent impact on pig breeding pollution. Implementing *EMD* will increase the intensity of government ER and improve the awareness of pig farmers to adopt green production methods. Similarly, it will promote the optimisation of regional social services and drive the diffusion of cleaner production technology and terminal pollution control technology for pig farmers. At the same time, nationwide environmental inspections can easily make some polluting pig farmers use opportunism to create false appearances, increasing the difficulty and authenticity of environmental monitoring and thus increasing environmental pollution penalties. However, local governments use social networks and reputation mechanisms to conduct more scientific and authentic evaluations and inspections of local pig farmers; thus, under the influence of reputation mechanisms, pig farmers are forced to engage in clean production.

Table 3 presents the carbon reduction effect of pig breeding caused by *ED* and different types of *ED*. According to the results, *ED* substantially reduces the carbon emission from pig breeding and has a negative association with the intensity of carbon emissions, which is significant at 1 %. Regarding different types, the performance of *EMD* is consistent with that of *ED*, passing the 10 % significance level test; however, the *EAD* and *ESD* did not perform the critical carbon reduction function as expected. *EMD* allows local governments greater autonomy in monitoring the time under the central macro direction and overall objectives, thus avoiding 'free riding' behaviour and cross-border pollution problems. This monitoring method adapted to local development will directly affect the production behaviour of pig farmers and will exert greater pressure on pig farmers to learn new technologies and introduce advanced equipment. The method will also build scientific and low-carbon pig farms and encourage pig technological transition and advancement to cut carbon emissions. The decentralization of environmental supervision is consistent with existing research findings; however, the decentralization of environmental administration has not had a carbon reduction effect, which is inconsistent with most

Table 2
Pollution reduction effect of environmental decentralization.

VARIABLES	WRZ	WRZ	WRZ	WRZ
ED	−0.3300***			
	(0.0788)			
EAD		−0.0148		
		(0.0102)		
EMD			−0.0155*	
			(0.0088)	
ESD				−0.0086
				(0.0097)
Control	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2	0.2050	0.1830	0.1790	0.1670

Note: *, **, and *** denote significance at the levels of 10, 5, and 1%, respectively. The numbers in parentheses show the standard errors.

Table 3
Carbon reduction effect of environmental decentralization.

VARIABLES	EYH	EYH	EYH	EYH
ED	−101.8000***			
	(24.3400)			
EAD		−4.5600		
		(3.1600)		
EMD			−4.7760*	
			(2.7360)	
ESD				−2.6670
				(3.0210)
Control	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2	0.2140	0.1860	0.1880	0.1840

Note: *, **, and *** denote significance at the levels of 10, 5, and 1%, respectively. The numbers in parentheses show the standard errors.

existing research findings. The reason is that currently, pig farming is large-scale, and pig farmers have a certain amount of capital influence in the local area, making it easy for them to engage in 'rent-seeking' behaviour. This situation leads to some pig farmers violating environmental protection policies and being exempt from punishment, gradually weakening the advantages of environmental administrative decentralization.

Table 4 presents the impact of *ED* on E_C, indicating that the correlation coefficient between *ED* and E_C is 0.339, which is significant at 5 %. The strengthening of *ED* contributes to the synergy of *Ec* in pig breeding. Zhang et al. (2022) [84] did not examine the reasons for the synergistic effect; they only explained that carbon reduction policies have the same effect on both pollution reduction and carbon reduction, that is, the synergistic effect of pollution reduction and carbon reduction. In contrast, this study further revealed the positive impact mechanism of *ED* on the synergistic effect of pollution reduction and carbon reduction, finding that *EAD* helps to promote the synergistic effect of pollution reduction and carbon reduction. Local governments are familiar with the reasons for the increase in pollutants and carbon emissions in the area, which helps local governments consider the role of pollution reduction when formulating carbon reduction policies and thus achieve the goal of synergistic efficiency reduction. The decentralised environmental management system is more conducive to local governments to strengthen carbon reduction measures when implementing pollution reduction policies and pay attention to reducing waste emissions when implementing carbon reduction environmental regulations. In particular, because pollution and carbon reduction have the same root and origin, the marginal cost of reducing carbon emissions is lower when implementing the pollution reduction policy. During such implementation, it is also convenient to use the collected pollution information of farmers for pollution control. The impact coefficient of *EAD* on carbon reduction synergy is significantly positive at 10 %.

Through the administrative demolition and rectification of unqualified pig farms, the total amount of pig breeding decreases, effectively reducing the carbon emissions from pig intestines, stomach and respiration and decreasing pollutants, such as pig manure, with the synergistic effect of pollution and carbon reduction; however, the impact coefficient of *EMD* on E_C is negative and significant at 5 %. The downwards shift of environmental monitoring power is not conducive to realising the synergistic effect of pollution and carbon reduction in pig breeding. Local governments with too much autonomy in environmental protection monitoring may quickly generate the 'rent-seeking' phenomenon. Some illegal pollution information is hidden, resulting in information asymmetry, which affects the fairness of environmental governance and reduces the efficiency of environmental pollution governance. Specifically, when higher-level government emphasises reducing carbon emissions, the local government reduces the monitoring of pig pollutants for job promotion. This action eases environmental governance to create the illusion of increased regional economic growth at high rates,

Table 4
Impact of environmental decentralization on the synergy of pollution and carbon reduction.

VARIABLES	Ec	Ec	Ec	Ec
ED	0.3390**			
	(0.1340)			
EAD		0.0185*		
		(0.0107)		
EMD			−0.0393**	
			(0.0156)	
ESD				0.0299
				(0.0894)
Control	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2	0.1850	0.1340	0.1680	0.1940

Note: *, **, and *** denote significance at the levels of 10, 5, and 1%, respectively. The numbers in parentheses show the standard errors.

making the coordinated development of pollution and carbon reduction not realised. Furthermore, the monitoring department faces the control of pollution emissions. If emission reduction and carbon reduction become the responsibilities of local governments simultaneously, achieving a two-way balance in the environmental monitoring process will be challenging. Moreover, the gradual *EMD* power requires the local government's monitoring to be increasingly strict or frequent, leading environmental protection personnel to local environmental monitoring practices. Overly strict local monitoring may not favour the top-level design and research of pollution and carbon reduction synergy policies.

5.2. Moderator effect

To explore whether the scale of pig breeding will affect the impact of *ED* on E_C in pig breeding, the *Scale* is introduced as an adjustment index. Table 5 presents the regression results, where the interaction coefficient between *ED* and *Scale* is positive and significant at 5 %. This result indicates that with the increasing scale of the pig breeding industry, the more significant synergistic effect of *ED* on *Ec*. From the decomposition indicators of *ED*, the coefficient of *ESD* is significantly positive and significant at the level of 5 %, while the coefficients of *EAD* and *EMD* are insignificant. The rationale is that environmental supervision is an essential basis for the crucial foundations of better environmental administration and environmental monitoring and intuitive, dynamic data reflection. In the process of pig breeding, the environmental protection department can easily detect the enormous scope of operations and more severe pollution of large-scale farmers. Pig breeding pollution figures are difficult to falsify; locals may readily complain to the authorities about the pollution the pigs are causing and receive punishment. Therefore, the effect of *ED* on the restriction and supervision of large-scale farmers is more pronounced, which can effectively curb the pollution behaviour of large-scale farmers. This finding shows that the scale of pig breeding has promoted the synergy of *ED*, pollution and carbon reduction, while the environmental protection role of local environmental supervision autonomy has gradually emerged.

5.3. Empirical results of heterogeneity analysis

The results in Table 6 show an imbalance in the effect of *ED* among different areas of pig breeding. The key development area is the pig breeding industry's main force and industrial cluster. *EAD* and *EMD* can help regional control of pollution and reduce carbon emissions. Through the *EAD* method, the local government can issue a coordinated treatment policy for pollution and carbon reduction suitable for the development of the breeding industry, improve the level of standardised scale pig breeding and promote the high-quality development of the pig industry. Through *EMD*, the local government regularly implements an environmental protection law enforcement monitor that carries out standardised monitoring of pig breeding and avoids the occurrence of pig breeding pollution from the source. *EAD*, *EMD* and *ESD* in the restricted development zone are insignificant. In areas with potential growth, too frequent and overly strict daily environmental supervision requires significant human and material supervision costs, creating an imbalance between implementing local pollution and carbon reduction policies. The foundation of pig breeding in the moderately developed region is weak, and *ED*'s gradual improvement has significantly strengthened the environmental requirements and resource constraints on pig breeding. This situation drives the pig farmers in the region to integrate new technologies and transform them into green development.

5.4. Endogenous treatment

The explanatory and explained variables could be mutually causal, which may lead to endogenous problems. Following Liu et al. (2016) [85], the mean value of *ED* of neighbouring provinces in the same year is used as the instrumental variable for *ED* in this region. The synergy of pollution and carbon reduction of pig breeding in this region is not affected by the *ED* of other provinces and thus meets the exogenous requirements. The *ED* of neighbouring regions influences the *ED* in this region, and the decentralization settings and pollution treatment methods are also very similar due to the mutual imitation behaviour characteristics between the governments of

Table 5
Regulation effect of pig breeding scale.

VARIABLES	Ec	Ec	Ec	Ec
Scale*ED	0.0192**			
	(0.0083)			
Scale*EAD		−0.0015		
		(0.0177)		
Scale*EMD			−0.0049	
			(0.0130)	
Scale*ESD				0.0125**
				(0.0054)
Control	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2	0.2140	0.1930	0.2050	0.1390

Note: *, **, and *** denote significance at the levels of 10, 5, and 1%, respectively. The numbers in parentheses show the standard errors.

Table 6
Heterogeneity analysis of the synergistic effect of pollution and carbon reduction in different areas of pig breeding.

VARIABLES	Ec				Ec			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
	Key areas	Restricted areas	Potential areas	Modest areas	Key areas	Restricted areas	Potential areas	Modest areas
ED	0.7420	−1.6020	0.6540	5.2840**				
	(1.7520)	(1.2590)	(2.6960)	(2.5970)				
EAD					0.2419***	−0.3890	−0.9460	0.1500
					(0.0527)	(0.2460)	(0.6780)	(0.1480)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	112	176	96	96	112	176	96	96
R^2	0.1650	0.1130	0.1980	0.2180	0.1750	0.1180	0.2170	0.1870
VARIABLES	Ec				Ec			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
	Key areas	Restricted areas	Potential areas	Modest areas	Key areas	Restricted areas	Potential areas	Modest areas
EMD	0.3580*	−0.2110	−0.3070	0.0033				
	(0.2080)	(0.1530)	(0.5230)	(0.1260)				
ESD					0.1430	−0.1426	−0.3859***	0.1120
					(0.1790)	(0.1810)	(0.1064)	(0.1500)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	112	176	96	96	112	176	96	96
R^2	0.1890	0.1150	0.2010	0.1770	0.1690	0.1080	0.1990	0.1820

Note: *, **, and *** denote significance at the levels of 10, 5, and 1%, respectively. The numbers in parentheses show the standard errors.

neighbouring provinces. The endogenous results are shown in Table 7.

The two-stage least squares first-stage regression coefficient is 0.2518, which passes the 1 % significance level test, indicating that the selected instrumental variables have a certain correlation with *ED*. The regression coefficient of *ED* is 0.3479 and significant at the level of 1 %, indicating that *ED* positively affects the synergy of pollution and carbon reduction. The F-test value is 67.3921 and is significant at the 1 % level, indicating no weak instrumental variable problem. The results for instrumental variables are consistent with the previous text, indicating that the benchmark regression results are robust.

5.5. Robustness check

(1) **Replace the dependent variable.** This paper replaces the explained variables with the unassigned synergy index of pollution and carbon reduction in each province to ensure the robustness of the benchmark results. Table 8 presents the empirical test, indicating little change in the direction and significance level of the correlation coefficient between the explained and explanatory variables. The robustness test results are consistent with the benchmark regression; thus, the research conclusion is credible.

(2) **Sub-sample test.** Various factors, such as resource endowment, consumption status, agricultural development model and economic base, indicate a certain regional imbalance in the pig breeding industry. Since the special status and policy orient of the municipality directly under the central government, the output value of pigs accounts for a relatively low proportion in these cities. If the data of municipalities directly under the central government and other regions are in mixture regression, the

Table 7
Endogenous test results.

VARIABLES	ED	Ec
	Phase I	Phase II
ED		0.3479***
		(0.0471)
Average environmental decentralization of neighbouring provinces	0.2518***	
	(0.0246)	
Control	Yes	Yes
Year	Yes	Yes
N	480	480
Wald test		89.6254
F test value	67.3921***	
R^2	0.2035	0.1729

Note: *, **, and *** denote significance at the levels of 10, 5, and 1%, respectively. The numbers in parentheses show the standard errors.

Table 8
Robustness test.

Panel A VARIABLES	Ec			
	(1)	(2)	(3)	(4)
	Replace the dependent variable	Excluding municipalities	Add control variable time trend	High-dimensional fixed effect
ED	0.1384** (0.0669)	0.5382*** (0.1527)	0.4183** (0.2014)	0.3201*** (0.0739)
EAD	0.1783* (0.1029)	0.0489** (0.0211)	0.3720* (0.1987)	0.1105* (0.0634)
EMD	−0.2894** (0.1187)	−0.0386*** (0.0102)	−0.1485* (0.0832)	−0.6629** (0.3108)
ESD	0.0382 (0.2537)	0.0157 (0.8461)	0.7392 (0.6899)	0.5382 (0.8364)
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	No	Yes	Yes
N	480	416	480	480
R^2	0.1940	0.1890	0.2360	0.1730

Panel B VARIABLES	Ec		
	(1)	(2)	(3)
	Add other control variables	Interaction between provinces and years	1 % shrinkage treatment
ED	0.8933*** (0.2467)	0.4475*** (0.1066)	0.1893** (0.0138)
EAD	0.8271** (0.4168)	1.8326** (0.8935)	0.1049* (0.0588)
EMD	−0.5639*** (0.1082)	−0.4855*** (0.1161)	−0.7384** (0.3617)
ESD	0.0548 (0.2744)	0.2981 (0.8896)	0.7389 (6.2247)
Controls	Yes	Yes	Yes
Year	Yes	Yes	Yes
Province	Yes	Yes	Yes
N	480	480	480
R^2	0.2180	0.1770	0.2990

Note: *, **, and *** denote significance at the levels of 10, 5, and 1%, respectively. The numbers in parentheses show the standard errors.

estimated model parameter results will be somewhat biased; therefore, Beijing, Shanghai, Tianjin and Chongqing are excluded. The research conclusion has not changed significantly, indicating the robustness of the results.

(3) **Add control variable time trend.** Angrist and Pischke (2009) [86] believed that adding the cross-product of the control variable and time trend in the empirical model could effectively control the time change of the explained variable's influencing factors and somewhat alleviate the parameter estimation error caused by the change of other factors over time. This paper includes the benchmark model's time trend term of control variables. The regression results are shown in column (3) of Table 8, indicating that after adding the above cross-factor, the impact coefficient and direction of *ED* on *Ec* have not changed substantially, indicating that the benchmark regression results are relatively stable.

(4) **High-dimensional fixed effect.** Some regional factors that change with time may affect the effect of pollution and carbon reduction; therefore, this paper uses the control high-dimensional fixed-effect model to control the regional characteristic factors that change with time. The results show that the influence coefficient and direction of the core explanatory variables *ED*, *EAD*, *EMD* and *ESD* have not changed substantially. The estimation results of high-dimensional models provide supporting evidence for the robustness of this paper's conclusions.

(5) **Add other control variables.** This paper adds other control variables to avoid the estimation error caused by missing variables. The new control variables include the carbon emission trading pilot policy, the green industrial transformation pilot policy and the environmental protection supervision resident system. The test results are shown in column (1) of panel B in Table 8, and the conclusion is still reliable.

(6) **Control the interaction between provinces and years.** This paper further adds the interaction item of province and year, controlling the fixed interaction effect of province and year. The results are shown in column (2) of panel B in Table 8, showing that the conclusions drawn in this paper are still robust.

(7) **Shrink tail treatment.** The continuous variables were shrunk by 1 % to enhance the reliability of the research conclusion. The robustness test results are shown in column (3) of panel B in Table 8. The positive effects of *ED* on regional *Ec* have passed the significance level test, similar to the benchmark regression results.

5.6. Mechanism test

Empirical testing is conducted according to the previous theoretical deduction. Panel A in Table 9 shows that *ED* helps to improve the supporting facilities for pig breeding and environmental protection. *EAD*, *EMD* and *ESD* all significantly positively impact the construction of pig breeding environmental protection supporting facilities. With the expansion of local government autonomy, the information advantages brought by decentralization have gradually become prominent. Administrative penalties for farmers who do not meet environmental protection requirements, supervision over the use of environmental protection facilities and decentralization can effectively improve treatment efficiency. Under the effect of decentralization, local governments are more familiar with the necessity and efficiency of biogas digester construction for farmers, which helps allocate and use subsidy funds for biogas digester

Table 9
Mechanism test.

Panel A				
VARIABLES	Ec			
	(1)	(2)	(3)	(4)
	HBS	HBS	HBS	HBS
ED	0.9150*** (0.2810)			
EAD		0.0567* (0.0332)		
EMD			0.0634*** (0.0151)	
ESD				0.0673** (0.0331)
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2	0.1546	0.2364	0.2316	0.2332
Panel B				
VARIABLES	Ec			
	(1)	(2)	(3)	(4)
	LSL	LSL	LSL	LSL
ED	102.8000 (75.6700)			
EAD		20.0200*** (6.6390)		
EMD			−11.0600 (14.4640)	
ESD				15.7100** (7.7740)
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2	0.4027	0.4021	0.4019	0.4013
Panel C				
VARIABLES	Ec			
	(1)	(2)	(3)	(4)
	ZZC	ZZC	ZZC	ZZC
ED	804.6000*** (67.2000)			
EAD		137.4000 (160.0000)		
EMD			183.0000*** (52.9700)	
ESD				−27.0900 (55.1900)
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2	0.3851	0.3698	0.3672	0.3699

Note: *, **, and *** denote significance at the levels of 10, 5, and 1%, respectively. The numbers in parentheses show the standard errors.

construction. Furthermore, decentralization can also better formulate subsidy standards, thereby increasing the enthusiasm of farmers to use biogas to absorb pig manure and ultimately promoting the synergy of pig farming to reduce pollution and reduce carbon.

Panel B presents the results of *ED* on the use of green feed for pig breeding, indicating that *EAD* and *ESD* can effectively encourage pig farmers to increase the use of green standardised feed; however, *EMD* has little effect. The feed for pig farming is related to the industrialisation organisations that the farmers join; for example, if the farmers join the Greenhouse Group, they must use the group's pig feed. Under the influence of the authority, the local government can monitor and punish feeds with excessive veterinary drugs or additives, which can also help prevent farmers from using low-quality and substandard feeds; however, the quality review of feed still requires strict checks by relevant national quality inspection departments.

ED can significantly improve the degree of pig industrialisation organisation. *EMD* has a significant positive impact on the development of pig industrialisation organisations, while *EAD* and *ESD* have little impact. From the industrial organisation theory perspective, expanding local government autonomy will help local governments introduce leading pig enterprises and develop pig cooperatives based on their resource endowment advantages. The organisation's environmental protection will consciously constrain farmers that join cooperatives and enterprises, thereby reducing the government's environmental protection supervision cost and achieving the synergistic effect of pollution reduction and carbon reduction. Furthermore, Chinese local governments can use special funds for socialisation services to help farmers absorb manure. This situation can help more farmers join industrial organisations such as cooperatives, thereby strengthening the clean production of pig breeding.

5.7. Spatial spillover effects

Table 10 shows that the *ED* system implemented in China has a significant spatial spillover effect on E_C, while *ED* has no significant spatial spillover effect on *Ec*. The reason is that all regions have issued and implemented *ER* policies to promote the transformation of green pig production nationwide. Driven by the establishment and application of the agricultural big data platform, instituting the *ED* system in all regions increases the transparency of regulations, rewards and punishment laws for pig breeding pollution. Effective

Table 10
Test of spatial spillover effect.

Panel A			
VARIABLES	Ec		
	(1)	(2)	(3)
	SDM	SAR	SEM
ED	0.1149	0.1341	0.2443
	(0.1920)	(0.2470)	(0.4370)
W*ED	6.8342		
	(1.4990)		
Control	Yes	Yes	Yes
Observations	480	480	480
R-squared	0.0200	0.0180	0.0180
Panel B			
VARIABLES	Ec		
	(1)	(2)	(3)
	SDM	SAR	SEM
ED	−0.4779***	−0.4288***	−0.4322***
	(-6.3660)	(-6.0610)	(-6.0540)
W*ED	−1.1963**		
	(-2.0880)		
Control	Yes	Yes	Yes
Observations	480	480	480
R-squared	0.0010	0.0050	0.0050
Panel C			
VARIABLES	Ec		
	(1)	(2)	(3)
	SDM	SAR	SEM
ED	−147.5597***	−132.3912***	−133.4363***
	(-6.3660)	(-6.0610)	(-6.0540)
W*ED	−369.3541**		
	(-2.0880)		
Control	Yes	Yes	Yes
Observations	480	480	480
R-squared	0.0010	0.0050	0.0050

Note: *, **, and *** denote significance at the levels of 10, 5, and 1%, respectively. The numbers in parentheses show the standard errors.

policies for pollution and carbon reduction in pig breeding can play a role in imitating and demonstrating the surrounding areas and also prevent the cross-border pollution of pig breeding. However, coordinating pollution and carbon reduction policies requires a common goal between the government and farmers and consistency across all regions in the pig breeding environment, breeding practices, government environmental protection objectives and farmers' awareness of environmental protection. Otherwise, copying the pollution and carbon reduction policies and implementation plans will lead to 'two lines' of pollution and carbon reduction decisions. In this case, regions are not coordinated in management and data, and forming a coordination mechanism for pollution and carbon reduction is difficult. As a result, the pollution reduction policy will increase carbon emissions, or the carbon reduction policy will increase the emissions of pollutants from pig breeding. Simultaneously, the regulation of greenhouse gases lacks legal basis and supervision. The *ED* system's regional environmental laws vary significantly, creating challenges for the synergy of pollution and carbon reduction and leading to the insignificant spatial spillover effect of the impact of *ED* on *Ec*.

6. Conclusions and implications

The 'Fourteenth Five-Year Plan' has just begun, and China's ecological civilisation construction is at a new stage of 'pollution and carbon reduction and coordinated governance'. It is crucial to determine how to encourage the green and low-carbon development of the livestock and poultry breeding industry, encourage the synergy of pollution and carbon reduction and accomplish the thorough green transformation of economic and social development. This paper explores the relationship with *ED* from the bilateral perspective of 'pollution reduction' and 'carbon reduction'. We theoretically analyse the impact mechanism of *ED* on the synergy of pollution and carbon reduction in pig breeding and empirically test the impact mechanism and empty spillover effect. The study finds that moderate *ED* can reduce the environmental pollution caused by pig breeding and control carbon emissions. Furthermore, *ED* promotes the synergy of pollution reduction and carbon reduction by improving the environmental protection facilities of pig breeding and the degree of organisation. For different types of *ED*, *EAD* positively affects the synergy of pollution and carbon reduction in pig breeding. *EMD* is not conducive to the synergy of pollution and carbon reduction, and *ESD*'s positive promotion weakens. With the increasing scale of the pig breeding industry, the synergistic effect of *ED* on pollution and carbon reduction is becoming increasingly significant. Simultaneously, the impact of *ED* on the synergy of pollution and carbon reduction has regional heterogeneity. In key development areas, *EAD* and *EMD* significantly impact the synergy of pollution and carbon reduction in pig breeding; however, the *EAD*, *EMD* and *ESD* are insignificant in the restricted development zone. *ESD* will lead to an imbalance between local pollution and carbon reduction in areas with potential growth. The foundation of moderately developed regional pig breeding is weak, and improving *ED* will help the transformation and green development of pig breeding. Furthermore, *ED* has a positive spatial spillover effect on pollution reduction or carbon reduction in neighbouring regions; however, *ED* has no significant spatial spillover effect on the synergistic effect of pollution and carbon reduction in pig breeding.

According to the above findings, this study proposes the following policy conclusions. (1) It is necessary to clarify the responsibilities of the central and local governments in various fields of environmental management and appropriately adjust the degree of *ED*, giving local governments greater environmental governance freedom. It is crucial to fully support local governments' leadership in the joint practice of reducing pollution and carbon emissions and to formulate a system of rewards and penalties for environmental protection. In the context of having the right to independent management, local governments must improve the policy design and implementation capacity in pig breeding industry regulation, capital allocation and environmental governance. Furthermore, a local vertical management system with clear powers and responsibilities should be established to ensure that communication between governments at all levels and environmental protection departments is effectively implemented towards environmental protection administrative power. Furthermore, the focus should be on strengthening the optimisation of the personnel structure of environmental administrative departments and the training of professional personnel while improving the transparency and credibility of administrative law enforcement. Additionally, local governments must have full support regarding the cost and information advantages to realise the effective allocation of resources. (2) The differences in regional economic development levels and geographical conditions must be fully considered, and appropriate environmental protection policies should be formulated according to the scale of aquaculture. The division of environmental responsibilities of local governments should fully consider local realities, promote *ED* and act according to local conditions and different regional characteristics. The government should optimise and focus on developing a regional *ED* system, improve the green development level and competitiveness of the pig breeding industry in the region and improve the supporting measures for pig manure and waste gas treatment in combination with *ED*. Furthermore, giving certain subsidies to pig farmers in the transformation of green production and encouraging qualified and capable enterprises to participate in the green development of pig breeding are suitable methods. Green and low-carbon technologies, such as the recycling of livestock and poultry manure, should be promoted; the return of manure and biogas slurry to the field could boost China's pig breeding cycle and green and low-carbon development. (3) The regional cooperation mechanism should be strengthened, and the coordination of pollution and carbon reduction should be promoted in all links of the pig industry chain in the neighbouring regions. Furthermore, due to the spatial correlation between regional carbon emissions and aquaculture pollutants, a single local government may be inefficient in dealing with pig breeding pollution. Local governments should implement cooperation in regional environmental governance, including cross-regional joint prevention and control at multiple levels, such as carbon emissions and pollution data sharing of pig breeding and allocation of technical personnel. Similarly, the local government should strengthen regional environmental protection cooperation, cross-law enforcement and joint governance, build a coordinated ecological environment management pattern of regional 'joint prevention and control' and avoid 'bottom competition'. (4) The organisational development of the hog industry should be promoted, and the system construction and subsidies for hog cooperatives should be increased. At the same time, the technical breeding training and inter-regional exchanges of cooperatives should be strengthened, and the failure of epidemic prevention should be reduced along with control caused by information asymmetry. Finally, hog breeding cooperatives should be continually encouraged to cooperate with family farms and leading pig enterprises to reduce the competition between industrial organisations.

This study's shortcomings lie in the fact that the government only collected provincial-level data on the measurement of *ED* indicators; data on the number of environmental administrative personnel in each province were only collected until 2017. The relevant data for 2017–2022 is missing. No statistical data is currently available on measuring *ED* at the prefecture, county or village levels. Further research on the impact of grassroots *ED* on the synergistic effect of pollution reduction and carbon reduction in pig farming cannot be conducted. According to China's national conditions, significant differences exist in the degree of *ED* among different counties or villages, making it challenging to analyse the heterogeneity of grassroots *ED*. Therefore, future research can further investigate the heterogeneity of grassroots *ED* areas and examine the impact of grassroots *ED* on the synergistic effect of pollution reduction and carbon reduction in different production stages of pig farming. For example, future research can explore the impact of *ED* on the synergistic effect of pollution reduction and carbon reduction in the three stages of source prevention, process control and end treatment of pig farming.

Data availability

Data will be made available on request.

Funding

National Natural Science Foundation of China (NSFC_71273136); National Natural Science Foundation of China (NSFC_72073068); Postgraduate Scientific Research Innovation Project of Jiangsu Province (KYCX23_0832).

CRediT authorship contribution statement

Yanjun Jiang: Conceptualization, Data curation, Writing – original draft, Methodology, Writing – review & editing. **Yue Zhang:** Conceptualization, Formal analysis, Funding acquisition, Validation, Writing – original draft, Writing – review & editing. **Robert Brenya:** Supervision. **Kai Wang:** Data curation, Methodology, Funding acquisition.

Declaration of competing 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.

References

[1] C. Sun, H. Wu, Assessment of pollution from livestock and poultry breeding in China, Int. J. Environ. Stud. 70 (2) (2013) 232–240, https://doi.org/10.1080/00207233.2013.773716.

[2] P.J. Gerber, H. Steinfeld, B. Henderson, A. Mottet, Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities, in: Food and Agriculture Organization of the United Nations, Food & Agriculture Org, 2013.

[3] J. Li, Q. Li, L. Liu, Carbon emissions from smallholder pig production in China: a precise account based on farmers' survey, Environ. Sci. Pollut. Res. 29 (17) (2022) 25651–25664, https://doi.org/10.1007/s11356-021-17720-y.

[4] J. Zheng, X. Cao, C. Ma, N. Weng, S. Huo, What drives the change of nitrogen and phosphorus loads in the Yellow River Basin during 2006-2017? J. Environ. Sci. 126 (2023) 17–28, https://doi.org/10.1016/j.jes.2022.04.039.

[5] V. Cistulli, Environment in Decentralized Development: Economic and Institutional Issues, Food & Agriculture Org, 2002.

[6] K. Lo, How authoritarian is the environmental governance of China? Environ. Sci. Pol. 54 (2015) 152–159, https://doi.org/10.1016/j.envsci.2015.06.001.

[7] H. Wu, Y. Hao, S.Y. Ren, How do environmental regulation and environmental decentralization affect green total factor energy efficiency: evidence from China, Energy Econ. 91 (2020) 18, https://doi.org/10.1016/j.eneco.2020.104880. ARTN 104880.

[8] H. Sigman, Transboundary spillovers and decentralization of environmental policies, J. Environ. Econ. Manag. 50 (1) (2005) 82–101, https://doi.org/10.1016/j.jeem.2004.10.001.

[9] J. Bai, L. Nie, Is environmental decentralization really exacerbating haze pollution? China population, resources and environment 27 (12) (2017) 59–69.

[10] K. Wang, B. Zhao, L. Ding, Z. Miao, Government intervention, market development, and pollution emission efficiency: evidence from China, Sci. Total Environ. 757 (2021), 143738, https://doi.org/10.1016/j.scitotenv.2020.143738.

[11] G. Zhang, W. Liu, H. Duan, Environmental regulation policies, local government enforcement and pollution-intensive industry transfer in China, Comput. Ind. Eng. 148 (2020), 106748, https://doi.org/10.1016/j.cie.2020.106748.

[12] L. Jiang, H. Zhou, S. He, The role of governments in mitigating SO(2) pollution in China: a perspective of fiscal expenditure, Environ. Sci. Pollut. Res. 27 (27) (2020) 33951–33964, https://doi.org/10.1007/s11356-020-09562-x.

[13] T.C. Kuo, I.H. Hong, S.C. Lin, Do carbon taxes work? Analysis of government policies and enterprise strategies in equilibrium, J. Cleaner Prod. 139 (2016) 337–346, https://doi.org/10.1016/j.jclepro.2016.07.164.

[14] K. Du, Y. Cheng, X. Yao, Environmental regulation, green technology innovation, and industrial structure upgrading: the road to the green transformation of Chinese cities, Energy Econ. 98 (2021), https://doi.org/10.1016/j.eneco.2021.105247.

[15] Y. Song, T. Yang, Z. Li, X. Zhang, M. Zhang, Research on the direct and indirect effects of environmental regulation on environmental pollution: empirical evidence from 253 prefecture-level cities in China, J. Cleaner Prod. 269 (2020), https://doi.org/10.1016/j.jclepro.2020.122425.

[16] J.S. Shapiro, R. Walker, Why is pollution from US manufacturing declining? The roles of environmental regulation, productivity, and trade, Am. Econ. Rev. 108 (12) (2018) 3814–3854, https://doi.org/10.1257/aer.20151272.

[17] X. Wu, H. Deng, H. Li, Y. Guo, Impact of energy structure adjustment and environmental regulation on air pollution in China: simulation and measurement research by the dynamic general equilibrium model, Technol. Forecast. Soc. Change 172 (2021), 121010, https://doi.org/10.1016/j.techfore.2021.121010.

[18] W. Du, F. Wang, M. Li, Effects of environmental regulation on capacity utilization: evidence from energy enterprises in China, Ecol. Indicat. 113 (2020), https://doi.org/10.1016/j.ecolind.2020.106217.

[19] Y. Song, X. Zhang, M. Zhang, The influence of environmental regulation on industrial structure upgrading: based on the strategic interaction behavior of environmental regulation among local governments, Technol. Forecast. Soc. Change 170 (2021), 120930, https://doi.org/10.1016/j.techfore.2021.120930.
[20] Q. Zhou, X. Zhang, Q. Shao, X. Wang, The non-linear effect of environmental regulation on haze pollution: empirical evidence for 277 Chinese cities during 2002-2010, J. Environ. Manage. 248 (2019), 109274, https://doi.org/10.1016/j.jenvman.2019.109274.
[21] J. Lin, C. Long, C. Yi, Has central environmental protection inspection improved air quality? Evidence from 291 Chinese cities, Environ. Impact Assess. Rev. 90 (2021), 106621, https://doi.org/10.1016/j.eiar.2021.106621.
[22] R. Zhang, W. Ma, J. Liu, Impact of government subsidy on agricultural production and pollution: a game-theoretic approach, J. Cleaner Prod. 285 (2021), 124806, https://doi.org/10.1016/j.jclepro.2020.124806.
[23] B. Bye, M.E. Klemetsen, The impacts of alternative policy instruments on environmental performance: a firm level study of temporary and persistent effects, Environ. Resour. Econ. 69 (2) (2016) 317–341, https://doi.org/10.1007/s10640-016-0081-8.
[24] J. Lu, Can environmental protection tax aggravate illegal pollution discharge of heavy polluting enterprises? Environ. Sci. Pollut. Res. 29 (22) (2022) 33796–33808, https://doi.org/10.1007/s11356-021-18002-3.
[25] Y. Hu, S. Ren, Y. Wang, X. Chen, Can carbon emission trading scheme achieve energy conservation and emission reduction? Evidence from the industrial sector in China, Energy Econ. 85 (2020), 104590, https://doi.org/10.1016/j.eneco.2019.104590.
[26] H. Liang, Y. Zeng, X. Jiang, Y. Li, Dynamic evaluation of low-carbon development in China's power industry and the impact of carbon market policies, Heliyon 9 (2) (2023), e13467, https://doi.org/10.1016/j.heliyon.2023.e13467.
[27] Q. Guo, Z. Su, C. Chiao, Carbon emissions trading policy, carbon finance, and carbon emissions reduction: evidence from a quasi-natural experiment in China, Econ. Change Restruct. 55 (3) (2021) 1445–1480, https://doi.org/10.1007/s10644-021-09353-5.
[28] P. Yu, R. Hao, Z. Cai, Y. Sun, X. Zhang, Does emission trading system achieve the win-win of carbon emission reduction and financial performance improvement? -Evidence from Chinese A-share listed firms in industrial sector, J. Cleaner Prod. 333 (2022), 130121, https://doi.org/10.1016/j.jclepro.2021.130121.
[29] Y. Zhang, S. Li, T. Luo, J. Gao, The effect of emission trading policy on carbon emission reduction: evidence from an integrated study of pilot regions in China, J. Cleaner Prod. 265 (2020), https://doi.org/10.1016/j.jclepro.2020.121843.
[30] Y.-J. Zhang, Y.-L. Peng, C.-Q. Ma, B. Shen, Can environmental innovation facilitate carbon emissions reduction? Evidence from China, Energy Pol. 100 (2017) 18–28, https://doi.org/10.1016/j.enpol.2016.10.005.
[31] L. Zou, J. Xue, A. Fox, B.O. Meng, The emissions reduction effect and economic impact of an energy tax vs. A carbon tax in China: a dynamic cge model analysis, Singapore Econ. Rev. 63 (2) (2018) 339–387, https://doi.org/10.1142/s021759081740015x.
[32] R. Owen, G. Brennan, F. Lyon, Enabling investment for the transition to a low carbon economy: government policy to finance early stage green innovation, Curr. Opin. Environ. Sustain. 31 (2018) 137–145, https://doi.org/10.1016/j.cosust.2018.03.004.
[33] Y. Yu, N. Zhang, Low-carbon city pilot and carbon emission efficiency: quasi-experimental evidence from China, Energy Econ. 96 (2021), 105125, https://doi.org/10.1016/j.eneco.2021.105125.
[34] H.F. Chang, H. Sigman, L.G. Traub, Endogenous decentralization in federal environmental policies, Int. Rev. Law Econ. 37 (2014) 39–50, https://doi.org/10.1016/j.irle.2013.07.001.
[35] S. Lovo, Effect of environmental decentralization on polluting firms in India, Econ. Dev. Cult. Change 67 (1) (2018) 55–94, https://doi.org/10.1086/697558.
[36] Y. Hao, Z. Gai, G. Yan, H. Wu, M. Irfan, The spatial spillover effect and nonlinear relationship analysis between environmental decentralization, government corruption and air pollution: evidence from China, Sci. Total Environ. 763 (2021), 144183, https://doi.org/10.1016/j.scitotenv.2020.144183.
[37] W. Zhang, G. Li, Environmental decentralization, environmental protection investment, and green technology innovation, Environ. Sci. Pollut. Res. 29 (9) (2022) 12740–12755, https://doi.org/10.1007/s11356-020-09849-z.
[38] W.E. Oates, R.M. Schwab, Economic competition among jurisdictions: efficiency enhancing or distortion inducing? J. Publ. Econ. 35 (3) (1988) 333–354, https://doi.org/10.1016/0047-2727(88)90036-9.
[39] E. Magnani, The Environmental Kuznets Curve, environmental protection policy and income distribution, Ecol. Econ. 32 (3) (2000) 431–443, https://doi.org/10.1016/s0921-8009(99)00115-9.
[40] D.L. Millimet, Assessing the empirical impact of environmental federalism, J. Reg. Sci. 43 (4) (2003) 711–733, https://doi.org/10.1111/j.0022-4146.2003.00317.x.
[41] G. Li, F. Guo, D. Di, Regional competition, environmental decentralization, and target selection of local governments, Sci. Total Environ. 755 (Pt 1) (2021), 142536, https://doi.org/10.1016/j.scitotenv.2020.142536.
[42] A. D'Amato, E. Valentini, Enforcement and environmental quality in a decentralized emission trading system, J. Regul. Econ. 40 (2) (2011) 141–159, https://doi.org/10.1007/s11149-011-9153-4.
[43] P.G. Fredriksson, J.R. Wollscheid, Environmental decentralization and political centralization, Ecol. Econ. 107 (2014) 402–410, https://doi.org/10.1016/j.ecolecon.2014.09.019.
[44] R.K. Goel, U. Mazhar, M.A. Nelson, R. Ram, Different forms of decentralization and their impact on government performance: micro-level evidence from 113 countries, Econ. Model. 62 (2017) 171–183, https://doi.org/10.1016/j.econmod.2016.12.010.
[45] Q. Ran, J. Zhang, Y. Hao, Does environmental decentralization exacerbate China's carbon emissions? Evidence based on dynamic threshold effect analysis, Sci. Total Environ. 721 (2020), 137656, https://doi.org/10.1016/j.scitotenv.2020.137656.
[46] H. Yi, L. Zhao, Y. Qian, L. Zhou, P. Yang, How to achieve synergy between carbon dioxide mitigation and air pollution control? Evidence from China, Sustainable Cities Soc 78 (2022), 103609, https://doi.org/10.1016/j.scs.2021.103609.
[47] K. Nam, C. Waugh, S. Paltsev, J. Reilly, V. Karplus, Synergy between pollution and carbon emissions control: comparing China and the United States, Energy Econ. 46 (2014) 186–201, https://doi.org/10.1016/j.eneco.2014.08.013.
[48] J. Bollen, C. Brink, Air pollution policy in Europe: quantifying the interaction with greenhouse gases and climate change policies, Energy Econ. 46 (2014) 202–215, https://doi.org/10.1016/j.eneco.2014.08.028.
[49] O. Braspenning Radu, M. van den Berg, Z. Klimont, S. Deetman, G. Janssens-Maenhout, M. Muntean, et al., Exploring synergies between climate and air quality policies using long-term global and regional emission scenarios, Atmos. Environ. 140 (2016) 577–591, https://doi.org/10.1016/j.atmosenv.2016.05.021.
[50] W. Du, M. Li, Assessing the impact of environmental regulation on pollution abatement and collaborative emissions reduction: micro-evidence from Chinese industrial enterprises, Environ. Impact Assess. Rev. 82 (2020), https://doi.org/10.1016/j.eiar.2020.106382.
[51] X. Gao, N. Liu, Y. Hua, Environmental Protection Tax Law on the synergy of pollution reduction and carbon reduction in China: evidence from a panel data of 107 cities, Sustainable Prod. Consumption 33 (2022) 425–437, https://doi.org/10.1016/j.spc.2022.07.006.
[52] J. Liu, W. Zhou, J. Yang, H. Ren, B. Zakeri, D. Tong, et al., Importing or self-dependent: energy transition in Beijing towards carbon neutrality and the air pollution reduction co-benefits, Clim. Change 173 (3–4) (2022) 18, https://doi.org/10.1007/s10584-022-03413-z.
[53] L. Chen, D. Wang, R. Shi, Can China's carbon emissions trading system achieve the synergistic effect of carbon reduction and pollution control? Int. J. Environ. Res. Publ. Health 19 (15) (2022) 8932, https://doi.org/10.3390/ijerph19158932.
[54] Z. Dong, C. Xia, K. Fang, W. Zhang, Effect of the carbon emissions trading policy on the co-benefits of carbon emissions reduction and air pollution control, Energy Pol. 165 (2022), https://doi.org/10.1016/j.enpol.2022.112998.
[55] X. Liu, X. Yang, Impact of China's environmental decentralization on carbon emissions from energy consumption: an empirical study based on the dynamic spatial econometric model, Environ. Sci. Pollut. Res. 29 (48) (2022) 72140–72158, https://doi.org/10.1007/s11356-022-18806-x.
[56] X. Wei, Q. Tong, I. Magill, P. Vithayasrichareon, R. Betz, Evaluation of potential co-benefits of air pollution control and climate mitigation policies for China's electricity sector, Energy Econ. 92 (2020), 104917, https://doi.org/10.1016/j.eneco.2020.104917.
[57] B. Wang, Y. Wang, Y. Zhao, Collaborative governance mechanism of climate change and air pollution: evidence from China, Sustainability 13 (12) (2021) 6785, https://doi.org/10.3390/su13126785.

[58] P. Tollefsen, K. Rypdal, A. Torvanger, N. Rive, Air pollution policies in Europe: efficiency gains from integrating climate effects with damage costs to health and crops, Environ. Sci. Pol. 12 (7) (2009) 870–881, https://doi.org/10.1016/j.envsci.2009.08.006.
[59] A. Gu, F. Teng, X. Feng, Effects of pollution control measures on carbon emission reduction in China: evidence from the 11th and 12th Five-Year Plans, Clim. Pol. 18 (2) (2016) 198–209, https://doi.org/10.1080/14693062.2016.1258629.
[60] X. Yang, F. Teng, Air quality benefit of China's mitigation target to peak its emission by 2030, Clim. Pol. 18 (1) (2018) 99–110, https://doi.org/10.1080/14693062.2016.1244762.
[61] B. Zhao, T. Wang, Z. Jiang, Y. Gu, K.N. Liou, N. Kalandiyur, et al., Air quality and health cobenefits of different deep decarbonization pathways in California, Environ. Sci. Technol. 53 (12) (2019) 7163–7171, https://doi.org/10.1021/acs.est.9b02385.
[62] Z. Bai, X. Fan, X. Jin, Z. Zhao, Y. Wu, O. Oenema, et al., Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population, Nat Food 3 (2) (2022) 152–160, https://doi.org/10.1038/s43016-021-00453-z.
[63] Y. Yang, S.P. Kirychuk, Y. Si, M.C. Martel, H. Guo, B.Z. Predicala, et al., Reduction of airborne particulate matter from pig and poultry rearing facilities using engineered water nanostructures, Biosyst. Eng. 218 (2022) 1–9, https://doi.org/10.1016/j.biosystemseng.2022.03.013.
[64] B. Shi, S. Wang, J. Jiao, G. Li, C. Yin, Recognition on characteristics and applicability of typical modes for manure & sewage management in pig farming: a case study in Hebei, China, Waste Manag. 148 (2022) 83–97, https://doi.org/10.1016/j.wasman.2022.05.018.
[65] J.B. Zhou, M.M. Jiang, G.Q. Chen, Estimation of methane and nitrous oxide emission from livestock and poultry in China during 1949–2003, Energy Pol. 35 (7) (2007) 3759–3767, https://doi.org/10.1016/j.enpol.2007.01.013.
[66] J. Min, L. Zhou, Has systematization reduced the carbon emissions of large-scale pig farmers? Evidence from 229 large-scale pig farmers in three cities of Jiangsu, Agricultural Economic Issues 35 (9) (2014) 35–42 (In Chinese).
[67] W.E. Oates, On the evolution of fiscal federalism: theory and institutions, Natl. Tax J. 61 (2) (2008) 313–334, https://doi.org/10.17310/ntj.2008.2.08.
[68] L.G. Zhao, J. Lin, J.M. Zhu, Green total factor productivity of hog breeding in China: application of SE-SBM model and grey relation matrix, Pol. J. Environ. Stud. 24 (1) (2015) 403–412, https://doi.org/10.1007/s11356-021-17720-y.
[69] C. Zheng, Y. Liu, B. Bluemling, A.P. Mol, J. Chen, Environmental potentials of policy instruments to mitigate nutrient emissions in Chinese livestock production, Sci. Total Environ. 502 (2015) 149–156, https://doi.org/10.1016/j.scitotenv.2014.09.004.
[70] Y. Shen, Q. Tong, Y. Li, J. Shi, X. Zhang, Y. Shao, et al., Effect of straw pretreatment on Cu and Zn passivation and dissolved organic matter in mixed anaerobic fermentation of straw and pig manure, Bioenergy Res 15 (3) (2022) 1626–1638, https://doi.org/10.1007/s12155-021-10381-2.
[71] Z. Bai, J. Zhao, Z. Wei, X. Jin, L. Ma, Socio-economic drivers of pig production and their effects on achieving sustainable development goals in China, J. Integr. Environ. Sci. 16 (1) (2019) 141–155, https://doi.org/10.1080/1943815x.2019.1671463.
[72] L. Wang, Z.-G. Yang, Analysis on risk avoidance behaviors and influential factors of epidemic disease among pig farmers, Afr. Asian Stud. 21 (1–2) (2022) 90–111, https://doi.org/10.1163/15692108-12341531.
[73] J. Hou, L. Zhou, J. Ifft, R.-y. Ying, The role of time preferences in contract breach: evidence from Chinese poultry farmers participating in contract farming, J. Integr. Agric. 22 (2) (2023) 623–641, https://doi.org/10.1016/j.jia.2022.12.013.
[74] H. Hao, J. Guanghui, G. Yang, High-quality development of Chinese pig breeding industry: realistic Needs，Connotation features and path selection, Issues in Agricultural Economy 12 (2022) 32–44.
[75] A. Chmielowiec-Korzeniowska, L. Tymczyna, Ł. Wlazło, B. Trawińska, M. Ossowski, Emissions of gaseous pollutants from pig farms and methods for their reduction – a review, Ann. Anim. Sci. 22 (1) (2022) 89–107, https://doi.org/10.2478/aoas-2021-0015.
[76] S.L. Feng, B. Sui, H.M. Liu, G.X. Li, Environmental decentralization and innovation in China, Econ. Model. 93 (2020) 660–674, https://doi.org/10.1016/j.econmod.2020.02.048.
[77] H. Wu, Y. Li, Y. Hao, S. Ren, P. Zhang, Environmental decentralization, local government competition, and regional green development: evidence from China, Sci. Total Environ. 708 (2020), 135085, https://doi.org/10.1016/j.scitotenv.2019.135085.
[78] FAO, Livestock's Long Shadow: Environmental Issues and Options, Food and Agriculture Organization of the United Nations, Rome, 2006.
[79] IPCC, IPCC Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry and Other Land Uses, Intergovernmental Panel on Climate Change, 2006.
[80] J. Zhou, P. Qing, T. Yan, Technological progress, transformation of production mode and greenhouse gas emission reduction of pig breeding in China, Journal of Huazhong Agricultural University (Social Science Edition) 4 (2018) 38–45 (In Chinese).
[81] X. Mao, A. Zeng, S. Liu, T. Hu, Y. Xing, Study on the evaluation of the synergistic control effect of sulfur, nitrogen and carbon in the technical emissions reduction measures of the iron and steel industry, J. Environ. Sci. 32 (5) (2012) 1253–1260 (In Chinese).
[82] Y. Zhang, Q. Wu, S. Sun, Influential factors and spatial effects of pig breeding scale - based on the study of 13 superior pig breeding provinces, China Rural Economy 1 (2019) 62–78 (In Chinese).
[83] M. Herrero, P. Havlik, H. Valin, A. Notenbaert, M.C. Rufino, P.K. Thornton, et al., Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems, Proc. Natl. Acad. Sci. U. S. A. 110 (52) (2013) 20888–20893, https://doi.org/10.1073/pnas.1308149110.
[84] Y. Zhang, Q. Sun, J. Xue, C. Yang, Analysis of the synergistic effect of pollution reduction and carbon reduction and its path exploration, China Population, Resources and Environment 32 (2022) 1–13 (In Chinese).
[85] Y. Liu, J. Martinez-Vazquez, A.M. Wu, Fiscal decentralization, equalization, and intra-provincial inequality in China, Int. Tax Publ. Finance 24 (2) (2016) 248–281, https://doi.org/10.1007/s10797-016-9416-1.
[86] J.D. Angrist, J.S. Pischke, Mostly Harmless Econometrics: an Empiricist's Companion, Princeton University Press, Princeton, 2009.