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Does the agricultural co-agglomeration help reduce livestock and poultry pollution? From the perspective of planting and breeding combination in China

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ABSTRACT

Given the problem of considerable livestock and poultry pollution and the differentiation of the regional agricultural layout in China, the combination of planting and breeding (CPB) forms an agricultural co-agglomeration to recycle manure waste into croplands to reduce livestock and poultry pollution. This study aims to evaluate CPB co-agglomeration and empirically examine its effects on livestock and poultry pollution. Based on provincial data from 1997 to 2020 in China, this study constructed three indicators to evaluate CPB co-agglomeration, summarized its temporal and spatial characteristics, and conducted a spatial analysis using the Spatial Lag Model (SLM) to empirically investigate its effect on livestock and poultry pollution. The results showed that: first, from 1997 to 2020, the overall level of CPB co-agglomeration in China declined and the region with higher CPB co-agglomeration level transferred from the central provinces to the west provinces. Second, livestock and poultry pollution in most provinces had significantly positive spatial correlations with adjacent regions. The co-agglomeration of CPB had a significantly positive effect on reducing livestock and poultry pollution; however, the effect had no significant spatial spillover. Third, the breeding industry agglomeration and the moderate expansion of breeding industry scale significantly reduced pollution. These findings provide a reference for reducing livestock and poultry pollution by promoting CPB co-agglomeration to establish a waste recycling system. Optimizing the layout of the planting and breeding industry helps achieve the goal of long-term sustainable development of the breeding industry.

1. Introduction

Green production in agriculture is key to achieving modernized transformation and sustainable development of agriculture in China. With the rapid development of the breeding industry, livestock and poultry manure have become a major problem for environmental protection and human health [1–3]. The Ministry of Agriculture has reported that manure waste amounts to up to a billion tons and has become China's third major pollution source, leading to serious agricultural non-point source and water pollution [4,5]. To solve the contradiction between the expansion of livestock and poultry farming and environmental protection, manure recycling is a critical way to achieve the dual goals of waste management and resource reuse. However, the current recycling ratio of livestock

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manure is only less than 40% [6]. Livestock manure that cannot be recycled is discharged indiscriminately, causing air and water pollution [7]. The loss of livestock manure has led to the overuse of alternative chemical fertilizers. The national fertilizer application rate increased from 78,000 tons in the 1950s to 54.036 million tons in 2019 [8]. Excessive fertilizer application has become the main source of agricultural non-point source pollution [9]. To solve the dual pollution sources of livestock manure and excessive fertilizer, to optimize the layout for the planting and breeding has become the major concern in policy making in China [10]. The central government proposed the objective that the recycling rate of livestock manure should be more than 75%. After 2010s, the central government has issued a series of policies in recent years, requiring to adjust of the industrial structure and regional layout of planting and breeding, and further establish the recycling agricultural system.

The industrial co-agglomeration of industries, proposed by Ellison & Glaeser [11], is one of the possible ways of industrial layout optimization. It characterizes inter-industry co-agglomeration of several industries with horizontal linkages or upstream and downstream linkages in a certain geographic area, which may manifest as cost and commodity correlation, resource concentrating and sharing, waste recycling and knowledge spillover among industries [12–14]. Through these paths, industrial co-agglomeration helps achieve coordinated industrial development, and further improves the regional economic advantages [15]. In the agriculture sector, the high dependence on resources makes agricultural industries prone to agglomeration. The mode of combination of planting and breeding (CPB) proposed by China's government fosters agricultural co-agglomeration through resource sharing and waste recycling [7,16]. The waste recycling system is constructed based on adjacent spatial location through reusing livestock manure and crop straw as vital nutrients (as shown in Fig. 1) [17,18]. It provides a feasible way to reduce pollution from the scaled breeding and improve the coordinated development of planting and breeding [19].

The mode of CPB has attracted increasing attention in academic research and policy discussions. The mode of CPB was initially implemented in traditional within-household agriculture in China, where small-scale livestock rearing matched household-contracted croplands [20]. Consequently, the majority previous research focused on qualitative case studies that explain the resource recycling mechanism and economic and ecological benefits of CPB [21–23]. Economic benefits included cost reduction and efficiency improvement of resource use [24]. Croplands' capacity to absorb livestock manure could lower the cost of pollutant treatment. Furthermore, the geographical proximity of croplands to feedlots could reduce the transportation cost of manure waste. Ecological benefits included reduced fertilizer application and manure emissions [24,25]. The CPB contributed to reducing fertilizer applications, greenhouse gas emissions, and water pollution [26,27], as well as improving resource and energy efficiency [28,29], which led to good economic and environmental outcomes [19]. Furthermore, the agglomeration of breeding and planting optimized the industrial structure and supplied a beneficial way for farmers and entities to adopt cleaner production [30,31]. A few empirical studies have been conducted from the perspective of farmers' willingness and behaviors to adopt CPB [32–34]. It has been claimed that income increases [35], policy subsidy incentives [36], and farmers' knowledge of agriculture [37] are the main determinants stimulating their adoption of CPB.

Collectively, these studies outlined a critical role of CPB for forming a system of recycling waste and reducing pollution. However, there are still research gaps on the mode of CPB and its effect on pollution from the perspective of agricultural co-agglomeration. First, most previous studies on the agglomeration of agriculture as a whole or single breeding industry [28,38,39]. There is a lack of research that clarifies and evaluates the inter-industrial co-agglomeration of planting industry and breeding. It was noted that the geographic agglomeration of breeding industry shows a tendency to increase in China [40]. Determined by resource endowment, agricultural productivity, market and policy, the agglomeration degree of breeding industry presented spatial heterogeneity. The hotpots of production with a higher agglomeration degree are mainly in southwest Sichuan Basin, Northeastern China and North China Plain [41]. For the specific species of animals, the area with higher agglomeration degree of live pigs and meat ducks also showed an evolution trend from north to south [42,43]. By contrast, the quantity of grass-feeding livestock (beef cattle, sheep and dairy cow) had a higher growth rate in northern China than that in the south [44,45]. As for the changes of planting layout. Li et al. [38] found that from 1981 to 2008, the planting industry shifted to the south and west of China, and the national spatial agglomeration of the planting industry strengthened. However, it is found that croplands are overloaded with livestock manure in the majority provinces [39,46]. The CPB co-agglomeration level needs to be evaluated and analyzed thoroughly.

Secondly, the exist qualitatively research on individual cases were insufficient for revealing the industrial characteristics of the CPB

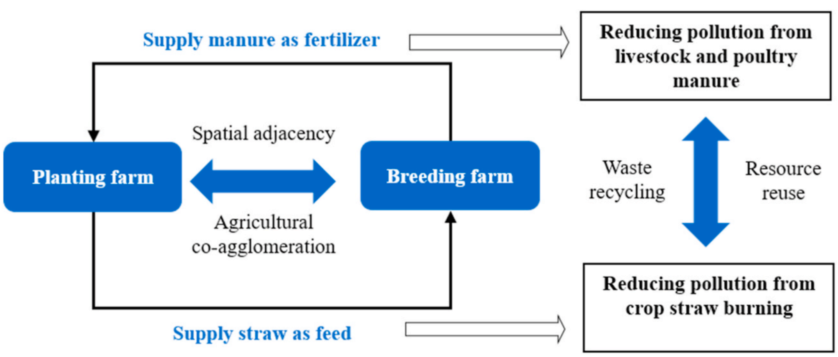

Fig. 1. System of waste recycling and pollution reduction of the CPB mode.

mode. The macroscopic industrial planning and layout cannot be ignored. In practice, the traditional within-household CPB mode has gradually changed with the transformation of agriculture into a large-scaled and specialized. Across China, rural households' share in livestock rearing and crop planting declined from 71% in 1986 to 12% in 2017 [5]. Contrary to the mixed mode of planting and breeding in small farm backyards, the specialization of small farmers also driven the separation of planting and breeding [47]. The breeding industry's scale expansion and industrial transition also made feedlots far from croplands [38]. Consequently, the decoupling of breeding and planting industry has become increasingly prominent in China, causing multiple pollution problems in agriculture [3,5]. Given the decoupling trend of the planting and breeding, due to the necessity of optimizing agricultural industrial layout, it is urgent to explore the characteristics of regional planting and breeding co-agglomeration at the mesoscopic industry level.

Furthermore, few studies have empirically analyzed the effect of CPB co-agglomeration on pollution. Given the trend of scale operation of breeding industry, the spatial spillover of livestock and poultry pollution cannot be ignored. Prior studies mostly focused on the breeding agglomeration on pollution [48]. Moreover, livestock and poultry pollution may have a strong spatial correlation, and CPB co-agglomeration is based on the proximity of industrial positions. It suggests that the effect of CPB co-agglomeration on pollution may have spatial spillover. Owing to the homogeneity of factor endowments, technology, and economic levels in neighboring regions, there was a kind of "stickiness" of the agricultural industry in adjacent areas—farmers and corporations tended to avoid environmental policy regulation and prioritize surrounding areas with convenient transportation and small technological differences [49]. Second, livestock-rearing activities in one area had a demonstrative effect on adjacent areas. Mutual imitation and catching up among farmers led to the spillover of knowledge and technology, which strengthened the spatial interaction of factors [50]. Therefore, it is necessary to investigate the effects of CPB on regional livestock and poultry pollution by incorporating the possibility of spatial dependence.

The motivation of this study was the notice of China's urgent demand for agricultural industrial layout optimization of agriculture when seeking the dual goal of agriculture growth and pollution reduction. This study contributed to the literature in three ways. First, on the basis of previous studies on the agricultural agglomeration as a whole or single industrial layout and agglomeration, we further evaluated the inter-industrial co-agglomeration of planting industry and breeding industry. By adopting multiple indicators to evaluate the co-agglomeration, our study offers credible evidence to the background of the geographic decoupling of planting and breeding industries. The results may provide empirical reference for the macroeconomic regulation of China's nationwide and regional crop-livestock geographical layout. Secondly, different from the microscopic studies describing the farm-level integrated crop-livestock system from the perspective of resource allocation and pollution emission, this study focused on the co-agglomeration of planting and breeding industries perspective of mesoscopic industrial layout. We adopted the industrial data of 31 provinces in 1997–2020 to characterize the long-term temporal evolution and nationwide spatial layout of CPB co-agglomeration. This contributes to the field by providing a holistic description of the regional agricultural co-agglomeration evolution in China. Thirdly, given the trend of scale operation of breeding industry, we examined the effect of CPB co-agglomeration on pollution on the premise of considering the spatial correlation of livestock pollution and discovered that the CPB co-agglomeration had significant effect on reducing livestock and poultry pollution. By addressing this issue, this study provides supplementary macro evidence for studies on pollution emissions within livestock farms, and offers valuable insights to reducing regional livestock pollution through planting and breeding co-agglomeration. The rest of this paper was organized as follows. Section 2 introduced the data materials and methods, including the data sources, measurement of CPB co-agglomeration, variables and estimation methods of spatial analysis. Further, Section 3 presented the results of the CPB co-agglomeration and discussed the study's empirical results. Finally, Section 6 presented the conclusions and policy implications.

2. Materials and methods

2.1. Data sources

This study applied provincial data from 1997 to 2020 in China collected from *China Statistical Yearbook, China Population & Employment Statistics Yearbook, and China animal husbandry and veterinary yearbook.* The agricultural agglomeration measurement was from 1997 to 2020, in which provincial grain and meat yield required by location entropy calculation are from *China Rural Statistical Yearbook*. Further, data of municipal grain and meat yield required by the special GINI index were from statistical yearbooks of each province. The spatial models applied the provincial data of 30 provinces in 2011–2015 because the variable of breeding industry pollution was summarized in *Annual statistic report on environment in China* only in 2011–2015.[1] As the Hainan Province is a geographically isolated island, it was excluded from the sample of spatial analysis.

2.2. Measurement of CPB co-agglomeration

The co-agglomeration of planting and breeding refers to the matching of scale and spatial layout [51]. The measurements of co-agglomeration include Ellsion–Glaeser (EG) index [13], the Duranton–Overman (DO) index [52], the relative difference of location entropy index [53,54] and spatial Gini Coefficients [55]. Considering the data availability and regional comparability, we constructed 3 indicators to accurately measure provincial CPB co-agglomeration.

[1] The statistical indicator regarding COD has been changed to *total volume of COD discharged of large sized livestock farms pollution* in the 2016–2019, which is not consistent with the indicator of 2011–2015.

2.2.1. Basic ratio indicator of CPB co-agglomeration (CPB_r)

Firstly, referring to Lu and Feng [48] revealing the load of cropland to absorb manure waste, we constructed a basic ratio indicator (*CPB_r*) to reveal the gap of breeding and planting industries. The indicator of *CPB_r* was constructed using the ratio of meat yield to grain area, as shown in Equation (1), where $meat_j$ is the output of meat in province *j*, and $grainarea_j$ is the grain area of province *j*. A higher ratio indicates that the breeding industry has a more rapid growth than the planting industry, indicating a lower level of CPB co-agglomeration. Notably, we used the grain area rather than the grain output to better reveal the bearing capacity of the planting farm, as the grain area directly determines how much manure can be absorbed. Grain output may be affected by production technology and planting strategy, which may induce bias in CPB measurement.

$$CPB\_r_j = \frac{meat_j}{grainarea_j} \tag{1}$$

2.2.2. Location entropy indicator of CPB co-agglomeration (CPB_l)

Furthermore, to better reveal the industrial association and spatial dependence of CPB co-agglomeration, we adopted the indicators commonly used to measure the manufacturing and producer services industrial co-agglomeration—the relative difference of single industrial agglomeration. Single industrial agglomeration is measured using location entropy and the Spatial GINI Coefficient [53,54,56,57]. Location entropy reflects the degree of specialization and industry advantage in a region and can eliminate the interference of the regional scale, which is commonly used to measure industrial agglomeration. This is expressed by Equation (2):

$$LQ_{ij} = \frac{\dfrac{Y_{ij}}{\sum_{i=1}^{m} Y_{ij}}}{\dfrac{\sum_{j=1}^{n} Y_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} Y_{ij}}}, i = \begin{cases} 1, planting\ industry \\ 2, breeding\ industry \end{cases} \tag{2}$$

where LQ_{ij} denotes the location entropy of industry *i* in province *j*. Further, Y_{ij} denotes the output value of the planting industry ($i = 1$) or breeding industry ($i = 2$) in province *j*, represented by *provincial grain yield* or *meat yield*. $\sum_{i=1}^{m} Y_{ij}$ denotes the total output value of the planting and breeding industries in province *j*, represented by the *provincial gross output value of agriculture*.[2] Moreover, $\sum_{j=1}^{n} Y_{ij}$ denotes the total output value of the planting industry ($i = 1$) or breeding industry ($i = 2$) of all provinces, represented by *national grain yield* or *national meat yield*, respectively. $\sum_{i=1}^{m}\sum_{j=1}^{n} Y_{ij}$ denotes the total output value of the planting and breeding industries of all provinces, represented by the *national total output of agriculture*. The higher the value of LQ_{ij}, the higher the level of provincial industrial agglomeration. When $LQ_{ij} > 1$, the industrial development in the province is relatively advantageous across the nation.

Based on the location entropy of the planting and breeding industries, the indicator of CPB co-agglomeration can be constructed using the relative difference, as shown in Equation (3), where CPB_l_j is the CPB co-agglomeration indicator of province *j* by location entropy, and LQ_{1j} and LQ_{2j} represent the location entropy of the planting and breeding industries of province *j*, respectively. The higher the indicator, the higher the CPB co-agglomeration level.

$$CPB\_l_j = 1 - \frac{|LQ_{2j} - LQ_{1j}|}{LQ_{2j} + LQ_{1j}} \tag{3}$$

2.2.3. Spatial GINI coefficient indicator of CPB co-agglomeration (CPB_g)

The Spatial GINI Coefficient is another measure of industrial agglomeration proposed by Krugman [58]. This reflects the spatial agglomeration of industries in different geographical units, denoted by Equation (4).

$$GINI_{ij} = \frac{1}{2n^2\mu}\sum_{m=1}^{n}\sum_{k=1}^{n}|\lambda_{im} - \lambda_{ik}|, i = \begin{cases} 1, planting\ industry \\ 2, breeding\ industry \end{cases} \tag{4}$$

where $GINI_{ij}$ is the Spatial GINI Coefficient of industry *i* in province *j*. Further, *n* is the number of cities in a certain province,[3] and λ_{im} is the ratio of the yield of the planting industry ($i = 1$) or breeding industry ($i = 2$) of city *m* to that of province *j*. Moreover, λ_{ik} is the ratio of the yield of the planting industry ($i = 1$) or breeding industry ($i = 2$) of city *k* to that of province *j* ($m \neq k$), and μ is the mean of the yield ratio. The Spatial GINI Coefficient was in the range (0–1). As defined in the measurement of location entropy, the output of the planting industry is represented by the city-level *grain yield, and* the city-level meat yield represents the output of the breeding industry. The higher the Spatial GINI Coefficient, the higher the industry's agglomeration level.

The CPB co-agglomeration indicator can be constructed using Equation (5), where CPB_sg_j is the co-agglomeration indicator of province *j* by the Spatial GINI Coefficient, and $GINIp_j$ and $GINIb_j$ represent the spatial GINI coefficients of the planting and breeding

[2] This is denoted as the regional gross output value of Agriculture, Forestry, Animal Husbandry and Fishery and related indices.

[3] City-level data of industrial output are applied to calculate the provincial Spatial GINI Coefficient.

industries of province *j*, respectively. The higher the indicators, the higher the level of CPB co-agglomeration.

$$CPB\_g_j = 1 - \frac{|GINI_{2j} - GINI_{1j}|}{GINI_{2j} + GINI_{1j}} \tag{5}$$

2.3. Models and variables of spatial analysis

2.3.1. Variables

(1) Dependent variable

Pollution from livestock rearing *(PCOD)*. The total chemical oxygen demand emission (COD) was the predominant emission and most commonly used to reveal the pollution of livestock manure. We adopted the ratio of COD emission to the output value of livestock and poultry production as the proxy of pollution. The data were from *Annual statistic report on environment in China*.

(2) Independent variables

CPB co-agglomeration *(CPB_r, CPB_l and CPB_g)*. As defined in the previous section regarding the measurement of CPB co-agglomeration, a basic ratio indicator and two relative difference indicators were used to represent the provincial CPB co-agglomeration level. The ratio indicator *CPB_r* is a negative indicator defined as the ratio of meat yield to grain area. *CPB_l and CPB_g* are positive indicators. *CPB_l* is the co-agglomeration indicator of location entropy, and *CPB_g* is the co-agglomeration indicator of the Spatial GINI Coefficient.

(3) Control variables

Referring to Pan [59] and Zhao et al. [31], we incorporated other determinants of livestock and poultry pollution from the aspects of the development of the breeding industry, local economic development and industrial structure, and government environmental supervision. The specific control variables are as follows.

Agglomeration of planting industry *(Agglo_gl, (Agglo_gg)* and breeding industry *(Agglo_ml, Agglo_mg)*. The agglomeration of single industries may also affect pollution emissions. In line with the co-agglomeration measurements, the agglomeration of a single industry was also measured using local entropy and the Spatial GINI Coefficient.

The scale of livestock and poultry farms *(Scale)*. The scale of livestock and poultry farms is the primary determinant of pollution. As there are no statistics on the total scale of provincial breeding farms. We used the number of breeding farms (or households) to calculate the relative scale, referring to Kong [60]. In Equation (6), $Scale_j$ denotes the scale of the breeding farm of province *j*. Further, $i = 1,2,3,4,5$, respectively, denotes the five main types of breeding animals: pigs, dairy cows, beef cattle, layers, and broilers. Moreover, x_{1i}, x_{2i}, and x_{3i} denote the number of small-, medium-, and large-scale farms of type *i*, respectively.[4] The range of $Scale_j$ is (1, 3). The closer the *Scale* is to 1, the smaller the breeding farm scale. Data were obtained from the *China animal husbandry and veterinary yearbook*.

$$Scale_j = \frac{\sum \frac{x_{1i} + 2x_{2i} + 3x_{3i}}{x_{1i} + x_{2i} + x_{3i}}}{i}, (i = 1, 2, 3, 4, 5) \tag{6}$$

Share of the breeding industry (*Livestock*). *Livestock* is the ratio of the output value of the livestock industry to the GDP. Table 1 presents definitions and descriptions of the variables.

Environmental Regulations *(Regulation)*. Environmental regulation by local governments can reduce pollution emissions by regulating the production mode and pollution control measures of enterprises or farms. Referring to Lu and Feng [55], we defined this as local government investment in environmental governance. Data were obtained from the *China Environmental Yearbook*.

Economic development *(PerGDP)*. Economic development is provincial GDP per capita (converted to 2011 price levels). Data were obtained from *China Statistical Yearbook*.

Industrial structure *(Tertiary)*. The industrial structure reflects the relative importance of the three industries within a region. *Tertiary* denotes the ratio of the output value of the tertiary sector to the GDP. Data were obtained from *China Statistical Yearbook*.

Agricultural population *(Agrpop)*. We define the agricultural population as the ratio of people engaged in agriculture to the total population of a province. Data were obtained from the *China population & employment statistics yearbook*.

[4] The scale of each type of animal is defined as follows: the slaughter number of pigs is 50–499 for a small scale, 500–2999 for a medium scale, and more than 3000 for a large scale. The stock number of dairy cattle is 10–49 for a small scale, 50–199 for a medium scale, and more than 200 for a large scale. The slaughter number of beef cattle is 10–49 for a small scale, 50–499 for a medium scale, and more than 500 for a large scale. The stock number of laying hens is 500–9999 for a small scale, 10,000–49999 for a medium scale, and more than 50,000 for a large scale. The slaughter number of broilers was 2000–9999 for a small scale, 10,000–49999 for a medium scale, and more than 50,000 for a large scale.

Table 1
Definition and description of variables.

Definition of variables		N	Mean	Sd.	Min.	Max.
Dependent variable						
PCOD	Ratio of COD emission to output value of breeding industry	150	395.406	213.105	63.061	1027.695
Independent variables						
CPB_r	Basic ratio indicator of CPB co-agglomeration (%)	150	0.993	0.615	0.162	3.500
CPB_l	Location entropy indicator of CPB co-agglomeration	150	0.146	0.146	0.378	0.995
CPB_g	Spatial GINI Coefficient indicator of CPB co-agglomeration	150	0.872	0.129	0.271	0.999
Control variables						
Agglo_ml	Location entropy of breeding industry	150	1.051	0.370	0.494	2.437
Agglo_mg	Spatial GINI Coefficient of breeding industry	150	0.402	0.163	0.127	0.952
Agglo_gl	Location entropy of planting industry	150	1.005	0.459	0.256	2.460
Agglo_gg	Spatial GINI Coefficient of planting industry	150	0.394	0.128	0.122	0.854
Scale	Scale of livestock and poultry farm	150	1.217	0.120	1.068	1.693
Livestock	Ratio of output value of breeding industry to GDP (%)	150	0.053	0.027	0.003	0.113
Regulation	Ratio of government investment in environmental governance to GDP (%)	150	1.538	0.794	0.400	4.660
Tertiary	Ratio of output value of the tertiary sector to GDP (%)	150	0.435	0.091	0.321	0.979
PerGDP	Per capita GDP (10,000 yuan/person)	150	1.370	0.185	1.081	1.828
Agrpop	Ratio of agricultural population to total population (%)	150	0.596	0.208	0.057	0.926

2.3.2. Estimation models

(1) Baseline OLS model

We constructed an empirical model to examine the effects of CPB co-agglomeration on pollution. First, the baseline model applies the ratio indicator of CPB co-agglomeration, as specified in Equation (7). X_{it} is the vector of control variables, α_0, α_1, and β are associated parameters or parameter vectors to be estimated, a_i represents the individual effect, and ε_{it} is the random error term.

$$ln\ PCOD_{it} = \alpha_0 + \alpha_1 CPB\_r_{it} + X_{it}\beta + a_i + \varepsilon_{it} \tag{7}$$

Furthermore, we extended the model to apply spatial indicators to represent the co-agglomeration of CPB. Referring to Cheng and Yu [61], we also introduced a single industrial agglomeration indicator for a single industry to control for its effect on pollution. The extended model is expressed in Equation (8).

$$ln\ PCOD\_A_{it} = \beta_0 + \beta_1 CPB_{it} + \beta_2 Agglo\_g_{it} + \beta_3 Agglo\_m_{it} + X_{it}\theta + b_i + \omega_{it} \tag{8}$$

Here, CPB_{it} is the relative difference indicator of co-agglomeration *CPB_l and CPB_g*, and $Agglo\_g_{it}$ and $Agglo\_m_{it}$ are agglomeration of the planting and breeding industries, respectively. Further, $\beta_0 \sim \beta_3$, θ are associated parameters or parameter vectors to be estimated, b_i represents the individual effect, and ω_{it} is the random error term.

(2) Spatial correlation analysis

We adopted global and local spatial autocorrelation tests to examine the possible spatial correlation inherent in the samples. If the results indicate a spatial correlation between livestock and poultry pollution, spatial econometric models must be applied. In the global spatial autocorrelation test, the Moran's Index ($Moran's\ I$) was used to test the spatial dependence of the breeding industry pollution [62]. In the local spatial autocorrelation test, local Moran's Index (I_i) and Moran's scatterplot were further applied to supply supplementary details of provincial spatial correlation. Detailed procedure could be found at Supplementary files.

(3) Spatial econometric model

A spatial econometric model was applied to examine the effects of CPB co-agglomeration on pollution. Typical spatial models include the Spatial Lag Model (SLM), Spatial Error Model (SEM), and Spatial Durbin Model (SDM). The SDM shown in equation (9) is a general starting point for examining spatial association.

$$Y_{it} = \rho W_i Y_t + X_{it}\beta + W_i X_t \theta + \alpha_i + \varepsilon_{it} \tag{9}$$

Here, Y_{it} is the pollution from livestock and poultry production, $\rho W_i Y_t$ ($W_i Y_t = \sum_{j=1}^{n} w_{ij} y_{jt}$) denotes the spatial effect of pollution in neighboring province j in province i, w_{ij} is the spatial weight matrix, and ρ is the spatial autocorrelation coefficient. A significantly positive ρ indicates a strong spatial effect of pollution in neighboring regions, and X_{it} is a vector of an explanatory variable with the associated parameters β. Further, $W_i X_{it}\theta$ ($W_i X_t \theta = \sum_{j=1}^{n} w_{ij} x_{jt}$) denotes the spatial effect of a series of determinants of neighboring province j on province i, θ are associated parameters, and α_i denotes the regions' individual effects. Additionally, ε_{it} ($\varepsilon_{it} \sim (0, \sigma^2)$) are error terms that are normally independently and identically distributed.

When $\theta = 0$, there are no spatial interactions between the determinants of neighboring provinces and the local, provincial pollution. The spatial model specification becomes an SLM as shown in equation (10).

$$Y_{it} = \rho W_i Y_t + X_{it}\beta + \alpha_i + \varepsilon_{it} \tag{10}$$

Furthermore, when there is no significant spatial correlation of pollution between neighboring provinces, the spatial model turns into SEM, incorporating the spatial effect in the random error term, which is specified as equation (11).

$$Y_{it} = X_{it}\beta + \alpha_i + \varepsilon_{it}, \varepsilon_{it} = \lambda W_i \varepsilon_t + \mu_{it} \tag{11}$$

where λ is the spatial error coefficient, and μ_{it} and ε_{it} are the error terms. Based on the baseline OLS models (7) and (8), the spatial model can be specified as equations (12) and (13), respectively. We used the SDM form as the starting point to examine the spatial effect.

$$lnPCOD\_S_{it} = \alpha_0 + \rho W_i \ ln \ PCOD_t + \alpha_1 CPB\_r_{it} + X_{it}\beta^{'} + W_i CPB\_r_{it}\theta + W_i X_{it}\theta^{'} + a_i + \varepsilon_{it} \tag{12}$$

$$\begin{aligned} lnPCOD\_SA_{it} = {} & \beta_0 + \rho W_i \ ln \ PCOD_t + \beta_1 CPB_{it} + \beta_2 Agglo\_g_{it} + \beta_3 Agglo\_m_{it} \\ & + X_{it}\beta^{'} + W_i CPB_{it}\theta_1 + W_i Agglo\_g_{it}\theta_2 + W_i Agglo\_m_{it}\theta_3 + W_i X_{it}\theta^{'} + a_i + \varepsilon_{it} \end{aligned} \tag{13}$$

3. Empirical results and discussions

3.1. Decoupling of planting and breeding production

To discover the changes in the layout of the planting and breeding industries, we summarized the growth rate of provincial grain and meat yields from 1997 to 2020 (Fig. 2 (a) and (b)). Considering the reality of China's agricultural development, grain yield, which contributes the largest share, was used to represent the development of the planting industry. The meat yield of livestock and poultry production was adopted to represent the development of the breeding industry. The results indicated that the spatial layouts of the planting and breeding industries were separated. Higher grain yield growth rates were observed in the northeast, whereas higher meat yield growth rates were observed in the west.

Specifically, as shown in Fig. 2(a), grain yield in most provinces increased from 1997 to2020,[5] with a significant change in spatial layout. Higher growth rates were observed in northern China, with the share of grain yield in the north increasing from 45.7% in 1997 to 59.3% in2020.[6] This indicates that the core area of China's grain production has shifted from south to north, with fertile land resources and climatic advantages. Heilongjiang Province (HLJ), located in northeastern China, had the highest grain yield growth rate (142%). The provinces with significantly declining grain production were mainly distributed in two regions: the first was southeast coastal area, including Shanghai (SH) city (−60.3%), Zhejiang (ZJ) province (−59.4%), and Fujian (FJ) province ((−47.78%). Although it was due to these provinces' scarcity of land resources, rapid economic development in this region has brought more non-agricultural employment opportunities, which has driven the dominant industry to transform from agriculture to secondary and tertiary industries. The other area with declining grain production was the west-central region, including Qinghai (QH) province (−15.83%), Guangxi (GX) province (−11.32%), and Chongqing (CQ) province (−6.59%), which have an unsuitable climate and terrain for grain production.

In comparison, as shown in Fig. 2(b), except BJ (−91.27%), SH (−84.47%) and ZJ province (−10.62%), meat output in other provinces showed an increasing trend from 1997 to 2020. Northwest China had a high growth rate, leading to a change in the spatial layout of meat production. The share of meat yield in the southern provinces decreased from 58.25% in 1997 to 55.42% in 2020. Under strict environmental protection policies and the transformation of the industrial structure, the number of pigs slaughtered in the southern provinces has reduced significantly. Northern provinces have gradually undertaken pig rearing based on the advantages of resource endowment and feed supply [39,63].

The different growth rates of planting and breeding indicated the decoupling trends of the two industries. First, it was restricted by geographic and climatic conditions and regional resource endowments. The direction of regional industrial development and planning may diverge and may not support CPB. Moreover, the transition to rearing livestock on large industrial farms has resulted in the decoupling of small-scale planting and large-scale breeding [21]. With the expansion of the breeding scale, the feedlots had to move to remote areas far from the croplands—there was insufficient arable cropland to consume livestock manure [64]. Therefore, the decoupling of planting and breeding made it difficult to form CPB co-agglomerations within a region, which may lead to further difficulties in pollution treatment.

3.2. Temporal and spatial characteristics of CPB co-agglomeration

3.2.1. Temporal evolution of CPB co-agglomeration

We measured the provincial and average national levels of CPB co-agglomeration indicators from 1997 to 2020. The overall

[5] There are nine provinces with declining grain yield: BJ, SH, ZJ, FJ, CQ, GD, GX, HI and QH.

[6] The northern provinces include: SD, HA, SX, SN, GS, QH, XJ, HE, TJ, BJ, NM, LN, JL, HLJ, NX and XZ. The southern provinces include: JS, AH, HB, CQ, SC, YN, GZ, HN, JX, GX, GD, FJ, ZJ, SH.

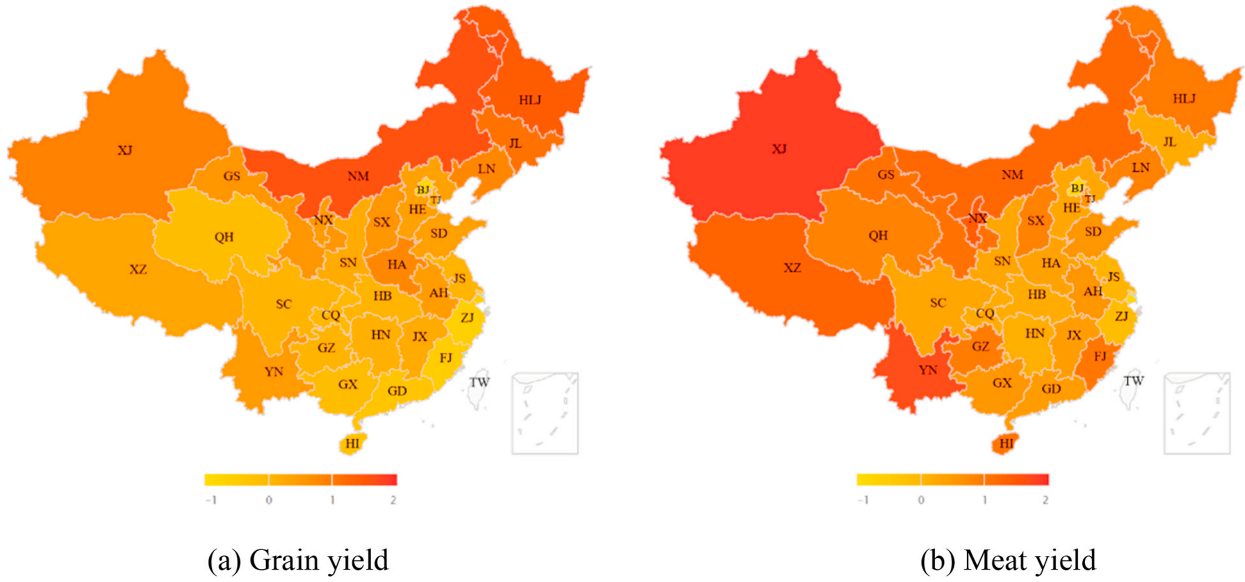

Fig. 2. Growth rate of grain yield (a) and meat yield (b) from 1997 to 2020 (%)
Data source: *China Rural Statistical Yearbook (1998–2021)*.
Note: Abbreviations of provinces are marked in Fig. 2. AH: Anhui; BJ: Beijing; CQ: Chongqing; FJ: Fujian; GD: Guangdong; GS: Gansu; GX: Guangxi; GZ: Guizhou; HA: Henan; HB: Hubei; HE: Hebei; HN: Hunan; HI: Hainan; HLJ: Heilongjiang; JL: Jilin; JS: Jiangsu; JX: Jiangxi; LN: Liaoning; NM: Inner Mongolia; NX: Ningxia; QH: Qinghai; SC: Sichuan; SD: Shandong; SH: Shanghai; SN: Shannxi; SX: Shanxi; TJ: Tianjin; TW: Taiwan; XJ: Xinjiang; XZ: Tibet; YN: Yunnan; ZJ: Zhejiang.

temporal evolution of CPB co-agglomeration was shown in Fig. 3. Generally, the ratio indicator *CPB_r* showed a rising trend, *CPB_l* and *CPB_g* showed a decreasing trend, which indicated a general decline of CPB co-agglomeration level. Specifically, the first stage was from 1997 to 2003, the three indicators consistently showed a decreasing of CPB co-agglomeration. Secondly, in 2003–2006, *CPB_r* decreased with a fluctuation, *CPB_l* slightly decreased and *CPB_g* increased. It suggested that the gap between the total output of planting and breeding narrowed in that period (*CPB_r* decreased), and the co-agglomeration at the city level within a province increased (*CPB_g* increased). However, the co-agglomeration at provincial industrial level was not achieved (*CPB_l* decreased). Combining the evolution of the three indicators, it appeared that the provincial breeding industry expanded rapidly in the period of 1997–2003 but was still within the range of the carrying capacity of the planting industry. Therefore, although the output gap widened, it manifested as a slight increase in co-agglomeration within a province.

In the third stage (2006–2017), the three indicators consistently showed a generally decreased co-agglomeration level. This indicated that the gap between breeding and planting continued to widen. Moreover, increasing livestock manure exceeded the cropland load. This was partly due to the continuous increase in meat yield relative to grains. Another important reason was the geographical mismatch between provinces dedicated to developing planting and breeding industries. There was a gradual trend in the separation of planting and breeding industries. In the long run, regional specialization and industrial advantages had solidified, further hindering CPB co-agglomeration. After 2017, *CPB_r* turned to decrease and *CPB_l* turned to increase, indicating an increased CPB co-agglomeration at province level. *CPB_g* still decreased in this period, suggesting the layout of planting and breeding industries continuously was getting even more mismatched at city level.

To explain the fluctuations of *CPB_g* curve, we calculated the Spatial GINI Coefficient of each industry from 1997 to 2020. As shown in Fig. 4, the planting industry agglomeration gradually increased, except for a slight decrease from 2000 to 2003. After 2016, the planting industry agglomeration increased rapidly to the range of 0.502–0.503. Contrary to the planting industry, the breeding industry agglomeration exhibited a fluctuating downward trend. From 1996 to 2004, the agglomeration level increased slowly. After 2006, the breeding industry agglomeration leveled off after a sharp decline and kept in the range of 0.436–0.441. In 2019 and 2020, the breeding industry agglomeration dropped to less than 0.430. This indicates that at the national average level, the centralization of grain production and the decentralization of meat production provided evidence for separating the planting and breeding industries.

3.2.2. *Spatial heterogeneity of CPB co-agglomeration*

To further investigate the spatial heterogeneity of CPB co-agglomeration, provincial-level indicators of CPB co-agglomeration were calculated and summarized from 1997 to 2020. Fig. 5 shows the results of provincial CPB co-agglomeration in 1997, 2007, and 2020 of

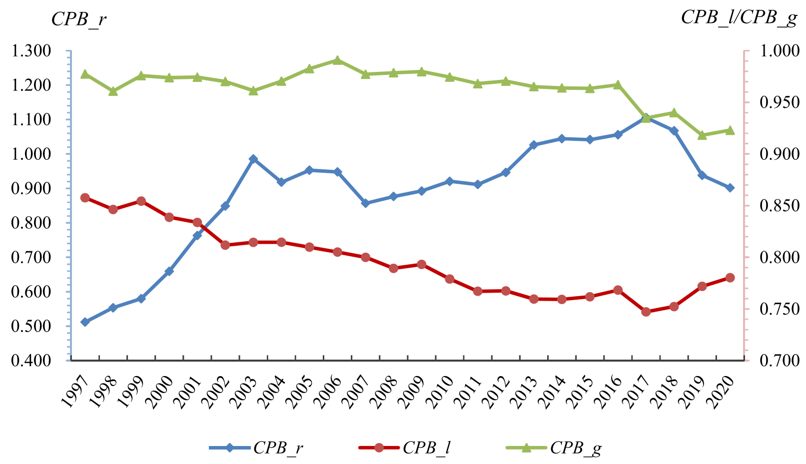

Fig. 3. National CPB co-agglomeration level in 1997–2020
Data source: *China Rural Statistical Yearbook (1998–2021).*

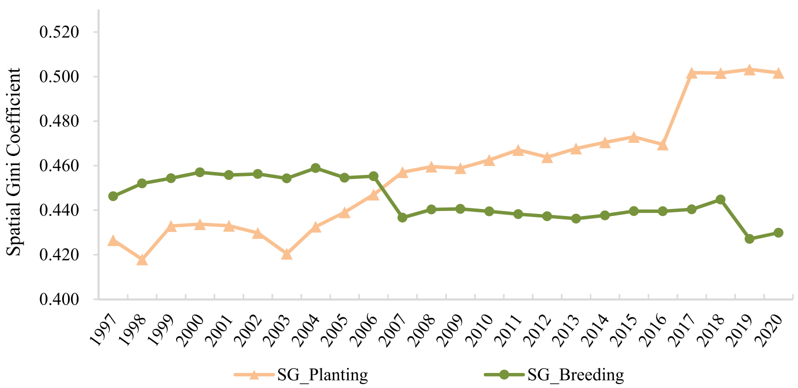

Fig. 4. Spatial GINI Coefficient of planting and breeding industries in 1997–2020
Data source: *China Rural Statistical Yearbook (1998–2021).*

the three indicators.[7] As *CPB_r* of most provinces increased in this period (Fig. 5 (A)–(C)), China's growth in the breeding industry in most regions increased more rapidly than that of the grain area.[8] As for the results of *CPB_l and CPB_g*, the overall CPB co-agglomeration levels in most provinces decreased from 1997 to 2020 (Fig. 5 (D)–(I)). This finding aligned with the results of the temporal evolution of the national average CPB co-agglomeration. The variation in CPB co-agglomeration showed significant spatial heterogeneity. In 1997, there were higher CPB co-agglomeration in central region (Fig. 5 (A), (D) and (G)). After the evolution of 24 years, the co-agglomeration of CPB in the majority of eastern provinces decreased, whereas it increased in the west, and remained stable or decreased slightly in the center and northeast. Taken together with the previous temporal analysis (Fig. 3), this suggested that the unbalanced development and decoupling of the planting and breeding industries within a region are the causes of spatial heterogeneity. This may be due to variations in resource endowments and industry structure adjustments among provinces. The provinces with the highest levels of CPB co-agglomeration in 1997 produced a significant amount of grain and were primarily located in the northeast and center. This demonstrates that China's traditional agricultural production in these regions has achieved a within-household mode of CPB co-agglomeration. A higher level of CPB co-agglomeration in the western region was caused by rapid growth in planting and breeding due to the relaxation of environmental and climatic restrictions effected by technological progress. While experiencing economic change, the southeastern area concentrated on growing its secondary and tertiary sectors. The decoupling of planting and breeding was due to the decreased grain area.

[7] All the figures showing provincial CPB co-agglomeration from 1997 to 2020 measured by CPB_r, CPB_l, and CPB_g can be found in supplementary files.
[8] Five of the all provinces are with decreasing ratio: HLJ, NM, SX, SN, and GS.

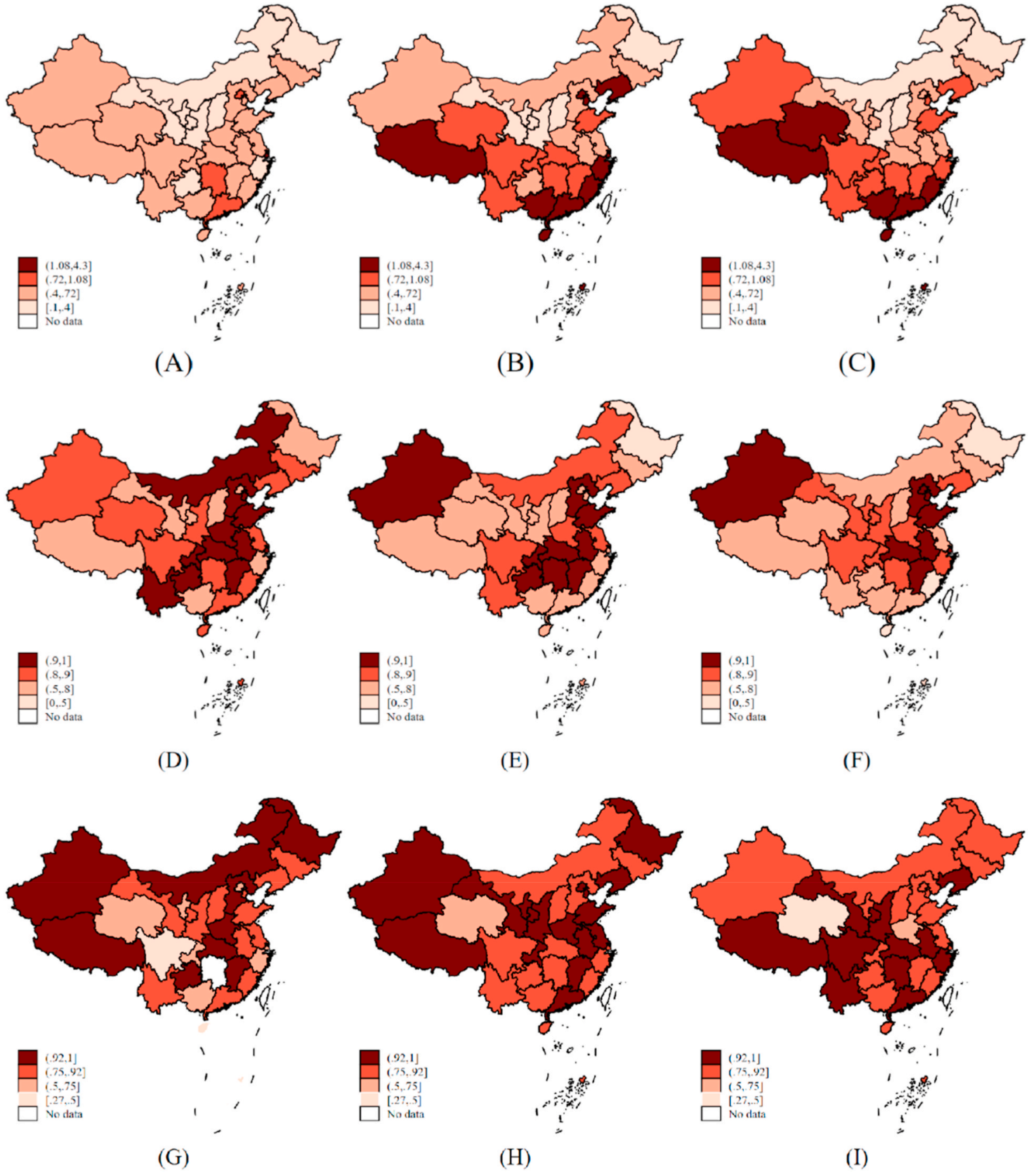

Fig. 5. Spatial heterogeneity of CPB co-agglomeration level in 1997, 2008, and 2020. (A)–(C) are provincial CPB co-agglomeration level measured by basic ratio indicator (*CPB_r*). (D)–(F) are provincial CPB co-agglomeration level measured by location entropy indicator (*CPB_l*). (G)–(I) are provincial CPB co-agglomeration level measured by Spatial GINI Coefficient indicator (*CPB_g*)
Data source: *China Rural Statistical Yearbook (1998–2021)*.

3.3. Empirical results of spatial analysis

3.3.1. Result of spatial autocorrelation analysis

The results of the global spatial autocorrelation tests were presented in Table 2. *Moran's I* for 2011–2015 was significant at the 1%

Table 2
Results of *Moran's I* of livestock and poultry pollution.

Year	*Moran's I*	Z	*P*-value
2011	0.322	3.052	0.001
2012	0.317	3.016	0.001
2013	0.338	3.203	0.001
2014	0.356	3.340	0.000
2015	0.412	3.828	0.000

Data source: China's environmental yearbook (2012–2016).

level, indicating that livestock and poultry pollution had a significant spatial autocorrelation. Generally, *Moran's I* showed a fluctuating upward trend during 2011–2015 and rose sharply from 2014 to 2015, indicating that livestock and poultry pollution had a spatial propensity to cluster. Additionally, Fig. 6 (a, b) displays Moran's scatterplot based on the outcomes of the local spatial autocorrelation tests conducted in 2011 and 2015. Most of the points in Moran's scatterplot were spread in the first and third quadrants, showing that the pollution levels in neighboring provinces were similar to pollution intensity (high–high or low–low). This demonstrated that livestock and poultry pollution in neighboring provinces are mostly positively spatially correlated.

Furthermore, we sorted the quadrant distribution of the provinces in Moran's scatterplot to conduct a detailed analysis of the pollution situation, as shown in Table 3. The first quadrant was dominated by provinces in the northern and western regions and did not change from 2011 to 2015. The high–high relationship between these provinces was partially due to the extensive free-range rearing of livestock and poultry based on underdeveloped economics. Moreover, the supervision of local governments was insufficient, leading to major manure pollution problems. The central and eastern coastal provinces were mostly located in the third quadrant and have a low–low relationship. This positive interaction benefited from substantial regional efforts toward pollution control and demonstration. Nevertheless, from 2011 to 2015, the number of provinces in the third quadrant decreased, implying that livestock and poultry pollution had become serious.

3.3.2. Results of spatial panel models

We adopted the test of *Moran's I* to identify the spatial correlations. As Table 4 shows, *Moran's I* test results for all three indicators were significant, suggesting that a spatial econometric model is necessary. To justify the fitness of the different spatial models, multiple tests of LM error and Robust LM-error (for the fitness of the SEM model), LM lag, and Robust LM-lag (for the fitness of the SLM model) were performed. For all co-agglomeration indicators, the SLM model is better because both the tests of the LM lag and RLM-lag significantly reject the null hypothesis, and the Robust LM-error results are not significant. Therefore, the SLM is more appropriate for spatial analysis in this study. This suggests a spatial correlation of livestock and poultry pollution between neighboring provinces, but the effect of CPB co-agglomeration on pollution has no significant spatial spillover.

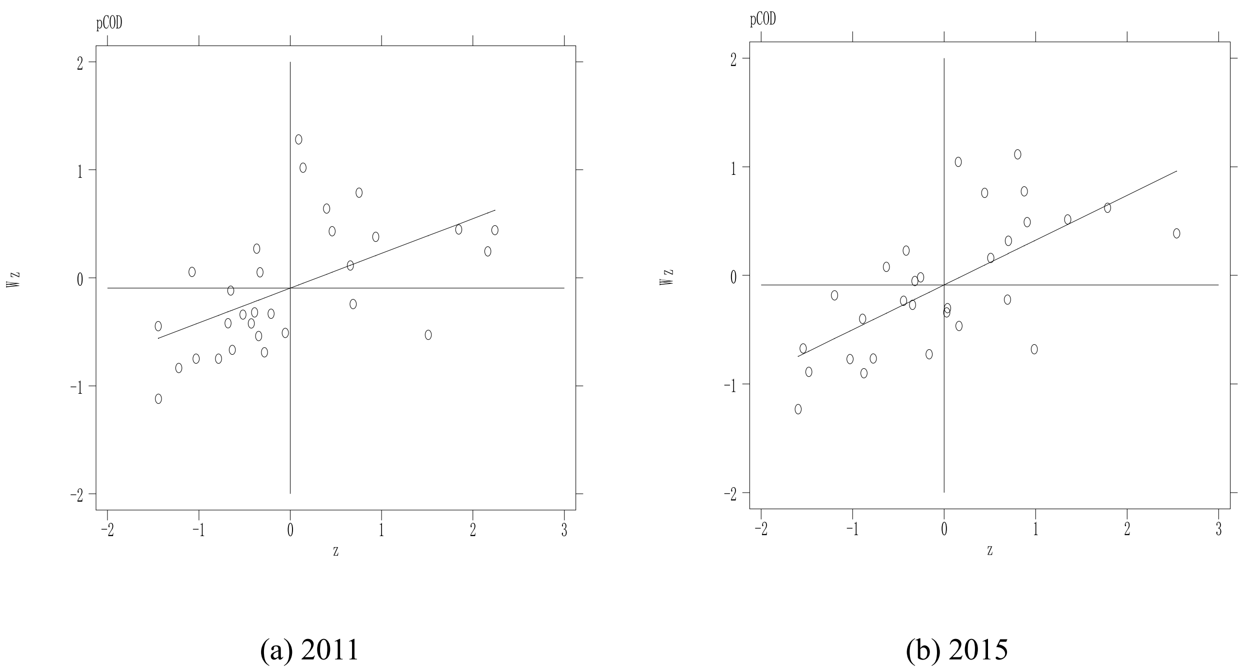

Fig. 6. Moran's scatterplot in 2011(a) and 2015 (b)
Data source: *China's environmental yearbook (2012–2016)*.

Table 3
Quadrant distribution of provinces in Moran scatterplot (2011 and 2015).

2011		2015	
2nd quadrant (L–H) SN, QH, HA	**1st quadrant (H–H)** JL, NM, HE, LN, GS, SX, HLJ, NX, BJ, TJ	**2nd quadrant (L–H)** SN, QH, HA, JS, HA, FJ	**1st quadrant (H–H)** JL, NM, HE, LN, GS, SX, HLJ, NX, BJ, TJ
3rd quadrant (L–L) XZ, YN, GZ, GX, SC, CQ, HB, JX, AH, FJ, ZJ, SH, GD, HN, JS	**4th quadrant (H–L)** SD, XJ	**3rd quadrant (L–L)** XZ, YN, GZ, GX,SC, CQ, HB, JX, AH, ZJ, SH, HN	**4th quadrant (H–L)** SD, XJ, GD

Data source: China's environmental yearbook (2012–2016).
Note: The abbreviation of provinces is the same with Fig. 2.

Table 4
Tests of spatial correlation and fitness of spatial models.

	CPB co-agglomeration indicators		
	CPB_r	CPB_l	CPB_g
Moran's I	2.048**	2.910***	2.832*
LM-error	3.136*	6.457 **	0.404
Robust LM-error	0.257	0.305	2.056
LM-lag	5.832**	9.014 ***	3.557*
Robust LM-lag	2.953*	2.862*	5.209**

Using the ratio indicator *CPB_r* as the baseline, the results of the empirical models are presented in Table 5. According to the Hausman test of the panel model, we used a two-way fixed effects model to control for both years and provinces. Model (1) is the least squares dummy variable (LSDV) with no spatial effect as a baseline, and Models (2) and (3) are the SEM and SLM, respectively. The coefficients of *CPB_r* in all three models were significantly positive, with little difference in values, and the signs of the other variables were basically the same, indicating the models' robustness. Among the three models, the SLM was superior, owing to the fitness test (Table 4) and the outcomes of Likelihood and R^2. The SLM results showed that the spatial autoregressive coefficient ρ in the SLM model was significantly positive at the 5% level, which verified the strong spatial dependence of livestock and poultry pollution. Local pollution rises by 0.195 units for every unit increase in pollution in neighboring provinces.

The extended models introduced the relative difference indicators *CPB_l* and *CPB_g* and single-industrial agglomeration indicators and their squares (*Agglo_gl, Agglo_gg, Agglo_ml,* and *Agglo_mg*). The results are shown in Table 6. Models (4)–(6) are LSDV, SEM, and SLM

Table 5
Results of spatial panel model (with *CPB_r*).

Variables	Model (1)	Model (2)	Model (3)
	CPB_r-LSDV	*CPB_r*-SEM	*CPB_r*-SLM
CPB_r	0.125***	0.131***	0.141***
	(0.028)	(0.025)	(0.025)
Scale	4.211*	5.096**	5.852**
	(2.493)	(2.340)	(2.349)
Scale2	−1.443	−1.799*	−2.093**
	(0.989)	(0.936)	(0.934)
Livestock	−9.813***	−10.352***	−10.500***
	(1.272)	(1.142)	(1.134)
Regulation	0.004	0.003	0.005
	(0.010)	(0.009)	(0.009)
Agrpop	0.250**	0.231**	0.234***
	(0.098)	(0.093)	(0.088)
Tertiary	0.705**	0.840***	0.876***
	(0.305)	(0.305)	(0.305)
PerGDP	−0.0045	0.0150	0.007
	(0.0457)	(0.0619)	(0.056)
Year	Yes	Yes	Yes
Province	Yes	Yes	Yes
ρ			0.195**
			(0.099)
lambda		0.135	
		(0.151)	
R^2		0.155	0.259
Likelihood	137.916	258.119	259.589

***p < 0.01, **p < 0.05, *p < 0.1. The values in brackets are standard error.

Table 6
Results of spatial panel model (with *CPB_l* and *CPB_g*).

Variables	Model (4)	Model (5)	Model (6)	Model (7)	Model (8)	Model (9)
	CPB_l-LSDV	*CPB_l*-SEM	*CPB_l*-SLM	*CPB_g*-LSDV	*CPB_g*-SEM	*CPB_g*-SLM
CPB_l	−0.405***	−0.330***	−0.473***			
	(1.125)	(1.092)	(1.075)			
Agglo_ml	−0.294	−0.495*	−0.526**			
	(0.296)	(0.262)	(0.267)			
Agglo_gl	−0.165	−0.758	−0.858			
	(0.652)	(0.573)	(0.586)			
Agglo_gl2	0.010	0.119	0.147			
	(0.143)	(0.125)	(0.127)			
CPB_g				−0.072	−0.3010*	−0.456**
				(0.291)	(0.154)	(0.191)
Agglo_mg				−0.058	−0.195	−0.387**
				(0.232)	(0.127)	(0.155)
Agglo_gg				−1.509	−1.531***	−1.142*
				(0.939)	(0.411)	(0.591)
Agglo_gg2				1.207	1.537***	1.212**
				(0.908)	(0.390)	(0.564)
Scale	6.957***	7.808***	8.097***	−4.719	2.527	−6.310
	(2.681)	(2.549)	(2.569)	(6.076)	(3.200)	(4.020)
Scale2	−2.583**	−2.923***	−3.013***	2.136	−0.837	2.565
	(1.065)	(1.022)	(1.023)	(2.429)	(1.286)	(1.609)
Livestock	−8.148***	−9.092***	−9.231***	−4.678*	−10.221***	−4.355***
	(1.544)	(1.515)	(1.518)	(2.477)	(1.307)	(1.568)
Regulation	0.002	0.001	0.001	0.019	0.013	0.004
	(0.011)	(0.009)	(0.009)	(0.021)	(0.009)	(0.013)
Agrpop	0.141	0.133	0.143	0.037	0.015	0.265**
	(0.106)	(0.100)	(0.098)	(0.227)	(0.108)	(0.119)
Tertiary	0.697*	1.027***	1.047***	−5.182	0.421	−1.052***
	(0.375)	(0.379)	(0.385)	(0.000)	(0.325)	(0.357)
PerGDP	0.089*	0.122	0.086	0.068	0.154***	−0.080
	(0.049)	(0.077)	(0.070)	(0.080)	(0.056)	(0.081)
Year	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
ρ			0.195*			0.652***
			(0.101)			(0.083)
lambda		0.170			0.897***	
		(0.127)			(0.028)	
R^2		0159	0.241		0.350	0.456
likelihood	144.186	253.487	259.566	49.402	168.696	171.894

***p < 0.01, **p < 0.05, *p < 0.1. The values in brackets are standard error.

with *CPB_l,* and models (7)–(9) are LSDV, SEM, and SLM with *CPB_g.* The SLMs were also superior because of the results of Likelihood and R^2. In line with the model with *CPB_r*, ρ in SLMs were significantly positive, suggesting the spatial dependence of livestock and poultry pollution. The subsequent interpretation was primarily based on *CPB_r*-SLM, *CPB_l*-SLM, and *CPB_g*-SLM.

The effect of CPB co-agglomeration on pollution reduction was significantly positive as expected, which was significant at the 1% level in *CPB_r*-SLM and *CPB_l*-SLM and the 5% level in *CPB_g*-SLM. This suggested that the expansion of livestock and poultry production within a region makes it difficult for croplands to absorb livestock and poultry pollution, which may aggravate pollution intensity. The co-agglomeration of CPB can help reduce pollution by recycling manure into croplands, which can establish a virtuous circle of waste utilization and lowers the cost of waste management. The agglomeration of the breeding industry had a significantly negative effect on pollution, as revealed by the significant coefficients of *Agglo_ml* and *Agglo_mg* at the 5% level. Intra-industry agglomeration of the breeding industry increases labor market sharing, intermediate input sharing, and technology and knowledge spillover effects, which may promote the spread of cleaner production technologies [58]. The concentration of similar enterprises reduced the cost of pollution treatment [65]. Not as expected, the effect of environmental regulation (*Goverate*) was not significantly positive. It suggested that government investment in environmental controls did not significantly reduce livestock and poultry pollution. A plausible reason for this may be that the funds for environmental governance were mainly invested in industrial projects but not livestock and poultry pollution control. This reveals the inadequacy of economic measures for livestock and poultry pollution governance.

The results of *CPB_l*-SLM and *CPB_g* -SLM models showed divergences in the scale effect of the breeding industry on pollution. In *CPB_r*-SLM and *CPB_l*-SLM, the effect of the breeding industry scale and its square (*Scale* and *Scale2*) on pollution was significant at a 5% level, indicating a non-linear relationship existed of these two variables. Due to the negative coefficient of *Scale2,* the relationship between breeding industry scale and pollution were shown to be “inverse U-shaped”. This suggested that medium-scale farmers who do not receive effective treatments may experience increased manure pollution. Small-scale farmers have a relatively low pollution intensity, whereas large-scale farmers are in the stage of economies of scale in pollution control and emission reduction. Large-scale farms are under strict government control and have the financial capacity to introduce clean treatment equipment to improve pollution control measures.

Nevertheless, the effect of scale was not significant in *CPB_g*-SLM. This inconsistency may be due to the characteristics of the Spatial GINI Coefficient used to measure industrial agglomeration. The Spatial GINI Coefficient measures the spatial inequality in industrial distribution within a province. A high Spatial GINI Coefficient may result from two situations: the concentration of a few leading large-scale farmers in the region and the clustering of numerous small-scale farmers in the region [66]. Therefore, the effect of scale may be incorporated into the industrial agglomeration computed by the Spatial GINI Coefficient (*Agglo_mg*), resulting in the insignificant outcomes of *Scale* and *Scale2* in *CPB_g*-SLM. What merits further discussion is that the two situations with higher spatial GINI coefficients correspond exactly to the two situations of the development of the breeding industry, which could bring about the share growth of the breeding industry. Accordingly, the development of the breeding industry on pollution worth further discussion compared to the other two findings. First, the effect of breeding industry share (*Livestock*) on pollution is consistent and significantly negative. Second, the effect of breeding industry agglomeration (*Agglo_m*) on pollution is consistent and significantly negative. Thus, the development of the breeding industry in China was driven mainly by the agglomeration of small-scale farmers.

4. Conclusions and policy implications

This present study focused on the characteristics of regional CPB co-agglomeration in China and investigated its effect on livestock and poultry pollution. This study found that the CPB co-agglomeration declined in general from 1997 to 2020, with significant regional heterogeneity that the region with higher CPB co-agglomeration transferred from the central provinces to the west provinces. The second major finding was that the CPB co-agglomeration and breeding industry agglomeration have significantly positive effect on reducing regional livestock and poultry pollution. These findings suggest that as a typical mode of agricultural co-agglomeration, CPB achieves manure waste recycling to reduce pollution. This study contributes to the literature by providing a new interpretation of CPB from the perspective of agricultural co-agglomerations, measuring and characterizing CPB co-agglomeration at the regional scale, as well as providing empirical evidence of its positive effects on reducing regional pollution. The findings will provide insights for optimizing agricultural layouts and reducing livestock pollution. The practicality of this research, on the one hand, is to provide empirical reference for the macroeconomic regulation of China's nationwide and regional crop-livestock layout. On the other hand, it offers valuable insights to reducing regional livestock pollution through planting and breeding co-agglomeration. The results obtained from this research will help to achieve the dual goal of agricultural layout optimization and pollution reduction. Reasonable scale and position of breeding industry should be determined by the fully consideration of local natural geographical characteristics and the carrying capacity of croplands. For regions with significant spatial correlation of pollution, integrated CPB strategies and corresponding environmental regulations should be formulated.

This study is limited by data accessibility. We measured CPB co-agglomeration from 1997 to 2020 but only obtained livestock and poultry pollution data from 2011 to 2015. This limited the analysis of the effects of CPB co-agglomeration on pollution in the short term. Second, regional CPB co-agglomeration may affect pollution treatment by farmers and corporations. Future research could be extended in two ways. First, it is meaningful to collect refined city-level or county-level data, maybe in specific regions with typical CPB modes and complete data, to explore the detailed spatial layout as well as the characteristics of planting and breeding co-agglomeration. Secondly, microscopic studies with large-scale sample will make sense to explain the internal mechanism of the effect of CPB co-agglomeration, for example, the hierarchical analysis combining regional CPB levels and individual decision-making, and generating geographical relationship of livestock farms and cropland to characterize the crop-livestock system.

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Data availability

The datasets used in the study are available from the corresponding author on reasonable request.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17821.

References

[1] Z.H. Bai, W.Q. Ma, L. Ma, G.L. Velthof, Z.B. Wei, P. Havlik, O. Oenema, M.R.F. Lee, F.S. Zhang, China's livestock transition: driving forces, impacts, and consequences, Sci. Adv. 4 (2018) 7.

[2] E.R. Campagnolo, K.R. Johnson, A. Karpati, C.S. Rubin, D.W. Kolpin, M.T. Meyer, J.E. Esteban, R.W. Currier, K. Smith, K.M. Thu, M. McGeehin, Antimicrobial residues in animal waste and water resources proximal to large-scale swine and poultry feeding operations, Sci. Total Environ. 299 (2002) 89–95.

[3] B.J. Gu, Recoupling livestock and crops, Nat Food 3 (2022) 102–103.

[4] F.H. Wang, W.Q. Ma, Z.X. Dou, L. Ma, X.L. Liu, J.X. Xu, F.S. Zhang, The estimation of the production amount of animal manure and its environmental effect in China, China Environ. Sci. 26 (2006) 614–617.

[5] S.Q. Jin, B. Zhang, B. Wu, D.M. Han, Y. Hu, C.C. Ren, C.Z. Zhang, X. Wei, Y. Wu, A.P.J. Mol, S. Reis, B.J. Gu, J. Chen, Decoupling livestock and crop production at the household level in China, Nat. Sustain. 4 (2021) 48–55.

[6] B.J. Gu, X.T. Ju, S.X. Chang, Y. Ge, J. Chang, Nitrogen use efficiencies in Chinese agricultural systems and implications for food security and environmental protection, Reg. Environ. Change 17 (2017) 1217–1227.

[7] C.Z. Zhang, S. Liu, S.X. Wu, S.Q. Jin, S. Reis, H.B. Liu, B.J. Gu, Rebuilding the linkage between livestock and cropland to mitigate agricultural pollution in China, Resour. Conserv. Recycl. 144 (2019) 65–73.

[8] S.Q. Jin, H. Zhang, J.L. Tang, On Progress in implementing zero growth of chemical fertilizer use and the target&path of fertilizer reducing in the "14th Five-Year Plan", J. Nanjing Tech. Univ. (Soc. Sci. Edition) 19 (2020) 10.

[9] X.X. Shen, J.Y. Duan, C. Peng, Theoretical logic, stakeholders' performance logic and sustainable mechanism for crop straw resources reuse, Chinese J. Agric. Res. Region. Plan. 43 (10) (2021) 120–128.

[10] D.D. Zhao, H. Zhou, J.L. Gu, Agricultural production agglomeration: can it promote cultivated land use efficiency? Re-Inspection based on a panel threshold model, J. Agrotec. Econ. (2022) 49–60, https://doi.org/10.13246/j.cnki.jae.2022.03.006.

[11] G. Ellison, E.L. Glaeser, Geographic concentration in U.S. Manufacturing industries: a dartboard approach, J. Polit. Econ. 105 (1997) 889–927.

[12] D. Puga, A.J. Venables, Agglomeration and economic development: import substitution vs. trade liberalisation, Econ. J. 109 (1999) 292–311.

[13] G. Ellison, G. Kerr, What causes industry agglomeration? Evidence from co-agglomeration patterns, Am. Econ. Rev. 100 (2010) 1195–1213.

[14] J.J. Chen, J.J. Chen, The research on the co-location between producer services and manufacturing: the empirical analyses based on the 69 cities and regions in Zhejiang Province, China Indust. Econ. 6 (2011) 141–150.

[15] C. Han, G. Wang, Y. Zhang, L. Song, L. Zhu, Analysis of the temporal and spatial evolution characteristics and influencing factors of China's herbivorous animal husbandry industry, PLoS One 15 (2020), e0237827, https://doi.org/10.1371/journal.pone.0237827.

[16] X.H. Meng, H.C. Zhou, H.W. Zhou, Balancing of planting-breeding on a region scale and factors affecting willingness of livestock farms for planting-breeding combination: a case study in Jiangsu Province, J. Ecol. Rural Environ. 34 (2018) 132–139.

[17] R.D. Garrett, M.T. Niles, J.D.B. Gil, A. Gaudin, R. Chaplin-Kramer, A. Assmann, T.S. Assmann, K. Brewer, P.C. de Faccio Carvalho, O. Cortner, R. Dynes, K. Garbach, E. Kebreab, N. Mueller, C. Peterson, J.C. Reis, V. Snow, J. Valentim, Social and ecological analysis of commercial integrated crop livestock systems: current knowledge and remaining uncertainty, Agric. Syst. 155 (2017) 136–146.

[18] Z. Bai, X. Fan, X. Jin, Z.Q. Zhao, Y. Wu, O. Oenema, G. Velthof, C.S. Hu, L. Ma, Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population, Nat Food 2 (2022) 3.

[19] J.C. Dos Reis, G.S. Rodrigues, I. de Barros, R.D.R. Rodrigues, R.D. Garrett, J.F. Valentim, M.Y.T. Kamoi, M. Michetti, F.J. Wruck, S. Rodrigues, P.E.O. Pimentel, S. Smukler, Integrated crop-livestock systems: a sustainable land-use alternative for food production in the Brazilian Cerrado and Amazon, J. Clean. Prod. 283 (2021), 124580.

[20] W.N. Chang, H.P. Zhou, Y. Gao, Balance between crop-planting and livestock-raising perspective of agricultural pollution reduction, J. Agro-Environ. Sci. 32 (2013) 2118–2124.

[21] H.M. Dong, L.L. Zuo, S. Wei, Z.P. Zhu, F.B. Yin, Establish manure nutrient management plan to promote green development of integrated crop-livestock production system, Bull. Chin. Acad. Sci. 34 (2019) 180–189.

[22] J.L. Tang, S.Q. Jin, Research hotspots and frontiers for the combination of planting and breeding in China——based on literature analysis since 1998, Chinese J. Agric. Res. Region. Plan. 42 (2021) 24–31.

[23] H. Meng, Y.G. Shen, Combination of planting and breeding in livestock and poultry breeding: typical models, operational points and promotion paths, Environ. Protect. 50 (2022) 34–38.

[24] Z.C. Wang, M.Q. Fan, X. Wang, J. Sheng, Y.F. Zhang, Z. Guo, J.C. Zheng, Y.X. Guan, Typical model of pig manure treatment based on integrated crop and animal production in Jiangsu: government-led type, Chinese Agric. Sci. Bulletin 35 (2019) 143–149.

[25] X.L. Lin, Y.H. Zhou, An analysis on the eco-environment effect of circular agriculture mode of planting-culture in the paddyfield, China Populat. Res. Environ. 22 (2012) 37–42.

[26] M.P. Russelle, M.H. Entz, A.J. Franzluebbers, Reconsidering integrated crop–livestock systems in North America, Agron. J. 99 (2007) 325.

[27] X.W. Chen, J.J. Lin, K.M. Tan, Y. Pei, X.L. Wang, Cooperation between specialized cropping and livestock farms at local level reduces carbon footprint of agricultural system: a case study of recoupling maize-cow system in South China, Agric. Ecosyst. Environ. 348 (2023), 108406.

[28] J.Z. Wu, Z.M. Ge, S.Q. Han, L.W. Xing, M.S. Zhu, J. Zhang, J.F. Liu, Impacts of agricultural industrial agglomeration on China's agricultural energy efficiency: a spatial econometrics analysis, J. Clean. Prod. 260 (2020), 121011.

[29] Z. Han, C. Han, Z.Z. Shi, J.K. Li, E.G. Luo, Rebuilding the crop-livestock integration system in China–Based on the perspective of circular economy, J. Clean. Prod. 393 (2023), 136347.

[30] C.M. Hu, Q. Zhu, Y. Li, P. Liu, W. Zhang, Phosphorus balance of manure and farmland load in a breeding farm, J. Anhui Agric. Sci. 42 (2014) 6210–6211+6424.

[31] J.W. Zhao, H. Jiang, Y.F. Chen, C.B. Yin, Analysis on influencing factors of manure pollution treatment in breeding: based on the perspective of willingness-to-behavior transformation, J. Nat. Resour. 34 (2019) 1708–1719.

[32] Y.P. Cai, J. Yue, Z.X. Du, Analysis on the treatment of livestock and poultry manure and its influencing factors in family farm and combination of planting and breeding farm: based on the monitoring data of the aquaculture and combination family farms in China, Ecol. Econ. 36 (2020) 178–185.

[33] M.J. Carrer, A.G. Maia, M.D.B. Vinholis, H.M. de Souza, Assessing the effectiveness of rural credit policy on the adoption of integrated crop-livestock systems in Brazil, Land Use Pol. 92 (2020), 104468.

[34] T.L. Jiang, F.M. Zhuxin, K.L. Shu, Positive effects, restrictive factors and policy suggestions for farmers to carry out the combination of planting and breeding, Econ. Review J. 6 (2022) 104–110.

[35] H. Yu, Interest-driven mechanism of low-carbon agriculture, Rural Economy 6 (2012) 33–36.

[36] M.H. Xing, J.B. Zhang, G.T. Huang, Perception of environmental protection of farmers' households not participating in circular agriculture and an analysis of the casual factors——based on surveys in Shanxi and Hubei Provinces, Chinese Rural Economy 4 (2009) 72–79.

[37] W.T. Xu, J.B. Zhang, S.M. Li, Analysis of influencing factors on farmer participating in circular agricultural project, China Populat. Res. Environ. 20 (2010) 33–37.

[38] E.L. Li, A.C. Pang, J.G. Zhu, Analysis of the evolution path and mechanism of China's agricultural agglomeration and geographic pattern, Geogr. Res. 31 (2012) 885–898.

[39] D.M. Han, S.Q. Jin, Y. Hu, T.L. Wu, Y.L. Chen, Environmental risks and precautions in pig husbandry location in China, Chin. J. Eco-Agric. 27 (2019) 951–958.

[40] X.H. Zhao, C.J. Xiong, Spatial and temporal characteristics, evolution law and improvement path of China's animal husbandry production pattern, Sustainability 14 (2022), 15794, https://doi.org/10.3390/su142315794.

[41] Z. Zhu, X. Zhang, H. Dong, S. Wang, S. Reis, Y. Li, B. Gu, Integrated livestock sector nitrogen pollution abatement measures could generate net benefits for human and ecosystem health in China, Nat Food 3 (2022) 161–168, https://doi.org/10.1038/s43016-022-00462-6.

[42] Y.X. Bi, L.Z. Liu, Analysis on the characteristics of agglomeration and evolution of China's meat duck industry, Chinese J. Animal Sci. 56 (2020) 176–180, https://doi.org/10.19556/j.0258-7033.20200401-11.

[43] J.Y. Jiang, J.M. Lai, Ting Ni, Effects of industrial agglomeration on production efficiency of pig breeding: take major hog producing provinces (autonomous regions and municipalities) as an example, J. Yunnan Agric. Univ. 16 (2022) 78–86, https://doi.org/10.12371/j.ynau(s).202110053.

[44] G. Wang, M. Wang, J. Wang, C. Yang, Y. Liu, Characteristics and influencing factors of grass-feeding livestock breeding in China: an economic geographical perspective, J. Geogr. Sci. 26 (2016) 501–512, https://doi.org/10.1007/s11442-016-1282-3.

[45] C. Han, G. Wang, Y. Zhang, L. Song, L. Zhu, Analysis of the temporal and spatial evolution characteristics and influencing factors of China's herbivorous animal husbandry industry, PLoS One 15 (2020), e0237827, https://doi.org/10.1371/journal.pone.0237827.

[46] X.M. Zhang, Y.H. Dong, H. Wang, D. Shen, Structure of livestock and variation of fecal nitrogen pollution load in China, Environ. Sci. 6 (2007) 1311–1318.

[47] A.J. Chen, R. Lin, Breaking of agricultural cycle and reconstruction strategy, Study & Exploration 7 (2018) 26–33.

[48] Y.Z. Liu, Y.Q. Ji, S. Shao, F.N. Zhong, N. Zhang, Y.S. Chen, Scale of production, agglomeration and agricultural pollutant treatment: evidence from a survey in China, Ecol. Econ. 140 (2017) 30–45.

[49] Q.Y. Lu, S.J. Wang, Research on the spatial correlation and influencing factors of agricultural non–point source pollution in China, On Economic Problems 12 (2015) 93–98.

[50] Y.G. Wu, K.W. Feng, G.C. Li, Population growth, structural adjustment and agricultural non-point source pollution——an empirical study based on spatial panel stirpat model, J. Agrotechn. Econ. 3 (2017) 75–87.

[51] G. Duranton, H.G. Overman, Testing for localization using micro-geographic data, Rev. Econ. Stud. 72 (2005) 1077–1106.

[52] H.C. Yang, F.M. Zhang, Y.X. He, Exploring the effect of producer services and manufacturing industrial co-agglomeration on the ecological environment pollution control in China, Environ. Dev. Sustain. 23 (2021) 16119–16144.

[53] H.C. Yang, X.Z. Xu, F.M. Zhang, Industrial co-agglomeration, green technological innovation, and total factor energy efficiency, Environ. Sci. Pollut. Res. 29 (2022) 62475–62494.

[54] O. Alonso-Villar, J. Chamorro-Rivas, X. Gonzalez-Cerdeira, Agglomeration economies in manufacturing industries: the case of Spain, Appl. Econ. 36 (2004) 2103–2116.

[55] M. Lu, H. Feng, An empirical analysis of how intra-province spatial distribution of industries affects pollution, J. World Econ. 37 (2014) 86–114.

[56] E. Aleksandrova, K. Behrens, M. Kuznetsova, Manufacturing, (co) agglomeration in a transition country: evidence from Russia, J. Reg. Sci. 60 (2020) 88–128.

[57] Q.X. Gong, G.X. Guo, S.P. Li, X.D. Liang, Examining the coupling coordinated relationship between urban industrial co-agglomeration and intensive land use, Land 10 (2021) 499.

[58] P. Krugman, Geography and Trade, MIT Press, Cambridge, 1991.

[59] D. Pan, F.B. Kong, An analysis of raisers' choice behavior for environmental friendly modes to deal with excrement of domestic animal and fowls——taking hog industry as an example, Chinese Rural Econ. 9 (2015) 17–29.

[60] X.C. Kong, Economic Analysis of Livestock Pollution and its Governance Policy, Dissertation, Jilin Agricultural University, 2017.

[61] Z.H. Cheng, B.B. Yu, Industrial agglomeration and regional wage gap——spatial econometric analysis based on Chinese urban data, Mod. Econ. Sci. 36 (2014) 86–94+125.

[62] P. Moran, Notes on continuous stochastic phenomena, Biometrika 37 (1950) 17–23.

[63] H. Hu, R.Y. Ying, J. Liu, The economic analysis of pig production area movement in China: the transformation from natural distribution to economic distribution, Chinese Rural Econ. 12 (2005) 46–52+60.

[64] Y. Su, Analysis and countermeasures against the obstacles of waste treating of intensive livestock and poultry farms in China, Chinese J. Animal Sci. 14 (2006) 31–34.

[65] X. Peng, C.H. Jiang, Industrial agglomeration, technological spillovers and regional innovation: evidences from China, China Econ. Quarterly 10 (2011) 913–934.

[66] Y.X. Pu, Understanding locational Gini Index: limitations and selection of benchmark distribution, Statist. Res. 28 (2011) 101–109.