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Analysis on Coupling Coordination Degree for Cropland and Livestock from 2000 to 2020 in China

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Abstract: The decoupling of cropland and livestock due to the industrialization of livestock production is a difficult problem for sustainable agricultural development in many global locations, including China. As population and urbanization increase, this decoupling is likely to become more serious. To date, the relationship between cropland and livestock has been mainly studied from a single perspective, and mostly at the regional and the local scales. Thus, the objective of our study is to systematically assess the coupling relationship between cropland and livestock from multiple aspects on a large scale. Here, we used a complex system covering cropland, livestock and environment subsystems to comprehensively analyze the spatio-temporal variation of the coupling coordination between cropland and livestock and its influencing factors in China over the past two decades. Elaborating on the data, we constructed a comprehensive system of evaluation indexes for cropland–livestock systems. We used a coupling coordination degree model to evaluate the coupling coordination relationship between cropland and livestock in 31 provinces of China during 2000–2020. The results show that the range of cropland–livestock and cropland–livestock–environment coupling coordination degree was 0.4–0.9. In most of the provinces, there was no risk of cropland and livestock decoupling; however, the coupling coordination degree needed to be increased. More attention should be paid to the coordinated development of cropland and livestock coupling in urbanized areas such as Beijing and Tianjin, where cropland and livestock decoupling was more likely to occur. Among the assessed 29 factors, 15 and 16 had an impact on the cropland–livestock and the cropland–livestock–environment coupling coordination degrees, respectively. Our study provides science-based evidence to support estimating the coupling relationship between cropland and livestock in the future.

Keywords: cropland–livestock systems; index system; coupling coordination degree; influence factor

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1. Introduction

Crops and livestock play a synergistic role in global food production and the livelihoods of farmers [1]. For centuries, crops and livestock have formed a coupled system of planting and breeding with a circular flow of material and nutrient elements. In the coupled system, livestock manure has been used as a nutrient source for crops [2], livestock can be used as draft animals in crop cultivation, and the cropland provides feed for the livestock. In traditional settings, the coupled livestock–cropland system has a high material circulation rate [3,4]. However, due to rapid urbanization and the sharp increase in population, the demand for livestock products has increased, and the response to the demand has led to drastic changes. One of the biggest changes is the emergence of large-scale, intensive and specialized industrial livestock production systems. Industrial livestock production has brought about changes in spatial allocation and land use, resulting in the spatial separation and lack of functional interaction between livestock and cropland and a decrease in the nutrient cycling rate between the two systems [5–7]. Furthermore, intensive and spatially separated livestock have increased the costs of applying livestock manure as a source of nutrients to croplands. Concomitantly, industrial fertilizers with low unit nutrient cost have replaced manure on croplands. This future hinders the effective recycling of nutrients in livestock manure, aggravating the decoupling of livestock and cropland [8–10].

The concentration of livestock in areas with little or no cropland has a great impact on the environment. The environmental impact is mainly related to the poor management of livestock manure, which can lead to the contamination of surface and ground waters with nutrients, organic matter and heavy metals [1,5,7]. The aggregation of livestock production systems and the accompanying large amounts of fertilizer and improperly managed manure may increase the adverse impacts on water quality, especially the enrichment of phosphorus, nitrogen and other nutrients in the water, leading to the eutrophication of water bodies [4,11]. In China, the high intensity of livestock production and its increasing proximity to urban areas has resulted in more than 1 billion people being exposed to intense nitrogen pollution in the air and water [8]. To alleviate the negative effects, circular agriculture with combined cropland and livestock has been proposed as a key strategy to promote sustainable agricultural intensification [9,12,13]. Since manure contributes to soil health and versatility by providing nutrients and improving soil properties, the partial replacement of industrial fertilizers with manure can improve crop productivity, enhance interactions within and among soil microbial communities, increase carbon sequestration on the surface, increase soil organic matter content, and reduce agricultural greenhouse gas emissions and nitrogen pollution [14–18].

Hence, in order to analyze the connection between cropland and livestock and alleviate environmental pollution, various aspects of coupled cropland–livestock systems have been studied using a variety of methods. At present, research on the relationship between cropland and livestock mainly focuses on the current situation and the recoupling of the cooperative relationship between cropland and livestock. Single indicators, such as livestock density and the nitrogen or phosphorus load of livestock into farmland, have been applied to establish the relationship between regional cropland and livestock [7,19,20]. The coupling relationship between cropland and livestock has been measured using the nutrient balance method or models based on nutrient balance theory [21–23]. Zhang et al. (2019) used the nutrient balance method to propose a cropland-based livestock production system from the perspective of agricultural production and human consumption to rebuild the linkage between livestock and cropland in China [24]. Kamilaris et al. (2020) and Li et al. (2021) used an objective optimization method to find the optimal flow mode of regional livestock manure to reconstruct the coupling relationship between intensive large-scale livestock and agricultural production [25,26]. Scenario analysis has been applied to explore the synergistic relationship between cropland and livestock in the future [27–29]. Index analysis, nutrient balance methods, evaluation models and scenario simulation are the most commonly used methods to research the coupling cooperative relationship between cropland and livestock.

Similar to the United States and many other developed countries, in China, the world's largest livestock breeding country, livestock production agglomeration and decoupling between livestock and cropland are increasing [8,24]. The Chinese coupling relationship between cropland and livestock has been analyzed using surveys and statistics to analyze the main obstacles affecting the interaction between cropland and livestock from the perspectives of material flow and environmental factors [30–32]. The changes in the coupling relationship between cropland and livestock in China in the past decades have been analyzed using the nutrient element flow balance method [20,27]. Zhao et al. (2015) employed the coupling coordination degree model to investigate the spatiotemporal variation characteristics of the coupling of farming and animal husbandry in agricultural areas located in the Tarim River Basin of China. Based on the findings, some suggestions were proposed [33]. The coupling relationship between cropland and livestock has been mainly explored from the perspectives of element flow, nutrient management, index analysis, and environmental and economic benefits. However, there is a lack of comprehensive analysis of the cropland–livestock coupling in which environmental factors are considered.

The coupling coordination degree model, developed based on the coupling theory, can reflect the degree of interaction and coupling between systems accurately. This model has been found suitable for evaluating the level of coupling and coordination development between systems in research on the regional coupling relationship between cropland and livestock [33,34]. Therefore, our assumption is that the use of the coupling coordination degree model can reflect the phenomenon of decoupling between cropland and livestock in various regions of China. This phenomenon has shown a trend of gradual expansion.

Our aims were to deepen the understanding of cropland and livestock coupling coordination in China over the past 20 years and to explore its spatiotemporal changes and main influencing factors. Based on previous studies, the innovations in our study: (1) we considered the environmental factors as an independent subsystem in the coupling relationship between cropland and livestock, constructed a comprehensive evaluation indicator system of cropland and livestock system; (2) we investigated the spatiotemporal changes of the coupled and coordinated relationship between cropland and livestock in China under the multiple influence factors.

2. Materials and Methods

2.1. Study Area

According to the main grain-producing areas in China, 31 provinces were divided into six regions [20]: Northeast, North China, Middle-lower Reaches of the Yangtze River, Northwest, Southwest and Southeast (Figure 1). Data for Hong Kong, Macao and Taiwan are not included in this paper.

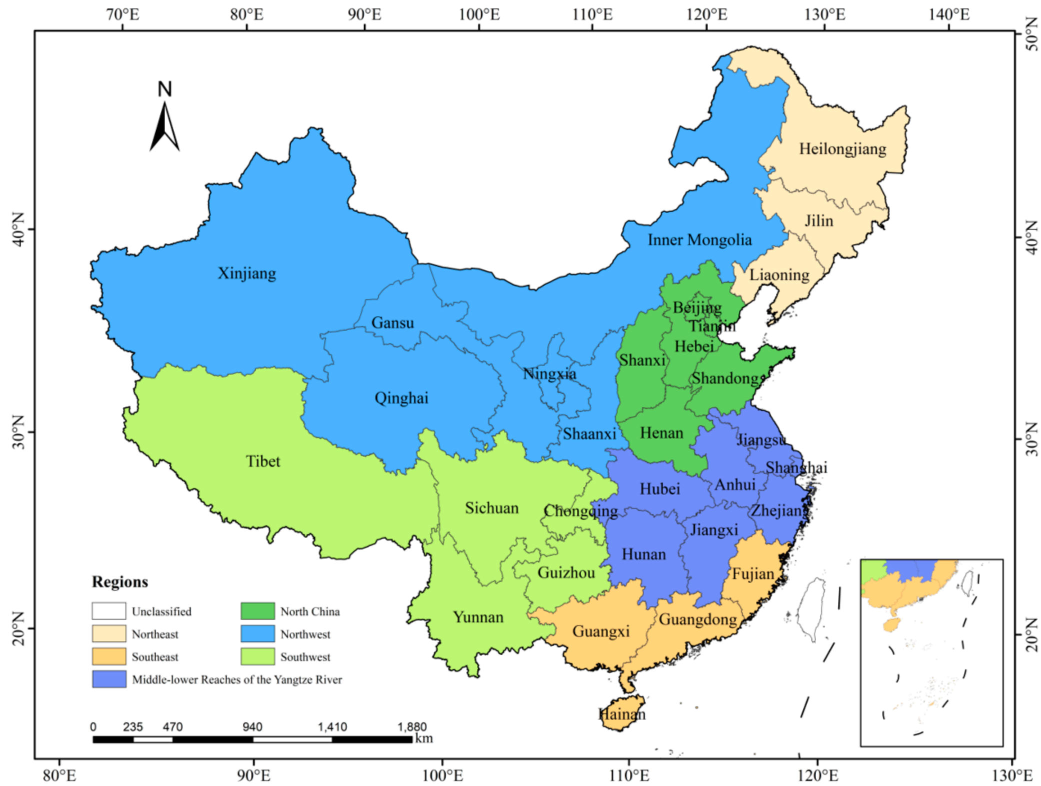


Figure 1. Division of the provinces of China into six study regions.

2.2. Research Framework

To explore the coupling relationship between cropland and livestock in China in the past two decades, we constructed a research framework consisting of four processes (Figure 2). The comprehensive evaluation of cropland–livestock systems and cropland–livestock–environment systems included the construction of an index system, weight calculation and comprehensive evaluation. In the coupling coordination degree model, the coupling degree (C), comprehensive reconciliation index (T) and coupling coordination degree (D) of cropland–livestock and cropland–livestock–environment systems were calculated. The spatial autocorrelation analysis of coupling coordination degree included calculating global Moran's I and local spatial autocorrelation analysis. The main influencing factors and the degree of coupling coordination degree were explored using the Geographical detector model.

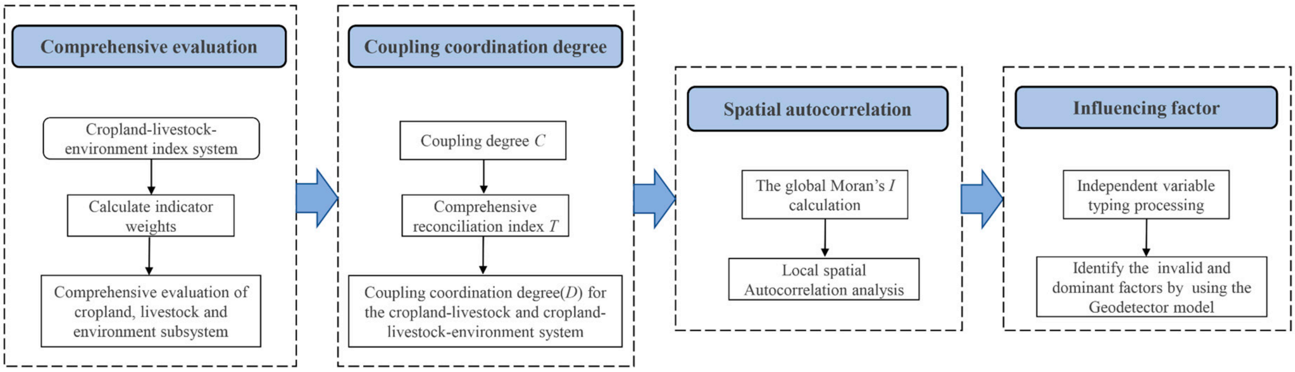


Figure 2. Research framework.

2.3. Indicator System Construction

2.3.1. CLE Indicator System

Following the principles of consistent objectives, comprehensiveness, validity, independence and measurability, and referring to previous studies, the comprehensive index system of cropland–livestock–environment was constructed (Table S5). The index system was finally constructed by using the multicollinearity method to screen 29 indexes in cropland, livestock and environment subsystems (Table 1). The cropland subsystem contains eight indicators, among which the output of farm crops is the sum of grain, cotton, oilseed, flax, sugar crop, tobacco, vegetable, and fruit yields. The grain crop straw yield index was calculated as shown in formula (1). The livestock subsystem contains eight indicators, among which the number of captive livestock, livestock density, the ratio of large-scale livestock farms, and livestock urine and manure production were defined and calculated in detail in Section S.1 of Supplementary Materials S1 [35–41]. In addition, this study's focus is on livestock species, including pigs, cattle, sheep (both wool sheep and goats), and poultry (layers, broilers, ducks, and rabbits). Considering the comprehensiveness and operability principle of index selection, the environment subsystem included 13 evaluation indexes from both natural and social aspects, among which annual total precipitation, annual total sunshine hours and annual average temperature were obtained from the meteorological data of major cities.

For the index of grain crop straw yield: in this study, the grain crop straw yield is the sum of rice, wheat and maize straw yields. The straw yield of grain crop was calculated based on the grain yield and the straw-to-grain ratio of three grain crops in different main grain-producing areas (Table S1) [35]. The formula is as follows:

$$TS = \sum\nolimits_{i=1}^{n} x_i \times R_i \tag{1}$$

where TS is the theoretical resource amount of straw (air-dried base), i is the ith grain crop, x is the economic yield of grain crops, and R is the straw-to-grain ratio of grain crops.

Table 1. Cropland–livestock–environment comprehensive evaluation index system.

Subsystem	Criteria	Indicator	Unit	Explaining
Cropland (C)	Input	Cultivated area	10^3 ha	
		Consumption of chemical fertilizers	10^4 tons	The quantity of chemical fertilizers applied in agriculture per year (volume of effective component)
		Irrigated area of cultivated land	10^3 ha	
		Total sown area of farm crops	10^3 ha	
	Output	Gross output value of farming	billion yuan	
		Output of farm crops	10^4 tons	
		Output of major grain per hectare	kg/ha	Output of Grain/Sown area of grain crops
		Grain crop straw yield	10^4 tons	Only include the straw of rice, wheat and corn
Livestock (L)	Input	Number of captive livestock	10^4 pig equivalents	Only confined livestock is included
		Livestock density	pig equivalent/km^2	Number of captive livestock/regional land area
		Number of pigs raised	10^4 heads	
		Total output of feed	10^4 tons	
		Ratio of large-scale livestock farms	%	Number of large-scale livestock farms/total number of livestock farms × 100
	Output	Gross output value of animal husbandry	billion yuan	
		Livestock urine production	10^4 tons	
		Livestock dung production	10^4 tons	
Environment (E)	Natural	Annual total precipitation	mm	
		Annual total sunshine hours	hours	
		Annual average temperature	°C	
		Per capita water resources	cu. m/person	
		Area of afforested land	10^4 ha	
	Social	Population	10^4 persons	
		Length of highways	km	
		GDP	billion yuan	
		Per capita GDP	yuan	GDP/population
		R&D investments	%	Expenditure on R&D/GDP × 100
		General public budget revenue	billion yuan	
		Environmental protection investment	%	investment in the treatment of environmental pollution/GDP × 100
		Rural family Engel's coefficient	%	Food, tobacco and liquor expenditure/living expenditure × 100

2.3.2. Data Sources

The data sources of this study include mainly statistical yearbooks and parameters or coefficients collected in technical guidelines and previous studies. (1) Statistical yearbooks: China Statistical Yearbook, China Rural Statistical Yearbook, China Animal Husbandry and Veterinary Yearbook, China Feed Industry Yearbook, China Environmental Statistics Yearbook and China Agricultural Yearbook, including data on cultivated area, number of captive livestock and total output of feed. (2) Collected parameters and coefficients: the data in this study, such as the straw-to-grain ratio of crops, conversion coefficient of pig equivalent and livestock feeding period were obtained from national technical guidelines and previous studies. Furthermore, due to the lack of data, per capita water resources and area of afforested land in 2000 were obtained from the China Statistical Yearbook in 2004. The data on environmental protection investment in 2000 and 2020 was based on the 2014 and 2018 China Environmental Statistics Yearbook, respectively. Cultivated area data for 2000 and 2015 came from statistical yearbooks of the provinces. The original data of each indicator from 2000 to 2020 are shown in Supplementary Material S2.

2.4. Comprehensive Evaluation

To avoid the influence of subjective factors on the results, the weight of each index was calculated using the entropy weight method, and the comprehensive evaluation values of cropland, livestock and environment subsystems were calculated using the weighted summation method [42]. The evaluation steps were as follows:

First, annual total precipitation, annual total sunshine hours and annual average temperature were transformed using the reciprocal distance method as follows:

$$T = \frac{1}{\sqrt[2]{(m_i - m_0)^2}} \tag{2}$$

where T is the transformed index, mi is the original index, and m_0 is the average of m_i.

Second, to eliminate the influence of dimension, magnitude and positive and negative orientation, the data were standardized using the following formulas:

$$y_{\theta ij} = \frac{x_{\theta ij} - min(x_{\theta ij})}{max(x_{\theta ij}) - min(x_{\theta ij})} \tag{3}$$

$$y_{\theta ij} = \frac{max(x_{\theta ij}) - x_{\theta ij}}{max(x_{\theta ij}) - min(x_{\theta ij})} \tag{4}$$

where $y_{\theta ij}$ is the standardized data, $x_{\theta ij}$ refers to the value of indicator j of city i in year θ, and min and max are the minimum and maximum values, respectively.

Third, weight calculation was conducted through the use of the entropy weight method. W_j is the weight of each index in the subsystems, calculated in three steps using the entropy weight method, as described earlier [43]. The calculation results are shown in Table S6.

Last, the comprehensive evaluation values of cropland, livestock and environment subsystems were calculated by using Equation (5):

$$Z_{\theta i} = \sum_{j=1}^{n} (y_{\theta ij} W_j) \tag{5}$$

where $Z_{\theta i}$ represents the comprehensive evaluation value of province i in year θ. $Z_{\theta i}(C)$, $Z_{\theta i}(l)$ and $Z_{\theta i}(E)$ were used to represent the comprehensive evaluation value of cropland, livestock and environment subsystems, respectively. The calculation results are shown in Table S7.

2.5. Coupling Coordination Degree Model

The coupling coordination degree model can reflect the interaction between systems or among subsystems within a system to estimate the development of coupling coordination of the system [42]. After continuous development, the current coupling coordination degree model includes eight model types with minor differences; the original model is the most commonly used coupling coordination degree model [43]. Hence, on the basis of the original model, we constructed the coupling coordination degree models of cropland–livestock and cropland–livestock–environment systems.

The coupling coordination degree model of cropland–livestock systems:

$$C_2 = Z_{(C)} Z_{(L)} / (\frac{Z_{(C)} + Z_{(L)}}{2})^2 \tag{6}$$

$$T_2 = \alpha Z_{(C)} + \beta Z_{(L)} \tag{7}$$

$$D_2 = \sqrt{C_2 \times T_2} \tag{8}$$

where C_2 is the coupling degree, reflecting the degree of mutual influence between systems, and $C_2 \in [0, 1]$. When C_2 is larger, the degree of coupling between the systems is greater. T_2 is the comprehensive reconciliation index. D_2 is the coupling coordination degree, the value of which is positively correlated with the degree of coupling coordination between systems. $Z_{(C)}$ and $Z_{(L)}$ represent the comprehensive evaluation value of cropland subsystems and livestock subsystems, respectively. α and β show the weight of the importance of the two subsystems, where $\alpha = \beta = 1/2$.

The coupling coordination degree model of cropland–livestock–environment systems:

$$C_3 = \left\{ Z_{(C)} Z_{(L)} Z_{(E)} / \left(\frac{Z_{(C)} + Z_{(L)} + Z_{(E)}}{3} \right)^3 \right\}^{1/3} \tag{9}$$

$$T_3 = \alpha Z_{(C)} + \beta Z_{(L)} + \gamma Z_{(E)} \tag{10}$$

$$D_3 = \sqrt{C_3 \times T_3} \tag{11}$$

where D_3 is the coupling coordination degree for the cropland–livestock–environment system, $Z_{(C)}$, $Z_{(L)}$ and $Z_{(E)}$ represent the comprehensive evaluation value of cropland, livestock and environment subsystems, respectively, where $\alpha = \beta = \gamma = 1/3$. The coupling degree C and comprehensive reconciliation index T are shown in Tables S8 and S9).

In previous studies, different methods were used to classify the coupling coordination degree [44,45]. In this study, the coupling coordination degree was divided into 10 types via the use of a continuous uniform distribution function (Table 2).

Table 2. The types and criteria of coupling coordination degree.

Category	D_n Value	Coupling Coordination Type
Uncoordinated development	$0 \le D_n \le 0.1$	Extreme decoupled maladjustment
	$0.1 < D_n \le 0.2$	Severe decoupled maladjustment
	$0.2 < D_n \le 0.3$	Moderate decoupled maladjustment
	$0.3 < D_n \le 0.4$	Mild decoupled maladjustment
Transformation development	$0.4 < D_n \le 0.5$	On the verge of decoupled maladjustment
	$0.5 < D_n \le 0.6$	Barely coupled coordination
Coordinated development	$0.6 < D_n \le 0.7$	Basic coupled coordination
	$0.7 < D_n \le 0.8$	Intermediate coupled coordination
	$0.8 < D_n \le 0.9$	Good coupled coordination
	$0.9 < D_n \le 1$	Excellent coupled coordination

2.6. Spatial Autocorrelation

Spatial autocorrelation reflects the correlation of a phenomenon or feature with neighboring regions, while global correlation is used to describe the spatial clustering or differentiation characteristics of a phenomenon or attribute in the whole domain [46]. Moran's I is an index commonly used for spatial autocorrelation analysis. We used global and local Moran's I to explore the spatial correlation of the coupling coordination degree for cropland–livestock and cropland–livestock–environment systems [34,47]. The formula of global Moran's I is as follows:

$$\text{Moran's } I = \frac{\sum_{f=1}^{n}\sum_{t=1}^{n} W_{ft}\left(D_f - \overline{D}\right)\left(D_t - \overline{D}\right)}{S^2\sum_{f=1}^{n}\sum_{t=1}^{n} W_{ft}} \tag{12}$$

where D_f and D_t represent the coupling coordination degree of region f and t, n represents the total number of regions, and W_{ft} represents the spatial weight matrix; $S^2 = \frac{1}{n}\sum_{f=1}^{n}(Df - \overline{D})$, and $\overline{D} = \frac{1}{n}\sum_{f=1}^{n} Df$. The value range of global Moran's I is $[-1,1]$, and the larger the absolute value, the greater the global spatial correlation. Some spatial phenomena or features not only have global correlation characteristics, but also have local regional spatial aggregation or heterogeneity. Thereby, the local Moran's I index was introduced to analyze the local spatial autocorrelation of the coupling coordination degree for cropland–livestock and cropland–livestock–environment systems. The formula of local Moran's I is as follows:

$$\text{Local Moran's } I = \frac{\left(D_f - \overline{D}\right)}{S^2}\sum_{f=1}^{n} W_{ft}\left(D_f - \overline{D}\right) \tag{13}$$

Hainan was not included in the spatial analysis because it has no border with other provinces.

2.7. Geographical Detector

Geographical detector is a new analytical method for exploring the factors behind spatial differentiation. Geographical detector has been applied in many fields of natural and social sciences. We used geographic detector to detect the influencing factors and effects of the coupling coordination degree for cropland–livestock and cropland–livestock–environment systems [48–50]. The specific calculation methods are shown in Section S.2 of the supplementary materials.

3. Results

3.1. Analyzing the Development of Chinese Cropland and Livestock in 2000–2020

The total sown area of farm crops in China increased gradually, accompanied by increases in grain and grain crop straw yields from 2000 to 2020. The consumption of chemical fertilizers increased till 2015 to the maximum application amount of 602.25 million tons and then decreased (Figure S1). Across the country, the biggest increases in farm crops sown area were in Heilongjiang, Jilin, Inner Mongolia and Xinjiang, with Heilongjiang adding 5.58 million hectares. Spatially, the largest changes in terms of the output of grain and grain crop straw yield were in North China, Northeast and the Middle-lower Reaches of the Yangtze River; the largest increases were in Heilongjiang, Henan and Shandong. In Henan, Shandong and Heilongjiang, which have the largest farm crops sown area, the amounts of applied chemical fertilizers were largest in Henan and Shandong (Figure S2).

During the past 20 years, the number of captive livestock in China fluctuated; the maximum was 1550.14 million heads (pig equivalent) in 2005, corresponding to a livestock manure production of 2.79 billion tons (Figure S3). The number of captive livestock in most provinces varied less than the livestock manure production. In North China, the number of captive livestock and the livestock manure production of Hebei, Henan and Shandong provinces have changed greatly (Figure S4).

3.2. Coupling Coordination Degree Analysis

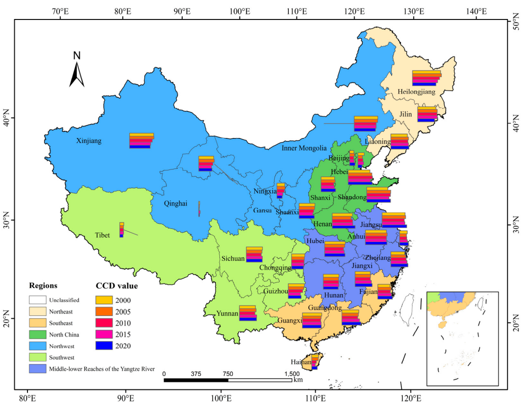
The coupling coordination degree for the cropland–livestock system ranged from 0.4 to 0.9, i.e., from being on the verge of decoupled maladjustment to good coupled coordination. Most provinces were in basic and intermediate coupled coordination. In the Middle-lower Reaches of the Yangtze River and Northeast, the coupling coordination degree values of cropland–livestock systems were all greater than 0.5, indicating that there was no risk of decoupled maladjustment in the regions. In some years, the coupling coordination degree values of cropland–livestock system exceeded 0.8, i.e., the level of good coupled coordination, in Heilongjiang, Hebei, Shandong and Jiangsu. From 2000 to 2020, Beijing, Qinghai and Tibet were on the verge of decoupled maladjustment state, as were Tianjin, Ningxia and Hainan in some years (Figure 3a). The within-region differences in the coupling coordination degree for the cropland and livestock system varied between regions. The within-region differences were smallest in Northeast and largest in North China and Northwest (Figure 3b).

Region	Province	2000	2005	2010	2015	2020
Northeast	Heilongjiang	0.7912	0.819	0.8511	0.8832	0.8689
	Jilin	0.6828	0.7297	0.7236	0.7270	0.7048
	Liaoning	0.7021	0.6952	0.6849	0.6946	0.6762
North China	Beijing	0.4909	0.4762	0.4685	0.4797	0.4715
	Tianjin	0.4702	0.4954	0.4844	0.4754	0.5060
	Hebei	0.8034	0.7713	0.8065	0.7976	0.7649
	Henan	0.7837	0.7429	0.7415	0.7154	0.7384
	Shandong	0.7981	0.7718	0.7960	0.801	0.7520
	Shanxi	0.6433	0.6224	0.6125	0.6360	0.6271
Middle-lower Reaches of the Yangtze River	Shanghai	0.5480	0.5296	0.5203	0.5163	0.5295
	Jiangsu	0.8126	0.7815	0.7711	0.7937	0.7848
	Zhejiang	0.6852	0.6690	0.6554	0.6477	0.6320
	Anhui	0.7614	0.7521	0.7530	0.7644	0.7522
	Hubei	0.7837	0.7429	0.7415	0.7154	0.7384
	Hunan	0.7405	0.7273	0.7154	0.7359	0.7456
	Jiangxi	0.6856	0.6727	0.6547	0.6587	0.6552

Region	Province	2000	2005	2010	2015	2020
Northwest	Inner Mongolia	0.7566	0.7668	0.7673	0.7919	0.7951
	Shaanxi	0.6561	0.6318	0.6446	0.6619	0.6657
	Ningxia	0.4887	0.4987	0.5232	0.5349	0.5313
	Gansu	0.6225	0.6124	0.6364	0.6596	0.6513
	Qinghai	0.4139	0.4239	0.4093	0.4134	0.4169
	Xinjiang	0.7459	0.7527	0.7796	0.8075	0.8044
Southwest	Chongqing	0.5994	0.6072	0.6101	0.6147	0.6208
	Sichuan	0.6663	0.6680	0.6499	0.6619	0.6697
	Guizhou	0.6156	0.6030	0.6412	0.6607	0.6698
	Yunnan	0.6868	0.6880	0.6600	0.6796	0.6678
	Tibet	0.4550	0.4640	0.4625	0.4628	0.4680
Southeast	Fujian	0.6440	0.6280	0.6103	0.6238	0.6052
	Guangdong	0.7179	0.6948	0.6635	0.6750	0.6831
	Guangxi	0.7156	0.7126	0.7065	0.7137	0.7241
	Hainan	0.4921	0.4597	0.4772	0.5096	0.5144

0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1
Extreme decoupled maladjudtment	Severe decoupled maladjudtment	Moderate decoupled maladjudtment	Mild decoupled maladjudtment	On the verge of decoupled maladjudtment	Grudging coupled coordination	Basic coupled coordination	Intermediate coupled coordination	Good coupled coordination	Excellent coupled coordination

(**a**)



(**b**)

Figure 3. The coupling coordination degree for the cropland–livestock system in 31 provinces of China from 2000 to 2020. (**a**): the coupling coordination degree values for the cropland–livestock system in 31 provinces; (**b**): the spatial distribution of the coupling coordination degree.

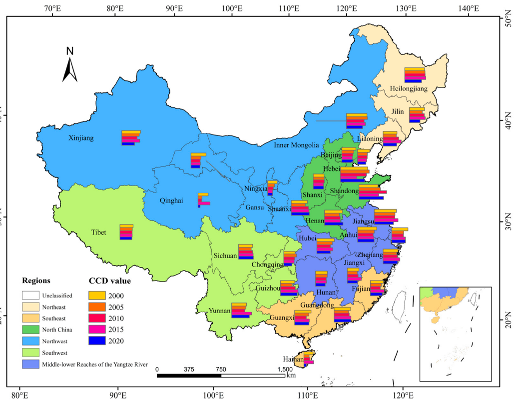
At the provincial scale, the coupling coordination degree value for the cropland–livestock–environment system ranged from 0.4 to 0.8, i.e., from being on the verge of decoupled maladjustment to the intermediate coupled coordination level. Most of the provinces were in a barely coupled coordination state. The provinces in Southwest, Northeast, the Middle-lower Reaches of the Yangtze River and North China coupling coordination degree values for the cropland–livestock–environment system were all greater than 0.5, i.e., there was no risk of decoupled maladjustment. In some years, the coupling coordination degree values in Ningxia, Qinghai and Hainan were between 0.4 and 0.5, indicating that these three regions were on the verge of decoupled maladjustment state (Figure 4a). There were significant spatiotemporal differences in the coupling coordination degree for the cropland–livestock–environment system. In terms of time, the coupling coordination degree of cropland–livestock–environment systems in Qinghai, Hebei, Shandong and other provinces showed great differences over the years. Spatially, the differences in the coupling coordination degree values for the cropland–livestock–environment system among provinces in Southwest, Northeast, Middle- lower Reaches of the Yangtze River and North China were small. While the differences among provinces were great in the Northwest (Figure 4b).

When the environment subsystem was added to the cropland–livestock system, the regional coupling coordination degree changed significantly (Figure 5). The coupling coordination degree values of most provinces decreased by two levels (Figures 3 and 4). Among them, the good coupled coordination state of Heilongjiang, Hebei, Shandong and Jiangsu decreased to the basic or barely coupled coordination state. However, the coupling coordination degree values of Beijing, Tianjin, Shanghai, Tibet and Qinghai increased, and the state changed from on the verge of decoupled maladjustment to barely coupled coordination in Beijing, Tianjin and Tibet. In addition, adding the environment subsystem changed the spatiotemporal difference of coupling coordination degree in most provinces and increased the degree of variation on the time scale, especially in the Middle-lower Reaches of the Yangtze River and North China.

Region	Province	2000	2005	2010	2015	2020
Northeast	Heilongjiang	0.6103	0.6633	0.6552	0.6535	0.6468
	Jilin	0.5330	0.5996	0.5870	0.5616	0.5906
	Liaoning	0.5709	0.6279	0.5954	0.5657	0.5741
North China	Beijing	0.5444	0.5311	0.5389	0.5495	0.5757
	Tianjin	0.5053	0.5160	0.5225	0.5241	0.5545
	Hebei	0.7052	0.6050	0.7266	0.7614	0.7422
	Henan	0.6317	0.5974	0.5973	0.5861	0.6267
	Shandong	0.7079	0.6464	0.7463	0.6683	0.6381
	Shanxi	0.5305	0.5284	0.5387	0.5362	0.5352
Middle-lower Reaches of the Yangtze River	Shanghai	0.5716	0.5703	0.5458	0.5489	0.6022
	Jiangsu	0.6411	0.6966	0.6574	0.6586	0.6771
	Zhejiang	0.5817	0.6092	0.5802	0.5703	0.5869
	Anhui	0.6070	0.6027	0.5945	0.6092	0.6400
	Hubei	0.6317	0.5974	0.5973	0.5861	0.6267
	Hunan	0.5693	0.5996	0.5703	0.5930	0.6193
	Jiangxi	0.5298	0.5756	0.5355	0.5251	0.5454
Northwest	Inner Mongolia	0.6030	0.6378	0.6222	0.6622	0.6570
	Shaanxi	0.6274	0.6210	0.6157	0.5752	0.6029
	Ningxia	0.4632	0.4635	0.4717	0.4872	0.5197
	Gansu	0.5137	0.5182	0.5154	0.5252	0.5889
	Qinghai	0.4253	0.5497	0.4454	0.4495	0.5273
	Xinjiang	0.5600	0.6244	0.5913	0.6186	0.6349
Southwest	Chongqing	0.5026	0.5293	0.5362	0.5600	0.5415
	Sichuan	0.5855	0.5826	0.5753	0.5580	0.5763
	Guizhou	0.6107	0.6195	0.5854	0.5447	0.5788
	Yunnan	0.6224	0.6506	0.5640	0.5775	0.5867
	Tibet	0.5496	0.5526	0.5520	0.5541	0.5643
Southeast	Fujian	0.5503	0.5738	0.5245	0.5373	0.5654
	Guangdong	0.6103	0.6097	0.5883	0.5821	0.6068
	Guangxi	0.5794	0.5837	0.5464	0.5777	0.6057
	Hainan	0.4315	0.5220	0.4740	0.4646	0.5146

0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1
Extreme decoupled maladjudtment	Severe decoupled maladjudtment	Moderate decoupled maladjudtment	Mild decoupled maladjudtment	On the verge of decoupled maladjudtment	Grudging coupled coordination	Basic coupled coordination	Intermediate coupled coordination	Good coupled coordination	Excellent coupled coordination

(**a**)



(**b**)

Figure 4. The coupling coordination degree for the cropland–livestock–environment system in 31 provinces of China from 2000 to 2020. (**a**): the coupling coordination degree values for the cropland–livestock–environment system in 31 provinces; (**b**): the spatial distribution of the coupling coordination degree.

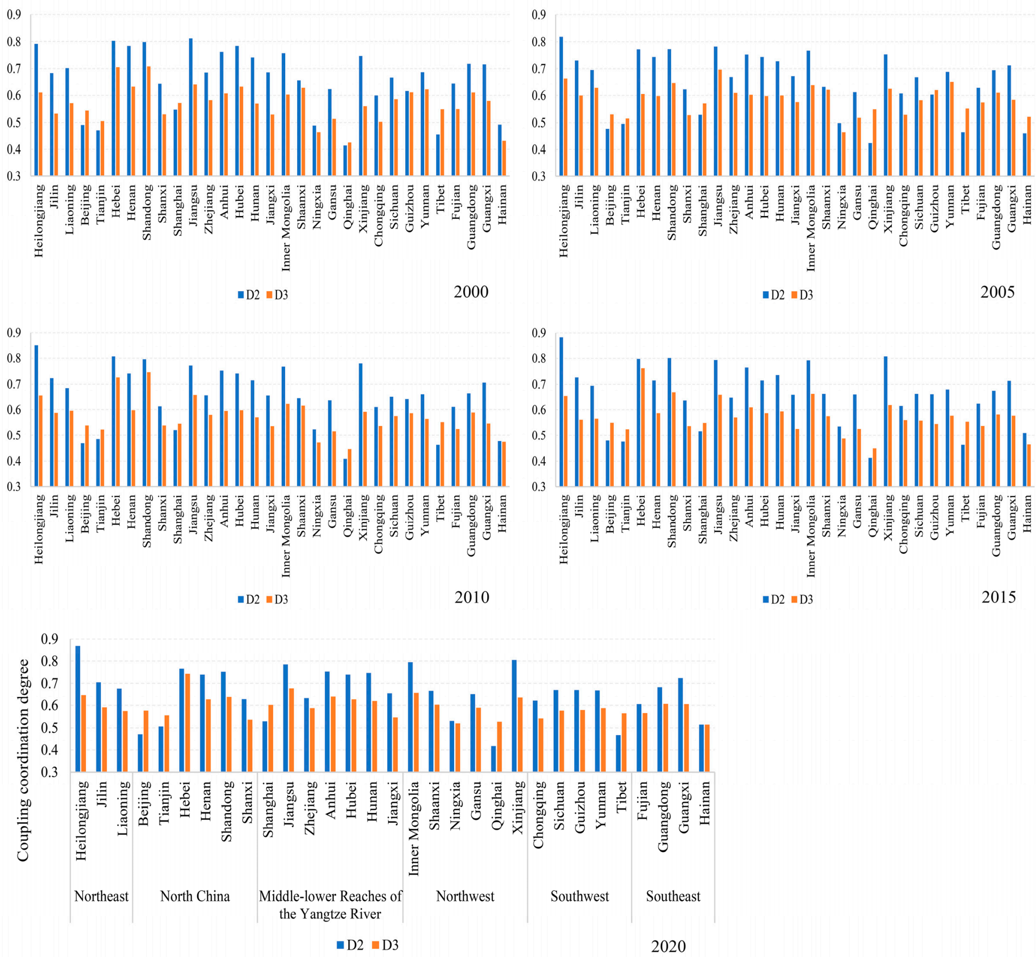


Figure 5. Coupling coordination degree comparison of cropland and livestock system in 31 provinces of China from 2000 to 2020.

3.3. Spatial Correlation Analysis

Global Moran's *I* was used to determine the global spatial autocorrelation of the coupling coordination degree for the cropland–livestock and cropland–livestock–environment systems. The global Moran's *I* *p* values of the coupling coordination degree for cropland–livestock and cropland–livestock–environment systems in 2000 were below 0.1, and the Z values were over 1.65, and in 2010, the *p* value of the coupling coordination degree for the cropland–livestock–environment system was below 0.05, and the Z value was over 1.96, indicating a significant spatial positive correlation (Table 3). Nevertheless, in other years the *p* values were all over 0.1, and the Z values below 1.65, indicating that there was no spatial correlation.

Table 3. Global spatial autocorrelation results.

Year (CLS CDD)	Global Moran's *I*	*p* Value	Z Value	Year (CLS CDD)	Global Moran's *I*	*p* Value	Z Value
2000	0.1755	0.0567	1.9057	2000	0.1451	0.0986	1.6517
2005	0.1459	0.1026	1.6326	2005	0.0300	0.5609	0.5816
2010	0.1378	0.1185	1.5621	2010	0.1864	0.0389	2.0654
2015	0.1112	0.1858	1.3232	2015	0.1098	0.1751	1.3560
2020	0.0914	0.2534	1.1442	2020	0.0529	0.4186	0.8089

CLS, cropland–livestock system; CLES, cropland–livestock–environment system.

There were four types of local spatial autocorrelation (Figure 6). At the national level, high–high clusters (H–H) were mainly distributed in Northeast, North China and the Middle-lower Reaches of the Yangtze River, including Jilin, Liaoning, Shandong, Henan, Anhui and Heilongjiang, indicating that the coupling coordination relationship between cropland and livestock in these cluster areas was better than in the surrounding provinces. Due to the consistent high–low outlier (H–L) characteristics, the coupling coordination degree values for the cropland–livestock system in Xinjiang were always higher than in the surrounding areas. The spatial relationship of the coupling coordination degree for the cropland–livestock system between Sichuan and neighboring provinces was complicated; the autocorrelation type changed from H–L to low–low cluster (L–L) and then back to H–L, indicating that the coupling coordination degree for the cropland–livestock system in Southwest and Northwest, centered on Sichuan province, had changed considerably.

The local spatial correlation differences of the coupling coordination degree for cropland–livestock–environment systems over time were large (Figure 7). The local spatial correlation was not significant in the Middle-lower Reaches of the Yangtze River and Southeast. Shandong, Hunan and Anhui formed a large H–H cluster in 2000 and 2010 and Shandong and Hunan in 2015 and 2020, indicating that the coupling coordination relationships between cropland, livestock and environment in the cluster areas were better than that in the surrounding provinces. From 2000 to 2020, the spatial correlation of the coupling coordination degree for the cropland–livestock–environment system in Tibet, Shaanxi, Sichuan, Liaoning, Shanxi, Tianjin and Shanghai changed significantly; the spatial correlation of Shaanxi, Tianjin and Shanghai changed only in one year.

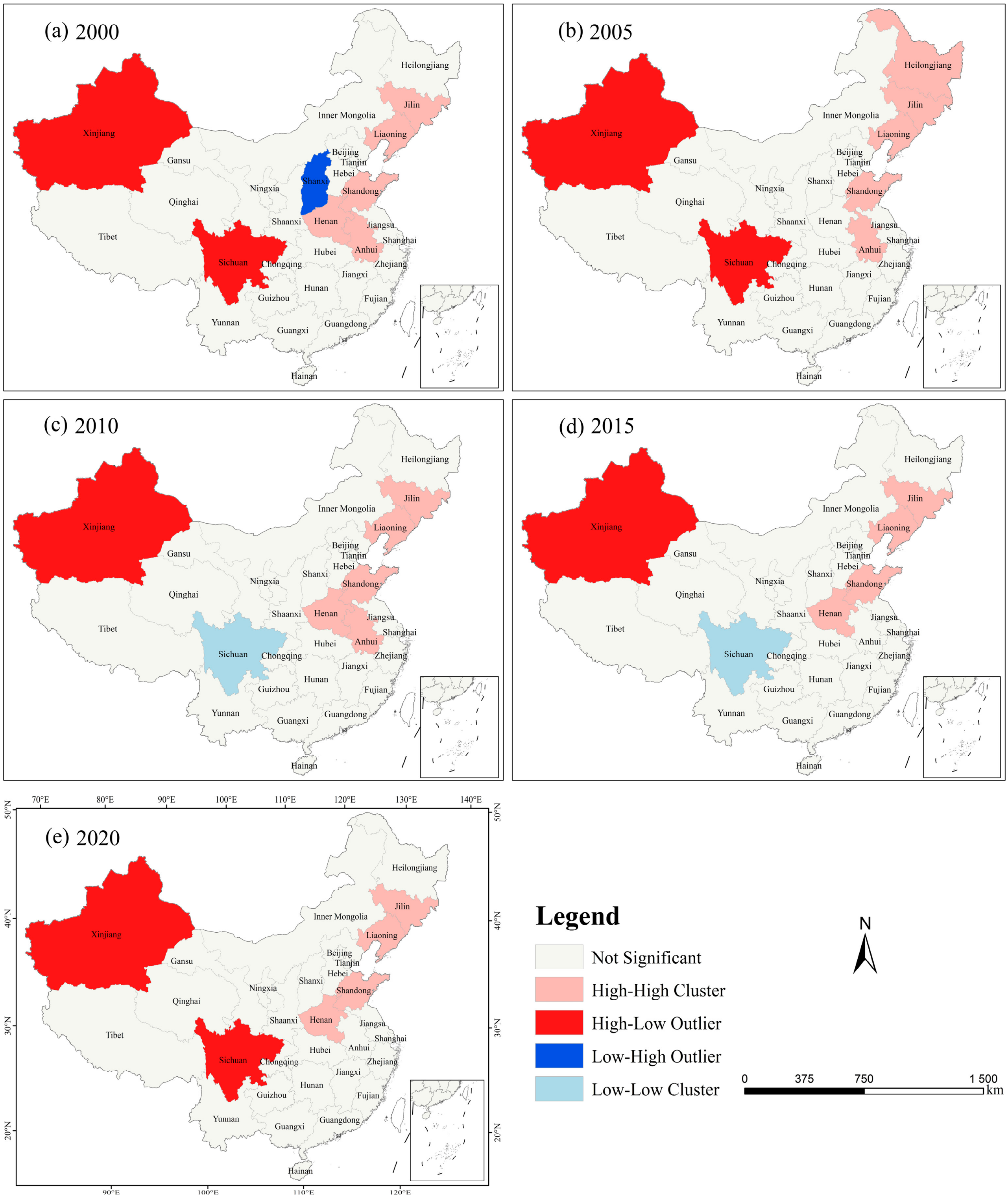


Figure 6. Local spatial association cluster maps of cropland–livestock coupling degree from 2000 to 2020.

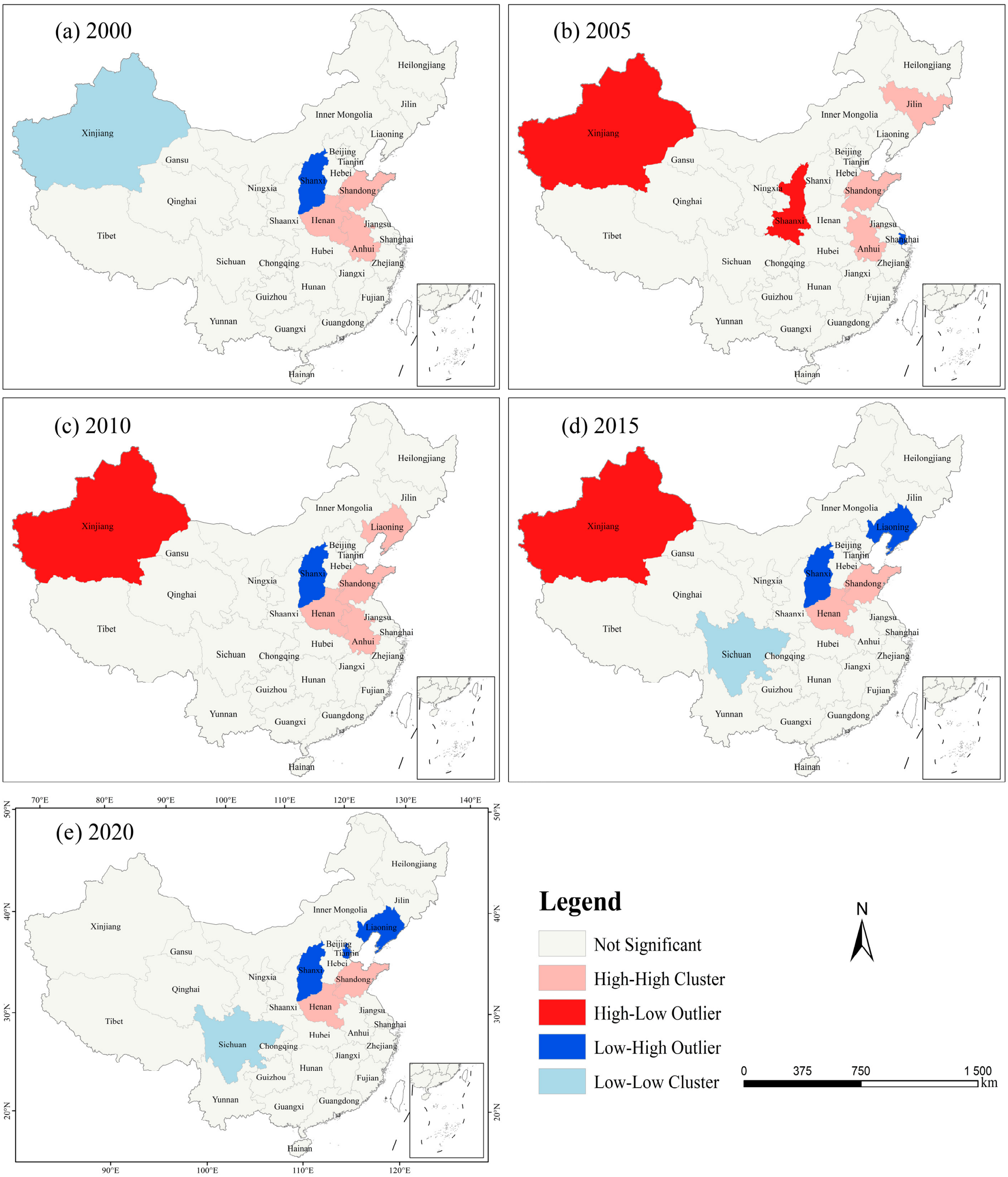


Figure 7. Local spatial association cluster maps of cropland–livestock–environment coupling degree from 2000 to 2020.

3.4. Influencing Factors

The q value and statistical significance reflect the influence degree of the factors on the coupling coordination degree. Except for the livestock density, all the factors had significant effects on the coupling coordination degree for the cropland–livestock system (Table 4). The q value of the irrigated area of cultivated land was 0.8643, indicating that it had the greatest influence on the coupling coordination degree. The livestock density had a negligible influence on the coupling coordination degree within the cropland–livestock system. The six primary factors with a substantial influence on the coupling coordination degree for the cropland–livestock system belong to the cropland subsystem, indicating its dominant role in affecting the degree of coupling coordination.

Table 4. Factors influencing the coupling coordination degree of the cropland–livestock system.

Factor	q Value	Factor	q Value
Irrigated area of cultivated land	0.8643 ***	Livestock urine production	0.6877 ***
Total sown area of farm crops	0.8097 ***	Cultivated land area	0.6751 ***
Output of farm crops	0.7995 ***	Livestock bung production	0.6590 ***
Consumption of chemical fertilizers	0.7887 ***	Number of pigs raised	0.5476 ***
Gross output value of farming	0.7669 ***	Total output of feed	0.3496 ***
Grain crop straw yield	0.7602 ***	Ratio of large-scale livestock farms	0.2838 ***
Gross output value of animal husbandry	0.7345 ***	Output of major grain per hectare	0.1506 **
Number of captive livestock	0.6970 ***	Livestock density	0.0217

*** and ** indicate statistical significance at q-value levels 0.01 and 0.05 respectively.

Sixteen factors influenced the coupling coordination degree of the cropland–livestock–environment system ($q < 0.01$) (Table 5). The factors with greatest influence were of the cropland subsystem; among all the factors, the irrigated area of cultivated land with q value 0.5414 had the biggest influence on the coupling coordination degree. Among the six factors of the livestock subsystem, the gross output value of animal husbandry has the biggest effect; and among the four factors of the environment subsystem, population had the greatest impact. The five most significant factors were all in the cropland subsystem, whereas general public budget revenue has the least significant impact. The factors not mentioned among the aforementioned 16 had negligible influence on the coupling coordination degree of the cropland–livestock–environment system.

Table 5. Factors influencing the coupling coordination degree of the cropland–livestock–environment system.

Factor	q Value	Factor	q Value
Irrigated area of cultivated land	0.5414 ***	General public budget revenue	0.2697 ***
Total sown area of farm crops	0.4370 ***	Total output of feed	0.2402
Output of farm crops	0.4357 ***	Annual average temperature	0.2269
Grain crop straw yield	0.4292 ***	Annual total sunshine hours	0.1885
Consumption of chemical fertilizers	0.4250 ***	Area of afforested land	0.1117
Gross output value of animal husbandry	0.4074 ***	Ratio of large-scale livestock farms	0.1107
Gross output value of farming	0.4052 ***	Output of major grain per hectare	0.1045
Population	0.3837 ***	Annual total precipitation	0.0958
GDP	0.3409 ***	Rural family Engel's coefficient	0.0831
Length of highways	0.3249 ***	Per capita GDP	0.0803
Livestock bung production	0.3266 ***	Per capita water resources	0.0411
Number of pigs raised	0.3251 ***	Livestock density	0.0397
Livestock urine production	0.3055 ***	R&D investments	0.0217
Number of captive livestock	0.3036 ***	Environmental protection investment	0.0209
Cultivated land area	0.3015 ***		

*** indicate statistical significance at q-value levels 0.01 respectively.

4. Discussion

Prior to the 1990s, China primarily focused on agricultural production, employing traditional coupled livestock and cropland. This approach yielded low agricultural productivity, although there existed a significant degree of integration between cropland and livestock. Following the 1990s, due to a continuous expansion in the inexpensive fertilizer market, there has been a significant decrease in the use of livestock manure as organic fertilizer in cropland, resulting in cropland decoupling from livestock and gradually worsening non-point source pollution in agriculture since 2000, with the significant development in agricultural mechanization and intensification, as well as increased public concern for environmental pollution. Consequently, new models for integrated crop-livestock farming have emerged, leading to the recoupling of livestock and cropland [8,24,51]. How has the development of rebuilding the linkage between livestock and cropland been since 2000?

Therefore, it is necessary to conduct a comprehensive analysis of the coupling coordination relationship between cropland and livestock and explore its driving factors [4,10]. We built a comprehensive evaluation indicator system of cropland and livestock system from three aspects: cropland, livestock and environment. Furthermore, we explored the spatiotemporal variation of the coupling coordination relationship for cropland–livestock systems in China during 2000–2020 based on a coupling coordination model and determined its key driving factors.

4.1. Enhancing the Coupling Coordination Relationship between Cropland and Livestock

Similar to a previous study [20], the results showed that most of the provinces in China were not at risk of the decoupling between cropland and livestock. From 2005 to 2020, the best coupling relationship between cropland and livestock was in Heilongjiang, possibly because the cultivated area in Heilongjiang is the biggest in China, chemical fertilizers are applied less and fewer livestock is raised than in the other provinces (Figure 3, Figures S2 and S4). Six provinces, including Beijing and Tianjin, are facing the risk of cropland and livestock decoupling, partly because there is less cultivated land to absorb livestock manure, large-scale farms account for a relatively high proportion, and the difference in the comprehensive evaluation values between cropland and livestock subsystems was significant in these provinces (Figure 3 and Table S7). The cropland and livestock system in Shanghai was also at risk of being decoupled, indicating that the risk of excess manure production in more urbanized areas is higher, making the cropland and livestock decoupling more likely [20,52]. However, the cropland–livestock coupling coordination degree was higher in Shanghai than that in Beijing and Tianjin, possibly because the Shanghai government has adopted and implemented stricter management measures for livestock manure [53]. Since 2000, the Central Government of China has paid more and more attention to the environmental pollution caused by livestock farming and issued a series of policies and regulations to manage and restrict livestock farming. However, due to that, farmers lack environmental protection awareness and fail to realize the importance of nutrient management and there is a lack of attention by some local governments; therefore, the coupling coordination degree of cropland and livestock in most provinces of China has not improved significantly from 2000 to 2020 (Figure 3) [27,53,54]. As individuals increasingly prioritize healthy dietary habits by reducing their consumption of animal-derived products, and with the implementation of more scientifically informed spatial planning for livestock production, there is an opportunity to align the development of cropland and livestock towards greater coupling coordination. However, the continuing trend of urbanization and rising population density has resulted in the gradual relocation of livestock farms from rural areas to suburban fringes, distancing them from cropland, which could potentially exacerbate the decoupling of cropland and livestock in certain regions [5,8,9,55]. Therefore, it is necessary to further enhance the degree of coupling coordination between cropland and livestock, especially in relatively developed areas with less cultivated land. Additionally, there is a need to strengthen the executive force of regulations and laws related to livestock production in the future.

4.2. The Role of Environmental Factors in Cropland–Livestock Coupling

When considering the environmental factors as an independent subsystem in the coupling relationship between cropland and livestock, the regional degree of cropland and livestock coupling had obviously changed. The coupling coordination degree value of most of the provinces decreased and was generally low, with a large decoupling risk. However, the coupling coordination degree value of Beijing, Tianjin and Shanghai increased (Figure 5). This was partly because of the rapid economic development of areas such as Beijing, with relatively high per capita GDP, convenient transportation and abundant resources for environmental pollution control [20,52]. Environmental factors such as population, GDP, traffic conditions and terrain were the main reasons for the decoupling of regional cropland and livestock system [8,56]. Furthermore, taking environmental, social and economic factors into full consideration is the key to the spatial planning of livestock production and the reconstruction of the spatial connection between cropland and livestock [56]. Therefore, environmental factors must be considered when analyzing the regional coupling relationship between cropland and livestock.

4.3. Key Drivers for the Coupling of Cropland and Livestock

The factors with the highest influence on cropland–livestock and cropland–livestock–environment coupling coordination were all from the cropland subsystem, indicating that the cropland subsystem plays a leading function in the coupling and coordination of cropland–livestock and cropland–livestock–environment systems. Interestingly, the irrigated area of cultivated land was the most influential factor in the coupling coordination relationship of both cropland–livestock and cropland–livestock–environment systems (Tables 4 and 5). Possibly the irrigated area of cultivated land is related to the consumption of freshwater resources in the region, which not only has a great impact on crop yield and gross output value of farming but also directly affects the supply of freshwater resources for livestock in the region [3,57,58]. Population, GDP, the length of highways and the general public budget in the environment subsystem had an impact on the coupling coordination relationship for cropland–livestock–environment systems (Table 5). Similar to earlier conclusions [8,11,56], population, GDP and the length of highways that determines the transportation distance of livestock were the influencing factors for cropland–livestock systems of the coupling relationship (Tables 4 and 5). Contrary to earlier results, livestock density was not an influencing factor for cropland–livestock or cropland–livestock–environment systems. The difference to earlier results may be due to a different definition of livestock density or to our comprehensive approach where more indicators were considered [5,7,19].

4.4. Limitations and Outlook of the Study

Different from previous studies where the synergistic effect of regional cropland and livestock were measured from limited perspectives, e.g., breeding quantity, animal density, crop-livestock nutrient balance and land carrying capacity [7,20,53], we used the coupling coordination degree model to comprehensively establish the coupling coordination relationship between cropland, livestock and environment subsystems. Although we constructed a relatively comprehensive evaluation index system from the three aspects and carried out a correlation analysis of indicators, a lack of evaluation of the suitability and risk of indicators with uncertainties remains. In addition, due to the limited access to data at the provincial level, the survey data, such as the area of livestock farms and livestock manure treatment methods, were not considered in the indicator system. Consequently, to make the quantitative results of the coupling relationship between cropland and livestock more accurate in future research, a comprehensive evaluation of the indicators related to the coupling relationship between cropland and livestock should be carried out, and a comprehensive evaluation indicator system for cropland–livestock could be constructed at different scales (e.g., county, city or district) and dimensions [59]. The data used in this study come from various statistical yearbooks in China, which are the most credible data sources in China. Calculated coefficients, e.g., straw-to-grain ratio, pig equivalent conversion coefficient and livestock feeding period, from previous studies and Chinese technical guidelines similar to the national statistics, are also reliable. However, the differences in the values of coefficients between our calculations and previous studies and national technical guidelines have resulted in uncertainty in the research [24].

5. Conclusions

There was no risk of decoupling between cropland and livestock in most of the provinces in China during 2000–2020, but the degree of coupling coordination was low down. Beijing, Tianjin and other more urbanized areas were more likely to undergo the decoupling of cropland and livestock, but it was also easier to reestablish the contact of cropland and livestock and increase the degree of coupling coordination in those areas. The spatial autocorrelation of cropland and livestock coupling coordination among provinces in China was not significant. In Hebei, Henan, Shandong and Sichuan, which are major agricultural and livestock breeding provinces, cropland and livestock system were not at the risk of decoupling. This indicates that the coupling coordination degree between cropland and livestock system is higher in areas with comprehensive development of planting and breeding industries. Our results showed that the cropland subsystem had the greatest influence on the coupling coordination between cropland and livestock systems. The irrigated area of cultivated land was the most influential factor in the coupling coordination relationship of both cropland–livestock and cropland–livestock–environment systems. Clearly, our research examined the national scale and did not involve analyzing the coordinated relationship between cropland and livestock under different policy contexts. Such an analysis would be more suitable for studying regional scales under uniform contexts. To fully understand the critical influencing factors of the coupling relationship between cropland and livestock, we suggest that in future research, an indicator system is constructed from multiple scales and multiple dimensions to compare the spatiotemporal characteristics of the coupling between cropland and livestock at different scales and to explore the key influencing factors and major barriers at multiple scales.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13071304/s1. The Supplementary Material S1 includes indicator definition and calculation, Geographical detector model introduction, figures and tables. Table S1: Straw-to-grain ratio of major grain crop in different regions; Table S2: Confined ratio of pastoral provinces from 2000 to 2020; Table S3: Different scale livestock farms division standard; Table S4: Daily bung/urine excretion and nitrogen/phosphorus content(fresh based) by various livestock and feeding period; Table S5: Cropland–livestock–environment original comprehensive evaluation index system; Table S6: Weight of each indicator; Table S7: Comprehensive evaluation value of cropland, livestock and environment subsystem from 2000 to 2020; Table S8: Coupling degree values for the cropland–livestock and cropland–livestock–environment system from 2000 to 2020; Table S9: The comprehensive reconciliation index values for the cropland–livestock and cropland–livestock–environment system from 2000 to 2020. Figure S1: The development of Chinese crop farming from 2000 to 2020; Figure S2: The crop farming development of 31 provinces in China from 2000 to 2020; Figure S3: The development of Chinese livestock farming from 2000 to 2020; Figure S4: The livestock farming development of 31 provinces in China from 2000 to 2020. The Supplementary Material S2 is the original data.

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