RESEARCH ARTICLE

Establishment and application of system dynamics models of agricultural development path from the perspective of circular economy

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The realization of a circular economy requires the formulation of a reasonable path for agricultural development. Therefore, a system dynamics model was introduced in this study to plan the development path. Entropy weight method and neural network were employed to optimize the weight calculation methods of the indicators to improve the performance of the model. The results showed that the biggest indicator affecting the agricultural development of Jiade, Linfen city, Shanxi, China was the total agricultural output with a weight value of 0.1751. The combination of traditional and circular agriculture development models led to the fastest increase in comprehensive evaluation scores. Under this development model, Jiade Township would achieve a comprehensive evaluation score of 0.7181 in 2040. In addition, the maximum prediction error of this designed model in agricultural gross domestic product and population were 2.41% and 3.26%, respectively. The maximum Area Under Curve (AUC) of the comprehensive evaluation model was 0.798. These results confirmed that using system dynamics models under circular economy could effectively plan the path of agricultural development, which was beneficial for the development of circular economy.

Keywords: circular economy; agriculture; system dynamics; entropy weight method; analytic hierarchy process.

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Introduction

Agricultural development (AD) is closely related to the construction of ecological civilization [1]. If people want to achieve a circular economy, they need to transform the development mode of traditional agriculture to promote sustainable development. System dynamics model (SDM) is a method used to analyze the feedback and interaction processes of research objects [2]. SDM can explore the problems existing in the research object and propose solutions and its simulation can use computers to simulate the path of AD [3]. When constructing SDM, it is necessary to assign weights to each element. Common methods include analytic hierarchy process (AHP), neural networks, cluster analysis, and entropy weight method (EWM) [4]. AHP can qualitatively and quantitatively analyze complex decision-making problems. However, AHP relies on expert judgment and has a certain degree of subjectivity when applied [5]. Backpropagation neural network (BPNN) can obtain more objective results through continuous weight updates and has high accuracy. EWM is an objective weighting method that assigns weights based on the degree of indicator variation [6].

Circular economy points out that, in achieving economic development, it is necessary to achieve harmony and stability between the economy and the ecosystem [7, 8]. The traditional AD method has the characteristics of high consumption and high emissions [9]. It is necessary to transform the development mode of traditional agriculture. Karthick *et al*. used SDM to analyze the tomato supply chain by conducting simulation experiments on the established SDM after investigation and data processing and confirmed that this model could provide favorable decisions [10]. Wei *et al*. showed that SDM could analyze the factors influencing carbon emissions, which effectively demonstrated the mutual influence mechanisms of various systems [11]. Wang *et al*. established a qualitative SDM to analyze claims for infrastructure projects such as subways and proved that the model could assist project decision-makers in developing appropriate claim strategies [12]. Turner *et al*. stated that SDM could solve its existing problems and applied SDM to study the sustainable development management strategies. The results showed that the model could provide effective suggestions and solutions [13]. Further, Askarizad *et al*. conducted a study on the planning of urban architecture by combining AHP and SWOT analysis to provide an effective method for urban planning [14]. Badapalli *et al*. proposed introducing AHP into the analysis of land geological conditions, which could help researchers to determine suitable agricultural land [15]. Kumari *et al*. used AHP to analyze the influencing factors that lead to natural disasters. This proposed method divided the research area into different regions to formulate different management policies [16]. In addition, Lu *et al*. conducted a comprehensive evaluation of fishery development using EWM. The method clearly demonstrated the spatial characteristics of leisure fishing in different regions [17]. Zhu *et al*. established a model using stepwise regression method and used BPNN for training. BPNN could effectively improve the accuracy of climate prediction [18]. Morkunas *et al*. combined these two methods with other methods to construct composite indicators, which could obtain more objective and accurate indicator weights than the simple method [19]. Mallik established a fuzzy AHP and improved the model accuracy through parameter updates, confirming the superiority of this method [20].

Previous studies showed that SDM could help decision-makers develop effective management strategies. AHP and EWM could analyze the indicator weights of relevant influencing factors. After training, BPNN could improve model accuracy. However, the application effect of a single method is relatively poor. In addition, the current rural production environment is complex with diverse business entities, low production technology level, weak awareness of circular economy, and poor agricultural production management. How to develop a circular agriculture economy in complex traditional agricultural production and operation is an important issue that current scientific workers need to pay attention to. Therefore, this article selected Jiade Township in Linfen city, Shanxi, China as the research object, which has obvious traditional agricultural characteristics. SDM was introduced in the study for the development path planning of Jiade Township. Due to the agricultural development path (ADP) planning involves many influencing factors, and considering the difficulty and cost of the method, a combination of AHP, EWM, and BPNN was chosen to establish the SDM for ADP planning to optimize the weight calculation methods of the indicators and improve the performance of the model. The results of this research would provide a scientific basis for the planning of ADP to achieve sustainable development and some references for the current development of rural areas, which is conducive to the reform of traditional agriculture.

Materials and methods

Establishment of system dynamics model

Jiade Township located in the southeast of Yaodu District, Linfen City, Shanxi Province, China borders with Xiandi Town to the east, Hejiazhuang Township to the southeast, Dengzhuang Town in Xiangfen County to the

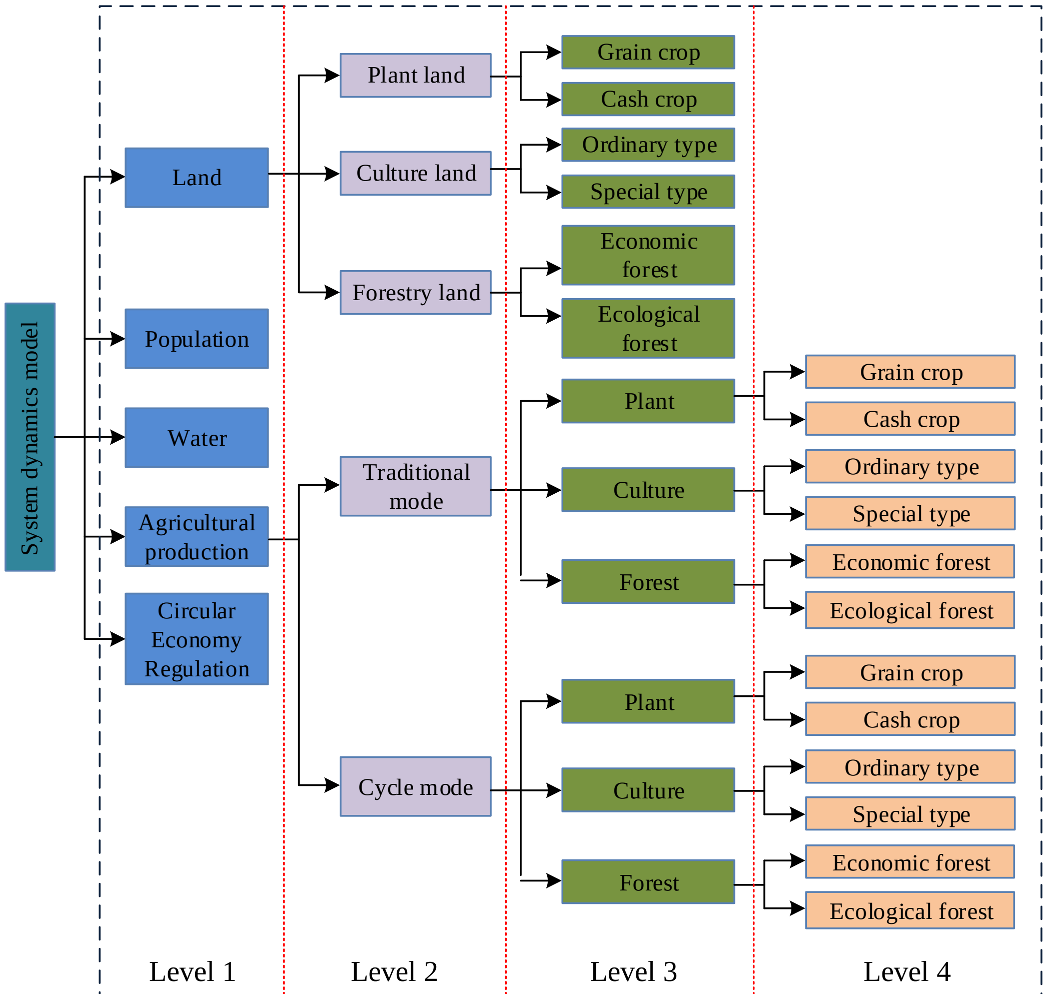

Figure 1. Hierarchy diagram of subsystems in the Jiade Township system dynamics model.

south, Yaomiao Town to the west, and Duandian Township to the north. The total administrative area is 89.68 km^2. Most of the area in Jiade Township is plain with a few villages in hilly terrain, which makes Jiade Township a good AD conditions and a key agricultural township for development. Therefore, Jiade Township was chosen for the case study.

The establishment of SDM requires analyzing the modeling conditions and then conducting causal analysis. The analysis of modeling conditions mainly includes model boundaries, main data, logical framework of modeling, and related main and auxiliary indicators. It is necessary to first determine the appropriate SDM boundary to exclude irrelevant content and ensure the closure of the research question according to the research purpose. The SDM established in this study included four levels of subsystems. The first subsystem closely related to AD in Jiade Township and mainly included population, water resources, land, agricultural production, and circular economy regulation. The second subsystem included traditional and circular agriculture, as well as land use subsystems for three purposes. The third level subsystem was a refinement of the second level subsystem including 12 subsystems. The fourth subsystem was an extension of some third level subsystems including 12 subsystems (Figure 1). The main structure established in the system structure was

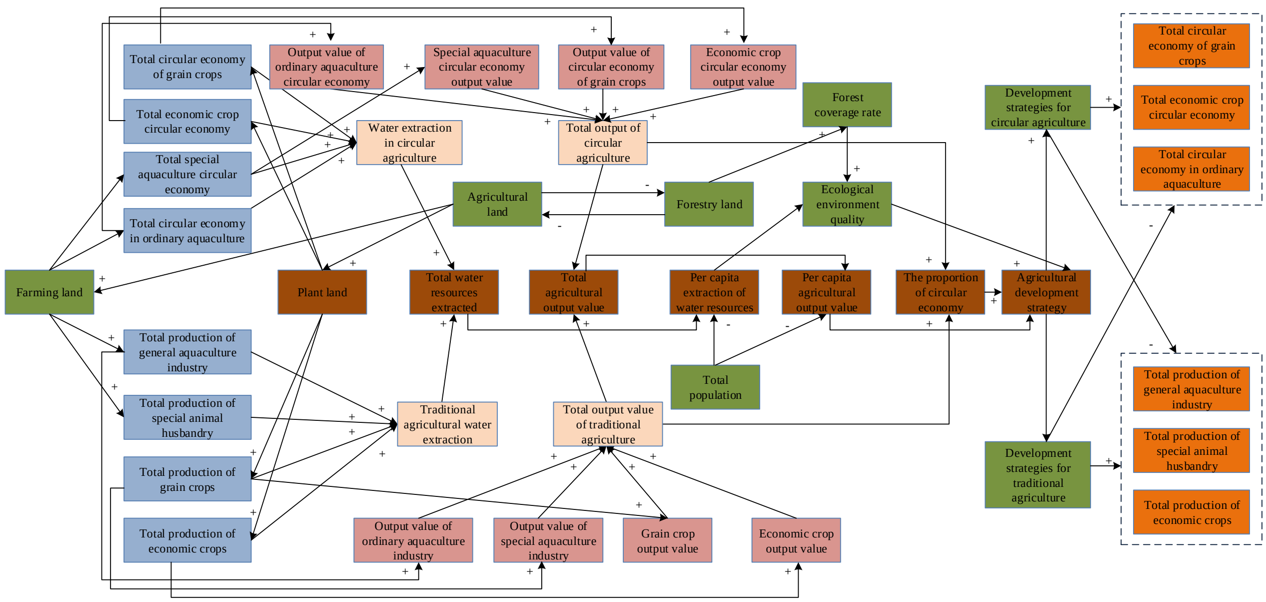

Figure 2. Analysis of causal relationships in the system dynamics of Jiade Township. +: would increase the value. -: would decrease the value.

the agricultural production system with land, water resources, population, and circular economy system as its four auxiliary systems and played a regulatory role. The agricultural production system and ecosystem would interact with each other. Different development paths would have different impacts on the ecosystem. Therefore, the logical basis of the model was the impact of the agricultural production system on the ecosystem and its own development status under four auxiliary systems. The SDM established in this research had 108 indicators, mainly including level, quota, and rate indicators. The level indicators mainly included land area, water demand, output value, and total industrial output. The rate indicators mainly included industrial value-added rate, industrial biogas rate, and organic fertilizer rate. The quota indicators mainly included fertilizer prices, crop unit prices, crop yields, and the proportion of economic output. Due to the involvement of multiple factors, causal analysis was required. A causal loop was obtained by analyzing the causal relationships between various elements, ultimately resulting in a model with constraining relationships (Figure 2). The SDM for Jiade Township ADP was then established based on causal analysis (Figure 3). The most important subsystems in this model were population, water resources, land, agricultural production, and circular economy regulation with the core being agricultural production. The per capita output and total output indicators of agriculture could reflect the AD status. The total value of animal husbandry and planting, the proportion of traditional economic output, and the output of food crops could reflect the development status of traditional agriculture. The output of circular economy and the total value of circular industries could reflect the development status of circular agriculture. The important regulatory subsystem in this model was the circular agriculture regulatory system, which was used to adjust the development path and promote the development of circular agriculture. The population, land, and water resource subsystems provided support for AD.

Improvement of development path evaluation method based on SDM

Path simulation and production mode analysis were conducted by establishing the SDM of Jiade Township ADP. Five different AD modes were obtained through simulation analysis including

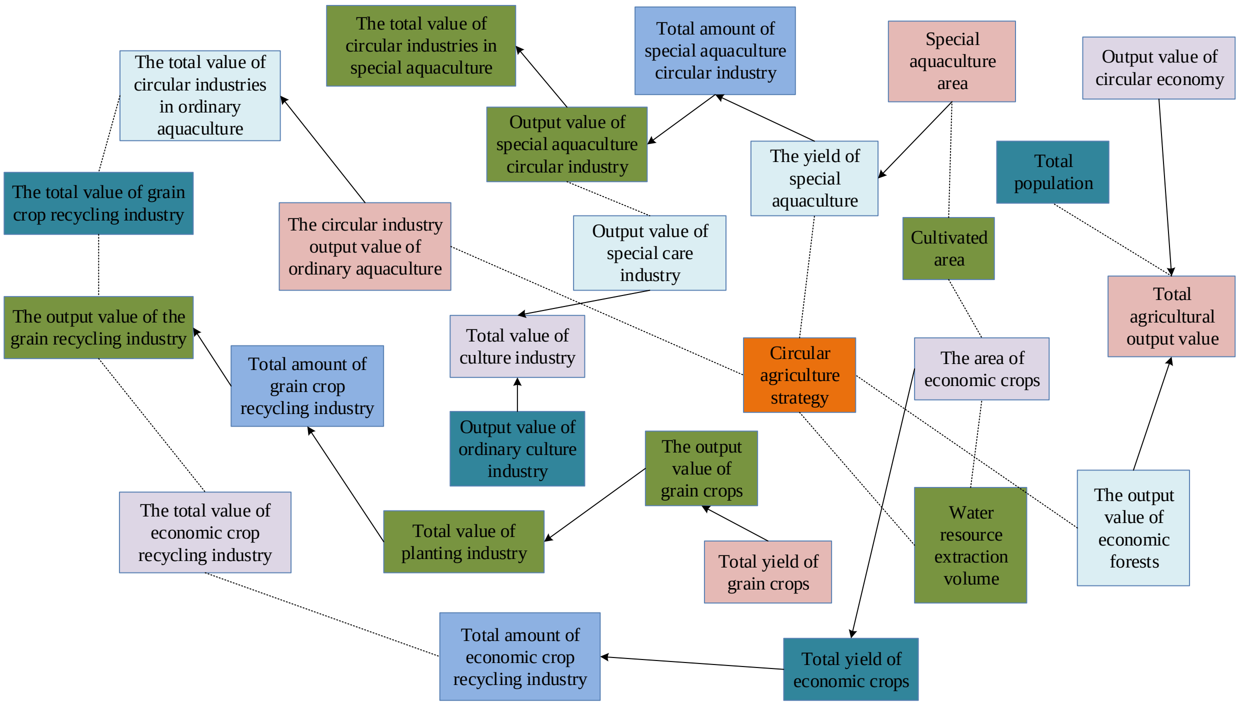

Figure 3. System dynamics model (SDM) of circular agriculture development in Jiade Township. Note: the solid line indicated a direct impact, while the dashed line referred to the presence of other influencing factors between two variables.

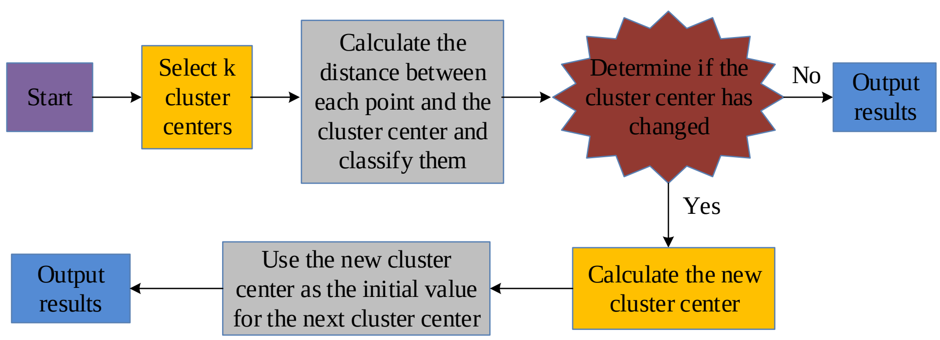

Figure 4. K-means clustering analysis.

traditional AD, primary, intermediate, advanced loop, and loop AD modes, respectively. The model was evaluated through the simulation experiment. A comprehensive evaluation was required first with 9 evaluation indicators including gross agricultural output value, mining output of water resources, economic proportion of circular agriculture, water demand proportion of planting industry, per capita agricultural output, *etc*. Due to the large number of evaluation indicators, K-means was first used for clustering analysis of the data (Figure 4). The k cluster centers were first selected. Then, the intra-class distance was calculated, and these data were classified. Next, it was necessary to determine whether the cluster center had changed. If there was no change, the result could be directly output. Otherwise, it was necessary to recalculate the cluster center and use it as the initial value for the next clustering, and finally output the results. The Euclidean distance was used for similarity calculation in clustering to reduce the squared intra-class distance to classify data. The objective function of clustering analysis was shown in equation 1.

$$L = \sum_{z=1}^{k}\sum_{v=1}^{m}\left\| x_v - u_z \right\|^2 \qquad (1)$$

where x_v referred to data, $v = 1, 2, ..., V$. u_z was the cluster center, $z = 1, 2, ..., k$. After classifying data, the evaluation indicators were applied for comprehensive evaluation. The combined method EWM-AHP was used for evaluation. EWM could be used for solving multi-objective evaluations, which provided objective weights for indicators after calculating information entropy. These data were first normalized using equation 2.

$$y_{ij} = \frac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)} \qquad (2)$$

where x_i was the data. x_{ij} was the data under indicator j . y_{ij} was the normalized data. The information entropy of these data was then calculated using equation 3.

$$p_{ij} = y_{ij} / \sum_{i=1}^{n} y_{ij} \qquad (3)$$

where p_{ij} was the information entropy. The indicator's entropy was calculated by equation 4.

$$H_j = -[1/\ln(n)]\sum_{i=1}^{n} p_{ij} \ln p_{ij} \qquad (4)$$

where H_j was the entropy value under indicator j . The weight coefficient was eventually represented by equation 5.

$$B_j = (1 - H_j) / \sum_{i=1}^{n} H_j \qquad (5)$$

where, if the information entropy was 0, the entropy was also 0. The evaluation indicators in ADP planning had characteristics of mutual constraints and connections. A single EWM could not solve such complex problems. Therefore, EWM was combined with AHP for comprehensive evaluation. Firstly, the indicator's weight was calculated and expressed using equation 6.

$$W_j = \sqrt[n]{\prod_{j=1}^{n} U_{aj}} \qquad (6)$$

where U_{aj} was the a th data under indicator j in the matrix. Then, the maximum eigenvalue was calculated using equation 7.

$$\lambda_{\max} = \frac{1}{n}\sum_{j=1}^{n}\frac{(AW)_j}{W_j} \qquad (7)$$

where A was the judgment matrix. Finally, the indicator's entropy was standardized and represented by equation 8.

$$\omega_j = W_j / \sum_{j=1}^{n} W_j \qquad (8)$$

where ω_j was the standardized weight of indicator j . After the calculation, the weight coefficients of EWM-AHP could be obtained. Then, the comprehensive weight of EWM-AHP could be calculated according to equation 9.

$$Z_j = \omega_j B_j / \sum_{j=1}^{n} \omega_j B_j \qquad (9)$$

The comprehensive score of the evaluation indicators was further calculated using equation 10.

$$K = Z_{1j}\omega_1 + Z_{2j}\omega_2 + ... + Z_{nj}\omega_n \qquad (10)$$

The comprehensive evaluation scores of different indicators were finally obtained

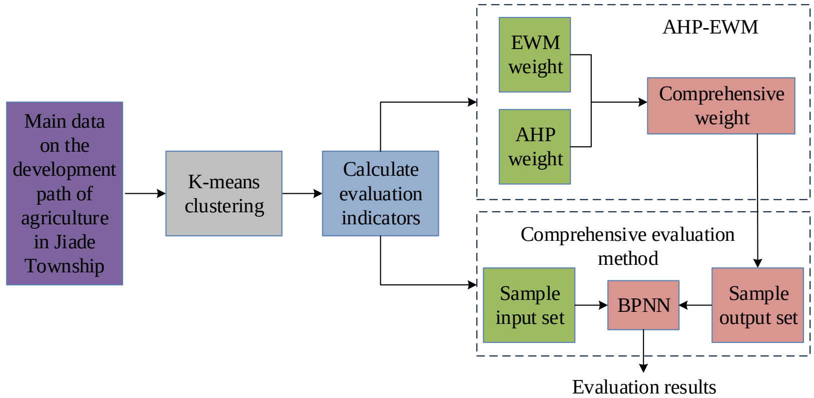

Figure 5. The process of calculating comprehensive weights.

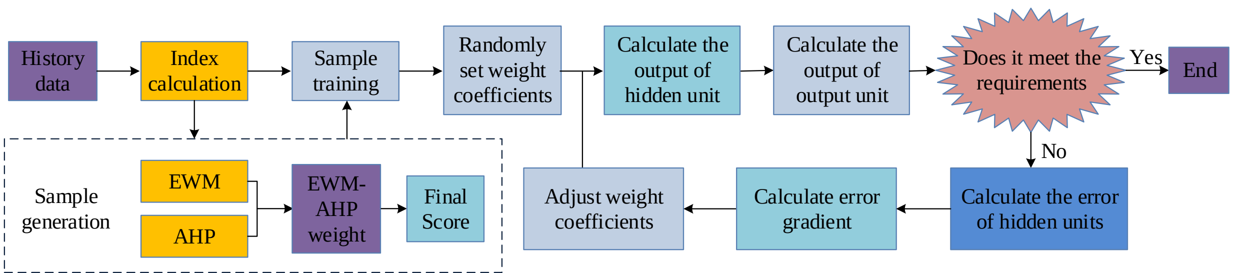

Figure 6. Sample generation and training of combination evaluation method.

through the above equations, which could be used for level classification and as training samples for BPNN after obtaining the comprehensive evaluation results of EWM-AHP (Figure 5). The combined EWM-AHP and BPNN comprehensive evaluation method showed that clustering analysis was first performed on the AD data of Jiade Township to obtain different data categories. Then, 9 evaluation indicators were obtained after calculation, which were weighted using the comprehensive evaluation method EWM-AHP to obtain the comprehensive score of the indicators. These scoring results were input into BPNN for training to obtain the final evaluation results. BPNN mainly consisted of three structures including input, implicit, and output layers, which required certain activation conditions and were represented by equation 11.

$$f(x) = \frac{1}{1+e^{-x}} \qquad (11)$$

where e referred to error. The nodes quantity in the input and output layers was determined by the properties of the function itself. The hidden layer had a difference, which was determined by equation 12.

$$S = \sqrt{m+n} + \alpha \qquad (12)$$

where m, n were the nodes numbers in the input and output layers. α was a constant. The loss function was used to evaluate whether the predicted and true values of a model were consistent. The small value indicated good robustness of the model. The loss function of BPNN was shown in equation 13.

$$E = \frac{1}{C}\sum_{c=1}^{C} e_c^2 \qquad (13)$$

where c was the number of neuron nodes. The weights of the parameters were revised based on

Table 1. Weights of nine indicators.

Target layer	Criterion layer	Indicator layer	Weight	Directivity
Agricultural development(A1)	Overall development of agriculture(B1)	Total agricultural output value(C1)	0.1751	+
		Per capita agricultural output value(C2)	0.1468	+
	Development of circular economy(B2)	The proportion of circular economy(C3)	0.1197	+
		Total output value of circular economy(C4)	0.1223	+
	Water resources utilization(B3)	Water demand ratio of planting industry(C5)	0.0617	-
		The proportion of water demand for circular economy(C6)	0.0711	+
		Comprehensive water use efficiency(C7)	0.0707	+
	Ecological effects of water resources(B4)	Per capita mining output of water resources(C8)	0.1154	+
		Per region mining output of water resources(C9)	0.1172	+

the obtained loss function. The amount of weight adjustment was shown in equation 14.

$$\mathrm{V}W_{bc} = -\eta \frac{\partial E}{\partial W_{bc}} \tag{14}$$

where η was the learning rate. W_{bc} was the weight of parameter. $\frac{\partial E}{\partial W}$ was the weight adjustment's gradient. The adjusted weight was represented by equation 15.

$$W_{bc}(n+1) = W_{bc}(n) + \mathrm{V}W_{bc} \tag{15}$$

The comprehensive evaluation model was trained in BPNN after parameter calculation and adjustment. Figure 6 demonstrated the sample generation and training.

Simulation study

The dynamic model of the Jiade Township system was constructed using Vensim DSS simulation software (Ventana Systems, Inc., Harvard, MA, USA). A simulation study was conducted on the real socio-economic system using SDM. The data were obtained from the government documents from 2010 to 2022 including statistical yearbooks of Linfen City and Yaodu District, Linfen Water Conservancy Bulletin, city chronicles, and on-site research materials. The simulation time for SDM was set from 2020 to 2040.

Validation of model effectiveness

The effectiveness of the model was validated using agricultural gross domestic product and population. Further, Receiver Operating Characteristic (ROC) curves were introduced to further validate the effectiveness of the design model. The Area Under Curve (AUC) was calculated using sensitivity and specificity indicators, which reflected the quality of model performance. Meanwhile, EWM-AHP-BPNN, EWM, AHP, and the technique for order of preference by similarity to ideal solution (TOPSIS) models were compared to verify the superiority of the designed method [21, 22].

Results

Simulation of agricultural development path planning based on system dynamics models

Nine evaluation indicators were selected in this study included gross agricultural output value, per capita water resources mining output, circular economy water demand ratio, and per capita agricultural output value, *etc*., which were used to measure the AD status, environmental impact, and water resource utilization efficiency in Jiade Township. The weights of these

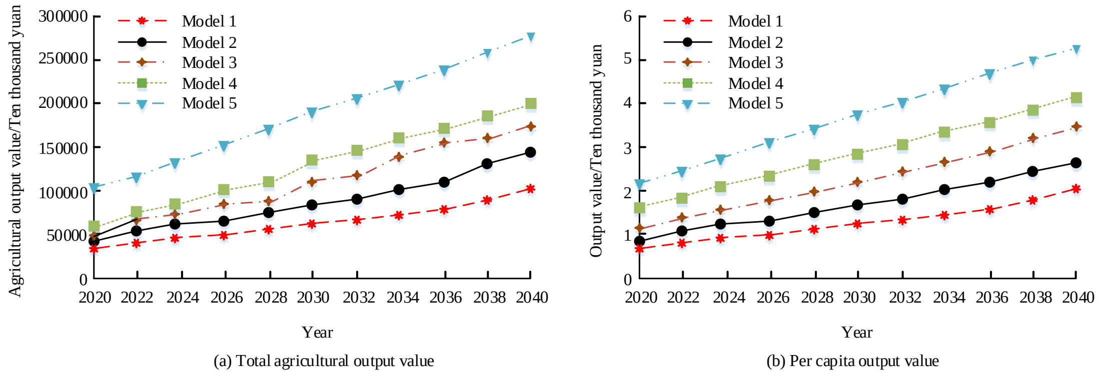

Figure 7. Total agricultural output value and per capita output value under five different paths.

Table 2. Comprehensive evaluation of agricultural development under five pathways.

Development path	Model 1	Model 2	Model 3	Model 4	Model 5
2020	0.2166	0.2217	0.2261	0.2238	0.2222
2021	0.2220	0.2308	0.2346	0.2343	0.2348
2022	0.2277	0.2404	0.2440	0.2457	0.2484
2023	0.2337	0.2506	0.2541	0.2582	0.2630
2024	0.2401	0.2613	0.2651	0.2713	0.2785
2025	0.2470	0.2727	0.2769	0.2855	0.2952
2026	0.2542	0.2849	0.2897	0.3005	0.3126
2027	0.2698	0.3111	0.3180	0.3336	0.3513
2028	0.2783	0.3252	0.3336	0.3517	0.3723
2029	0.2868	0.3401	0.3503	0.3707	0.3944
2030	0.2959	0.3557	0.3679	0.3909	0.4176
2031	0.3055	0.3721	0.3865	0.4121	0.4421
2032	0.3153	0.3894	0.4062	0.4343	0.4676
2033	0.3255	0.4075	0.4270	0.4576	0.4946
2034	0.3361	0.4264	0.4487	0.4822	0.5224
2035	0.3470	0.4459	0.4716	0.5079	0.5518
2036	0.3582	0.4667	0.4955	0.5346	0.5824
2037	0.3700	0.4878	0.5208	0.5625	0.6143
2038	0.3820	0.5101	0.5470	0.5918	0.6476
2039	0.3944	0.5332	0.5744	0.6220	0.6822
2040	0.4071	0.5570	0.6030	0.6536	0.7181

indicators were calculated using EWM-AHP-BPNN method (Table 1). The indicator with the highest value of 0.1751 was the total agricultural output value followed by 0.1468 of the per capita agricultural output value. The results confirmed that these two indicators had the greatest impact on AD in Jiade Township. Five different AD modes were obtained through simulation analysis. The development of Jiade Township belonged to the traditional development model, mainly focusing on agricultural production (Model 1). The traditional sources of cultivation were wheat and corn. Agricultural production was carried out through methods such as straw burning and flood irrigation. The primary circular development model followed the principles of primary to advanced, reuse, resource utilization, recycling, and reduction (Model 2). The

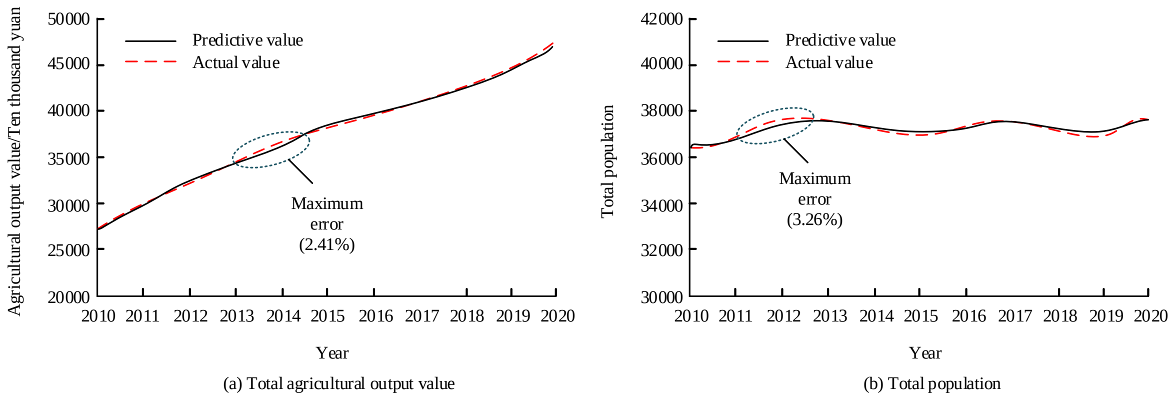

Figure 8. Error tests of agricultural gross domestic product and population.

intermediate circular development model was to convert agricultural production waste into energy on a primary basis, thereby improving production efficiency and extending the industrial chain (Model 3). The model of circular industrial parks was adopted to transform farmers into workers and improve management efficiency in advanced circular development (Model 4). This approach could effectively improve the quality of agricultural products and facilitate large-scale operations. The circular development model was a combination of traditional and circular AD models in agricultural production under the guidance of the circular economy theory in Jiade Township (Model 5), which was closer to the reality of AD and had a higher possibility of implementation. The simulation results of total agricultural output value and per capita agricultural output under different development paths were shown in Figure 7. The results showed that both indicators increased over time. However, the fastest growth rate of Model 5 suggested the superiority of this development model. The weight results were then used to calculate the comprehensive evaluation score. The AD situation of Jiade Township was calculated under different development paths. The comprehensive evaluation results under five different development paths between 2020 and 2040 were increased (Table 2). The combination of traditional and cyclic AD mode (Model 5) had the highest comprehensive evaluation score. The comprehensive evaluation of Jiade Township reached 0.7181 in 2040 under this development model, which indicated that this development model had the best practical application effect in Jiade Township.

Validation of model effectiveness

The results showed that the predicted value of this designed model had a small error compared to the actual value (Figure 8). The maximum prediction error in agricultural gross domestic product was 2.41%, while the maximum error in population prediction was 3.26%. Therefore, the effectiveness of this model was high. The comparison results of different models showed that EWM-AHP-BPNN had the highest AUC of 0.798, which increased by 3.2%, 5.6%, and 7.8% compared to EWM, TOPSIS, and AHP (Figure 9).

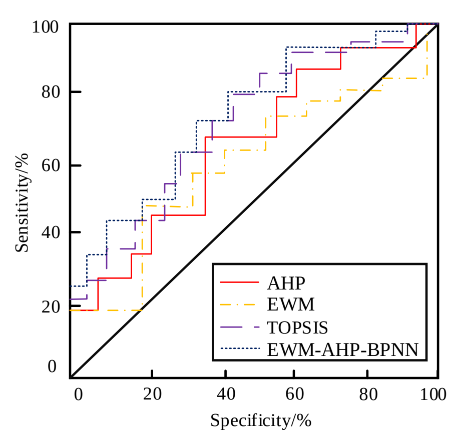

Figure 9. ROC curves of different models.

Discussion

The different ways of using agricultural land would bring different development outcomes. The use of agricultural land in the development of a circular economy would increase the production of aquaculture and planting industries, thereby increasing the total amount of circular economy. The use of agricultural land for ordinary aquaculture and planting industries would increase the demand for traditional agriculture. Agricultural development could be promoted by ignoring the use of land, while the AD strategy was beneficial for promoting cyclic AD, thereby weakening traditional AD. However, it should be noted that, when developing circular agriculture, the total production of grain, animal husbandry, and economic crops would decrease.

SDM can be used to study ADP under circular economy. The study of dynamical simulations of systems is characterized by synergy, wholeness, time-varying, and dynamical properties, which is often used in scientific research to study long-term, periodic, and conditional prediction problems. It is mostly suitable for complex socio-economic problems with low precision requirements and missing data such as the development path of circular agriculture in traditional agricultural areas studied in this research. The model proposed in this study was used to analyze AD in Jiade Township, Linfen City, Shanxi Province, China with the introduction of EWM-AHP and BPNN for method optimization to improve the accuracy of the model. The results demonstrated that the most important indicator affecting AD in Jiade Township was the total agricultural output with a weight of 0.1751 followed by the per capita agricultural output with a weight of 0.1468. The total agricultural output and per capita agricultural output of the five development paths all increased over time. However, the combination of traditional and cyclic AD models had the fastest growth rate. The comprehensive evaluation score of Jiade Township reached 0.7181 in 2040 under this development model. In addition, the maximum prediction errors of the designed model in agricultural gross domestic product and population prediction were 2.41% and 3.26%, respectively. The maximum AUC of EWM-AHP-BPNN was 0.798, which increased by 3.2%, 5.6%, and 7.8% compared to EWM, TOPSIS, and AHP models. The results confirmed that the designed model could provide an effective and accurate ADP and be used to design an appropriate development path for Jiade Township.

The results of this study confirmed that the designed model could provide an effective and accurate ADP. However, this study still has some limitations, which include that this model does not take into account the impact of variables such as population loss and price growth. Therefore, further analysis is needed. The choice of the development path of circular agriculture points out the development direction of regional agriculture for a certain period. However, how to implement the determined development path of circular agriculture in space is an important issue, which involves policy formulation for regional agriculture, selection and combination of development models for circular agriculture, willingness of farmers to develop circular agriculture, popularization of circular agriculture technology, and fundraising for circular agriculture. These issues require further research to effectively promote the implementation of the development path of circular agriculture. Therefore, further research on the implementation of the development path of circular agriculture will enhance the practicality of the development path of circular agriculture. This is also one of the important directions for future research on the development path of circular agriculture.

Acknowledgements

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